Indirect Measuring of Soil Conductivity for the Calculation of Pore Water Salinity in Tidal Marshes

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Zack Laforet
Project Advisor: Dr. Gregg Moore
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Abstract
Indirect measurement of soil conductivity in agricultural soils is well established but has yet to be established in tidal marshes. Tidal Marsh combines three soil properties that affect conductivity: clay; water content; salinity. The EM38 instrument was previously used to map salinity of the tidal marsh and found areas with conductivity higher than salinity values, measured with a refractometer, produce. A model and laboratory experiments were designed to find the reason behind the high conductivity values. Data showed presences of conductive clay minerals in the sediment. Also an iron sulfate was found in the sediment and could also lead to increased conductivity. Further studies and laboratory experiments need to be conducted to better calibrate model of tidal marsh.

Introduction
Conductivity values of soils are measured indirectly through the use of electromagnetism. Indirect measurement of conductivity for soils is commonly used in agriculture to create soil maps and measure salinity levels in the soil but in recent years has been applied to tidal marshes. Tidal marsh conductivity values are not well documented due to its relative recentness compared to other applications of indirect measuring. The tidal marsh environment adds together several new physical traits that affect conductivity values such as the addition of high clay and water content in the soil. The field locality is the Great Bay Estuary in Dover, New Hampshire. The reason for the locality is to help Dr. Gregg Moore of the University of New Hampshire map areas in danger of Phragmites invasion based on salinity values.

To measure values of conductivity indirectly electromagnetic induction is used. Electromagnetic induction is the generation of a current in a closed circuit by oscillating the magnetic flux interacting with the circuit. This property of electromagnetism is used in transformers and electric motors. Also running an oscillating current through a coil of wire creates a magnetic field. When implemented in instruments meant for measurement conductivity a solenoid (coil of conducting wire) is used to generate the changing magnetic field by running an alternating current through the coil of wire generating a primary magnetic field. The primary magnetic field then generates a current in the ground which in turns creates an induced magnetic field that is read along with the primary field by a receiver found at the end of the instrument (see Figure 1). The instruments onboard software subtracts the primary field from the measured field to calculate the induced field that is then used to calculate the bulk conductivity of the soil.
The value of bulk conductivity is controlled by pore water concentrations, clay content, and water content of the soil.

**Figure 2(Diagram of EM38 in Operation)** (Robinson, Lebron and Lesch)

Tidal marshes are marshes found along the coast. They contain water salinities ranging from saline, brackish, to freshwater. The flooding and general water content of the marsh is controlled by the movements of the tide. The substrate is generally composed mainly of silt, clay and fine sand. These physical traits of a tidal marsh greatly affect the conductivity values of the soil. The changes in salinity greatly change the electrolyte concentrations of the pore water in the soil. The changes in concentrations of electrolytes influence the conductivity of the soil by increasing it with higher concentrations and lowering it with lower concentrations. Clay is mainly composed of clay minerals. Clay minerals, which are abundant in tidal marshes, increase conductivity by introducing more ions to the pore water and producing their own current. The current produced by clay minerals is called surface conductivity and will be explained further in the theory section. Water content alters conductivity indirectly and directly. Saturation levels indirectly affect conductivity by influencing the value of surface conductivity produced by clay minerals. All these contributions to bulk conductivity make it difficult to isolate influence of one trait over another.

Dr. Moore used conductivity to create a salinity map of the Great Bay Estuary to show areas in danger of *Phragmites* invasion. He used the EM38, an electromagnetic induction instrument created by GEONICS LIMITED (Figure 2). The instrument is 1m long and can penetrate a 1.5m into the ground. The operating frequency of the magnetic field is 14.6 KHz (GEONICS LIMITED). The reasons behind using the EM38 over a refractometer or direct conductivity instrument were mobility of the instrument and size of the tidal marsh. A refractometer was still used to check accuracy of the collected data. The easy mobility allowed for a larger area of the tidal marsh to be covered in a quicker time. Also, to collect data with a refractometer, pore water had to be extracted through the use of tubes and pipettes that got clogged on a regular basis. The EM38 did not have problems collecting data since it did not need to be in direct contact with the ground. The data collected by both EM38 and refractometer were compared in the end to test accuracy and presented a problem.
The Data collected by both instruments did not correlate as expected. When the salinity measured by the refractometer was compared to the bulk conductivity value measured by the EM38 a natural log regression appeared (Figure 3). The problem with the natural log regression is conductivity should increase linearly with increased salinity values. The data should the conductivity increased quicker than the salinity. The increased values of conductivity are believed to be caused by the presence of clay minerals and high water content in the soils. To test the hypothesis laboratory experiments and a model were devised.

**Figure 3 (Measured Conductivity vs. Measured Salinity) (Moore, Burdick and Peter)**

**Theory**

There are three key properties to soil conductivity that help in the understanding and modeling of soil conductivity. The first being the conductivities of pore water, $\sigma_w$, and clay minerals (surface conductivity), $\sigma_s$, are oriented in parallel as part of the bulk conductivity, $\sigma_a$. To prove that the conductivity is comprised of two conductors in parallel Rhoades, Raats and
Prather (1976) drove the proof using a variety of electrical and hydrodynamic laws and equations. The final equation, Equation 1, showed that \( \sigma_a \) was dependent on the addition of \( \sigma_s \) and \( \sigma_w \). The equation also contained a water content, \( \theta \), and a transmission coefficient \( T \).

**Equation 1:** \( \sigma_a = \sigma_w \theta T + \sigma_s \)

If you take equation and break up it up based on what is getting added you get two independent terms. The first term, \( \sigma_w \theta T \), is independent of \( \sigma_s \). Since \( \sigma_s \) is independent of the first term then \( \sigma_s \) is independent of the saturation level of the soil. The transmission coefficient \( T \) accounted for the slowing down of ions near the liquid-solid and liquid gas boundaries in the soil. Also \( T \) took into account the complex path of the liquid through the soil. \( T \) is comprised of two empirical constants, \( \alpha \) and \( \beta \), based off of soil texture and water content, \( \theta \), (Equation 2).

**Equation 2:** \( T = \alpha \theta + \beta \)

The second principle is surface conductivity, \( \sigma_s \). Surface conductivity is the conductivity of the water layer surrounding the clay particle. The reason behind the conductivity in clay particles is they possess a negatively charged surface. The negative charged surface is due to the imperfections in the microcrystalline structure. Clay minerals have a large collection of cations on the surface due to the sheet like structure that provides a large surface area to volume. When a current is applied to a soil, clay cations move along the clay particle in the diffuse double layer (Mojid, Rose and Wyseure, A Model Incorporating the Diffuse Double Layer to Predict the Electrical Conductivity of Bulk Soil). The diffuse double layer is a thin layer of water coating the particle. The conductivity value is dependent on the type of clay mineral in the soil since they each have their own cation exchange capacity (McNeill).

Pore water conductivity, \( \sigma_w \), is the third principle. The conductivity of pore water is based on the concentration of ions in solution and the mobility of the ions, shown in equation 3 (McNeill).

**Equation 3:** \( \sigma_w = 96500 \sum C_i M_i \)

\( C_i \) is the number of grams equivalent weights of \( i^{th} \) ion per \( 10^6 \) cm\(^3\) of water. \( M_i \) is the mobility of \( i^{th} \) ion in m\(^2\)/sec \( \times \) V. The equation shows that with each ion concentration’s conductivity is independent from each other. An example is the addition of NaCl yields two ions, Na\(^+\) and Cl\(^-\), each ion concentration has its own conductivity value. Pore water conductance is also dependent on temperature, \( t \), as shown in Equation 4 (McNeill).

**Equation 4:** \( \sigma_w (t) = \sigma_w (25\,^\circ C)[1+\gamma(t-25\,^\circ C)] \)
For Equation 4 to work the conductivity at 25°C and the temperature coefficient, \( \gamma \), for the ion must be known. The temperature coefficient for NaCl is 0.022. The equation implies that with one change in degree the conductivity is increased by 2.2% (McNeill).

**Methods**

The mesocosm experiments take place in a 12.3825 m\(^3\) fiberglass tank. The tank is outside of the Jackson Estuarine Laboratory in Durham, New Hampshire (USA) (43° 5.53’N, 70° 51.85’W). The tank is filled with 9.906 m\(^3\) of freshwater. The tank will then have its salinity checked to be zero by refractometer. The YSI probe will also check that the salinity is zero and record a direct conductivity for a salinity of zero. The EM38 will then also take a measurement of the indirect conductivity of the freshwater to set a value for zero salinity. Measurements of zero salinity will be taken five times to give a better base value for conductivity. The tank will then have sea salt added to it to raise its salinity by 5 parts per thousand. The tank will then have its salinity checked and recorded by a refractometer. An YSI probe will then measure and record the salinity and direct conductivity of the tank. The probe will be washed with deionized water between all measurements. The EM38 will then measure the indirect conductivity for the tank. Measurements for each salinity level will be taken five times by the refractometer, YSI probe. Measurements of conductivity at each salinity level will be taken five times by the YSI probe and EM38. The salinity will be raised in the tank by 5ppt after every fifth measurement. The max salinity will be 35ppt, the same as mean ocean salinity.

The sediment experiment will take place in the same tank. To measure the salinity and conductivity of the sediment body the same steps taken in the mesocosm will be applied. The refractometer will use a pipette to collect a water sample from the sediment. The YSI probe will be washed between each measurement like in the mesocosm. The sediment body will be collected from the Great Bay Estuary. A portion will be sieved to gather particle size make up of the sediment. X-ray diffraction will be performed on the sediment to find the mineral make up of the sediment.

To analyze the data all measurements of salinity and conductivities will be averaged for each salinity level to give a better representation of actual salinity and conductivity values at the examined salinity level. The analysis of collected data will consist of regressions comparing direct conductivity to indirect conductivity, salinity to both direct and indirect conductivity. Each regression will contain both water only and sediment data on them to examine the difference.

The Model of tidal marsh conductivity will be based of Equation 1 and contain Equations 2-4 with in it. The Model will be a MATLAB function that plots out the salinity versus bulk conductivity. The inputs will be water content, \( \theta \), and t, temperature. The constants will be \( \alpha \), \( \beta \), \( \gamma \), \( M_i \) and \( \sigma_s \). The constants \( \alpha \), \( \beta \), and \( \sigma_s \) will be found empirically from the mesocosm and sediment experiments. The constant \( M_i \) will be taken from McNeill for the value of NaCl. \( \gamma \) will be a constant also taken from McNeill at .022. The model will then be compared to field data collected to test accuracy.
Results

The X-ray diffraction (XRD) showed the sediment was made up of quartz, albite (plagioclase feldspar), roemerite (iron sulfate), illite (clay mineral), and chlorite (clay mineral) (figure 4). The XRD was taken at 40mV and 30mA from a 2θ of 5° to 32°.

Discussion

The XRD showed that there were two conductive clay minerals, illite and chlorite, and an iron sulfate that is soluble in water. The two clay minerals are common for New England. Illite is made from the physical and chemical breakdown of white micas such as muscovite. Chlorite is the chemical breakdown of mafic minerals such as biotite and amphibole. Both minerals have the same cation exchange capacity of 10 to 40 m-equiv/100g (McNeill). With the same cation exchange rate the surface conductivity should be relatively similar. If there is a difference between surface conductivity it will be due to differences in particle surface area and shape. Iron sulfate was believed to be a biological input from the microbes living in the anoxic black mud. The iron sulfate can also have a possible affect on conductivity since the molecule is soluble in

Figure 4(XRD plot of 2θ vs. counts/sec)
water and iron is very conductive. More test focusing on the role iron sulfate has on soil conductivity would help in determining how much of a role it plays.

The mesocosm and sediment experiment were not carried out due to lack of time and weather. The experiments needed to happen on days with temperatures relatively close and no precipitation. The precipitation would have thrown off the water content and salinity values through the introduction of fresh rainwater. Also further research showed that they would have been lack luster in deriving the constants $\alpha$, $\beta$, and $\sigma_s$. The sediment experiment would have still yielded a value for the constants but the constants would have been statistically weak. Too make up for the lack of data another control experiment that could be done indoor was designed for future work.

The laboratory experiment would give the values of $\alpha$, $\beta$, and $\sigma_s$ for the soil body found in the Great Bay Estuary. The control experiment is similar in design to the one found in Rhoades et al. (1976). They used a direct conductivity probe on sediment cores and a pressure membrane apparatus to keep constant water content. The control I designed would consist of a small glass fish tank with two opposite walls removed and each replaced with a sheet of copper to act as electrodes. Two electrodes connected to a voltmeter would be spaced evenly inline with the copper walls. The tank’s top and bottom would have a pressure membrane consisting of a plastic wrap and a vacuum to keep water content constant. Sediment from the Great Bay Estuary would be collected and placed in the tank. To remove pore water all ready in the sediment, deionized water would be used leach the soil clean. Solutions with known concentrations would be added at various water content levels. For each solution, conductivity data would be taken at 5 water content levels, 0.1-1.0 at .1 intervals. Then following the methods in Rhoades et al. (1976) the values $\alpha$, $\beta$, and $\sigma_s$ would be extrapolate and calculate from the data. These values would then be entered into the model to give a more accurate graph of salinity versus bulk conductivity.

Conclusion

With further experimentation similar to Rhoades et al. (1976) an accurate model of a tidal marsh can be produced. The model may still have inaccuracies due to the lack of information on the affects of iron sulfate in the sediment. Another possible inaccuracy would be the movement of the sediment sample would change the “field setting” of the sediment which would alter properties such as porosity and compaction. These properties have a slight impact on bulk conductivity values. To truly create an accurate model a better understanding of physical characteristics of the sediment and clay minerals contained within the sediment must be studied.

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**Bibliography**


