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Application of an Ultrasonic Sensor to Monitor Soil Erosion and Deposition

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APPLICATION OF AN ULTRASONIC SENSOR TO MONITOR SOIL EROSION AND DEPOSITION

by

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APPLICATION OF AN ULTRASONIC SENSOR TO MONITOR SOIL EROSION AND DEPOSITION

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University of Nebraska, 2020

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While erosion and deposition are naturally occurring processes, these processes can be accelerated by human influences. The acceleration of erosion causes damage to human assets and costs billions of dollars to mitigate. Monitoring erosion at high resolutions can provide researchers and managers the data necessary to help manage erosion. Current erosion monitoring methods tend to be invasive to the area, record low frequency measurements, have a narrow spatial range of measurement, or are very expensive. There is a need for an affordable monitoring system capable of monitoring erosion and deposition non-invasively at a high resolution. The objectives of this research were to (1) design and construct a non-invasive sediment monitoring system (SMS) using an ultrasonic sensor capable of monitoring erosion and deposition continuously, (2) test the system in the lab and field, (3) and determine the applications and limitations of the system. The ultrasonic sensor measures the time of reflectance of sound waves to calculate the distance to the area non-invasively. The SMS was tested in the lab to determine the extent to which the soil type, slope, surface topography, change in distance and vegetation impact the SMS's ultrasonic sensor's measurement. It was found that the soil type, slope and surface topography had little effect on the measurement, but the change in distance of the measurement and the introduction of vegetation impacted the measurement. The error in measurement increased as the sensing distance increased, and vegetation interferes with the measurement. In the field during high flows, as erosion and deposition occur, the changes in distance were determined in near real-time, allowing for the calculation of erosion and deposition quantities. The system was deployed to monitor deposition on sandy streambanks in the Nebraska Sandhills and erosion on a streambank and field plot in Lincoln, Nebraska. The system was proven successful in measuring sediment change during high flow events but yielded some error; ±1.06 mm in controlled lab settings and ±10.79 mm when subjected to environmental factors such as temperature, relative humidity and wind.

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CHAPTER 1: INTRODUCTION

Erosion and Deposition Background

Erosion and deposition are naturally occurring processes that occur along the banks of rivers and streams, constantly shaping the channel. They also occur in rangeland and agricultural fields. While erosion occurs in some degree across all landscapes, not all erosion occurs at the same rate. There are two types of erosion: geological erosion and accelerated erosion. Geological erosion occurs slowly overtime and is responsible for soil formation, distribution and topographical feature creation like stream channels. Accelerated erosion is human or animal induced by the removal of natural vegetation and leads to the breakdown of soil and accelerates the removal of organic and mineral particles (Schwab, Fangmeier, & Elliot, 1996). Erosion reduces the productivity of agricultural lands due to soil and nutrient loss. Agricultural practices accelerate the loss of nutrients and soil at a far greater rate than it can be replenished through natural processes (Amundson, et al., 2015). In order to maintain productive agricultural lands to feed the world’s growing population, extensive resources are spent to recuperate lost productivity from soil degradation and the subsequent polluting of waterways. Annually, $44 billion is spent in the U.S. on erosion damage and control (Pimentel, et al., 1995) and the more than $1 billion on stream restoration (Bernhardt, 2005). Incorporating conservation practices into agricultural production was reported to reduce soil loss in South America by as much as 16% and in North America by as much as 12.5% (Borrelli, et al., 2017).

In order to manage areas with erosion problems, it is important to understand the factors that influence erosion. The main factors that affect soil erosion are climate, soil type, vegetation and topography (Schwab, Fangmeier, & Elliot, 1996). Climatic factors that affect erosion are mainly precipitation and wind; the rainfall energy and intensity influence the amount of erosion seen in a runoff producing rainstorm and wind can transport finer soil particles and cause significant erosion with winds of 20 to 30 kilometers per hour (FAO, Soil erosion by wind, 1978) and (Department of Environment and Resource Management, 2011). The physical properties of the soil also influence erosion; soil structure, texture, density and water content. The detachment of soil particles tends to increase as soil particles become coarser, but the transport of the soil particle increases with finer particles (FAO, Soil Erosion by water, 1978). Basically, sand particles can detach easier because they are coarser and allow water to penetrate them easier, but smaller clay particles transport easier (once detached) because they are a finer particle. There are three important effects vegetation has on soil erosion (1) protection of soil surface from direct rainfall to reduce runoff, (2) reduction of soil movement due to rooting of the vegetation, and (3) plant transpiration reduces the water content of the soil and probability of runoff. The final factor affecting soil erosion is the topography of the area. The degree of slope, shape, length of slope and watershed area. Steeper slopes produce runoff that is more erosive and transports sediments downhill easier (Schwab, Fangmeier, & Elliot, 1996).

Water erosion can cause four different types of erosion: splash, sheet, rill and gully erosion. Splash erosion is caused by the direct impact of water droplets from rainfall or irrigation striking the soil surface and displacing and washing away soil particles. Sheet erosion occurs when runoff washes a layer of soil from an entire field/ slope area. Humans have a hard time perceiving splash and sheet erosion due to the fine scales with which they remove sediment. Rill and gully erosion are much more pronounced and visible forms of erosion. Rill erosion occurs when enough runoff moves across a surface to cause small channels to form. As rill erosion progresses, channels become deeper and ultimately leads to gully erosion. Gully erosion is one of the most destructive forms of erosion as the runoff tends to concentrate in the gullies and enhance erosion rates. Gullies generally continue to grow as sediment is lost from the side walls, unless control measures are implemented to reduce and prevent erosion (Carey, 2006). Gully erosion can be attributed to as much as 80% of the total sediment production in a watershed while only making up approximately 1-5% of the area (Poesen, Nachtergaele, Verstraeten, & Valentin, 2003). Water erosion models tend to only include sheet and rill erosion and not gully erosion (Poesen, 2017). Gully erosion models are limited due to the little knowledge surrounding how gullies start, develop and infill in different environments and how they interact with other hydrological processes like infiltration, drainage and recharge to groundwater (Poesen, 2011). There is also no standardized method to monitor gully erosion rates and there is a lack of quality data to calibrate and validate the few models that do attempt to model gully erosion (Poesen, 2017).

The management of erosion depends on accurate and reliable data. Data that is long-term, continuous, accurate, and reliable are essential to quantify the timing and amount of erosion. The management of erosion depends on accurate and reliable data. In some cases, erosion is measured qualitatively by visual observation of erosion and classified as either none, slight, moderate or severe (Lal, 1994). It is difficult to determine quantitative amounts of erosion from these classifications. Without proper or with inaccurate measured erosion quantities, models cannot be developed and validated to predict erosion amounts. Erosion models are useful for management and policy decisions to understand future impacts of erosion processes.

One model that is used frequently for modeling streambank erosion and retreat is the Bank Stability and Toe Erosion Model (BSTEM). There have been few studies done evaluating BSTEM against long-term streambank erosion data. Using long-term erosion data with the BSTEM model can help identify which parameters are the most important for estimating streambank erosion and retreat (Midgley, Fox, & Heeren, 2012). The use of long-term and high frequency erosion data would provide even greater input into which parameters are most important and help to solidify the timing of erosion during the streambank retreat process. While Midgley et al. (2012) was able to closely predict the timing of erosion events in their study, they did not use continuous data, so their measurements occurred days to weeks after high flow events leaving uncertainty in their predictions of timing. Continuous erosion data would allow for the reduction in uncertainty of the prediction of the timing and could help identify the controlling parameters around those events. Calibration and validation of models, like BSTEM, would also be enhanced from having long-term, large scale, and high frequency erosion data (Poesen, 2017). Accurate predictions of erosion are essential for natural resource managers so they can manage areas that are most at-risk from erosion like crop fields and streambanks.

BSTEM also has the capability to model different stabilization techniques, making it an important tool for the management of streambank erosion. BSTEM is a process-based method that has the potential to determine the bank response, predicts initial and final sediment loads and bank retreat rates, to erosion control measures and aids in the design of bank stabilization practices (Klavon, et al., 2017). While BSTEM can be used as an important tool for mitigating erosion problems, the model has limitations and could benefit from quality, long-term streambank erosion data to validate the model and enhance model processes. Enhancing the model would make is more broadly applicable and accessible to managers allowing for better streambank stabilization practices to be implemented.

Review of Erosion and Deposition Monitoring Methods

There are a variety of methods and devices used to measure sediment changes (i.e. soil erosion or deposition). One conventional method is bank pins, which are stakes that are inserted into the area of interest (AOI) in a gridded pattern and measured over time to document the total quantity of sediment change (Thorne, 1981). Another traditional method is surveying techniques, which is the repeated measurement or survey of the bank width to document the location of the bank and its retreat (erosion) over time (Lawler, 1993 and Thorne, 1981). A more modern technique is the use of Photo-electric erosion pins (PEEP) which uses photovoltaic cells in series to sense incident light and outputs a signal, recorded continuously, proportional to the amount of rod exposed (Lawler, 2001). While PEEPs are typically installed to monitor erosion, they are also capable of monitoring deposition as well. Other monitoring systems include LiDAR/Terrestrial Laser Scanning (TLS) and satellite or drone imagery. LiDAR uses laser pulses and the measured reflected pulse to calculate the distance from sensor to bank surface. The lasers are sometimes mounted on a pan-tilt motor so the bank can be scanned, and sediment changes calculated (Plenner, Eichinger, & Bettis, 2016 and Lague, Brodu, & Leroux, 2013). The analysis of images from earth orbiting satellites or UAVs

(Cook, 2017) can also provide information on bank retreat and sediment changes. While most methods are deployed to monitor erosion, each has the capability to monitor deposition as well, except for surveying techniques as these tend to just monitor bank retreat. Aerial imagery analysis is also limited on monitoring deposition but Cook (2017) was able to quantify certain amounts of deposition as well as erosion. The following review of literature analyzes these different monitoring methods' frequency of measurement, scale of measurement, invasiveness to the measurement area, and affordability.

Of the six erosion monitoring methods reviewed, only half of them record data at a high frequency, while the others only provide data as often as the user manually conducts the measurement. The bank pins, stream surveys and satellite/ drone imagery are limited in their ability to perform high frequency measurements. Bank pins and stream surveys are simple to use and give accurate measurements of the total quantity of soil lost or gained, but they are labor intensive as each measurement requires additional visits to the study site (Thorne, 198 and Lawler, 1993). Finally, analysis of aerial imagery from UAVs or satellite provide a slightly higher frequency than bank pins or surveys, but are still limited by the frequency in which images can be taken (Cook, 2017). Each of these methods result in erosion measurements at a low temporal resolution and are unable to provide the timing of the erosional event (rainstorm) that caused the erosion.

The photo-electric erosion pins (PEEP) and LiDAR/ TLS both provide high frequency measurements. While these methods provide data at a high frequency there is variability in the consistency of the measurements. PEEP devices only have a high frequency in measurement during the day as the device is unusable at night without incident light to indicate the amount of exposed pin (Lawler, 2001). While not restricted by time of day, the TLS lacks consistency with length of time being deployed in the field. According to Plenner et al. (2016) the TLS was unable to capture bank profiles immediately after storm events because it was only used during low flow. Also due to the cost of the equipment, the device was only used during certain times and not left to monitor the bank continuously. This reduces the frequency in measurement and leaves knowledge gaps of erosion-causing events.

Quantifying sediment change not only means having continuous and accurate data, but data that is measured from a large area to understand the dynamics of the bank movement. Conventional methods were classified into two types of measurements, point measurements and bank measurements. The bank pins and PEEP devices are point measurements because data is only measured at the point of the pin. The LiDAR/TLS and aerial imagery can measure the sediment change of the whole bank. The TLS was mounted on a pan-tilt motor to scan the entire bank to measure the bank profile (Plenner, Eichinger, & Bettis, 2016). Aerial imagery can capture the change of a whole bank or changes over the area from taking multiple photos of the whole area, but the resolution of the data is variable. Cook (2017) found that there was 30 to 40 cm of variation between the affordable UAV images and analysis compared to that of the LiDAR system used to measure the same sediment changes. Drones designed for photogrammetry, which are typically pricy, can reduce this error but are still limited by photo resolution and analysis techniques (Lague, Brodu, & Leroux, 2013).

Bank pins and PEEP devices can be used in a gridded pattern to capture sediment change data over a larger area, but this can result in reduced bank stability due to the concentration of pins that must be inserted into the area which may influence the sediment change observed (Lawler, 2001). PEEPs are also particularly invasive due to the cables that also have to be dug into the bank for their operation and the vegetation that must be removed so direct light can strike the PEEP surface (Lawler, 1991 and Lawler, 2001). In order to reduce the influence of the monitoring technique on the AOI, the technique must be non-invasive. LiDAR/TLS and aerial imagery analysis are both non-invasive techniques to monitor sediment change. Imagery taken by UAV and satellites can observe the AOI from above and will not influence the area. Similarly, most LiDAR/ TLS systems are set a distance away from the AOI and observed remotely by using the time of reflectance of light pulses.

Study Objectives

From the review above, the most accurate, non-invasive, continuous monitoring device is the LiDAR/ TLS systems. While these systems do provide quality erosion data, they tend to be very expensive. Plenner et al. (2016) created an “affordable” TLS system for approximately $10,000. In order for multiple devices to be used for extended periods of time they must have significantly lower costs. As discussed, current erosion monitoring methods tend to be either invasive to the area, record low frequency measurements, have a narrow spatial range of measurement, or are very expensive. Thus, there is a need for an affordable monitoring system capable of monitoring erosion and deposition non-invasively at a high resolution. Objectives of this research were to (1) design and construct a non-invasive sediment monitoring system capable of monitoring erosion/ deposition continuously (2) test the system in the lab and field, (3) and determine the applications and limitations of the system. These objectives were met by utilizing ultrasonic sensors in conjunction with programmable electronics to develop a continuous, non-invasive erosion and deposition monitoring device for approximately $350.

CHAPTER 2: MATERIALS AND METHODS

Development of Sediment Monitoring System

The sediment monitoring system (SMS) consisted of the following components: ultrasonic sensor, Arduino Nano, data storage electronics, compact battery and temperature probe. The most important piece of equipment was the ultrasonic sensor of which we chose the MaxBotix HRXL-MaxSonar-WR MB7389. The sensor uses the principle of time of flight to determine range to the surface. A sound wave is emitted in the direction of the surface. Once the sound wave strikes the surface, part of the sound wave bounces back and is detected by the sensor. The time between emittance and detection is used in combination with the speed of sound to calculate the distance to the surface by the following equation.

$$D = vt \tag{1}$$

where D is the distance to the surface (m), v is the speed of sound (m/s) and t is the time of flight in seconds. The sensor determines the range to the largest object in the AOI (Maxbotix, HRXL-MaxSonar ®-WR ™ Series, 2012). When erosion or deposition occur, the sensor will measure the new distance to the AOI, thus enabling the quantity of erosion or deposition to be calculated. Erosion or deposition will have to occur over the majority of the area, nearly half, to be the largest object to be recorded by the sensor. The sensor is also designed to detect hard surface targets instead of soft surface targets, making it less susceptible to vegetation and rainfall influences. While the sound waves can penetrate vegetation and rainfall, these factors could still impact the sensors measuring capability.

The ultrasonic sensor monitors an area of 2,826 cm^2 as it has a circular beam pattern with a radius of 30 cm. This beam is dependent on the distance from the sensor. When within 30 cm, the sensor is unable to record the distance to the AOI as there is too much interference between the emitted and reflected sound wave. Outside of 30 cm the sensor maintains the 30 cm radius beam out to its maximum range. Our study utilized two sensors, with maximum ranges of five (HRXL-MaxSonar-WR MB7389) and ten meters (XL-MaxSonar-WRML MB7051).

In addition to the sensor's maximum range, there is also inherent error in the sensor's measurement. The manufacturer states an error of approximately 1% of the total sensing distance; this correlates to a ± 1 cm error range when sensing at a distance of 1 m. Measuring greater distances will therefore increase the error up to ±10 cm for the 10 m sensor. Along with the instrumental error inherent in the sensor as reported by the manufacturer, the speed of sound is impacted by environmental factors like temperature, relative humidity and wind (Bohn, 1988; Chen & Maher, 2004; and Ingard, 1953).

The distance measured by the ultrasonic sensor is recorded by routing the sensor's serial output to an Arduino Nano, which boots, initiates 50 measurements, records the median value of the measurements and timestamp on a SD card unit, and returns the system to sleep mode to save battery life when not taking measurements. The frequency of measurement (interval for sleep mode) and data filter can be changed within the Arduino code. For this study the frequency of measurement was set to 15 minutes. A deep-cycle 12-volt, 22 amp-hour battery was used to power the system approximately one month (28 days). The date and time are kept by the real-time clock (RTC) module which is connected to the Arduino Nano and logged to a 32-gigabyte microSD card held in the SD card module when the sensor takes a measurement. The electronics and battery were encased in a water resistant, weatherproof box to protect the unit from environmental conditions while deployed in the field (Figure 2.1).

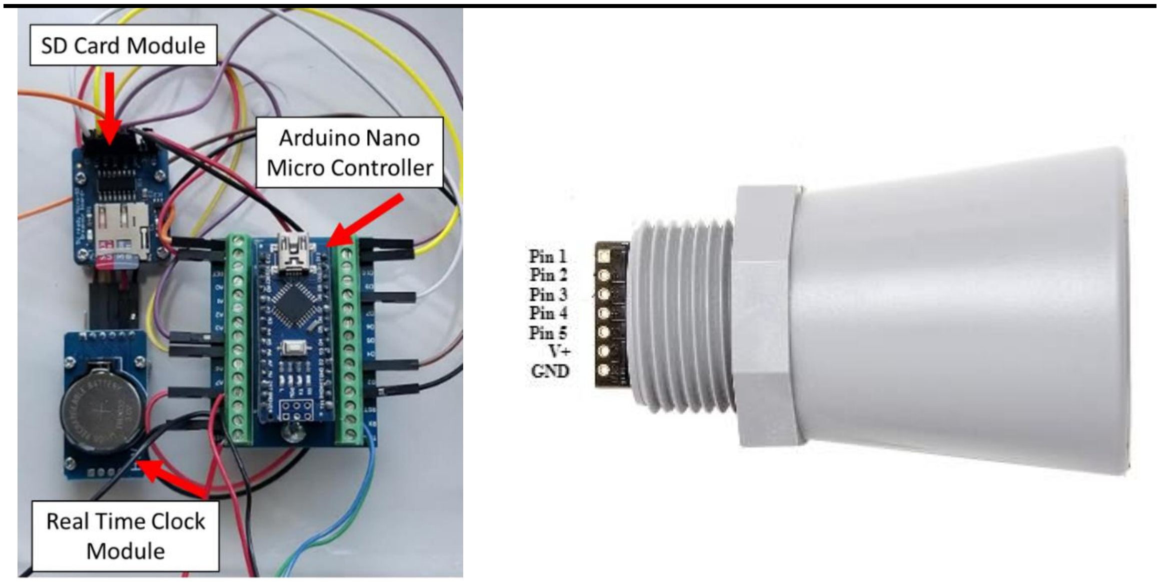

Figure 2.1 Components of the sediment monitoring system including the system electronics (Arduino Nano and RTC) and SD Card with module which are installed in weatherproof box and the 5 m ultrasonic sensor.

Also included in the monitoring system is an external temperature probe (MaxTemp) to correct the speed of sound for the current air temperature. In order to meet the National Weather Service (2018) recommendations for accurate measuring of air temperature, the temperature probe was mounted on the bottom side of the weatherproof electronics and battery housing box so it would be in a shaded and well-ventilated area. The temperature probe was connected directly to the ultrasonic sensor which automatically adjusted the speed of sound for the recorded air temperature to calculate the distance to the AOI by the following equation:

$$D = TOF\,\frac{20.05\sqrt{T_C + 273.15}}{2} \tag{2}$$

where *D* is the distance (m), *TOF* is the time of flight (s), and *Tc* is the air temperature (ºC). The temperature operation range of the MaxSonar ultrasonic sensor is -40C to

+65C, well within average daily temperature ranges (Maxbotix, Temperature Compensation Report).

Laboratory Controlled Experiments

The erosion monitoring system was first tested in a controlled lab setting (Figure 2.2a) to evaluate the manufacturer’s error specifications and determine the impact of multiple variables that may influence the distance measured by the sensor. The experiment was carried out in a secluded area (closet) to reduce any influence from external factors. The control box and battery were placed on a counter and the ultrasonic sensor was mounted on a ring stand facing down at a pan containing soil. The dimensions of the soil pan measured approximately 60 cm length by 45 cm width. The width is less than the ultrasonic sensor’s beam width, but the sensor measures the largest object in its field of view which was determined to be the soil pan since changes in the soil were measured by the sensor. Changes made during the control tests were confirmed by manually measuring the distance from the sensor to the soil to determine the artificial erosion and deposition amounts and distance changes in the different experiments conducted.

In order to determine the factors that influence and limit the SMS, investigations into different factors were conducted to help determine the extent to which they may influence the measurement. A total of seven scenarios were evaluated: erosion, deposition, slope, surface topography, soil type, vegetation and distance. Each experiment, except when testing multiple distances, were conducted with the ultrasonic sensor remaining stationary in the same location (approximately 1.25 m away). The first experiment investigated the SMS’s capability of monitoring erosion. Approximately 2.2

cm of artificial erosion (removal of sediment) was induced in the soil pan. The second experiment examined deposition where approximately 3.1 cm of sediment was added to the soil pan. The next experiment consisted of sloping the soil pan to create a slope with an angle of inclination of approximately 9° from the horizontal. Next, a mound measuring 12.8 cm in elevation was created in the center of the soil pan to investigate surface topography changes. Though the previous four experiments were conducted with a sandy soil, the soil was changed to a silt loam for the fifth experiment to evaluate the influence of soil type. The impact of vegetation (Figure 2.2b) was conducted using a spider plant that was approximately 12.2 cm tall with a pot height of 29 cm. The final test evaluated the sensor error at multiple distances: 1.25 m, 1.74 m and 2.14 m. These were created by increasing the height of the sensor from the soil pan on the floor.

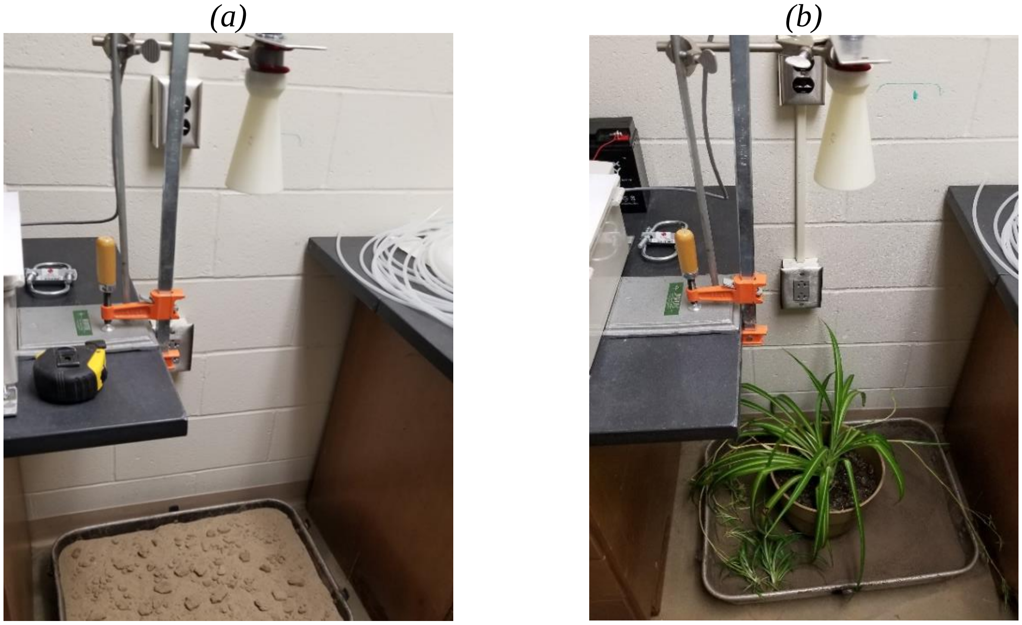

Figure 2.2 Shows (a) the in lab, controlled experimental set up and (b) the vegetation controlled experimental set up.

Field Experiments

Once the system was tested in the lab, four SMS's were installed at four study sites to monitor deposition on the inside of a meander (2), field erosion (1), and streambank erosion on the outside of a meander (1). Sediment deposition was monitored at two sites in the Nebraska Sandhills, the South Branch of the Middle Loup River (SBMLR) and Sand Draw Creek. Field erosion was monitored at a UNL research facility, Roger's Memorial Farm, east of Lincoln, NE. Streambank erosion was monitored on Beal Slough, a tributary to Salt Creek in Lincoln, NE.

Study Sites

The SMS was set up on a sandy stream bank on the SBMLR located within the Gudmundsen Sandhill's Laboratory (GSL). The facility, owned by the University of Nebraska-Lincoln, is a research ranch located in the heart of the Sandhills in western Nebraska. The Sandhills, dominated by sandy soils, is a dynamic system with erosion and deposition common during high flow events. The SMS was mounted on a horizontal arm facing downward to, non-invasively, monitor deposition (Figure 2.3a) along the stream bank opposite of a cut bank suffering from mass wasting events. The stream ran through a pasture; therefore, to protect the AOI and equipment from cattle rubbing, a fence was installed. While the system was able to monitor non-invasively, bank pins (Thorne, 1981) were used to confirm erosion/ deposition amounts occurring in the AOI. Four pins were inserted into the ground, each located 40 cm from the center of the AOI, outside of the ultrasonic sensor's sensing area. During each visit to the site, the bank pins were measured along with the distance from the sensor to the ground to act as a ghost bank pin for the center of the AOI. Site visits occurred approximately every 28 days to replace the battery, download the system’s data and record the bank pins. The SMS was deployed from the beginning of October to the end of November. The water height of these streams was monitored to compare the timing of sediment altering events to those captured by the monitoring system. The water and barometric pressure, converted to water depth, were measured using HOBO pressure transducers.

Sand Draw Creek is a small tributary to the Niobrara River in north central Nebraska. The study site is located near Ainsworth, NE in Brown County and is in the Middle Niobrara Natural Resource District. Although this stream is located on the edge of the Sandhills, the predominant soil type is still sand. The SMS was installed in a privately owned pasture with cattle grazing occurring during the monitoring time. Like the study site located on SBMLR, a fence was set up around the AOI and monitoring system to protect it from cattle. The ultrasonic sensor was mounted on a horizontal arm and faced downward to monitor deposition (Figure 2.3b). Bank pins were also installed to track the deposition and HOBO pressure transducers were used to monitor the stream depth to compare with deposition events. The system was set up from August until September when a large flooding event destroyed the system. The new system was then re-installed from the beginning of October until the end of November and checked approximately every 28 days to replace the battery and record the bank pin information.

Roger’s Memorial Farm is a research farm owned and operated by the University of Nebraska-Lincoln for conducting research experiments on agriculture lands. The farm has historically been a no-till farm and uses terraces on the sloping fields to help control sediment loss. The dominate soil type is a silty clay loam which has slow infiltration rates. Evidence of past erosion can be seen before the use of no-till and terrace practices

(Nebraska-Lincoln, 2020). This farm was not expected to produce many, if any, erosional events due to its management but was used due to its proximity to campus and the appeal of testing the sensor in a different setting. The sensor was mounted on a horizontal arm and pointed downward to monitor a small patch of slightly sloped ground that had been tilled for a microplastics study; this was to increase the possibility of catching an erosion event. The non-invasiveness of the system (Figure 2.3c) was paramount to not interfere with the other scientific study being conducted on that area; consequently, erosion pins were not used at this site, but manual measurements from the sensor to ground measurements were conducted. This system was set up from the beginning of September 2019 to early spring 2020; with an updated temperature probe being installed on October 14th.

The final system that was deployed was in the south part of Lincoln, NE on a large cut bank causing erosion near a high voltage power pole on the urban waterway Beal Slough. The system was mounted on the cut bank to monitor erosion (Figure 2.3d). The original design was for the SMS to monitor streambank erosion from the bank opposite of the AOI. Due to the range constraints of the ultrasonic sensor, an extended cable was attached to the ultrasonic sensor so it could monitor erosion from the same bank but set back a couple meters to avoid interference or damage from erosion forces. The cable was run through a 2.4 m pipe staked to the ground which over hung the eroding bank. The sensor was then mounted to a 1.2 m pipe protruding vertically down from the overhanging pipe (see Appendix A: Figure A.1a). Due to the limited accessibility to the large and steep cut bank, erosion pins were not used at this site and manual sensor to AOI measurements were unable to be conducted. Like the sites located in the Sandhills, a

HOBO pressure transducer was used to monitor the stream depth. This SMS was deployed from mid-October 2019 to January 2020. This site was unique due to its location in an urban area, likelihood of receiving flashy runoff, and due to its monitoring of at-risk infrastructure.

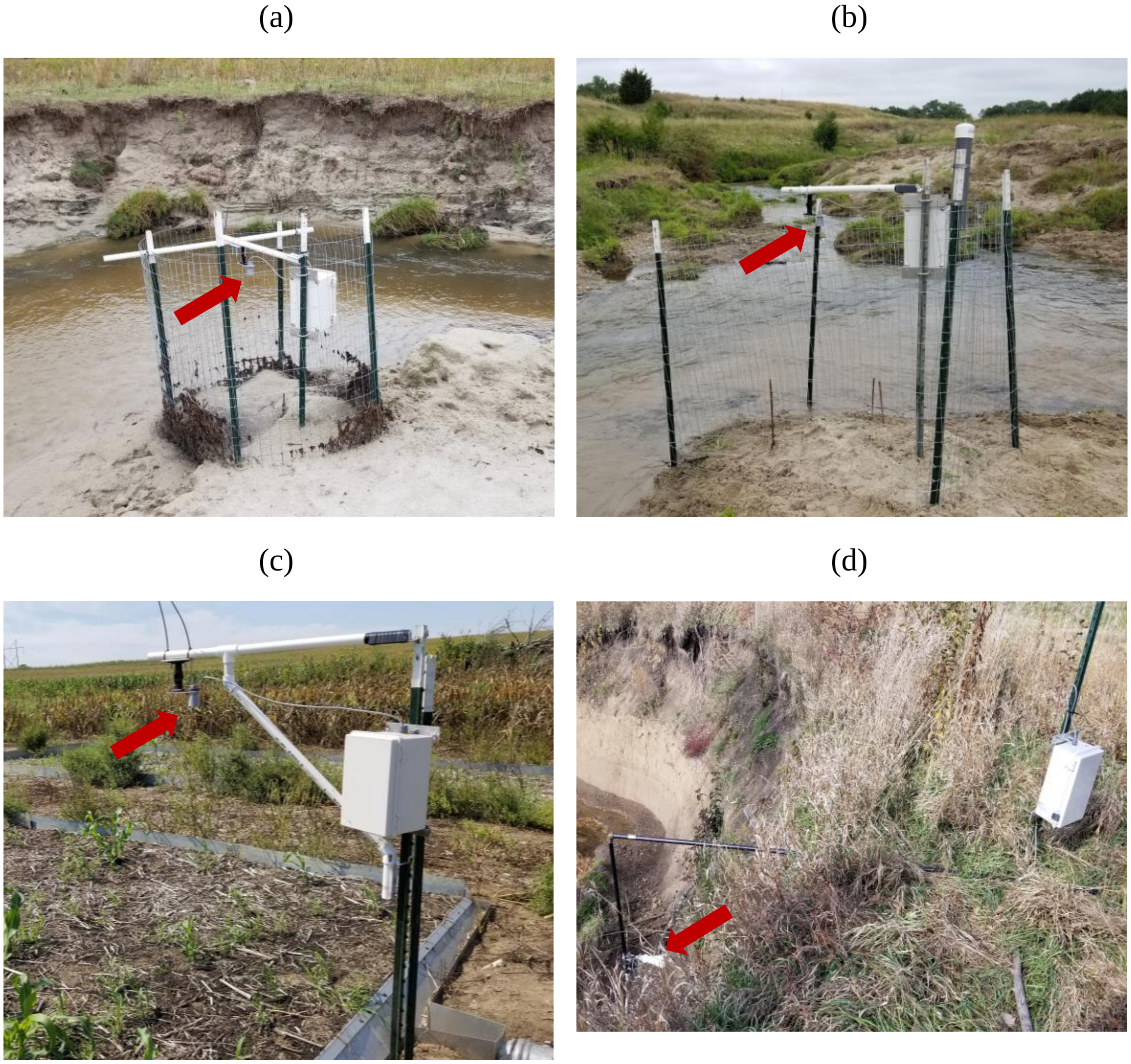

Figure 2.3 The four sites used to monitor erosion and deposition using the sediment monitoring system (a) South Branch of Middle Loup River (deposition), (b) Sand Draw Creek (deposition), (c) Roger's Memorial Farm (field erosion), (d) Beal Slough (streambank erosion). Red arrows depict where the ultrasonic sensor is located.

Data Analysis

Data was analyzed using Excel and R. Plots were constructed illustrating the measured distances against the date-time values to determine where and how much erosion or deposition occurred. Water level was also plotted, where applicable, to help determine when events occurred that would cause erosion or deposition. Once events were determined, the raw data for each event at each site was processed using the R data language. Outliers were removed based on box plot statistics with outliers lying outside the inner fences (NIST, n.d.). Once outliers were removed, the daily median value was determined to help smooth the data and reduce the noise of the measurement. The standard deviation was then calculated for each event to determine the error range of the measurement. Finally, plots were reconstructed with the filtered and smoothed data and water level data to quantify and show when erosional or depositional events occurred.

CHAPTER 3: RESULTS AND DISCUSSION

Control Experiments

The laboratory-controlled testing helped to evaluate potential factors that would affect the results of the SMS. Initially, erosion and deposition were tested using a sandy soil. Figure 3.1a shows the different artificial erosion and deposition events that were created. The SMS recorded a 23 mm change, with an error of ± 0.979 mm, from ***BASE*** to ***ERO***, indicating approximately 2.3 cm of erosion. This compares to the approximate 2.2 cm of actual erosion created. Similarly, there was 29 ± 0.945 mm of deposition from ***ERO*** to ***DEP*** which is comparable to the approximate 3.1 cm of actual deposition created. These findings confirm that the SMS accurately measures erosion and deposition events.

Figure 3.1b illustrates the results from testing the system at approximately 1.25 m (***X***), 1.72 m (***Y***) and 2.14 m (***Z***). The variation was ±1.06 mm for 1.25 m and then increased as the distance increased. At 1.74 m and 2.14 m the variation was ±4.66 mm and ±8.02 mm respectively, which is within the manufacturers stated 1% error of the distance measured. Due to the increases in the variation of the measurement over longer distances, field studies were conducted to keep the ultrasonic sensor ~1 m away from the AOI. This would provide limited variation in measurement while still being non-invasive.

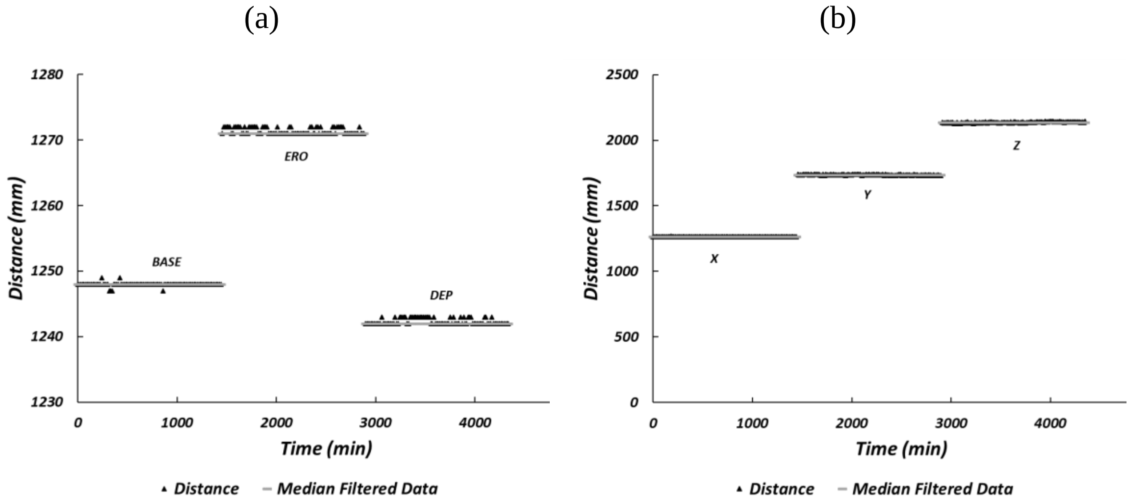

Figure 3.1 Results from the controlled experiments in the lab. Plot (a) Shows the control **BASE**, *an artificial erosion event* **ERO**, *and an artificial deposition event* **DEP**. *(b) Shows the differences in height* **X** *at 1.25 m,* **Y** *at 1.74 m and* **Z** *at 2.14 m. Note that most of the measured distance measurements occur at the same distance as the median filtered data and are hard to denote behind the median filtered line.*

After the effects of multiple distances were evaluated, changes in the topography were investigated. Figure 3.2a shows the results of the sloped and mounded experiments. The variation in measurement of the sloped experiment was ±1.28 mm and the mounded experiment had a variation of ±1.18 mm. The sensor read to the top of the mound, nearest target, during the experiment. This suggests that small changes in surface topography does not have a significant impact on the error in the measurement; however, it is important to note that steeper slopes could create more error in measurement and that the sensor will only measure the nearest target so the whole sensing area will be assumed to have similar sediment change.

Figure 3.2b provides the results of the change in soil type to a silt loam and the vegetation experiments. The silt loam soil had a variation in measurement of ±1.00 mm which is comparable with the variation of error of the sandy soil of ±1.06 mm, both experiments were conducted at approximately 1.25 m. Therefore, the SMS should provide accurate results across different soil types. The spider plant was measured, with a ruler, to be 121.92 mm tall and the SMS records a change in distance of approximately 123.50 mm between the start of the experiment to the end. This suggests that the system was picking up the plant near the beginning of the experiment and then sound waves were able to penetrate the vegetation and the distance to the soil in the pot was recorded. These results indicate that vegetation is an important factor that can influence the reading of the sensor. The impacts of the vegetation on readings was seen in the field during the beginning of the study period at the Roger's Memorial Farm.

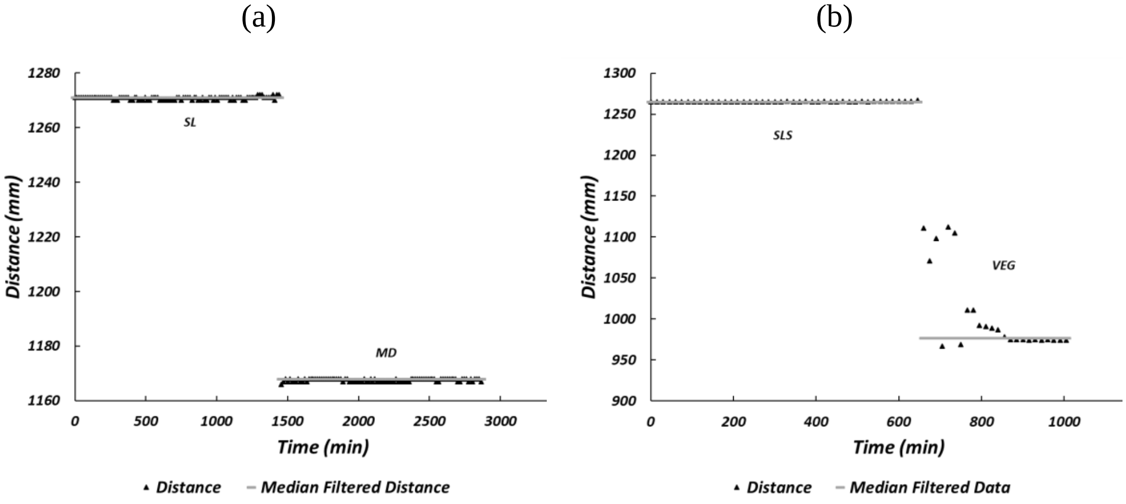

Figure 3.2 shows the results from the controlled experiments in the lab. Plot (a) shows the sloped **SL** *and mounded* **MD** *experimental results. (b) Shows the silt loam soil type* **SLS** *and the vegetation trial* **VEG** *with a spider plant placed above the silt loam soil.*

Field Experiments

After controlled experiments were conducted, the SMS was tested in the field. For the system monitoring deposition on the SBMLR, there was slight water level fluctuation and little sediment change observed by the SMS during the beginning of the monitoring period (October 2nd to October 28th) (Figure 3.3a). This confirms that the SMS was able to provide stable readings during a time when there were no major changes in the AOI.

The variation in measurement during this time was calculated to be ±11.40 mm. In the latter part of the study period (November 8th to November 29th), the water levels started to fluctuate which could be the cause of the larger variations measured by the SMS. The sandy banks at this site provide a dynamic system that is especially vulnerable to changes in streamflow (i.e. water level). Small variations of sediment change across the area can be seen in the bank pin data (Table 3.1).

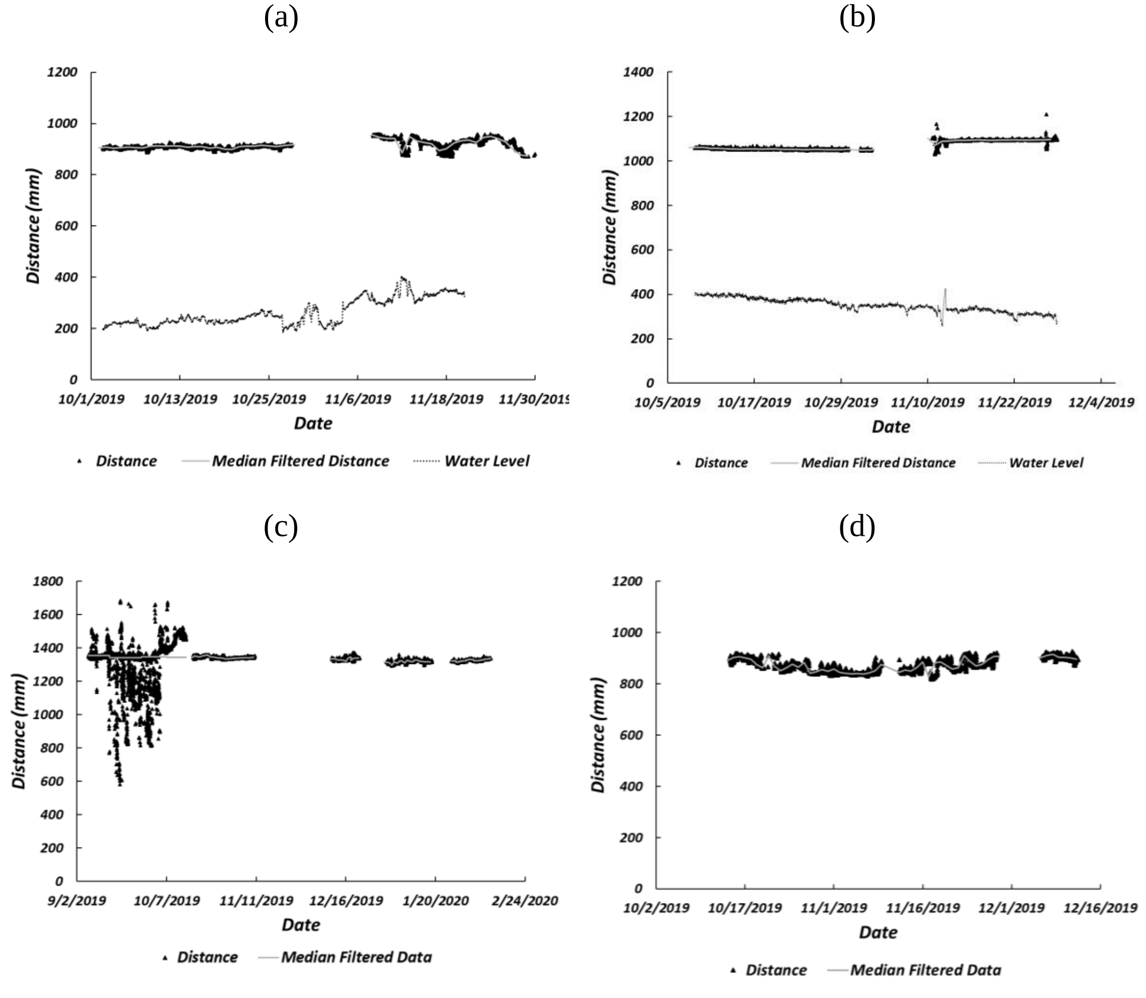
(a) (b) (c) (d)

Figure 3.3 shows the results from the field sites. (a) Data on the SBMLR, (b) Sand Draw Creek post-flooding, (c) Roger's Memorial Farm, (d) Beal Slough.

The measured distance to ground from October 2nd to November 8th indicates that 3.0 cm of erosion occurred. The SMS showed little overall change over that timeframe, but this highlights how non-uniform topography changes of the AOI could be missed by the SMS. The SMS data (Figure 3.3a) does show possible erosion during the time period when the system was without power. Although the average bank pin data indicated deposition over the October 2nd to November 8th timeframe, pin 2 indicated erosion. The inconsistencies of the data can be attributed to the uneven erosion and deposition that occurred across the surface.

The fences installed to protect the SMS influenced the erosion/ deposition of the area as debris caught in the fence and altered the flow across the area. At this site specifically, more deposition was observed on the upstream side of the sensing area (pin 2) than the downstream side (pin 4). Visual observation of the site also indicated the uneven sediment changes that occurred due to debris in the fence. It is also important to understand that the pins were checked after the SMS lost power, so they are not the exact conditions from when the system powered down. In the period from November 8th to January 3rd (snowstorms prevented access to the site) there was measured deposition from the bank pins and significant deposition measured from the distance to ground. The bank pin measured deposition was due to the snow and ice that had accumulated over the sensing area. While the conditions on January 3rd are not going to represent the conditions of the sensor when it lost power on November 30th, the SMS data was indicating a trend of deposition which could be due to the accumulations of ice during the colder winter temperatures.

Table 3.1 shows the results of the bank pins that were inserted just outside of the sensing area on the SBMLR.

Date	Distance to Ground (cm)	Pin 1 (cm)	Pin 2 (cm)	Pin 3 (cm)	Pin 4 (cm)	Average Change (cm)
10/2/2019	90.0	26.0	17.0	7.0	31.0	-
11/8/2019	93.0	23.7	18.3	7.0	23.5	2.1
1/3/2020	86.0	20.0	16.0	5.0	15.5	4.0

From Table 3.2 for the system at Sand Draw Creek it is clear that erosion occurred in the sensing area. The results of the bank pins were much more consistent in this area than the SBMLR. From October 8th to November 10th there was an average of 4.8 cm of erosion according the pins which is confirmed by the approximate change of 4.9 cm from the distance to ground measurements. The SMS data (Figure 3.3b) also supports the erosion measured by the pins (change of 5.3 cm). While there was erosion recorded by pins and the SMS system, the exact timing is not clear as most of the erosion is apparent in the brief period the SMS was out of power. Slight erosion was also measured from November 10th to December 7th by the bank pins but the distance to ground measurement indicated little change, 0.7 cm, which is concurrent with the SMS data (Figure 3.3b). The little change is likely due to the water level covering the sensing area. Since water was covering most of the area, the decrease in water level could be the cause of the “erosion” that was measured. The measured water level decrease was 3.9 cm, which is a greater reduction than was measured by pins (2.0 cm), distance to ground (0.7 cm) or the SMS (2.2 cm). The transducer was located upstream and may have had a larger change in water level than the bank location. The variation in measurement from

October 8th to November 10th was ±6.1 mm and from November 10th to November 27th it was ±11.5 mm indicating that due to environmental factors the error was greater than the lab results.

Lawler (1991) found similar non-changing results for a time period in their study. The results from monitoring deposition at Sand Draw Creek confirm that no significant sediment change occurred in the AOI during the study period. Lawler (1991) indicates that the use of low frequency measurements cannot draw this conclusion as there is the possibility of "complex, but balanced, sequences of sediment deposition and removal" that can occur between measurements. Only the use of continuous timeseries data can affirm that no significant change was measured.

Table 3.2 shows the results of the bank pins that were inserted just outside of the sensing area at Sand Draw Creek after the system was re-installed post-flooding.

Date	Distance to Ground (cm)	Pin 1 (cm)	Pin 2 (cm)	Pin 3 (cm)	Pin 4 (cm)	Average Change (cm)
10/8/2019	105.4	28.5	26.7	55.3	25.8	-
11/10/2019	110.3	41.0	27.0	55.5	30.7	-4.8
12/7/2020	109.6	44.6	29.5	55.0	33.3	-2.0

Results from the system at the Roger's Memorial Farm are shown in Figure 3.3c. The beginning of the monitoring period has a lot of noise and variation in the measurement and then becomes much more consistent, only suffering gaps in the data when the system was without power. The noise in the data is due to vegetation, specifically corn, that started growing in the AOI. The data indicates that the corn grew to about 52.0 cm through the month of September and was removed on October 4th. While the SMS measured the growth of the corn, it also picked up the ground and had a median value of 134.3 cm. The monitoring of the ground and vegetation are consistent with the in-lab testing results. Even though the vegetation influenced the measurement, a consistent measurement of the ground was also observed and showed minimal sediment change. It was found that the system had a manufacture indicated defect in the temperature probe during the start of the study period until it was replaced on October 14th.

After the temperature probe was replaced, the SMS did not measure a significant sediment changing event and had a variation in measurement of ±14.9 mm. While there was not a single sediment changing event, there was gradual sediment change from December to mid-January where a total of approximately 2.0 cm of sediment was gained. This could be due to environmental factors like melting snow and rainfall slowly removing soil particles from upslope and carrying them down slope. While not designed to pick up snow, the SMS could have measured the accumulation of snow contributing to the variability in the measurement. Using the measuring tape, there was a change of 1.27 cm from the sensor to the ground from December 10th to January 18th, indicating that there was some slight accumulation of sediment during this time.

Also, during the study period, the temperatures became colder and impacted the battery life of the SMS which is especially apparent in the timeseries data from the Roger’s Farm. There were frequent gaps in the data because the battery life was reduced due to the colder temperatures. Typically, the battery life was approximately 28 days, but the cold temperatures reduced the battery life to approximately 12 days. Cold temperatures caused the SMS, at all sites, to have reduced battery life and to become inactive until new batteries were installed.

Figure 3.3d shows the timeseries data from the erosion monitoring SMS at Beal Slough. This time series has a larger variation in the data visually. While there were no bank pins used at this site, visual inspection of the bank during checks indicated that no significant erosion occurred. Water levels were always significantly lower than the AOI which was located near the top of the cut bank and should not have impacted the AOI. The variation in measurement was ±52.4 mm, which is significantly higher than errors from other sites. More error may be present in this site for a couple reasons. The longer cable the SMS used to monitor erosion could be picking up external noise and impacting the signal. It is also possible that there is more audio noise present in this urban location that is impacting the ultrasonic sensor. Finally, a culmination of environmental factors compounding on one another is likely another reason more error is seen in this measurement, as environmental factors caused greater error at other sites. Each factor has small impacts that amounted to a large error range.

Results from the field studies revealed greater error in measurement than compared to the lab results. This is likely due to environmental impacts. While the SMS has many applications and benefits from traditional monitoring methods, it is limited by its accuracy in measurement from environmental factors. The most influential factor affecting the speed of sound is the air temperature. Changes in air temperature can cause the speed of sound to change. As temperatures get warmer, speed of sound increases and as temperatures get cooler the speed of sound decreases (Bohn, 1988). This can cause measurement error with the ultrasonic sensor as the temperature changes throughout the day and was why a temperature probe was included in the SMS to correct for temperature effects on the speed of sound. While temperature was corrected for, there could still be slight error in measurement from temperature as the temperature profile changes from the ground upward. The proximity to flowing water could also impact the temperature and relative humidity of the air.

Another important environmental factor that can affect the speed of sound is the moisture content of the air or the relative humidity. Relative humidity is dependent on air temperature as warm air is able to hold more moisture than cooler air. The relative humidity impacts the speed of sound because sound waves travel through the air medium and as the medium changes, sound wave propagation will change. When at a temperature of 20 Celsius, the speed of sound can change by approximately 1 meter per second when the relative humidity changes from 0% to 100%, increasing in speed as the relative humidity increases (Chen & Maher, 2004). Coupling in the effects of temperature and relative humidity, in general the speed of sound travels even faster in warm, moist air. This means that even when accounting for temperature, the speed of sound is still changing as the relative humidity changes with temperature. Thus, correcting for the relative humidity would allow for even more precise measurements.

Wind impacts sound by changing the speed of sound depending on which direction the sound waves is traveling with respect to the wind direction. The sound wave is a mechanical wave traveling through a moving medium (air), so as the speed of the medium changes the speed of sound changes. The speed of sound is relative to that of the medium; meaning relative sound velocity is the sum of the sound velocity and wind velocity. The wind, along with temperature, can also cause the refraction of sound waves, though this tends to happen over large distances and should be negligible within distances covered in this study (Ingard, 1953 and Chen & Maher, 2004).

While there are limitations of the SMS with respect to environmental factors, variations in measurement could also have been impacted by the slight sediment changes. Lawler (1991) found that even in periods of suspected inactivity, minimal water level fluctuations, there was frequent, small-scale changes in sediment recorded by the PEEPs. The SMS found similar small-scale changes during varying time periods at all the sites. While there was no suspected activity to cause sediment changes, wind erosion and splash erosion could play significant roles of contributing to these small-scale sediment changes. The dynamics of sediment change account for the fluctuations seen in measurements during periods of suspected inactivity, like at the Roger's Memorial Farm and Beal Slough. These small-scale changes could have contributed to having increased error in measurements.

While the SMS is affected by environmental factors, the error in measurement is comparable and even better than some sediment monitoring methods. We found an error in measurement of ±6.1 - 52.4 mm for the SMS in the field (±1.0 – 8.0 mm for the lab). The low end of our interval, and in lab testing, is comparable to Lawler's (2001) resolution of ±2 - 4 mm, but not as good as Plenner's (2016) TLS error of 0.36 mm between actual and measured results. While not as good as some other methods, the SMS was significantly better than Cook's (2017) UAV imagery analysis error of 30 - 45 cm.

While the SMS may not provide the highest resolution results, it does have advantages over other current monitoring methods. The SMS is able to continuously monitor an AOI, day or night, for extended periods of time unlike Lawler's PEEPs that only work during daytime and Plenner’s TLS which is only set up for short periods of time and only during low flow events. The SMS is designed to have water levels rise above the sensing area so it can capture the exact sediment altering events. This ability is showcased in Figure 3.4, which depicts data from Sand Draw Creek during the flooding stages of the stream. While the data recorded was not on the most up-to-date SMS, defect temperature probe and average filter instead of median filter, the SMS was still able to accurately measure the exact timing of the water level rise and subsequent deposition as water levels dropped. The first water level peak occurred on August 12th as measured by the pressure transducer. The water level rise was also measured by the SMS as it rose above the sensing area. As the water level decreased, sediment was deposited as measured by the SMS to be 24.8 cm. There was another water level peak measured by the pressure transducers on September 2nd and also measured by the SMS. When the water level dropped 18.7 cm of deposition was recorded by the SMS. The flood waters altered the SMS set up and eventually debris build up caused the mounting posts to bend and flood the system. While the SMS was ruined, the data was able to be removed from the SD card. The bank pins that were inserted during this time were unable to be located after the significant sediment build up.

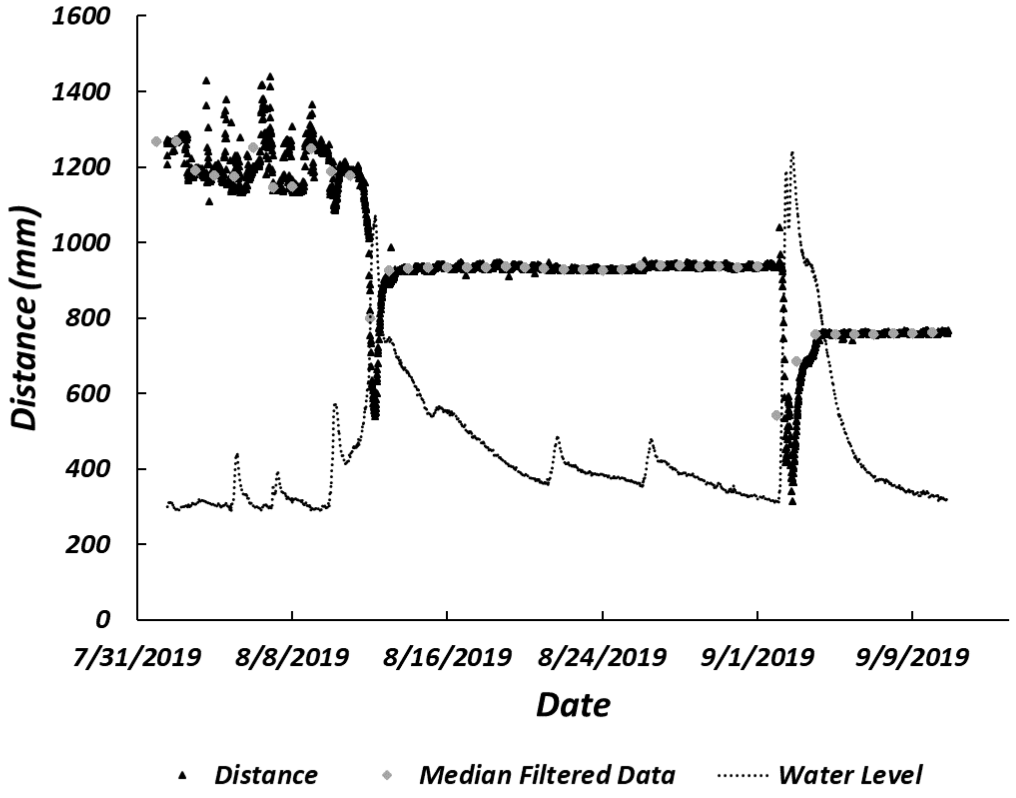

Figure 3.4 highlights the SMS ability to capture timing of deposition causing events. Two large rainfall events at the Sand Draw Creek site caused major water level rise, flooding and sediment deposition.

The results demonstrate two things, first the SMS has the capability of measuring the timing of erosion and deposition events and second can provide accurate measurements (within 5 cm) of sediment change in the AOI. While the SMS can provide sediment change data with a resolution within 5 cm, the accuracy could be improved by combining the SMS with another traditional monitoring method to get finer measurements. Using a traditional monitoring method would also be necessary to obtain sediment change information across a larger area. While the SMS monitors an area of 2,826 cm^2, it does not currently provide information of an entire bank like the TLS, aerial imagery or gridded bank bins. Combining the SMS with another affordable method, like gridded bank pins, would allow for precise measurements of an entire bank while also providing the timing of when sediment changes occur.

Though limited in measurement resolution for small sediment changes, locations that undergo large sediment changing events can be monitored by the SMS with little issues in recording the quantity of sediment. The high flow events at Sand Draw Creek highlight the SMS capability. The SMS recorded a total deposition amount of 43.5 cm with an error of ±10.79 mm. Comparing this result to Midgley et al. (2012)'s study, where approximately 7.9 to 20.9 m of bank laterally eroded on a Barren Fork Creek in northeastern Oklahoma. They used BSTEM to model the failure events, but the model under predicted the quantity of erosion by a couple meters, though accurately predicted the timing of the erosion events. The SMS was able to provide more accurate results during the high flow events of this study. This shows that the SMS can accurately monitor large sediment changing events, capturing both the timing and quantity.

CHAPTER 4: RESILIENCE, POLICY AND OUTREACH IN RIPARIAN ECOSYSTEMS

One possible application of the SMS would be for the monitoring of alternative state thresholds. In rangeland or riparian ecosystems there are two contrasting states that can occur, vegetated and bare/ sparsely vegetated states which influence erosion processes (Chartier & Rostagno, 2006). In resilience theory, alternative stable states refer to the potential alternative configuration of functions, processes and abundance and composition of a system (Angeler & Allen, 2016). For a regime shift to occur, a threshold must be surpassed. The threshold can be described as a tipping point in which the ball resides in a different basin of attraction (Gunderson, 2000). Chartier et al. (2006) defines a site conservation threshold as the point at which the rate of soil erosion increases markedly. This spike in erosion rate is due to the reduction in vegetation and marks the transition into an alternative state from vegetated to sparsely vegetated. The change in state can also move the other way. A sparsely vegetated, significant erosion prone area can recover into a vegetated, reduced erosion prone area if the perturbation, loss of vegetation, is reduced or halted (Kauffman, Case, Lytjen, Otting, & Cummings, 1995). A long-term, continuous monitoring erosion device like the SMS is required to measure when a threshold is surpassed, and the system moves into a new state.

In order to identify the site conservation threshold when the erosion rate increases significantly, a monitoring device is needed that is able to record data at a high frequency so the erosion rate can be measured and the timing of the regime change can be monitored. It is also important that the device be non-invasive so as not to alter the structure of the area and influence erosion rates. Both of these aspects are accounted for in the SMS. Erosion is a natural process that occurs in all systems at varying degrees of severity. The management of erosion should not focus on stopping the process, but on managing areas to reduce the erosion rate, supporting systems to withstand perturbations and monitoring the eroding areas to track erosion rates and identify when a regime shift occurs. Understanding the regime changes in riparian areas can help improve the resilience, the ability of a system to maintain structure, function, and relationships while experiencing (perturbations) pressure to change (Holling, 1973), of the streambank to withstand greater perturbations before experiencing a regime shift. It will also allow managers insight into how to restore a riparian area into a more desirable state, usually a vegetated state with reduced erosion.

One way managers can help reduce erosion and maintain desired states is to use riparian buffers. Riparian buffers are undeveloped strips of land that flank water ways. Using riparian buffers reduces the effects of vegetation loss due to farming, grazing, or urban development. The buffers should be planted over with native grasses, shrubbery, or trees to help with the filtration of nutrients from runoff and to help stabilize soil and reduce erosion. While there are many benefits of riparian buffers such as water quality improvements, reduction in erosion and habitat for wildlife and shading for aquatic life (Burden, 2015); it also takes away from the amount of land that is available to develop, whether that is for agriculture or industry.

There are agencies at multiple levels that work to manage riparian areas through the use of riparian buffers. Examples include the USDA-NRCS at the federal level and different state level departments, like Nebraska’s Department of Natural Resources (NeDNR). There are also local agencies like Nebraska’s Natural Resource Districts

(NRDs) which focus on smaller regional management of water resources. Other organizations work to support streambank restorations and riparian buffers like The Nature Conservancy and Pheasants Forever. While there are many management agencies, without policies requiring riparian buffers, implementation is strictly voluntary. Solutions for effective soil sustainability, like riparian buffers, will require interdisciplinary communication between policy makers, public institutions, and natural resource managers (Amundson, et al., 2015). An example of utilizing policy makers to take action can be seen in Minnesota with their 2017 policy mandating all waterways have a 50ft buffer and all drainage ditches have buffers of 16.5 ft (MN Stat. § 103F.48). This policy includes provisions for the local water resource management agency to work with landowners on implementing these buffers. As of July 2019, there was a 98% compliance rate with the law. This compliance includes lands that are in planning stages riparian buffer development. In order to achieve high compliance with this law, engagement and outreach techniques were likely used to encourage landowners to make the needed changes in a timely manner.

Outreach and engagement can be a powerful tool for implementing best management practices for the improvement of natural resources. Riparian buffers can be considered a best management practice (BMP) that any landowner can implement along waterways. Proper engagement and outreach require the involvement of the landowners during the planning process. This means informing the landowners, providing channels for their ideas and concerns to be voiced and most importantly addressing the ideas and concerns (Twyford, Waters, Hardy, & Dengate, 2006). Communicating with landowners in the process of implementation of riparian buffers or any other BMP will help build trust and assist with reaching compliance of implementation. Busse et al. (2015) found that outreach is not always effective in getting the desired message out to as wide of an audience as desired, however individuals that did receive the message showed positive changes in their attitude.

Beyond effective communication with landowners, understanding the demographic and challenges faced by landowners from the expected change are essential in having a successful adoption of new policies. Busse et al. (2015) also found that the best way to ensure successful outreach efforts is to understand the public perceptions on topics related to solution implementation as well as determining what type of outreach would be most effective for the demographic. This means that it is important to tailor outreach and engagement efforts to each situation and not try a blanket approach.

Understanding the demographic being engaged ensures the correct messaging can be deployed to the correct audience. For example, there are multiple levels of comprehension and perceived responsibility between agricultural and non-agricultural residents regarding water quality and nutrient pollution (Busse, et al., 2015). Each group requires different outreach processes to help them better understand water quality and nutrient pollution. It is also important to understand how the demographic perceive and trust outreach personnel. Hoorman and Spencer (2002) highlight the need for trust in a community during outreach through their work with Amish communities. The authors show that the best way to engage these particular communities is to bring outreach activities directly to their homes and businesses in order to build trust within the community. Many landowners and agricultural producers tend to trust and receive messages better from University Extension, Soil and Water Conservation Districts, and

Natural Resource Conservation Service personnel (Mase, Babin, Prokopy, & Genskow, 2015). Building trust in communities when conducting outreach is vital for the success of the outreach and engagement programs. The implementation of policies can quickly be applied through outreach and engagement processes, so the best management of natural resources can be conducted across broad areas.

CHAPTER 5: CONCLUSTIONS AND FUTURE WORK

Lab testing demonstrated that the SMS has a measurement error of approximately ±1.06 mm when measuring at a distance of 1.25 meters and increases slightly as the distance increases. Field testing revealed that there are environmental factors that influence the SMS measurements. While temperature is being corrected for, wind and relative humidity could still be impacting the measurement. The measurement error for the field sites ranged from ± 6.12 to 52.42 mm, with the latter error likely being influenced by urban noise, signal noise from an extended cable and other environmental factors. The SMS was used to accurately measure the timing and quantity of two deposition causing events after high flows were observed on Sand Draw Creek. While the magnitude of these deposition events were unable to be confirmed with erosion pin data, due to loss of pins, the previous testing has indicated that the total measured 43.5 cm of sediment deposited between the two high flow events is within approximately 10.79 mm (average error of three measured errors, excluding extraneous error value 52.42 mm) of the actual amount. Coupling the SMS with another erosion monitoring method would allow for more precise measurements to be taken on sediment change amounts while still being able to understand the timing of sediment changing events.

Future work will focus on correcting for other environmental factors, such as relative humidity and wind, that can affect the sensing capability of the SMS. Increasing the battery life of the SMS is also important for the continuation of long-term erosion and deposition studies. Ideally extending the battery life to 3 months and incorporating a solar panel would reduce the time spent in the field and the gaps in data. Finally, incorporating telemetry technology to transmit data from the SMS directly to users would decrease field time and ensure data is captured and not lost if high flows were to destroy the SMS.

The SMS has the capability of measuring sediment change continuously and non-invasively for extended periods of time. Since there is a need for a greater understanding of gully erosion, the SMS would be ideal for monitoring gullies as they get deeper and wider due to erosion. This data could then be used to help develop better models for predicting gully erosion or for better quantifying the amount of gully erosion occurring in landscapes and helping to improve the management of erosion prone areas. Using interdisciplinary approaches, major challenges of managing erosion and deposition can be addressed and solutions formed.

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APPENDIX A: USER GUIDE

This guide covers the construction and installation of the Sediment Monitoring System.

Construction:

1. Gather electronics components, the following is a list of components used:
   a. Arduino Nano ~ $22.00
   b. Gikfun SD Storage Board TF Card Memory Shield Module for Arduino (Arduino Shield) ~ $8.00
   c. Adafruit DS3231 Precision RTC Breakout Board (RTC) ~ $14.00
   d. SanDisk microSD Card and Memory Card Adapter ~ $12.00
   e. MaxTemp Temperature Probe ~ $10.00
   f. MaxBotix Ultrasonic Sensor (MB7389 HRXL-MaxSonar-WRMT) with shielded cable ~ $173.00
   g. Mighty Max 22 amp-hr 12V deep cycle battery ~ $45.00
2. Connect the Arduino Nano to the Arduino Shield to make wiring easier. Wire Arduino Nano/ Shield, RTC and SD card adapter components according to the wiring guide found in Appendix B. Some components may require soldering to secure wires or wiring pins.
3. Drill holes in housing box for the ultrasonic sensor wire and temperature probe wires to run through. Using water resistant gromets run ultrasonic sensor wire and temperature probe wires through holes.

   (Note: Before running ultrasonic sensor wire through the gromet and hole, ensure the mounting hardware has been attached to the ultrasonic sensor. This was a metal plate with holes for U-Bolts and a hole allowing the cable and back end of the sensor through. A pipe fitting was screwed onto the sensor's back end to secure the sensor in place.)
4. Secure the electronics components and mount in weather resistant box. Electronics were mounted to plexiglass, using electronics screws and spacers, which was screwed into housing box.
5. Wire the ultrasonic sensor and temperature probe into Arduino system according to Appendix B. The temperature probe is wired to the temperature compensation wire on the ultrasonic sensor (Pin 1, white wire) and then to ground.

6. Attach mounting brackets to housing box. These were machined metal brackets to allow U-Bolts to fit through and secure to T-Posts.

Installations:

1. Upload code to the Arduino Nano (consult Appendix C: Code). Ensure code matches sensor range and proper measurement frequency is set.

   (Note: When uploading code, the sensor wires (blue and green) need to be detached from the *RX* and *TX* inputs to the Arduino Nano.)
2. Determine the area-of-interest (AOI) for observing. This should be an area experiencing erosion or likely to have deposition occur. Make sure the location will allow for secure placement of the SMS.

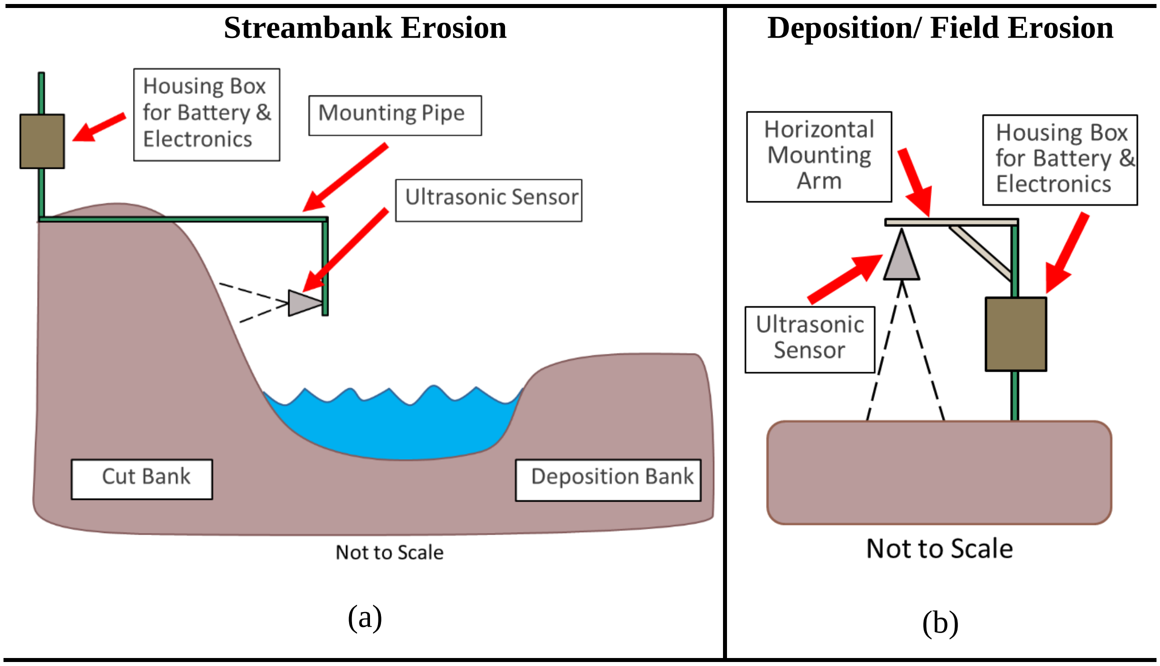
   (Note: If installing near a stream, confirm that the housing box can be mounted at an elevation above high water marks. This can be done by mounting it near the top of the T-Post.)
3. Installation and ultrasonic mounting styles will vary based on what is to be observed and on limits from each site. Ensure that the ultrasonic sensor is facing perpendicular to the AOI (See figure A.1 below).

   (Note: If using T-Posts to mount the SMS and using a horizontal mounting arm with a T-Post bracket, ensure the "T" of the T-Post is facing towards the AOI. Also, make sure the horizontal mounting arm is braced to prevent it from swaying and bouncing in the wind.)
4. Insert SD card into SD card adapter. Make sure there is a click denoting that the SD card was fully inserted into the adapter.
5. Connect the battery to the system and start collecting data. To ensure the system is recording the AOI, refer to the lights on the Arduino to determine if a measurement has been taken. The *TX* light should always be on, when the SMS is taking a reading the *RX* light will flash. Once the reading is taken the *RX* light will blink solid as it saves to the SD card and then turn off until the next reading.

   (Note: To force the system to record a measurement, press the reset button on the Arduino, white rectangle in the middle of the board adjacent to the system lights. This triggers the SMS to take a measurement and reset the measurement frequency timer.)

Maintenance:

1. Charge and replace batteries as needed. (Approximately 28 days with MightyMax 12V-22amp-hr battery)
2. When downloading data from SD card, cut power to the SMS, eject the SD card and download onto computer. Delete data from SD card but keep the TEST.txt file to ensure the system recognizes a file to store data to. Replace SD card and re-connect power to continue monitoring.
3. Check and update that the date and time is accurate during measurements. Sometimes the RTC is reset when the system is without power for extended periods of time.
4. Always keep the ultrasonic sensor mounted in the same position while moitoring an area. Changing the position will influence the distance reading and will give inaccurate values of erosion or deposition when compared to the previous position.
5. Ocasionally check the cone of the ultrasonic sensor to ensure no obstructions have lodged themselves in the cone and blocked the sensor's view.



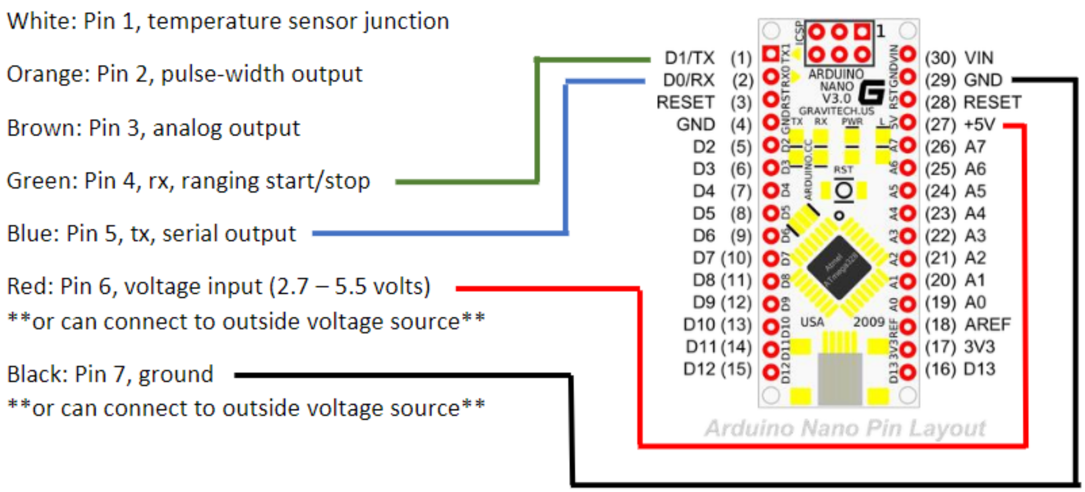
(a) (b)

Figure A.1 shows two different mounting techniques used for different SMS installations.

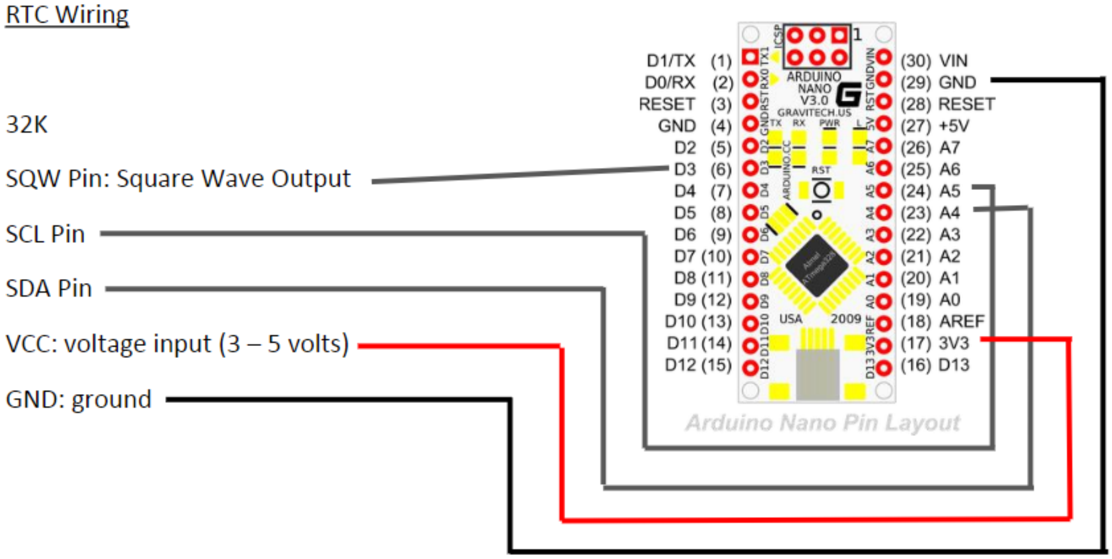
APPENDIX B: WIRING GUIDE

Included is the wiring diagram which shows how to connect the ultrasonic sensor, RTC and SD card module to the Arduino Nano. The pins connections shown here reflect the pin connections as defined in the code used for operation.

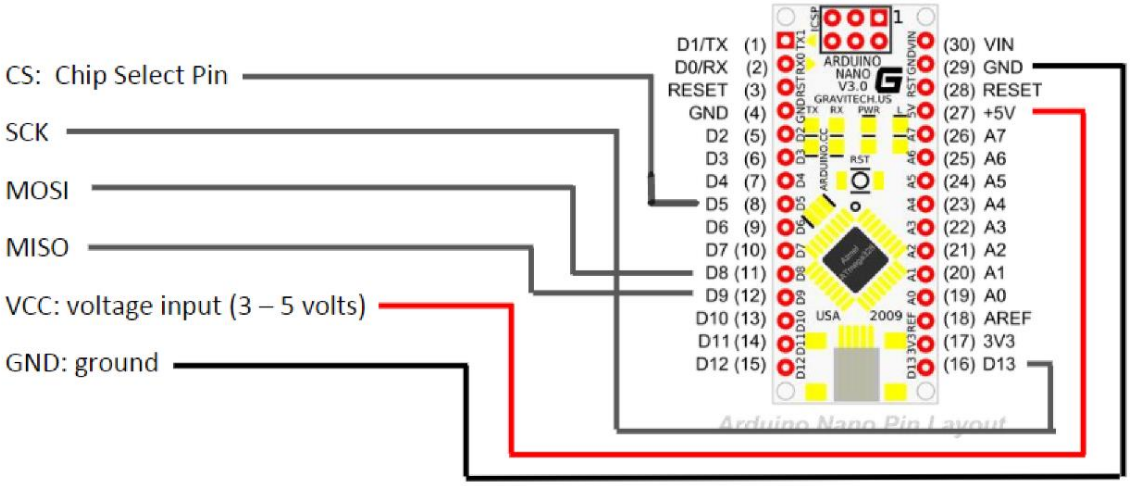
Sensor Wiring



RTC Wiring

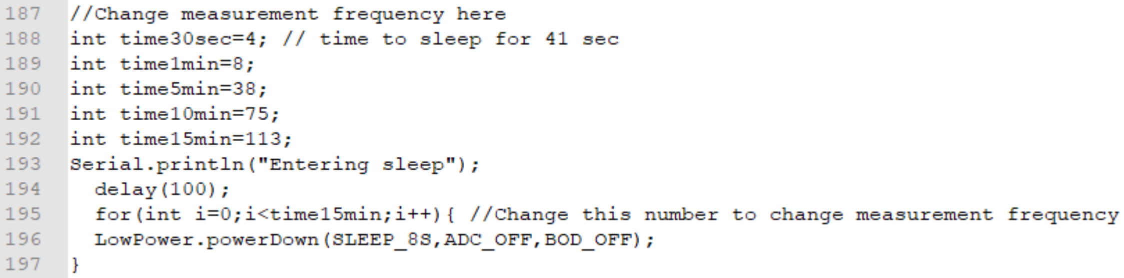


SD Card Module Wiring



APPENDIX C: CODE

Full scripts of the code used to control the SMS can be downloaded at https://github.com/jejohnson14/Sediment-Monitoring-System. Below are a couple lines of code showing how to change the frequency in measurement for the SMS.



```
//Change measurement frequency here
int time30sec=4; // time to sleep for 41 sec
int time1min=8;
int time5min=38;
int time10min=75;
int time15min=113;
Serial.println("Entering sleep");
  delay(100);
  for(int i=0;i<time15min;i++){ //Change this number to change measurement frequency
  LowPower.powerDown(SLEEP_8S,ADC_OFF,BOD_OFF);
}
```

The code is in total 213 lines and should be run using the Arduino code interface for ease of editing and uploading to the Arduino Nano microcontroller. Depending on the range of the ultrasonic sensor used, there are two scripts available on GitHub: MedianReading10M.ino and MedianReading5M.ino. They are the same script except the limiting distance for which an error in reading is thrown is changed to the corresponding range limit. Also included are scripts to help set the RTC clock and test the SD card module connection.