Integration of a real-time wastewater pond leak detection with precision livestock systems

B. L. Woodbury[1,*]
[1]*USDA, ARS-U.S. MARC, State Spur 18D, Clay Center, NE 68933, USA*
[*]Corresponding author: Bryan Woodbury, bryan.woodbury@usda.gov

Abstract

Wastewater generated during animal production contains contaminants that can degrade soil and groundwater quality as well as impact human health. Typically, wastewater is stored in earthen-holding ponds until it can be properly disposed. Subsurface leakage from these ponds is detected using monitoring wells. Monitoring wells have many difficulties inherent with them for effectively detecting leakage. An alternative was developed using resistivity arrays (RA). This technology improves monitoring by measuring multiple sides of a pond using one array and creates a near, real-time flow of information allowing for early leak detection. To automate the technology, a near-surface data analysis protocol was developed that had user-set thresholds to allow scaling of instrument sensitivity. The protocol used a statistical-based process for calibrating the reference data for a wide range of geological and geographical settings. This protocol allowed for the RA technology to continuously measure for leakage and when thresholds are exceeded, send an alert message to managers of potential problems. These advantages provide substantial improvements to production livestock managers for protecting soil and groundwater quality from wastewater pond leakage. The objectives of this paper are to detail the technology development, discuss the advantages with its real-time flow of more responsive information, and illustrate the application of the technology for incorporation with precision livestock management.

Keywords: groundwater quality, resistivity array, wastewater leak detection

Introduction

Runoff from animal feeding operations contains manure, pharmaceuticals, and endocrine disrupting compounds. Runoff is stored in holding ponds temporally to settle solids before being applied to agricultural land as an irrigation water. Protecting the environment from these contaminants is critical for environmental sustainability and human health.

Monitoring wells are the principle tool used for detecting leakage from holding ponds. Locating wells to intercept leaking contaminants requires detailed site geologic and hydrologic knowledge; however, this information is rarely available. Monitoring wells are costly to install and, if not properly sealed, can be a conduit to groundwater. Geophysical technologies have potential for improving leak detection while reducing risks with monitoring wells.

Materials and methods

One geophysical tool with the potential to improve leak detection is resistivity arrays (RA). The successful application of the RA technology for early detection of contaminant leakage relies on two principles: 1) positioning the technology close to the point of the leakage and 2) differentiating in the resistivity between the parent material and the contaminant plume that fills the pore space. The RA design used during the studies outlined in this paper were a four electrode, Wenner-Alpha configuration (Figure 1). An array of electrodes was placed in the soil at a predetermined equal spacing "a." A known current (I~) was applied to electrodes C1 and C2 creating a current in the bulk soil. The voltage potential (ΔV) was measured using electrodes P1 and P2. A resistivity measure of the bulk soil was determined using:

$$\rho = 2\pi aR$$

where ρ is the resistivity and R is the instrument reading (voltage/current)

The resistivity measure representative of the soil volume measured was located halfway between electrodes P1 and P2 at a depth of a/2. Using this concept, multi-electrode arrays of equally space electrodes can be placed near a pond perimeter. Measuring all four-electrode combinations with equal spacing created a curtain of measures at various lateral locations and depths near the pond perimeter (Figure 2).

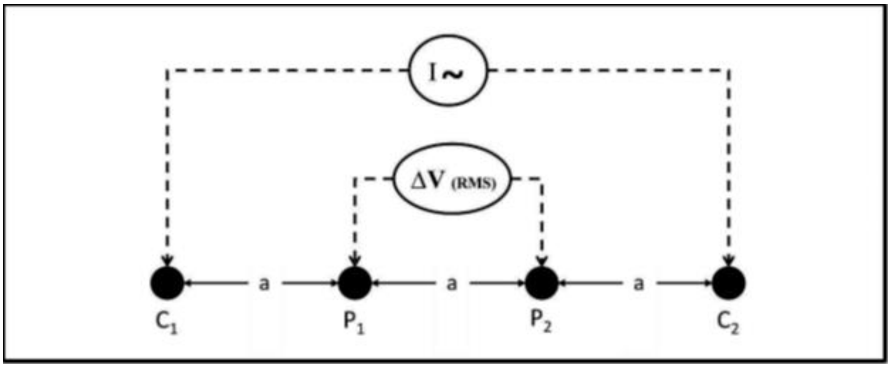

Figure 1: Representation of a four-probe array used to determine soil resistivity. C1 and C2 have current applied and P1 and P2 are used to measure electrical potential (Wenner-Alpha).

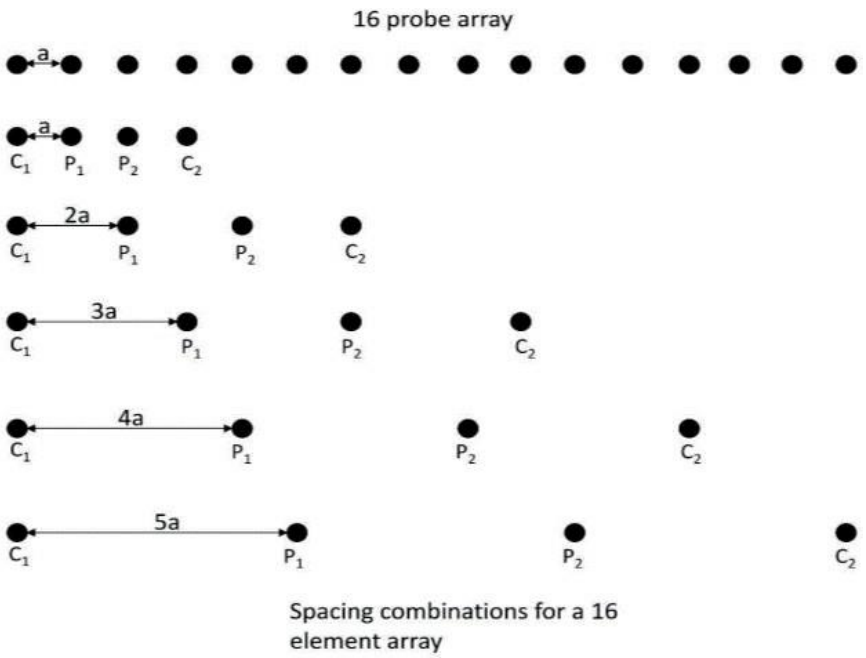

Figure 2: Representation of a series of four electrode combinations of a 16-electrode array.

A series of four studies were conducted developing the technology. The limitation of this paper prohibits sufficient details, so the reader is encouraged to reference Eigenberg and Woodbury, (2012); Woodbury et al. (2015); Woodbury et al. (2016), Woodbury et al. (2018). This paper will focus on improvements, data analysis and automation.

Two RA systems were proposed to be installed at a University of Nebraska's, Eastern Nebraska Research, Extension and Education Center (ENREEC) near Mead, NE (Figure 3). These sites required non-collinear arrays to allow for site limitations. The development and testing of non-collinear arrays are detailed in Woodbury et al. (2016); however, a brief description follows.

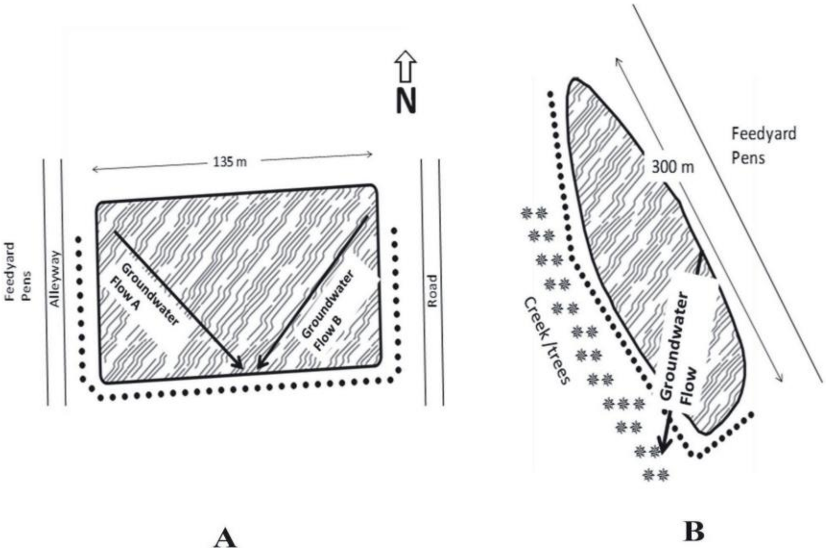

Figure 3: Schematics of A) north and B) south pond. Black dots denote RA electrodes.

The proposed electrode locations for the two arrays at the ENREEC site were geo-referenced using RTK GPS. The relationship of these coordinates was trans-located to a site so the exact configuration could be re-created at a test location with a uniform soil electrical conductivity (EC) depth profile (33.5 ± 10.8 mS m^{-1} average over all depths). The test site was a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls) with less than 1% slope and a depth to groundwater of 45 m. The test site's uniform EC profile allowed for the measured geometry factors (GF_m) to be back calculated the GF_m using an averaged value of the apparent resistivity for the given electrode spacing. Based on equation 3, GF could compensate for angular arrays for comparative purposes. The determination of a calculated geometry factors (GF_c) was accomplished using Telford et al. (1990) equation for two current electrodes (i.e., four probes) at the surface with excitation (current) across C1 and C2 and potential measurement between P1 and P2 (Figure 1) and the lengths between geo-referenced probes.

$$\Delta V = I/2\pi \{(1/C1P1 - 1/C2P1) - (1/C1P2 - 1/C2P2)\} \quad (1)$$

Where: C1P1 is the distance between probes C1 and P1

C2P1 is the distance between probes C2 and P1

C1P2 is the distance between probes C1 and P2

C2P2 is the distance between probes C2 and P2

ΔV is the potential difference between P1 and P2

I is the current flowing through C1 and C2

Solving for soil resistivity, ρ:

$$\rho = \Delta V/I * K \quad (2)$$

Where the geometry factor is defined as:

$$K = 2\pi/\{(1/C1P1 - 1/C2P1) - (1/C1P2 - 1/C2P2)\} \quad (3)$$

Discussion

It was hypothesized the GF_m could be used to validate GF_c, then site specific array configurations can use geo-referenced electrode locations as an input file for software designed for processing RA data. For comparison, the GFs were normalized by taking the measured resistivity values at the sub-surface sample location associated with each four-probe combination along the array divided by the average of all resistivity values for that depth. Equation 3 was used to calculate geometric correction factors along the array with probe locations determined by GPS coordinates; calculated values were normalized by dividing by the geometric factor of an equivalent collinear array.

A Kolmogorov-Smirnov-Test (KS-test) was performed to compare the calculated and measured data distributions. The KS-test seeks differences between two datasets; it is non-parametric and distribution free. The null hypothesis was that there is no difference between the two distributions and is rejected if the P value is smaller than the 0.05 test statistic. Additionally, linear regression was performed to determine the correlation between the calculated and measured datasets.

Figure 4 illustrates the similarities between the GF_m and GF_c. There is a slight deviation between the GF_m and GFc along the array primarily due to surface accumulation of organic matter accounted for in the GF_m and not in GF_c. The KS-text indicated no difference between the two methods; therefore, the GF_c is an acceptable method for correcting non-collinear arrays to be used for comparative purposes. The proposed methodology allows leak detection systems to be installed that conform to specific site geometries. It should be noted the correction of the proposed, permanently installed non-linear array was to improve detection (i.e., change with respect to time) and not accuracy of the measure relative to the volume of soil evaluated.

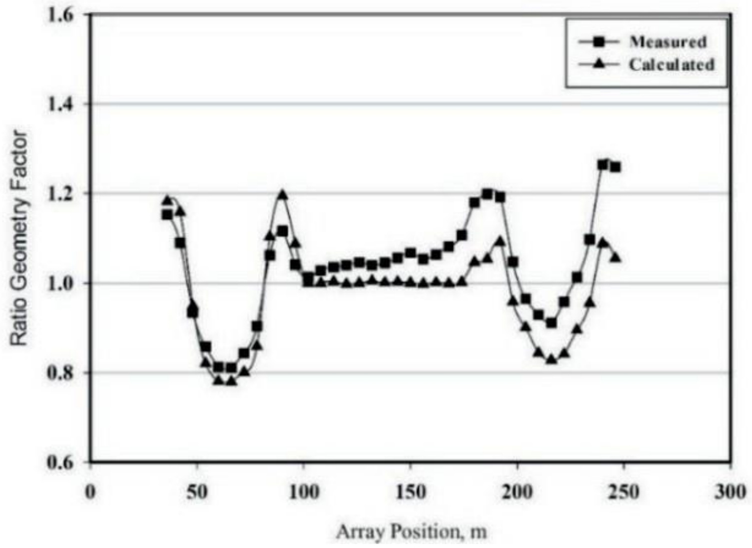

Figure 4: Resistivity readings were taken along a non-collinear array. Normalized measured values are the ratio of the resistivity at a location along the array divided by the average of all resistivity values for that spacing of a = 18m (n=3). Equation 3 was used to calculate GF along the array with probe locations determined by GPS coordinates; calculated values were normalized by dividing by the geometric factor of an equivalent collinear array.

Near-surface analysis for early warning leak detection

Traditional data processing of RA data was insufficient for detecting leakage near surface. Therefore, a new method was specifically designed to meet the needs for the new use of the RA. The new method needed to be statistically based and have user-set thresholds to facilitate adaptation to varied geological and geographical locations. Also, it was anticipated this protocol could be incorporated into software for detection. This would allow the technology to continuously measure for leakage and automatically alert a manager of potential problems, making a near real-time detection system.

The data from a 32-probe RA system is represented in Figure 5. Each black dot represents a centroid measure for a discrete volume of soil around the perimeter of a pond. Because probes are installed permanently, the volume of soil does not change from reading to reading. The collection of these values for a specified period establishes a reference data set that are used to determine a mean, standard deviation, and distribution. With these statistical parameters, a Z-score is used to determine if current volume readings are different from the reference set:

$$Z = (x - \mu)/\sigma \,, \tag{4}$$

where x is the current measured sub-surface location (MSL) resistivity value; μ is the mean resistivity of that MSL established by the reference data, and σ is the standard deviation of μ. The Z-score indicates whether a current apparent conductivity for a discrete soil volume is equal to (Z-score = 0), below (Z-score < 0) or above (Z-score > 0) the mean of the reference date. For example, with a sufficiently large number of reference conductivity measures for a particular soil volume, about 68% of the elements have a Z-score between -1 and 1; about 95% have a Z-score between -2 and 2; and about 99.7% have a Z-score between -3 and 3. Typically, leak analysis will focus on increases or positive Z-scores; however, negative Z-scores can provide additional insights into the function of the pond liner or wastewater conveyance system.

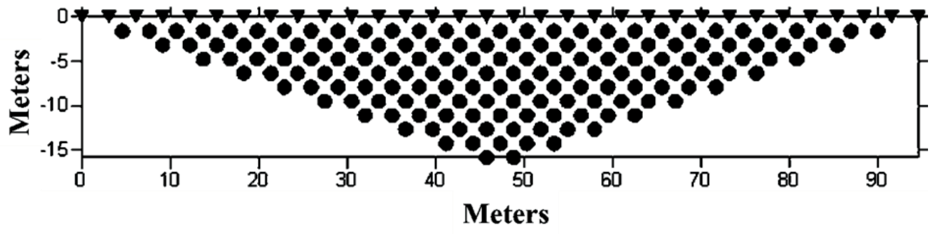

Figure 5: Representation of a 32-electrode (top row, inverted triangles) array showing the general location for each measured subsurface location (black dots). Statistical parameters are determined for each measured subsurface location to be used as the reference data set.

User-set thresholds are established in the statistical inferencing by Z-score. The first is the establishment of the reference data set. For most applications, the collection of reference data for an entire year provided a complete reference for seasonal variability and the number of readings for the statistical power required for a critical Z-score review of the data. Analysis of the variability allows for review of the seasonal stability of the measure. Also, the collection of the reference data at the site can be used as comparison to values of the installed array. This is helpful for sites that have been in service for some time. An example of not using a complete year's data is a Central Nebraska site (Woodbury et al., 2015). During the winter months, the pond emptied, and soil conductivity measures decreased. When the pond filled, conductivity values increased. The seasonal variation for this situation made it difficult to detect significant changes using Z-score. When the reference values were selected that represented the period when the pond was empty, the sensitivity improved by reducing the standard deviation. More detail for this can be found in Woodbury et al. (2018).

The second threshold is the selection of the value of the Z-score that indicated changes in the soil quality. For most purposes, a Z-score of 3.0 is sufficient for most leak detection; however, more narrow values could alert manager of potential problems long before contaminants leak. Using narrower Z-score values and re-evaluating historical data allowed the identification of a conveyance structure of the wastewater control system that was not functioning as designed. During a re-evaluation of data from the ENREEC site using a narrower range of Z-scores, a problem in an underground conveyance system draining a series of feedlot pens to the wastewater holding pond was identified. This was not a leak but an inefficiency limiting transfer. This information was used by the facility manager to correct the conveyance system. Further evaluations of the data since the repair confirm the effectiveness.

The next user-set threshold is the number of discrete MSLs that exceed reference data during a specific sample time. Inherent in the RA data and electronics are spurious values that result in occasional false detection of soil quality changes. These spurious readings can be very transitory and random through the RA profile and generally don't persist from sample period to sample period. A threshold number of MSLs that exceed during a sampling time can be set to filter out false positives for leak detection. In the past, percentages between 5% and 10% have been effective for filtering out false-positive while still providing sufficient protection. It is anticipated this number will decrease as greater robustness and experience using the automated leak detection system improves.

The next threshold is the length of time the discrete soil volumes exceed the reference data. An example for this is one of the ponds at the ENREEC site. Much of the permanently installed array is in a flood zone of a nearby creek. After an intense precipitation event, water from this creek flooded the area with the array. This caused several discrete MSLs, primarily near surface, to exceed the reference data. With an automated system with telecommunication capabilities, this event would have triggered an automated leak alert. The water receded within a few days and the values returned to normal. In a case such as this, managers alerted of the potential problems could visually investigate whether the site was flooded causing the alert to be a false positive. Weather data at the site or image capture of the area could easily be incorporated with the RA system to aid in this determination remotely.

Conclusions

Wastewater ponds have been used for a very long time and many were constructed before leakage monitoring was required. Also, pond construction standards have evolved over time to the regional and national standards required today. This evolution has caused a wide range of concerns, particularly for older systems not constructed to current standards. The RA leak detection technology could provide a cost-effective alternative to monitoring wells, provide improved monitoring, near real-time information on pond seal integrity.

An established wastewater pond that has no monitoring is a situation replete with uncertainty. Environmental risk from this pond increases for water tables near the soil surface. Proper installation of monitoring wells is expensive, require detailed geologic information and generally take years of data before any conclusions can be made concerning leakage. Alternatively, construction of a new wastewater pond meeting current standards is also an unappealing solution due to cost. The RA technology could be installed and begin providing information on the integrity of the pond seal for contaminant. Though establishment of a site database may take up to a year to fully implement data analysis, insight on the pond seal could begin much sooner. For ponds where the groundwater is deep, and risk of contamination is low, temporary RA systems could be installed to periodically evaluate the pond seal integrity.

Early detection

Monitoring wells can detect contaminant leakage only after the contaminant reaches groundwater at which time it becomes diluted and very difficult to measure. Also, monitoring wells are physically sampled only a few times per year. As a result, leakage from ponds can go on for years before detection by monitoring wells.

Modification to traditional array designs allow for a dense curtain of soil and groundwater quality measures to be taken around the perimeter of a pond to depths of 100 feet or more. This puts the measures in very close proximity to the point where contaminants leak from the pond. Additionally, these measures can be taken daily thereby detecting leakage much sooner than monitoring wells. This allows the new technology certain advantages: 1) early detection for intervention before groundwater is catastrophically contaminated, 2) increased sensitivity to detect changes in soil and groundwater quality, 3) proximity of the quality measures eliminates the necessity of correctly locating monitoring wells in the pathway of complex subsurface flow to intercept contaminated groundwater, and 4) knowing where the seal breech is within the pond allows for quick repair.

Automated leak detection

The digital format of the leak detection technology allows for automation. A statistically based, analysis software was developed that greatly simplifies interpretation of the complex data. The analysis protocol use reference data collected at the site thereby allowing it to accommodate a wide range of geological and geographical settings. This analysis allows for pond managers to adjust detection thresholds to adapt the sensitivity specific for the site. Using different thresholds also allows the pond manager to be alerted earlier of potential problems before the contaminant reaches the groundwater. Also, it allows the pond manager a review of historic data to identify inefficiencies with the wastewater control structures. This approach was used to identify system inefficiencies in a couple of demonstration sites. These inefficiencies were not leaks but indications the control system was not functioning as designed. With this information, the systems were maintained to function as designed.

Finally, the leak detection system will constantly measure soil and groundwater quality, compare these values to reference data, like the operation of a household smoke detector. When thresholds are met, a message will be sent to the manager using telecommunication technology alerting them of potential problems. Managers can investigate and determine if there was leakage, or the alert was triggered by conditions not associated with leakage.

Future application of the leakage detection technology

The leak detection technology was originally designed for agriculture; however, industries outside of agriculture probably have the greatest potential for using the technology. Interest in the technology for wastewater pond management has come from mining, oil and gas exploration, electrical generation, municipalities, landfill and other wastewater generating industries. Each of these industries or municipalities have specific contaminants and situations that will require modification of the technology to meet their needs. Work continues to improve the efficacy of the technology for leak detection; however, the data presented illustrates advantages for improving environmental management.

Agricultural producers are pulled in many different directions from making decisions concerning production to business and finance management. Because of this, inspections and reporting for environmental compliance can become burdensome. The digital framework of the technology is adaptable for including most any digital instrumentation such as pond level measures, weather data, etc. Another advantage of the electronic format would be the incorporation of other control systems like irrigation systems. Precision application of the technology could automate management of the wastewater pond level. Precipitation forecasts could be additional information used in the programming. Additional applications will follow by innovations of managers searching for solutions to problems or improvements in efficiencies. The digital framework of the leak detection technology and potential for automation is a small component of a larger, more complex livestock production system attempting to achieve precision through the flow of information.

References

Telford, W.M., Geldart, L.P., and Sheriff, R.E. (1990) *Applied Geophysics*, 2nd ed.: Cambridge University Press, New York, NY.

Woodbury, B.L., Eigenberg, R.A., and Franz, T. (2015) Resistivity arrays as an early-warning system for monitoring runoff holding ponds. *Journal of Environmental and Engineering Geophysics* 20(4), 319-335.

Woodbury, B.L., Eigenberg, R.A., and Franz, T.E. (2016) Development of non-collinear arrays for use near wastewater holding ponds. *Journal of Environmental and Engineering Geophysics* 21(4), 231-236.

Woodbury, B.L**.,** Eigenberg, R.A., Minns, H.G., and Ndegwa, P.M. (2018) Data analysis protocol for using resistivity array as an early-warning wastewater pond leak detector. *Journal of Environmental and Engineering Geophysics* 23(2), 251-260.