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Resistivity Arrays as an Early Warning System for Monitoring Runoff Holding Ponds

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ABSTRACT

Monitoring wells are installed to intercept contaminants inadvertently discharged from in-ground structures designed to retain salt-affected wastewaters; however, several difficulties with collection and data interpretation limit their effectiveness. Therefore, improved monitoring methods are needed. The objective of this study was to evaluate the effectiveness of resistivity array technology as an early warning system to monitor for unintended basin discharge. Subsurface resistivity arrays were installed at two Nebraska sites: a beef cattle feedyard located at the U.S. Meat Animal Research Center, Clay Center, Nebraska (FyA) and a commercial cattle feeding operation (FyB). Monitoring well data did not identify any unintended discharge events during the study period. However, the resistivity array (RA) system detected a discharge event that was localized in the non-saturated zone adjacent to the pond at FyB within one day following a precipitation event. Monitoring the unsaturated portion allows the RA system a capacity beyond traditional monitoring wells, which can only intercept discharge carried in groundwater. Also, the RA system effectively measured a larger area (*i.e.*, a virtual curtain) compared to the point measure typical of monitoring wells. Therefore, RA technology provides broader coverage and is more tolerant to placement issues for intercepting discharge. Finally, the capacity to automate the RA system provides a means to continuously monitor unintended subsurface discharge from runoff holding ponds. This continuous monitoring system is more likely to detect discharge events than the bi-annual sampling typically required for monitoring wells. Automatic and continuous monitoring provides feedyard operators options to better manage environmental impacts associated with runoff holding ponds.

Introduction

Runoff holding ponds are used to store a variety of liquids including drilling waste, coal ash slurry, fracking fluid and agricultural runoff (Parker *et al.*, 1999a; Hilson and Murck, 2001; Schramm, 2011). Runoff storage facilities for CAFO (confined animal feeding operations), which are cattle feedyards with 1,000 head capacity or more, are regulated by the National Pollution Discharge Elimination System runoff storage rule. This rule states that runoff control systems must contain all manure/wastewater including runoff and direct precipitation from a 25-yr, 24-h storm event. In addition, these ponds must hold all runoff during the winter and early spring months when land application, used for dewatering the ponds, is impractical. Feedyards typically comply with the liquid runoff requirements through construction of holding ponds of sufficient size to meet required standards. Runoff

holding ponds contain elevated levels of suspended and dissolved organic compounds, mineral salts and other nutrients (including nitrate-nitrogen, ammonium, and chloride ions) (Gilley *et al.*, 2009). In addition, feedlot runoff may contain other compounds of environmental interest such as pharmaceuticals and endocrine disrupting compounds (Dolliver and Gupta, 2008; Bartelt-Hunt *et al.*, 2012). Thus, protecting the underlying soil and groundwater from unintended discharge of these constituents is critical.

Some states regulate animal runoff holding ponds by setting limits on either the maximum infiltration rate or the maximum saturated hydraulic conductivity of the media lining the pond (Parker *et al.*, 1999a). Additional studies have shown that organic solids in the manure form a seal as it passes through soil liners helping to reduce infiltration rates (Chang *et al.*, 1974; Cihan *et al.*, 2006). Numerous studies have been conducted to measure and predict infiltration flux with inconsistent

conclusions (De Tar, 1979; Culley and Phillips, 1982; Roswell *et al.*, 1985; Miller *et al.*, 1985; Barrington and Madramootoo, 1989). Tyner and Lee (2004) concluded that relying on the presence of a manure seal to limit flux may not be warranted since it is not present initially, and may sustain damage if the liquid manure is mixed and/or pumped. Also, a manure seal may not adequately limit infiltration on the pond side walls, which can be a major source of leakage (Parker *et al.*, 1999b). Monitoring potential seepage is necessary to ensure protection of groundwater and soil impacted by holding ponds.

Monitoring wells are the principal means used for detecting subsurface discharge from feedyard runoff holding ponds. For example, the state of Nebraska currently has 272 operations with a series of wells that require semi-annual monitoring (NDEQ, 2013). The proper location of a monitoring well requires close attention to the specific site's geologic and hydrologic characteristics. Detailed information of these characteristics for any particular site is rare; therefore, best estimates are made for determining the ideal number and location of monitoring wells required for proper site assessment. An additional consideration for the installation of monitoring wells is selection of well casing composition, well screen material, and size as well as casing sealing methods (Barcelona *et al.*, 1983). All these considerations can be costly and, if improperly constructed, can be a source of contamination via a direct conduit to the groundwater along the well casing wall (Barcelona *et al.*, 1985; Exner and Spalding, 1985; Ross, 2010). Alternative monitoring methods using geophysical techniques have the potential for providing subsurface information of the site, supplementing information on pond discharge performance, and reducing the total number of wells required for adequate monitoring.

One geophysical tool with the potential to enhance monitoring efforts is the resistivity array (RA). This technique has its origin in the 1920's based on work of the Schlumberger brothers (Loke, 2004). The basic array is constructed of four probes; the two outer probes supply current and the two inner probes are used to read the potential or voltage, which when combined with the excitation current yields an apparent resistance. The spacing between the probes establishes the approximate depth of the array's measurement. This basic construct has been used by geophysicists, archaeologists, mineral and oil prospectors, and geologists since its inception. More recently, such arrays have new applications including mapping of landfills to determine their extent of impact (Carpenter *et al.*, 1990). The successful application of these methods to monitoring of waste management sites relies on conductivity differences

between the parent material and the potential contaminant plume. Additionally, monitoring requires a stable and accurate measurement technology.

Agricultural applications of resistivity methods have been limited to field mapping systems (Allred *et al.*, 2008). One commercial system is the Veris® 3100 Soil EC Mapping System (Veris Technologies, Inc. Salina, Kansas). It uses six rolling steel coulters that penetrate the soil providing two depths via two Wenner arrays (Allred *et al.*, 2008). The Veris is typically pulled behind a towing vehicle that makes a serpentine path through a field and creates a two-dimensional map of the field to the specified depth. A capacitively coupled system called an OhmMapper TR1 (Geometrics, Inc., San Jose, California) produces readings similar to a conventional galvanic contact electrode array; however, the signals are coupled to the soil by a source signal of 12 to 20 kHz and a special cable to provide coaxial capacitive coupling. The OhmMapper is pulled through an agricultural field and apparent resistivities are collected by a datalogger. The use of galvanic resistivity methods in agriculture have concentrated on field scale, mobile units. The application of stationary, multi-electrode resistivity arrays have had limited application in agriculture since these systems typically require tedious/expensive switching systems and a cumbersome array of probes and wires. Currently available technology may alleviate some of the drawbacks, allowing the capabilities of these methods to be explored and utilized.

This study built on previous work that showed resistivity arrays had sufficient stability, resolution and sensitivity to monitor temporal dynamics at boundaries near cattle runoff holding ponds. A preliminary study was conducted to develop methods, investigate available technology, examine stability, consider seasonal influences, and test the practicality of the use of resistivity methods (Eigenberg and Woodbury, 2012). The objective of this investigation was to evaluate the effectiveness of resistivity array technology as an early warning system that can detect unintended discharge events from runoff holding ponds. Also, an evaluation was performed to compare the effectiveness of resistivity array technology and monitoring wells for detecting unintended discharge events from runoff holding ponds.

Materials and Methods

Feedyard Sites

Two sites were selected for testing: the first is located at the U.S. Meat Animal Research Center feedyard near Clay Center, Nebraska (designated as Feedyard A (FyA)), and the second is a producer cooperator located in central Nebraska designated as Feedyard B (FyB). The soil at FyA is a Crete silt loam

(fine, montmorillonitic, mesic Pachic Argiustolls). The landform setting for the soils at FyA are nearly flat (0 to 2% slope) interfluvial with a loess parent material. These soils are deep with depth to restrictive layer greater than 2 m. The saturated conductivity of these soils below the argillic layer is approximately 0.25 to 0.5 cm hr⁻¹. FyB has a fine loam over sandy or sandy-skeletal, mixed, superactive, calcareous, mesic Pachic Argiustolls. The landform setting of these soils is nearly flat (0 to 2% slope) flood plain with a stratified loamy alluvium material. The soils at FyB are deep with depth to restrictive layer greater than 2 m. The saturated conductivity of these soils below the surface layer would be approximately 2.5 to 5.0 cm hr⁻¹. Soils for both sites are formed above the Niobrara bedrock formation. Soil textural analyses by depth for each site are listed in Table 1. Depth to ground water is over 40 m at FyA; the groundwater level at FyB is approximately 4 m. Feedyard A is a 6,500-head feedyard with the holding ponds servicing approximately 3,500 head; Feedyard B is about 10,000 head with two holding ponds servicing the feedyard. The dimensions of the pond at FyA are 75 m × 30 m and at FyB are 150 m × 60 m. Annual average precipitation for both sites is approximately 70 cm.

Management of the Sites

Feedyard A contains four liquid impoundment structures connected in series; the first structure is used as a solids settling basin. The second pond in the series, which has a depth of approximately 5 m, was monitored using the resistivity array (Fig.1). The two additional ponds in the series are pumped as needed to maintain total runoff holding capacity; timing for discharge is determined by the holding capacity of the soils to which the effluent is applied.

Feedyard B is equipped with two holding ponds; one pond services the south series of pens and the second pond services the north series of pens. The north pond was selected as the subsurface monitored site since it was equipped with monitoring wells and had a history of site evaluation. This pond has a depth of approximately 2.3 m (Fig. 2). Effluent from both ponds is used for irrigation of cropland and irrigation events are scheduled according to crop requirements and water holding capacity of the soil. The FyB holding pond was recently replaced with a lined pond. Measurements at the old pond site were continued during the current study.

Pond Water Depth Monitoring

Holding pond water depths were monitored weekly beginning in July of 2011 at FyA and FyB using a staff gauge. Time-lapse WingSCAPES® model WSCT01-00114

Table 1. Soil textural percent sand, silt and clay by depth at feedyards A and B. Samples were collected at various locations along the lateral array element. Percentages varied slightly along the lateral, particularly at FyB; however, only one centrally located analysis from each site is presented to illustrate typical values.

Site	Array location	Depth cm	Sand %	Silt %	Clay %
FyA	8.5	152.4	13	59	28
FyA	8.5	213.4	15	53	32
FyA	8.5	274.3	11	63	26
FyA	8.5	335.3	17	55	28
FyA	8.5	396.2	13	61	26
FyA	8.5	457.2	15	57	28
FyA	8.5	518.2	15	59	26
FyA	8.5	579.1	17	53	30
FyA	8.5	640.1	25	49	26
FyA	8.5	701.0	27	41	32
FyB	18.5	30.5	53	30	17
FyB	18.5	91.4	31	43	26
FyB	18.5	152.4	51	23	26
FyB	18.5	213.4	89	7	4
FyB	18.5	274.3	93	3	4
FyB	18.5	335.3	85	11	4
FyB	18.5	396.2	91	5	4
FyB	18.5	457.2	88	10	2

cameras (EBSCO Industries, Inc., Birmingham, Alabama) were installed in April and May of 2012 at FyA and FyB, respectively. This setup provided three images per day of the staff gauge and water depth. A 93720 SDX Pressure Sensor (Stevens Water Monitoring Systems, Inc., Portland, Oregon) was installed in April and June, 2013 at FyB and FyA, respectively, to provide continuous readings of pond depth.

Monitoring Well Data

There are no monitoring wells installed at FyA. However, several sets of monitoring wells were present at FyB. Two sets of monitoring wells, MW-2 and MW-10, were selected for instrumentation. These wells were located adjacent to the east end of the pond (Fig. 2) and were selected because they are within three meters on either side to the permanently installed RA system. Each set of monitoring wells (*i.e.*, MW-2 and MW-10) are comprised of three separate wells with shallow (S), middle (M) and deep (D) screened depths that are 3, 4.5, and 10 m, respectively. A thin clay layer separated the middle and deep screened well depths. During June of 2012, the Nebraska Department of Environmental Quality instrumented these wells with groundwater

Figure 1. Feedyard A contains four liquid impoundment structures connected in series; the first structure is used as a solids settling basin. The second pond (shown in this schematic) is monitored by the resistivity array. Depth to groundwater is approximately 40 m.

Figure 2. Feedyard B is equipped with two holding ponds; the north pond (shown in this figure) was investigated since it was equipped with monitoring wells and had a history of site evaluation. Effluent from this pond is used for irrigation of cropland and is scheduled according to irrigation requirements and water holding capacity of the soil. Groundwater depth averages 4 m.

data loggers that continuously recorded water level, temperature, and electrical conductivity at the screened portion of each well. Shortly after the installation of the data loggers, the water level at the site dropped below the three meter depth. This drop in the water table left the shallow well depth dry and the data loggers were removed from the shallow depth wells.

Water samples were periodically collected from each well until the unintended discharge event that was identified from the RA; subsequently, samples were collected more frequently. Water samples were collected by a licensed Water Well Monitoring Technician following groundwater standard operating procedures GW-60, 61, 70, 100 and 140 (NDEQ, 2003). Water samples were removed from the wells using a submersible pump designed for sampling monitoring wells. Approximately five well volumes of water were purged from each well prior to collection of the water samples. The temperature, pH and EC of the water being purged from the well were periodically measured to determine stability. When the temperature, pH and electrical conductivity (EC) measures of the purged water were consistent, it was assumed the water being sampled represented aquifer water. Samples were transported to a commercial laboratory for analysis within 24 h after collection.

Resistivity Array Configuration

At FyA, a Miller 400D digital soil resistance meter (M.C. Miller Co., Inc., Sebastian, Florida) was used during this study. At FyB the same commercial resistivity meter was used until 1 October 2012, when a prototype of a remotely accessible soil resistivity meter was installed. Comparisons between meters were made to determine the consistency of the prototype with the commercial meter. After several tests it was determined that both meters provided comparable data.

Installation of the probes at each site is detailed in Eigenberg and Woodbury (2012); however, a brief description follows to aid the reader. At FyA, a 16-element array assembly was built that included a cluster of precut wires placed in a PVC conduit with a junction box every 6.1 m that was located in a 30-cm deep trench. These junction boxes served to provide access for a 60-cm stainless-steel probe that was inserted through the bottom of the box into the soil. An insulated wire was connected to the end of each probe; wires from all probes were directed to a central connection panel allowing combinations of probes to be selected and resistivity values read. The 16-element array had a 6.1-m probe spacing (overall length of about 91 m). This allowed collection of a subsurface vertical cross section of apparent resistivity to an approximate depth of 16 m. The array was operated as an in-line, four-electrode,

Wenner Alpha configuration. The Wenner-Alpha design has a high signal to noise ratio, making it a robust, stable configuration for monitoring fixed arrays (Loke, 2004). The four-electrode configuration was moved laterally across the region by sequentially incrementing the probes in the connection panel. Increasing depth is accomplished by enlarging the spacing between the probes.

At FyB, a 32-element array was constructed using the same Wenner-Alpha design. Wires and probes were buried in a trench to a depth of 60 cm for the portion of the array that was not under crop land and a minimum of 120 cm for that portion under cropland. The probe spacing was 3.05 m (an overall length of about 94 m), which allowed a subsurface vertical cross section to an approximate depth of 16 m. Feedyard A and B were both examined to the same depth; however, the closer probe spacing and increased number of probes at FyB resulted in over four times as many data points compared to FyA.

Data were converted to conductivities to be consistent with previous work involving subsurface electromagnetic soundings. These conductivities were presented as a pseudosection in which the data were interpolated using Surfer® (Golden Software, Inc., Golden, Colorado). While pseudosections are not applicable for more advanced and complex geophysical interpretations, these images provide a consistent representation of the subsurface EC profile. This allows for comparisons of the temporal and spatial changes in the EC profile. However, if site structural geologic details are needed, then inversions can be performed.

Weekly data collections were performed at both FyA and FyB. Each collection was analyzed by visual inspection for changes from the previous survey. Additional analysis included differenced maps that were produced by subtracting the previous week's profile from the current week. These difference maps provided a means to visually inspect for changes. Differenced maps are a powerful tool because they eliminate stable features that were common to both maps (*i.e.*, soil properties and geologic features) and they accentuate differences that occurred over the selected time period.

Soil Temperature Correction

Soil conductivities are affected by temperature (Corwin and Lesch, 2005). Therefore, temperature depth profiles were obtained at each site using thermocouple probes. A soil core was first removed to allow a 1.27-cm diameter pipe fitted with thermocouple sensors at specific intervals. An Omega OM-CP-OCTTEMP-A eight-channel thermocouple logger (Omega Engineering, Inc., Stamford, Connecticut) was used to acquire temperature profile data. The sensor intervals at FyA

were 0.5, 1, 2, 3, 4, 5, 6 and 7 m; while sensor intervals at FyB were 0.5, 1.5, 2.5, 3.5 and 4.5 m. Depth of installation at FyB was limited by the groundwater level.

Soil temperature data were collected from April 2012 through December 2013 at FyA and from November 2012 through December 2013 at FyB. Corwin and Lesch (2005) stated that electrolytic conductivity increases at a rate of approximately 1.9%/°C temperature. Sheets and Hendrickx (1995) developed a relationship that referenced the correction factor to 25°C as given by:

$$F(t) = 0.4470 + 1.4034e^{(-t/26.815)} \quad (1)$$

Temperature effects are an important consideration when developing threshold levels for distinguishing unintended discharge events from normal background fluctuations.

Electromagnetic Induction

A Dualem-1S (Dualem, Inc., Milton, Ontario, Canada) was used to measure soil conductivity at shallow depths in the vicinity of the ponds. This instrument was invaluable for initial site investigations and for quick assessments of subsequent unintended discharge events. The Dualem-1S is a dual geometry sensor that uses a transmitter and receiver horizontal coplanar (HCP) coil (*i.e.*, the coils lie in the same horizontal plane arrangement). The instrument incorporates a second receiver coil, which is perpendicular (PRP) to the first, that allows two signals and hence two depths to be measured simultaneously. The HCP and the PRP depths measure response volumes that are centered at about 1.5 and 0.75 m, respectively. The Dualem-1S was pulled on a sled by foot at about 1-2 m s⁻¹. A serpentine traverse was followed using 3-m spacing between transects lines. The Dualem data were recorded at a rate of 4 samples s⁻¹.

Soil Collection and Analysis

Soil samples were collected using a hydraulically operated hammer probe that collected a 3-cm diameter core. Samples were collected in the fall of 2012 adjacent to selected probes along the array at FyA down to 7.5 m and to 5.5 m at FyB. Cores were divided into 30-cm segments, placed in pans, homogenized and air dried. Once the soils were air dried they were placed in a soil bag and stored until they could be analyzed for pH (1:1), EC (1:1), NO₃-N, total nitrogen (TN) and total phosphorus (TP) by a commercial laboratory. These data were not included as no discernible patterns were identified. An additional set of soil samples were collected during the

fall of 2012 at each site to determine soil textures. Another set of soil samples were collected during the summer of 2013 at an identified unintended discharge site and analyzed for the same constituents.

Data Analysis

Analysis of data from the installed resistivity arrays relied heavily on visual interpretation of maps and plots. The initial collection interval was usually weekly or bi-weekly, depending on time of year, accessibility and resources available. Feedyard B was equipped with a remote access resistivity meter making frequent data collection feasible. Images were processed by creating 2-D data files that were then processed using Surfer®. These files were used to generate pseudosection images of the subsurface apparent conductivity, which were used to produce difference maps for evaluating EC profile changes during a selected time period. Interpolation methods within 2-D plotting programs tend to smooth out features making them less apparent. Additional analysis was incorporated in early 2013 using an alternative method. This method used a differenced plot (illustrated by Fig. 4(A-D)), which highlights changes over the time period in depth and position along the array.

Results and Discussion

Expanding on work evaluating the installation and operation of resistivity arrays as a monitoring system detailed in Eigenberg and Woodbury (2012), continuous RA data were collected from both FyA and FyB for approximately two and a half years to determine its efficacy for quickly responding to salt released from holding ponds. Evaluation of the pseudosection images of the EC profile as a time-lapse process confirmed cyclical expectations based on the hydrogeologic properties of the two study sites. The time-lapse EC profiles at FyA were relatively stable over the evaluation period. However, the time-lapse EC profiles at FyB were much more dynamic.

In general, unintended discharge events were driven by depth of water in the runoff holding pond. Depth of water in the ponds varied throughout the year depending on the precipitation received and the amount of water removed for irrigation. The typical irrigation season extended from late June through late August. The greatest depth of water in the ponds was typically recorded between April and September (Fig. 3).

Total annual precipitation at FyA for 2011 through 2013 was 701, 665, and 866 mm, respectively, and at FyB was 866, 407, 815 mm, respectively. The holding pond at FyA experienced similar precipitation patterns as FyB, with low precipitation during the summer 2012 and through the winter 2012/2013; this dry period was

Figure 3. Monthly precipitation totals and pond levels for feedyards A and B during the study period. Note the annual total list for each year of the study period.

followed by increased rainfall events beginning April, 2013. The majority of the precipitation at both sites was received from April through August (Fig. 3).

Feedyard A

The RA system was installed within 3 m of the full pond edge at FyA (Fig. 1). This location was chosen to prevent interferences with a nearby gas pipeline and

minimize its impact on the array readings. By comparison, the array at FyB was approximately 12 m from the edge of the full pond (Fig. 2). In retrospect, the array at FyA was too near the pond edge to effectively differentiate normal hydration zone fluctuations around the pond from unintended discharges.

The FyA data were very consistent for most of the monitoring period as the low hydraulic conductivity

Figure 4. Differenced plots (April 9th minus April 1st) showing the increase in apparent electrical conductivity at the 1.6, 3.2, 4.8 and 6.3-m depths. A zero change in conductivity would result in a straight line across the array length for the specified depth. Increases or decreases in EC_a during the period results in deviations above or below the assumed straight-line zero change. Note: the conductivity measured below the depth of 4.8 m is responding to the presence of ground water.

soils limited flow. However, a large precipitation event (76 mm) near the end of May resulted in a one meter rise in water level (Fig. 3). Resistivity array data were collected manually at FyA on a one or two week interval. Data collected on May 31, and analyzed on June 3, revealed a notable rise in soil conductivity. Resistivity data collected again on June 3 indicated that conductivities had returned to near pre-storm levels. Additional site investigation (vertical soundings and soil core data not shown) did not reveal any lingering impact from the large precipitation event. Even though FyA soils exhibit low hydraulic conductivity, the soil of the pond sides cracked creating channels away from the pond after an extensive dry period. This channeling was exacerbated by weed growth and the resulting roots that penetrate the pond bank (Parker *et al.*, 1999b). During late fall and winter these roots desiccate and left flow paths that were immediately filled at the onset of pond fill. Because of the location of the array near the pond

edge and the sensitivity to EC profile changes, the RA monitoring system responded to this channeling. Based on additional on-site investigation, it was determined the channeling was localized near the pond. Overall, the array data were consistent with a pond installation in low hydraulic conductivity soils with a zone of hydration that did not pose any immediate risk to subsurface groundwater 40 m beneath the surface (Tyner and Lee, 2004).

Feedyard B

The site at FyB demonstrated greater soil EC dynamics throughout the year when compared to FyA. During the study period several EC anomalies were identified. However, one anomaly that warranted further investigation occurred during the week of April 7–13, 2013. Approximately 80 mm of precipitation were received at FyB, which raised the water level in the pond approximately one meter (Fig. 3). This increase in water

level followed a relatively dry 2012 precipitation season and a winter with a pond that was empty (Fig. 3). Resistivity readings prior to this event showed a uniform profile south to north and top to bottom with conductivity values $<24 \text{ mS m}^{-1}$. Following the event, only a slight increase in profile conductivity on April 15, 2013, was visible by the pseudosection image. Endemic in pseudosection images is the interpolation process, which can marginalize differences unless these differences are systemic throughout the layers. A supplemental analysis tool was employed that displayed a change in conductivity by depth across the array length; these differenced plots provided visual cues of conductivity anomalies with good sensitivity and spatial resolution. Similar to differenced pseudosection images, differenced plots can display changes in conductivity over a fixed time sequence. This method has proven useful in detection of unintended discharge events.

Figure 4(A–D) illustrates the change in conductivity (April 1–9) for each EC_a point along the array profile. There was an approximate increase of 25% in EC_a near the middle of the 1.6-m depth profile during the time period (Fig. 4(A)). It is interesting that only the 1.6-m depth was affected by the perceived unintended discharge. This site has a water table that varied from 3 to 5 m. Therefore, all array EC measures below the 4.8-m depth were buffered by the presence of subsurface water. However, the differenced plots clearly showed an increase in conductivity coinciding with the increased pond level.

Based on the differenced plot, an unintended discharge was suspected and additional site investigations were warranted to determine what caused the increase in conductivity at that depth. To better determine the extent of the discharge event, a series of portable surface RA arrays were placed parallel to the permanent array at approximately 7.5-m increments east of the pond edge up to 22.5 m (Fig. 5(A)). An additional surface RA array was placed 45 m east of the pond to serve as a reference to compare with the near pond-edge array data. The surface arrays were comprised of a 16 probe (3.05-m spacing) system that was partially overlapped to provide greater depth detail near the suspected location of the discharge.

Figure 6 shows the 1.6-m depth EC data of the overlapped elements for the 0, 7.5, and 22.5 m distances. The portions of the lines that were elevated for the 0 and 7.5 m arrays are located approximately adjacent to the northeast corner of the pond (Figs. 5(B) and 6). Also, the amount of increase in the EC at that location along the array was greater for the 0 and 7.5 m arrays than for the 22.5 m array. This indicated that the unintended discharge was localized near the edge of the pond.

Data from these temporary arrays were inverted to get a clearer picture of the process that was causing the

anomaly. The inverted images from each of the temporary arrays and a cropped permanent array (cropped to allow visual comparison with the temporary arrays) are shown in Fig. 7(A–E). Figure 7(A) shows a narrow band of higher conductivity from the surface to approximately 2 m in depth at 45 m north along the array. This position places it very near the north east corner of the pond filled to the level when the anomaly appeared. The inverted image of the temporary array located 7.5 m to the east shows higher conductivity that ranges from 30 m to 55 m north along the array for the same depth (Fig. 7(B)). This higher conductivity dissipates for the 15 m and 22.5 m arrays and is not noticeable for the array located at 45 m to the east of the pond edge (Fig. 7(C–E)).

Additional site investigation tools were applied to further identify the extent of the unintended discharge. A one-meter EMI system (HCP mode) was used to create a 2-D EC image of the east end of the retention pond (Fig. 5(B)) using methods developed by Eigenberg *et al.* (2006). This image was superimposed on a geo-referenced satellite Google Earth Pro photo (Google, Inc., Mountain View, CA) to better illustrate subsurface regions of elevated soil EC (Figs. 5(B) and 6). Man-made features were added to the image to provide the reader with a better understanding of the site (Fig. 5(B)). It should be noted this one-time EMI image is not suggesting the zones of higher conductivity are necessarily the result of this particular discharge event; however, they may illustrate zones of historic discharge.

There are two zones of interest, one in the southeast corner and another in the northeast corner of the pond. Based on observations made during the study period, the zone near the southeast corner of the pond appears to be a result of historic leaky surface pipe connections. Even though the EMI instrument identified this zone, the irrigation system was not used during the month of April and, therefore, the southeast zone is not likely the source of the observed EC anomaly.

The zone that appears to be the most likely source of the anomaly was located in the northeast corner of the pond. It is not clear why this corner of the pond allowed the unintended discharge event; however, Fig. 5(B) indicates that high subsurface conductivity appears to emanate east from the pond nearly to the permanent array. One hypothesis for a pathway for an unintended discharge at this location is the possible response from several man-made features shown in Fig. 5(B). Some of these features include a buried irrigation transfer pipe running north-south along the east end of the pond to a surface riser and connecting to another buried irrigation transfer pipe running west from the riser junction. To install all of these features, extensive excavation and backfilling was required.

Figure 5. Schematic of feedyard B. Figure A illustrates the approximate location of the over-lapping surface resistivity arrays that were used during the site investigation following the suspected unintended discharge event on April 8, 2013. Figure B illustrates an EMI image layered on a satellite image showing the locations of suspected historic pathways conducting water away from the pond. Note the approximate location of installed monitoring wells and irrigation control equipment that required excavation of the soil at the site. Figure C illustrates the approximate location of 2-m deep soil cores taken to determine the source of the elevated conductivity.

Additional site disturbance was observed when solids, routinely removed from the bottom of the pond, were stored temporarily near the northeast corner and allowed to drain before being hauled away using heavy equipment. While not conclusive, these man-made disturbances likely caused atypical flow pathways that could channel water away from the pond and along the backfilled trench. This appears to be confirmed by the inverted image shown in Fig. 7(B). This temporary array was placed directly over the backfilled trench. During a precipitation event and subsequent rising pond level, water may have spilled into these atypical flow pathways causing flow away from the pond near the vicinity of the array resulting in the differenced plot response that was observed (Fig. 4(A–D)).

To verify the source of the anomaly, soil samples were taken approximately one month following the suspected discharge event to a two-meter depth in the region of the suspected zone to identify pond discharge by measuring chloride concentration in the soil. Chloride was selected as an indicator ion for manure salts because it is not typically found in high concentrations in the soils for the region, but is typical in high concentrations in waters containing beef manure. Since the region is intensively cropped using a corn/soybean rotation, nitrates in the ground water are typically high; therefore, separating out the source of the nitrate would be very difficult. There were three diagonal transects identified that had some points in the zone of suspected discharge and some points outside the suspected zone (Fig. 5(C)). The B transect was positioned to pass through the center of the suspected discharge zone. Three points at 0, 7.5 and 15 m east of the pond edge that existed during the time of the discharge event were sampled. In addition, a reference point 45 m east of the pond was sampled to provide a reference. Figure 8(A–C) shows the soil chloride concentration with respect to depth for each of the sites. Sample sites A-0, 7.5 and B-0, 7.5, 15 m had elevated chloride concentration in the depth profile. All of transect C and A-15 had chloride profiles that were similar to the profile at 45 m east of the pond. These data indicated that discharge water historically has migrated away from the pond in that corner. Though not visibly evident at the site, these soil data appear to corroborate the hypothesis concerning unintended discharge stated previously.

Monitoring Well Data

Two sets of wells (MW-2 and MW-10) were instrumented to continuously monitor water quality from May 2012 through December 2013 (Fig. 2). Three wells screened at different depths comprised a set of monitoring wells. They were designated as shallow, middle and deep (3.5 m, 4.5 m and 9.5 m, respectively)

Figure 6. Apparent electrical conductivities at feedyard B along the over-lapping, temporary arrays at various distances away from the pond. These arrays were used to identify the extent of the suspected unintended discharge event. The array at 45 m to the east of the pond is considered as a reference for comparison to the arrays' values closer to the pond.

depending on the well screen depth. The geology in the region has a confining layer that partially separates the middle and deep well screen depths. Shortly after the installation of the instruments, the groundwater level dropped below the 3.5-m depth and therefore

the instruments in the shallow wells were removed (Fig. 9(A)). The water EC levels for MW-10 are shown in Fig. 9(B). A vertical line marks the time when the rain event that caused the unintended discharge took place. There was little or no deviation in EC for either the

Figure 7. Inverted images of the temporary surface and permanent arrays at feedyard B illustrated in Fig. 5 for investigating the suspected unintended discharge event. Array A is 0 m from the edge of the pond, B is 7.5 m, C is the permanent array, D 23 m and E is 45 m.

Figure 8. Soil chloride concentration at feedyard with respect to depth for the soil cores taken at the site to determine the source of the elevated electrical conductivities. Note the increased concentrations of chloride were considered indicative of discharge from the pond.

middle or deep wells for approximately one month following the discharge (approximately 45 days). Starting in June, following the discharge event, the EC of the middle depth well began to demonstrate some variability. Similarly, the deep depth well began demonstrating EC variability approximately 75 days following the discharge event. Though there is insufficient data to adequately determine the cause of the variability, it

appears to coincide with the traditional irrigation season. During the month of June 2013, the static water level in the middle depth well began to fluctuate and steadily drop until approximately October 2013 (Fig. 9(A)). This region is typified by intensive corn/soybean production that relies heavily on supplemental groundwater irrigation. Similar EC variability for both the middle and deep wells was demonstrated during the period of June 2012 through the end of September 2012. However, more data is needed to better quantify whether this observed pattern is seasonal and determine cause and effect.

Shortly after the identified unintended discharge event, water samples were collected from each monitoring well. The chloride concentrations for each of these wells are shown in Fig. 10. Similar to the EC data, no discernible pattern could be determined from measurements of chloride concentration. The most likely explanation for the limited chloride concentration response in the monitoring wells would be the unintended discharge was localized in the non-saturated zone above the groundwater to the north of the monitoring wells. As a result, the monitoring wells would not be able to intercept the pond discharge. Based on this data, the monitoring wells would not have alerted the feedyard manager of any potential problems. Additional limitation to the effectiveness of monitoring wells, assuming they are positioned to intercept discharge, is the timing of well sampling. Currently, monitoring wells are required to be sampled twice annually, usually in the spring and fall of the year. This sampling frequency severely limits the probability of consistently collecting information during an unintended discharge event. As a result, identifying a discharge event from normal environmental dynamics with so few data may not be possible. Therefore, many years of data may be required to identify pond integrity issues. The consequence of such a delay may cause greater negative environmental impacts when compared to ponds monitored with a system capable of early warning.

Though not specifically addressed by this study, the physical installation of monitoring wells may cause potential risk to groundwater quality (Ross, 2010). During 1999, a consortium of private and Nebraska state representatives constructed a water well that had a transparent casing as an educational program. The objective of the project was to use the best technology available for sealing the annular space of a well and provide knowledge of design, construction and development. The group was surprised 16 months later during a dye test to find that cracks had formed in the grout columns allowing a preferential flow path to groundwater. As a result of this study, much knowledge

Figure 9. Plot A is a measure of the depth to ground water for monitoring well MW-10 – M during the study period at feedyard B. Only the middle screen well is presented because the depth to water of the deep screen well was identical. Plot B shows the electrical conductivity at feedyard B of the screened portion of the middle and deep monitoring wells during the study period. It should be noted that the area has a clay layer that separates the middle and deep well aquifers.

has been gained and design alternatives have been implemented to better protect groundwater quality. Regardless of the improvements in monitoring well design, there still exists a risk to groundwater quality. The use of RA has the potential to mitigate much of this risk by either replacing or minimizing the number of

monitoring wells required to adequately monitor potential unintended subsurface discharge from runoff holding ponds. Resistivity array installation requires that electrodes be placed at or near the ground surface. Therefore, very little disturbance to the site geology is required. RA technology could protect the integrity of

Figure 10. Feedyard B monitoring well water chloride concentrations of sampled well water collected at the on-set of the suspected unintended discharge event during the spring of 2012 and continuing into the fall. Note the chloride concentration difference between the middle and deep screen well depths, illustrating the clay layer that limits the movement of pond water to the deeper aquifer.

the natural barriers limiting movement of surface contaminants to groundwater aquifers.

Determining Threshold Values

Correction factors (referenced to 25°C, Eq. (1)) were plotted for the year 2013 and shown in Fig. 11. The soil temperature depth data were interpolated to provide depths that correspond to those measured by the resistivity array based on probe spacing used at Fyd A and B. Figure 11 shows the resulting curves to be very similar with each depth, resembling a sinusoidal curve with a progressive phase shift and reduced amplitude with increasing depth.

Temperature correction factors provide insight into the development of strategies for setting thresholds to be used for identifying unintended discharge events from normal environmental cycles and variability. For near-surface measure, Fig. 11 clearly shows that the correction factor can influence apparent resistivity values. This is particularly important when comparing images or point values that are separated by many days. Table 2 lists sensitivity factors for time shifts that might be associated with a moving threshold at differing depths. Typically, unintended discharge events result in a shift in the soil EC profile. Therefore, when a certain percentage shift in the profile is measured, an alert can be sent indicating an unintended discharge event. Based on this, if a threshold EC value is set using a particular time of year, then temperature correction values could

be used to normalize the readings, thus minimizing false positive and negative discharge determinations. If rolling averages of the previous few weeks were used to establish thresholds, then temperature correction may not be important.

Application of the Early Warning System Technology

The objective of this study was to develop an early warning system for detecting unintended discharge for permanently installed runoff holding ponds from beef feedlots. This is a narrow application of this technology and it could have more uses outside of production agriculture. Anticipated adaptations of the technology could extend to thermoelectrical generation, oil and gas exploration and mining industries. This approach could be useful for thermoelectric generation or other industries that have to store salt-containing wastewater generated from cooling towers used to remove heat from steam water. The early warning RA system could alert operators of these facilities that a breach in the lining system has occurred, and immediate response could take place long before contaminants are measured in monitoring wells. Similar applications could also be useful for monitoring unintended discharge from temporary storage facilities used to hold fracking fluids. Temporary storage of these fluids at the drilling sites could potentially contaminate surface and groundwater systems (Entrekin *et al.*, 2011; Vidic *et al.*, 2013).

Figure 11. Temperature correction factors based on measured soil temperature at feedyard A for the 1.58, 3.16 and 4.75-m depths. Feedyard B correction factors were nearly identical and therefore are not presented. These depths coincide with the approximate measurement depths for the installed arrays.

Conclusions

Two separate RA systems were installed down-gradient from two beef feedyard runoff holding ponds. The EC profiles adjacent to these ponds were monitored continuously for approximately two and a half years. The geology and the resulting hydraulic conductivities were very different between the two sites. The hydraulic conductivities at FyA were relatively low, while at FyB they were relatively high. As a result, the seasonal EC dynamics measured by the RA system were greater at FyB than at FyA.

Several anomalies were noticed during the study period at FyB; however, one anomaly that was more thoroughly investigated followed an 8-cm precipitation event. This event took place during the week of April 7–13, 2013 and resulted in an approximately one-meter rise in pond depth. An evaluation of a differenced plot showed a dramatic increase in apparent soil EC adjacent to the northeast corner of the pond. Based on the differenced plot evaluation, it appeared an unintended

discharge event took place. This evaluation prompted a detailed site investigation.

A 2-D EMI image was collected east of the pond as part of a detailed site investigation. The EMI image revealed a region of high conductivity that appeared to be associated with the unintended discharge. Soil samples were taken within and outside of the identified region. Elevated chloride concentrations within the identified zone were much greater than those outside the zone representing historic discharge. The 2-D EMI image, combined with the series of inverted RA images, indicates a back-filled trench remnant of a buried pipe. It appears that when the pond level reached a sufficient depth, water moved from the pond into the back-filled trench. This trench allowed the discharge to move away from the pond and alter the EC profile, such that the resistivity array could detect a change within one day following precipitation.

Monitoring well data did not identify any specific unintended discharge events during the study period. Frequent water quality samples taken from a monitoring

Table 2. Sensitivity to temperature by depth for select time delays. A moving threshold must allow for these in establishing values to identify an unintended discharge event. These values are based on the temperature correction curves (Fig. 11) from FyA.

Time shift/depth of estimate	1 day, % change	5 day, % change	10 day, % change	20 day, % change	30 day, % change	60 day, % change	90 day, % change
1.58 m	4.6	5.3	7.6	13.1	18.1	31.8	39.3
3.16 m	3.4	3.8	4.8	6.4	9.2	14.4	18.3

well adjacent to the pond edge showed little change from the time the RA system identified the unintended discharge through the fall when the pond was nearly empty. Instruments placed in the monitoring wells that continuously measured water depth and EC within the screened portion of the aquifer showed seasonal variations, but never illustrated a shift in quality that would indicate unintended discharge.

The RA system responded to a localized unintended discharge event within one day following discharge. The RA system appeared to provide early warning of the potential environmental risk by monitoring the unsaturated and saturated portions of the EC depth profile adjacent to the runoff holding ponds. Monitoring the unsaturated portion allows the RA system a capacity beyond traditional monitoring wells, which can only intercept discharge carried in groundwater. Also, the RA system, using probes installed at or near the soil surface, effectively measured a greater breadth and depth profile (a virtual curtain) compared to the point measure of a monitoring well. The ability to monitor contaminant movement at depth using probes installed at or near the surface minimized geologic disturbance and preserved natural barriers, limiting surface contaminant transport to groundwater aquifers. Therefore, resistivity arrays can provide broader coverage and improved sensitivity than monitoring wells.

Finally, the capacity to automate the RA system provides a means to continuously monitor for unintended subsurface discharge from a runoff holding pond. Continuous monitoring is less likely to miss discharge events when compared to bi-annual sampling typical for monitoring wells. Automatic and continuous monitoring also greatly expands management options. However, because of the sensitivity of the RA system, additional research is needed to develop protocols for filtering out unwarranted alerts caused by normal environmental dynamics. Part of these protocols should include standards on distance the RA is placed away from the pond edges. These standards will certainly require some judgment to account for site geology and acceptable hydration zones adjacent to ponds. Also, additional geophysical tools and methods need to be developed for detailed site assessments. Improved geophysical tools would provide feedyard managers with better information to develop options to mitigate unintended discharges.

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Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture

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