Intro

**PART I: Context of work**

Salts in the environment can be useful for humans, but detrimental to natural water systems. Various chloride and acetate salts are used for winter road salting, and nitrate and phosphate salts are extremely important as fertilizers for agriculture.

According to 2008 paper published by the St. Anthony Falls Laboratory at the University of Minnesota, the Twin Cities Metropolitan Area sees more than 317,000 tons of road salt applied to roads every year (Novotny, Murphy, & Stefan, 2008). While road salt is absolutely necessary to maintain road safety during Minnesota’s harsh winters, problems can arise when salt left over from the winter washes into watersheds during the spring melt. For lakes associated with urban areas, this additional salt may seriously disturb lake and river ecosystems; in some cases, salt concentrations may be high enough to force stratification of the water column, thus preventing the turnover which would usually bring oxygen to the bottom of the lake (Novotny et al., 2008).

Similarly, runoff of fertilizers from agricultural fields or stockyards can have negative effects on natural water systems. In fact, the most common impairment of surface waters in the United States is eutrophication caused by nitrogen and phosphorus pollution from nonpoint (usually agricultural) sources (Carpenter et al., 1998). Eutrophication can completely devastate a lake or river ecosystem; the algal bloom that frequently accompanies eutrophication consumes nutrients, decreases dissolved oxygen in the water and may cause fish kills. Toxins (such as microcystin) produced by cyanobacteria in a bloom may produce water treatment problems and cause water to be unsuitable for drinking and recreation.

Fortunately, much research is being done to find solutions to the problems caused by human-applied environmental salts. A quick search for “solutions to nonpoint source pollution” on Google Scholar reveals hundreds of highly-cited papers tackling the problem, with suggested solutions ranging from new governmental policies and regulations to novel devices and methods for capturing or eliminating the pollution. However, there are significant challenges to implementing these solutions: policy and regulation requires some way to enforce compliance and discover noncompliance, and mitigation methods usually require a way to identify specific targets. Both of these needs are satisfied if it is possible to spatially locate the source of the pollution.

Unfortunately, nonpoint pollution is exactly that – “nonpoint,” that is, a specific source of the pollution is difficult to spatially locate. Sometimes the cause of this difficulty is because the source of the pollution lies over a large area, or perhaps the source is intermittent. In other cases, the source might move, or the pollution might only be detectible after it has moved far from its source.

Typical methods for measuring levels of salt-based pollutants in water systems usually include taking water conductivity measurements. These measurements have been traditionally taken by hand at one location at a time, using a water conductivity sensing system (US EPA, 2012). Because of the limitations intrinsic to taking measurements by hand at discrete points in both space and time, it is very hard to locate or measure/monitor pollution sources that vary over space and/or time. Thus, the obvious solution is to increase the distribution of the sensing system in order to keep up with the distribution of the pollution; if a nonpoint pollution source needs to be measured, perhaps a nonpoint sensing system should be used.

This “nonpoint” sensing system can take the shape of a distributed sensing network. In a network of this sort, many sensors are distributed over a wide area. These sensors all constantly take measurements over time, and the measurements taken together can be used to obtain an idea of the spatial distribution of the measurement parameter over time. In the case of water conductivity, this network could take the form of many independent conductivity sensors distributed over a water body or watershed, all recording measurements in parallel and transmitting the data back to a single base station. For example, if the task at hand is to monitor a nonpoint source polluting a lake, the sensor network could consist of many sensors installed along the shoreline of the lake. If the goal is to find a nonpoint source in a watershed consisting of rivers and streams, the network might consist of sensors placed at each major branch in the river or stream network. In all of these cases, the output would be data that can be used to create a spatial map of water conductivity as it varies over time.

The challenges in establishing a sensor network as opposed to the traditional by-hand method of taking measurements is twofold: it must be possible to deploy an appropriate number of sensors without prohibitively high cost, and without prohibitively high maintenance requirements. Thus, for conductivity sensors, the sensors must be cheap, resistant to fouling or corrosion, and not require maintenance. Of course, to be useful the sensors must also be accurate, easy to calibrate and install, and sensitive over the range of expected water conductivity.

Currently, commercially available conductivity sensors are poor candidates for application in a distributed sensing network.

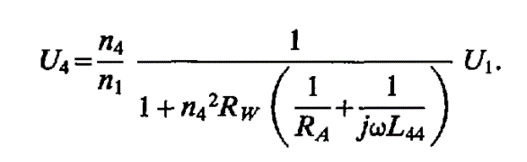
**PART II: Current state of the field**

Extant commercially available conductivity sensors come in two varieties: 1) direct-contact electrode resistance sensors and 2) magnetic induction conductivity sensors (Ramos, Pereira, Ramos, & Ribeiro, 2008). Both of these types of conductivity sensors have weaknesses that render them inappropriate for use in a distributed sensing network.

Direct-contact electrode type sensors are mechanically and electrically very simple. The sensor consists of 2 to 4 metallic electrodes that are kept submerged in the water to be measured. In 2 electrode sensors, a voltage is generated between the electrodes and the current flowing between the electrodes is measured. In 4 electrode sensors, two of the electrodes are used to generate a constant current, while the other two electrodes measured the voltage difference between them. Using Ohm’s Law:

which dictates the relationship of voltage (V) with current (I) and resistance (R), the resistance of the water can be found. Because conductivity is resistance over distance, conductivity of the water can be calculated by dividing the resistance by the distance between the electrodes (Ramos et al., 2008).

While direct-contact type sensors have advantages mostly stemming from their mechanical and electrical simplicity, they have serious deficiencies in monetary and maintenance costs. Metal supporting an electrical charge in direct contact with water experiences various electrochemical effects, which can lead to corrosion, fouling, or other types of deterioration. To avoid these issues, high end direct-contact sensors (such as those used by most research institutions) use platinum wire for their electrodes. Although platinum has excellent anti-corrosion properties, it has fairly poor pecuniary properties. Low end direct-contact sensors forgo precious metals for stainless or high-nickel steels, but these metals are not completely impervious to electrochemical effects and must be recalibrated (and eventually replaced) regularly. Both low and high end direct-contact sensors are vulnerable to fouling from biological and mechanical sources such as algae growth or sediment deposition.

Magnetic induction sensors are far more resistant to fouling but are much more electrically complex. These sensors consist of two mechanically parallel coils of wire (usually coiled around a core) separated by a set distance. A sinusoidally varying voltage is applied across one coil, and the current flowing through this coil results in a magnetic field perpendicular to the plane of the coil. This magnetic field induces a measurable voltage in the second coil through the principle of magnetic induction. The efficiency of this magnetic coupling between the two coils is related to the conductivity of the medium between the coils because the water *also* appears as a coil to the magnetic field and will steal some of the energy from the field (Wuliang Yin, Peyton, Zysko, & Denno, 2008). As the water conductivity increases, more of the magnetic field energy goes into inducing a voltage in the water, and proportionally less voltage appears on the second coil. This relationship is quantified by the following formula:

where U4 is the voltage on the second coil, Rw is the resistance of the water, U1 is the voltage on the first coil, n4 is the number of windings on the second coil, n1 is the number of windings on the first coil, RA is the resistance of a resistor used to terminate the second coil, L44 is the combined inductance of the two coils, j is the square root of -1, and ω is 2π multiplied by the frequency of the sinusoidal voltage applied to the first coil (Striggow & Dankert, 1985). Again, once the resistance of the water has been determined, conductivity can be calculated if the distance between the coils is known.

As can be seen, interpreting measurements from magnetic induction conductivity sensors is a much more complex affair compared to direct-contact sensors. However, because magnetic induction occurs without direct metallic contact, inductive sensors can be completely enclosed which greatly improves their resistance to corrosion and fouling compared to direct-contact sensors. Unfortunately, this improved ruggedness comes at the expense of sensitivity and power consumption. Inductive sensors have poor performance at low levels of water conductivity, and attempts to increasing sensitivity of these sensors involve either increasing the number of coil windings (which effects n1, n4, and L44), or increasing the supply voltage (U1). Both of these changes have the summary effect of vastly increasing power consumption to a degree such that magnetic induction sensors are only used for oceanographic purposes in seawater, which has a much higher nominal water conductivity than inland freshwater.

Thus, it can be seen that neither direct-contact type nor magnetic induction conductivity sensors are appropriate for the purposes of identifying nonpoint sources of salt-based pollution.

In this work, an attempt has been made to develop a third kind of sensor, based on the principle of capacitance. This sensor does not rely on direct contact of metals with water, but unlike the magnetic induction sensor this sensor retains usable sensitivity at the low end of the range of water conductivities normally encountered in freshwater studies and also does not have impractical power requirements. While there are a few cases of capacitive water sensors reported in the literature, these sensors sense only presence or absence of water and in some cases are used for water level (ie. Gauge) sensing (Reverter, Li, & Meijer, 2007). The development of the sensor reported in this work overcomes these and other limitations of currently available water sensors in order to produce a non-contact capacitance-based water conductivity sensor appropriate for use in a distributed sensor network application.