geoconvention
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September 21-23 2020
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Time-lapse Electrical Resistivity Imaging (ERI) reveals how rainfall, evapotranspiration, percolation and tile drainage affect soil moisture below a field of oats

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Summary

Time-lapse electrical resistivity imaging (ERI) is being used to investigate spatial and temporal changes in soil moisture associated with tile drains (TD) and diversion terraces (DT, i.e. earth berm and ditch) in sandy loam soils of the Saint John River Valley near Fredericton, NB. For fields under intensive agriculture use, a low permeability till substrate requires subsurface drainage (i.e. tile drains) to improve productivity. The effects of evapotranspiration, vertical percolation, and tile drainage on soil moisture content are illustrated here by time-lapse surveying over a two-week period spanning two intense rainfalls events in late summer, 2019. The effects of the tiles on the distribution of soil moisture were significant and were detectable as soon as the following day after an intense event.

Method

The main objective of this project is to assess the ability for time-lapse ERI to map changes in soil moisture caused by subsurface drainage laterally and with depth, over time. For this study, three trial plots (Figure 1) on a sloping field were established to investigate the effectiveness of their beneficial management practices (BMPs), including TD and DT. Field 1 has no BMPs implemented. Field 2 is subdivided into three subplots, each separated by a DT. Field 3 has the same berm and ditch layout as Field 2 and additionally two tile drains per subplot buried at a depth of approximately 90 cm. These fields are in a three year potato rotation (potatoes, barley or oats, and hay). For the first year, oats were planted and the field has not been fertilized.

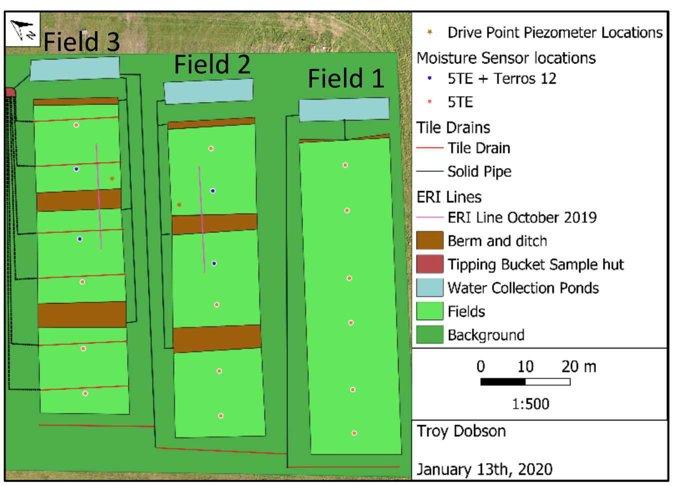

Figure 1. Fields at the Fredericton Development and Research Centre oriented downslope (northeasterly).

Two soil pits, excavated to a depth of 90 cm revealed that sediment texture, including the tillage layer, is predominantly sandy loam. Rees and Fahmy (1984) reported that the parent material for the uppermost layer was ablation till, which overlies more compacted lodgment till of relatively low permeability at ~1 meter depth, creating a perched water table in heavy rainfall conditions.

Two ERI survey lines, each consisting of 48 electrodes at 0.5 m spacing, and crossing over a DT structure, were set up in Fields 2 and 3, as shown in Figure 1. In Field 3, the line of electrodes also overlay two TDs. Surveys consisting of 1830 apparent resistivity measurements (including reciprocals) on each line were made autonomously at intervals of 4 to 12 hours using a low power (10 W) resistivity meter (Lippmann 4ptlight10w) with switching boxes, and a combination of dipole-dipole and Schlumberger arrays emphasizing lateral and vertical resolution respectively.

The data collected from the surveys were edited for reliability by filtering out measurements exhibiting poor repeatability or poor agreement with their reciprocal measurement. These filters typically removed less than 3% of the data from any survey. A smoothness-constrained time-lapse inversion algorithm (RES2DINV, by Geotomo Software) was chosen to invert the resistivity data. The goal was to create a model that would minimize the data misfit and model roughness in space according to L2 norms and through time using L1 norms. We emphasized horizontal smoothing over vertical (4:1) given that the shallow subsurface was predominantly horizontally layered. The L-Curve method was used to determine the optimum spatial and temporal damping factors (Loke et al., 2014). Using Archie's Law, the changes in resistivity obtained by time-lapse inversions were converted into changes in water saturation following the approach described under Additive Information below.

To measure field hydrogeological conditions, drive-point piezometers; and soil moisture, temperature and conductivity probes were installed. Drive-point piezometers screened at 1 m depth and equipped with Diver water level loggers were installed in each field in order to monitor perched water table conditions. The soil probes were installed near the tile drains, to monitor changes in temperature and soil moisture at two locations at 15, 40, 60 & 90 cm depth.

Results

A time-lapse series from Aug. 29th to Sept. 10th, 2019 while oats were growing shows the effects of water percolation, evapotranspiration and tile drains in response to two heavy rainfall events separated by 8 days (Figure 2). Spatiotemporal changes in saturation (inferred from changes in resistivity) are shown relative to conditions measured on Aug, 30th, 12 hours after the end of an intense 56 mm rainfall. Note that the colour scale shows positive desaturation or drying as warm colours (green to purple) and negative desaturation or wetting as cool colours (blues).

Before August 29th there had been no precipitation for a week, and only 25 mm in the preceding 2 weeks, with warm summer temperatures averaging 23°C. The desaturation image for Aug. 29th (Figure 2A) shows that the upper 30 - 80 cm of soil was up to 30% dryer than it was during the reference survey the next day(after 56 cm of rainfall).

The week following Aug. 30th (Figures 2B – 2E) shows drying of the shallow soil (<~50 cm depth) by percolation, evapotranspiration, and tile drainage. The effect of vertical percolation is evident in the region between ~0.5 and 1.5 m depth which was marginally wetter (mostly light blue, <2%) than the reference on Aug. 31st and up to 6% wetter (medium blue) on Sept. 3rd. The effect of the tile drains was clear five days after the August 29th rain (56 mm) with localized dryness above both tile drains. A second intense rainfall event (69 mm, from Hurricane Dorian) occurred late Sept. 7th and can be seen by the increase in the saturation throughout the profiles of 2F and 2G. The effects of the tile drains appeared faster after the second rain event (i.e. one day versus five days) possibly due to higher antecedent soil moisture conditions as evidenced by the soil moisture probes on Sept. 8th.

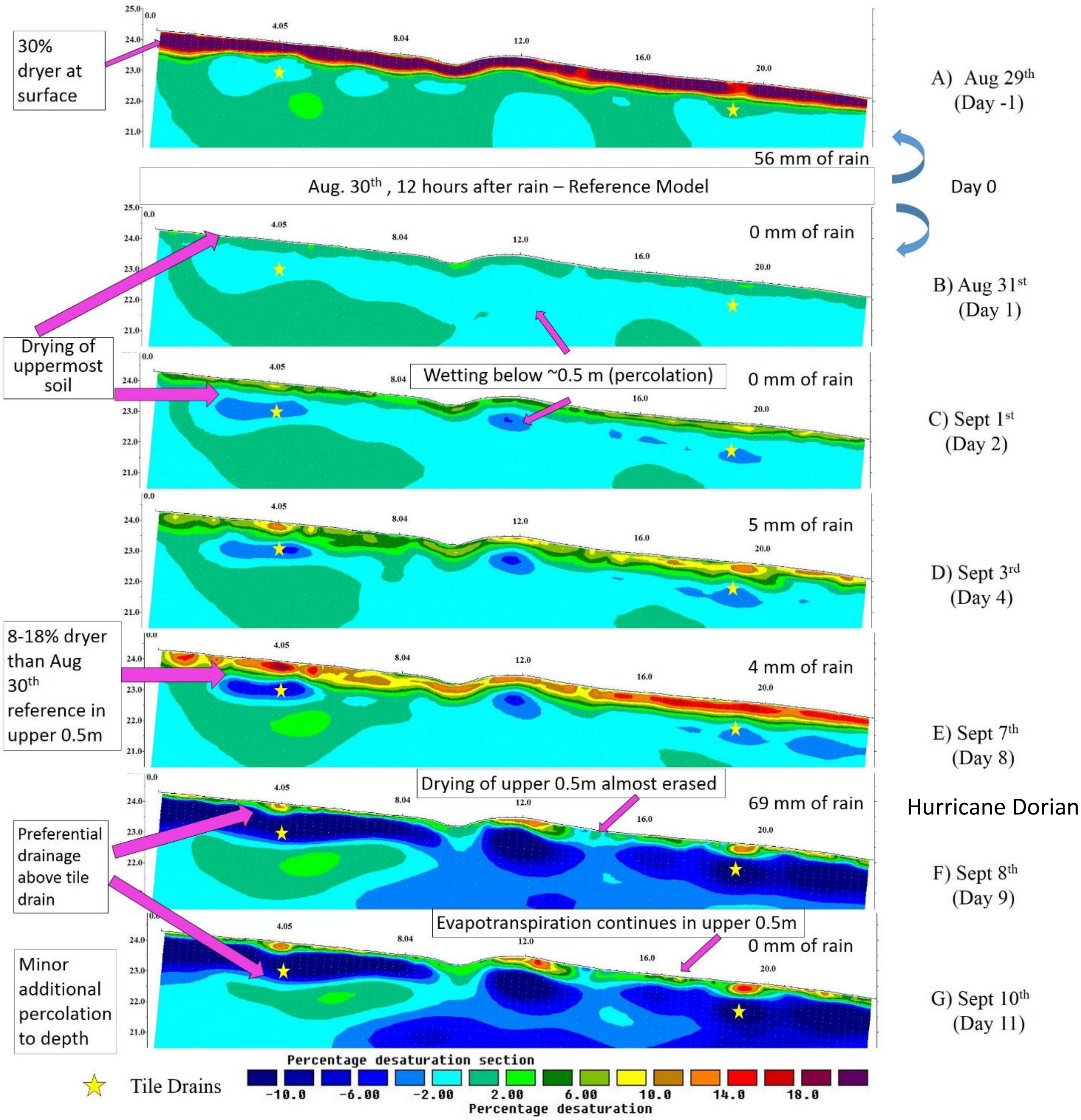

Figure 2. Time-lapse series displaying changes in desaturation in Field 3 using August 30th, 2019, as a reference. Tile drains (stars) are at a depth of 90 cm from surface.

Conclusion

A time-lapse series taken from August to September (2019) has shown promising results indicating that electrical resistivity surveys are capable of detecting changes in soil moisture caused by subsurface drainage, evapotranspiration and percolation. The results show drying throughout the first 30 to 80 cm of the entire profile with dryer spots above each tile drain and berm. After the second rain event of Sept 7th, the soil around the tile drains exhibits preferential drainage (I.e. a cone of depression feature). Future work will consist of ground-truthing the changes in soil moisture estimated by ERI with hydrogeological methods and examining more time-lapse series. An important monitoring period will be the spring snow melt where the soil moisture will near full saturation. Tile drain effluent will be observed using tipping buckets and more detailed monitoring of the perched water table using piezometers will allow for a better understanding of the migration of the perched water.

Additive Information

Archie's Law (1) is an empirically derived equation relating the bulk resistivity of a porous rock or sediment ($\rho(S_W)$) to its porosity (ϕ),the fraction of its pore space that is filled with water (S_W), and the resistivity of the water occupying the pore space (ρ_w). There are also empirical coefficients determined by lab experiments (a,m and n); notably the only coefficient to our interest is the water saturation factor (n) and is often estimated to 2 (Keller and Frischknect, 1966). Archie's Law assumes that all current is conducted through the bulk pore fluid (i.e. assumes negligible surface conduction and hence negligible clay content):

$$\rho\,(S_W) = a*(\phi^{m})*(S_w^{-n})*\rho_w \qquad (1)$$

We can define the water saturation and the resistivity at any given point (ideally when the water saturation is thought to be very high) as Sw_0 and ρ_0:

$$\rho_0 = a*(\phi^{-m})*(S_{w0}^{-n})*\rho_w \qquad (2)$$

The porosity and pore water resistivity are assumed to be invariable to compare the relative change in saturation from two resistivity measurements over the same region through time.

$$\frac{\rho_0}{\rho(S_w)} = \frac{S_{w0}^{-n}}{S_w^{-n}} = \frac{S_w^n}{S_{w0}^n} \qquad (3)$$

Assuming a "n" value of 2, we obtain the following expression for the soil saturation ratio:

$$\frac{SW}{SW_0} = \sqrt{\frac{\rho_0}{\rho(SW)}} \quad . \qquad (4)$$

To determine desaturation (D) between two measurements the relative saturation change is substracted from 1.

$$D = 1 - \frac{SW}{SW_0} \tag{5}$$

The results from a time lapse is given by desaturation. To determine the saturation of a future measurement rearranging equation 5 for:

$$Sw = (1-D)*SW_0 \quad . \tag{6}$$

For the purpose of a desaturating time lapse series, the reference resistivity model should contain the highest recorded saturation value (I.e. a SW_0 nearing 1) at every data point. Each successive model should then show a continuous drying of the subsurface.

Acknowledgements

We Thank Sheldon Hann and Patrick Toner for their expertise in soil classification. We also thank Daniel Boulay (UNB), Mona Levesque (FRDC), and Yulia Kupriyanovich (FRDC) who have put many hours helping in the field. This study was funded by AAFC through project “Landscape Integrated Soil and Water Conservation (LISWC) on sloping fields under potato production in Atlantic Canada”.

References

Keller G.V. and Frischknecht F.C.,1966. Electrical methods in geophysical prospecting. Pergamon Press Inc., Oxford.

Loke M.H., Dahlin T. and Rucker D.F. 2014. Smoothness-constrained time-lapse inversion of data from 3-D resistivity surveys. Near Surface Geophysics 12, 5-24.

Rees, H.W., and Fahmy S.H. (1984). Soils of the Agriculture Canada Research Station Fredericton, N.B. LRRI Research Branch Agriculture Canada.