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A Comparison of Electromagnetic Induction Mapping to Measurements of Maximum Effluent Flow Depth for Assessing Flow Paths in Vegetative Treatment Areas

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Abstract. *Vegetative treatment systems (VTSs) are one type of control structure that has shown potential to control runoff from open feedlots. To achieve maximum performance, sheet-flow over the width of the vegetative treatment area (VTA) is required. Tools, such as maps of flow paths through the VTA, are needed to aid producers in locating concentrated flow paths and in determining the most effective approach to redistribute flow. Members of the USDA-ARS USMARC laboratory have developed remote sensing techniques using Electromagnetic Induction (EMI) to measure spatial nutrient distribution, and identify possible flow paths, within VTAs. The objective of this study was to determine whether apparent soil electrical conductivity maps can be used to locate concentrated flow paths in the VTA. Effluent flow paths in the VTA were determined by measuring the maximum height of flow at different locations within the VTA. In this study, PVC stakes were coated with a water sensitive paint and located throughout the treatment area during effluent release from solid settling basin to the VTA. The maximum depth of flow at each stake was recorded following a release event from the settling basin. The flow maps generated from the data were compared to* EC_a *maps measuring salt build-up in the soil due to basin discharge. The flow paths identified in the EMI maps were generally in agreement with measured water depths in the VTA. Therefore, techniques that use EMI technology can be used by regulators to monitor VTS performance, by design engineers to improve system performance, and by producers to better manage their systems.*

Keywords. Electromagnetic induction, feedlot runoff, vegetative treatment systems, flow paths

Introduction

Runoff from open lot livestock operations has long been considered a potential water quality pollutant. As such, animal feeding operations of all sizes are looking for runoff control systems to minimize the risk associated with improper disposal of feedlot runoff. Vegetative treatment systems (VTSs) are a possible alternative technology that has the potential to achieve signification pollution reduction (Koelsch et al., 2006). A VTS is a combination of treatment components, at least one of which utilizes some form of vegetative treatment, designed to utilize nutrients and water in the feedlot runoff (Koelsch et al, 2006). One common vegetative treatment component is a Vegetative Treatment Area (VTA). A VTA is a vegetative area that is level perpendicular to the designed flow direction and has a slight slope (less than 5%) parallel to the designed flow direction. These areas are planted and managed to maintain dense, permanent vegetation (Moody et al., 2006). Operation of the VTA involves applying effluent evenly across the top width of the VTA (Moody et al., 2006). This effluent then flows down the length of the VTA where the nutrients and water are used for plant growth.

Researchers have investigated the use of vegetative treatment to reduce runoff contaminant concentrations and transport for more than twenty years (Young et al., 1980; Dickey and Vanderholm, 1981; Woodbury et al., 2003; Woodbury et al., 2005; Koelsch et al., 2006). In these investigations, researchers have shown that performance of a VTA is dependent on the amount of channelizing of flow occurring within the VTA. Work by Dickey and Vanderholm (1981) showed that channelized flow VTAs need to be at least five times longer than sheet flow VTAs to achieve similar concentration reductions. An investigation by Dillaha et al. (1988) confirmed that lower removal efficiencies occurred in VTAs with concentrated flows than in VTAs with sheet flow. Moreover, channelization of surface flows in VTAs results in non-uniform nutrient and hydraulic loadings (Koelsch et al., 2006) within the VTA, increasing the opportunity for a VTA release and groundwater contamination.

Maintaining sheet flow over the VTA is important to maximize nutrient removal. Numerous VTA design guidance documents (Blume, 2006; Woodbury et al., 2006; NRCS, 2008) discuss how this can be done during the design and construction of the VTA. Ideas for maintaining sheet flow include the use of a concrete distribution weir or gated pipe at the up-gradient end of the VTA to initiate sheet flow, followed by gravel, rock, or geotextile spreaders within the VTA to maintain sheet flow (Woodbury et al., 2006). To achieve more even distribution down the length of the VTA, Woodbury et al. (2006) suggests using multiple outlets from the settling basin down the length of the VTA or using a sprinkler irrigation / pressure dosing system. No matter which initial design is chosen, it is important that the system is routinely inspected for flow concentrations and the formation of depressions within the treatment area. The NRCS (2008) suggests inspecting and repairing treatment areas after storm events to fill in gullies and depression areas, removing flow disrupting sediment accumulations, and grading the VTA as necessary. Maps of flow paths within the VTA would aid producers in locating concentrated flow areas and determining the most effective approach to redistributing flow. Eigenberg et al. (2008) has proposed the use of apparent soil electrical conductivity maps as a possible tool in locating flow paths; however, these maps have not been tested against measurements of flow paths within the VTA.

The objective of this study was to determine if apparent soil electrical conductivity maps can be used to identify flow paths within the VTA. Specific objectives included developing flow path maps from the change in apparent soil electrical conductivity and monitored flow depths, comparing the flow paths predicted by these maps, and then using the EC_a data combined with measured flow data to generate regression models that predict flow depth throughout the VTA.

Additionally, the maps generated as part of this research are interpreted in terms of the operational characteristics of the runoff control system.

Materials and Methods

Site Description

The feedlot site, Central Iowa 1, was a 4.2-ha earthen open beef feedlot with a permitted capacity of 1,500 cattle located in central Iowa. The VTS at this site consisted of two solid settling basins, a vegetative treatment area (VTA) divided into three channels, a containment berm located at the southeast corner of the VTA, and a vegetated waterway (located on the eastern edge of the VTA). The VTS was divided into two portions, the pilot and the non-pilot system. The western lot (labeled Feedlot Area 1 in Figure 1) was the pilot portion of the feedlot. This was a 3.09-ha earthen feedlot area permitted for 1,000 head of cattle. Feedlot runoff drained into a solid settling basin (labeled SSB 1) designed to hold 4,289 m^3 of effluent. Effluent captured in the settling basin was then released onto the two western channels of the VTA (labeled VTA 1 and VTA 2). These two VTAs were operated in parallel, i.e., effluent was released onto both VTAs (VTA 1 and VTA 2) at the same time; both channels received similar effluent loadings. Each of these VTAs was 24 m wide with an average length of 311 m, giving a VTA to feedlot area ratio of 0.5:1. During 2008, three earthen berms were constructed within each of the VTAs. These berms helped slow the flow of water through the VTAs, redistribute effluent over the width of the VTAs, and provide some effluent storage within the VTAs. A final berm, prior to the outlet from the pilot VTA, was added in mid-June 2008.

Initial treatment of the feedlot runoff occurred in the solid settling basins. The downstream end of the settling basin was surrounded by concrete walls, while earthen berms were used for the settling basin sidewalls. The settling basin has a maximum depth of 1.2 m with 223 m^2 of concreted area. The remainder of the SSB bottom was constructed with a compacted earth bottom. The settling basin was designed with a porous dam outlet; the outlet was constructed on the downstream end of the settling basin with vertical pieces of 2” x 4” lumber spaced 1.9 cm apart. After flowing through the porous dam outlets the effluent entered two, 20-cm diameter pipe outlets which directed flow to VTA 1 and VTA 2. During the summer of 2007, a V-notch weir and knife-gate were added behind the porous dam outlet of the pilot system settling basin in an attempt to improve solids retention in the SSB. The knife-gate provided the producer with more control over when, how much, and at what rate effluent was released from the settling basin onto the VTA.

The effluent in the settling basin was released onto concrete pads which direct the effluent into a concrete level spreader at the upper end of each VTA. The level spreaders were the width of the VTA, 3 m long, and 0.15 m deep. The spreaders encourage uniform application of the settling basin effluent over the width of the VTA. The three VTA channels were constructed parallel to each other and “stair stepped” down in elevation with VTA 1 being the highest and VTA 3 the lowest. This design minimized the amount of cut-and-fill required during construction of the VTAs. The VTAs were designed to have a 0.5% slope along the length and to be level across its width. As mentioned, during the summer of 2008 the producer added three earthen flow spreaders to each VTA. These earthen spreaders were installed to increase effluent retention time in the VTA and to improve flow distribution over the VTA. Only the flow distribution of VTA 2 was monitored as part of this study.

Figure 1. Layout of Central Iowa 1 and the VTS used to control and treat runoff generated by the facility.

Apparent Electrical Conductivity Measurement

Specific details on the electromagnetic induction equipment and techniques used for this study are described in Eigenberg et al. (2008). Briefly, a DUALEM-1S meter (Dualem Inc., Milton, ON, Canada) was used to collect apparent electrical conductivity (EC_a) data from the VTA. The meter was positioned on a non-metallic trailer and pulled at approximately 2.5 m s^{-1} on approximate 7 m intervals across the VTA. Path spacing was maintained using a Trimble EZ-Guide GPS/Guidance System (Trimble Navigation Limited, Sunnyvale, CA). The DUALEM-1S meter simultaneously records both perpendicular (PRP) and horizontal coplanar (HCP) orientations; however, only the more shallow (depth measured centroid at approximately 0.75 m) penetrating PRP orientation was used for the statistical analysis to focus the measure in the most dynamic range of the root zone. Simultaneously, GPS coordinates of the meter's position within the VTA were determined using an AgGPS 332 receiver with OminiSTAR XP correction resulting in 10 to 20 cm accuracy (Trimble Navigation Limited, Sunnyvale, CA). Coordinated GPS and EC_a data were collected at a rate of five samples per second and stored in a Juniper System Allegro (Juniper System, Inc., Logan, UT) data logger. Edge effects were clipped from the EC_a data set before the sampling design was determined.

Twenty sampling sites were co-located with EC_a data using the spatial response surface sampling design (RSSD) program contained in USDA-ARS ESAP (EC_e Sampling, Assessment, and Prediction) software package (Lesch et al., 2000). These sites were selected to optimize the understanding of the EC_a variability while maintaining independence of the individual sites. Justifications for the sampling procedures used during this study are provided in Eigenberg et al. (2008) and Woodbury et al. (2009). The ESAP-Calibrate program in the ESAP suite was used to analyze the data and develop the MLR models for predicting water depth based on EC_a values. Contained in the GPS data are positional elevation measures (approximately 20-40 cm accuracy). These high density elevation data were used to construct an elevation map of the VTA (Figure 2).

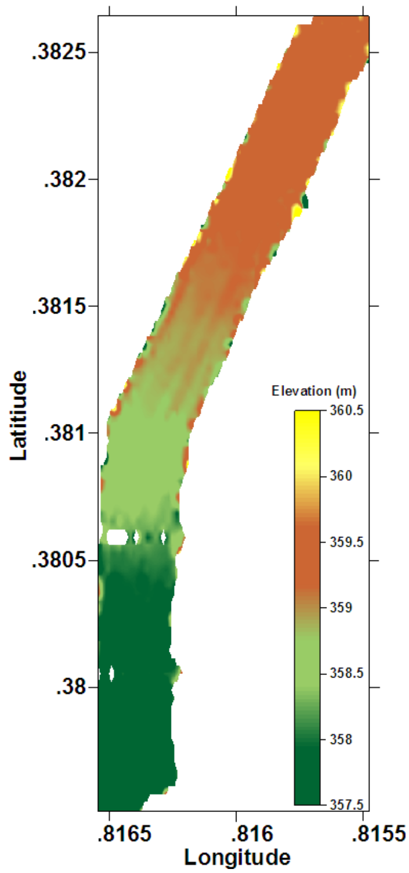
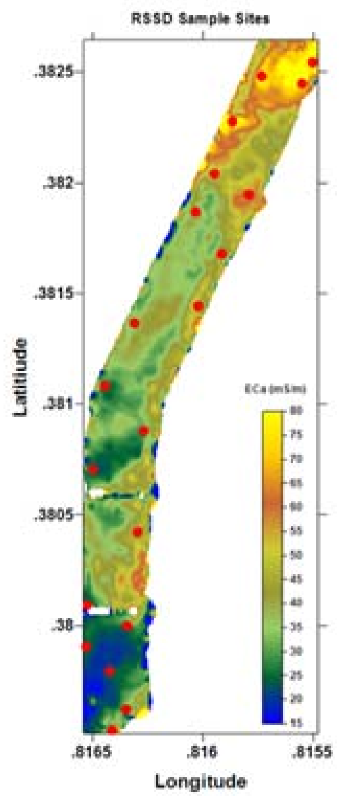


Figure 2. Elevation survey of the VTA conducted in 2008. Areas in dark green represent the lowest elevation and areas in yellow the highest elevation.

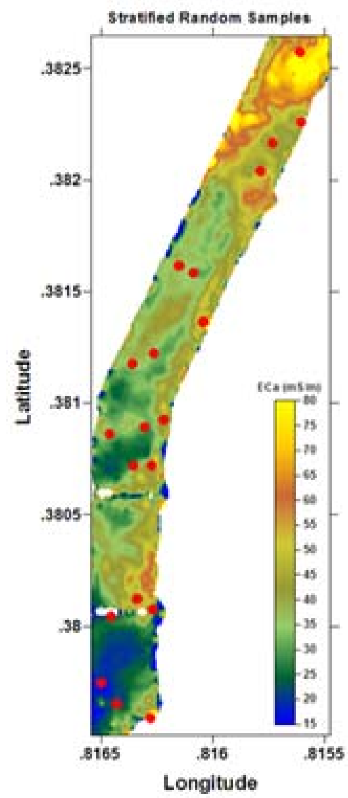
Depth of Flow Measurement

During three controlled SSB release events, maximum depth of flow was monitored at sixty locations throughout the VTA. The flow depths were monitored using sections of PVC pipe coated with a water sensitive paint. The PVC pipes were driven 7.6 cm into the ground at each of the sixty locations. During the SSB release event, the paint washed off the PVC up to the maximum depth of effluent flow. The flow depths were recorded the following day by measuring the height above the ground level to which paint had been removed.

Of the 60 locations monitored, twenty were located based on grid sampling, twenty were chosen randomly within the VTA, and twenty were determined using the 2007 EC_a data and RSSD program in the ESAP software suite. The RSSD sampling points are shown in Figure 3a. Locations of the random sampling locations are shown in Figure 3b. Additionally grid samples were collected. The grids were laid out along transects at 0.38014, 0.38068, 0.38106, 0.38160, and 0.38213. Four sample points were installed along each transect. These points represented a location of 1/8, 3/8, 5/8, and 7/8 of the distance along each transect.



(a)



(b)

Figure 3. Maps of the ESAP-RSSD selected sampling locations (a) and the random sampling locations (b) overlaid on top of the apparent conductivity map from 2007. Areas in blue represent the lowest apparent conductivity and areas in yellow represent the highest apparent conductivity

Measurements of the flow depths at these sixty locations were recorded after three release events from the SSB. None of these SSB releases resulted in a release from the VTA. The three release events were on 6/23/08, 7/28/08, and 8/28/08. The release volumes were 146 m^3, 30 m^3, and 118 m^3 respectively. If the flow was evenly distributed over the VTA surface, these events would have resulted in equivalent depths of 2 cm, 0.4 cm, and 1.6 cm. These release events were typical in size and duration to those used by producers managing the SSB water level. Average flow depths by location were calculated and used to produce the depth plots and for comparison with a differenced electrical conductivity map illustrating changes in EC_a from 2007 to 2008.

Results and Discussion

Apparent Electrical Conductivity Measurement

A map showing the change in apparent electrical conductivity of VTA 2 between 2007 and 2008 is shown in Figure 4. In general it appears that the first ¼ of the VTA area saw the largest increase in apparent electrical conductivity followed by two areas farther down the VTA. These two additional areas are located in front of two of the earthen spreader berms that were constructed in the VTA. It appears that many of the other areas actually saw a decrease in apparent electrical conductivity. Specifically, the eastern edge of the VTA tended to see the largest decrease in apparent electrical conductivity. Apparent electrical conductivity surveys in previous years tended to indicate that these areas were seeing the largest increase in apparent electrical conductivity. Thus it would appear the management changes, such as installation of the earthen berm spreaders within the VTA had a large impact on flow distribution within the VTA.

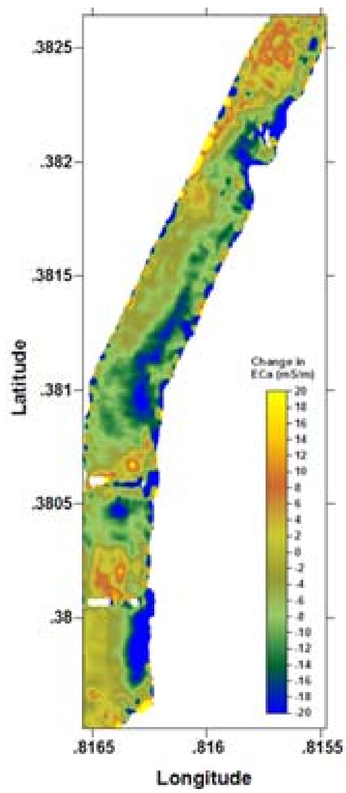


Figure 4. A map showing the difference in apparent electrical conductivity from the fall of 2007 to the fall of 2008. Areas in blue represent a decrease in apparent conductivity areas in green represent no change in conductivity, and areas in red and yellow represent an increase in conductivity.

Depth of Flow Measurement

A map of flow paths was generated based on the flow depth measurements using all sixty locations. A krigged image plot of the flow depths is shown in Figure 5. A visual comparison of the flow depth map and the change in apparent electrical conductivity map allowed an assessment of the uniformity of the two measurement methods. There are three areas that appeared to have received higher loadings of effluent. Two of these areas were located just ahead of the earthen berms in the VTA. The third area is near the inlet of the VTA and is located up-gradient of the first berm in the VTA. Comparing this data with the change in apparent electrical conductivity in the soil we see a good correspondence between the increase in apparent electrical conductivity and the flow depth, especially for the two locations just ahead of the earthen berm. In general there was good correspondence between the measured flow depths and the increase in apparent electrical conductivity; however, this correspondence was not as strong near the inlet of the VTA. Specifically, the areas were flow depth was monitored to be the deepest saw little to no increase in apparent electrical conductivity. This may have been due to rainwater accumulating in the area. This accumulated rainwater would have low electrical conductivity, but still result in reading a significant depth of flow reading. Additionally, this map tends to indicate that deeper flow paths tended to be along the eastern edge of the VTA. This is not in agreement with the EC_a generated map, which suggested that this edge of the VTA actually saw a decrease in EC_a.

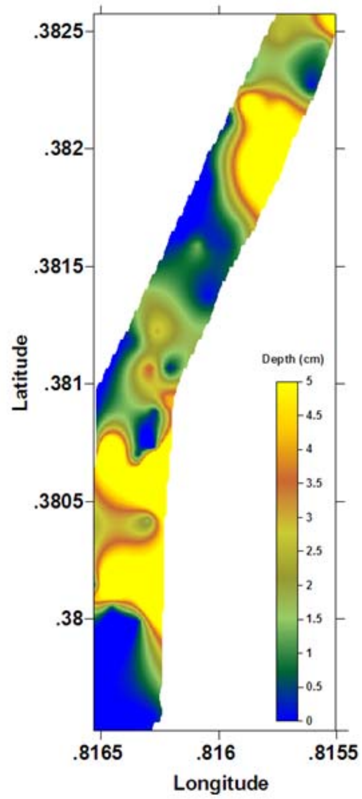


Figure 5. Map of the measured flow depths within the VTA. Areas in blue and green represent the shallowest flow areas. Areas in orange and yellow represent the deepest flow areas.

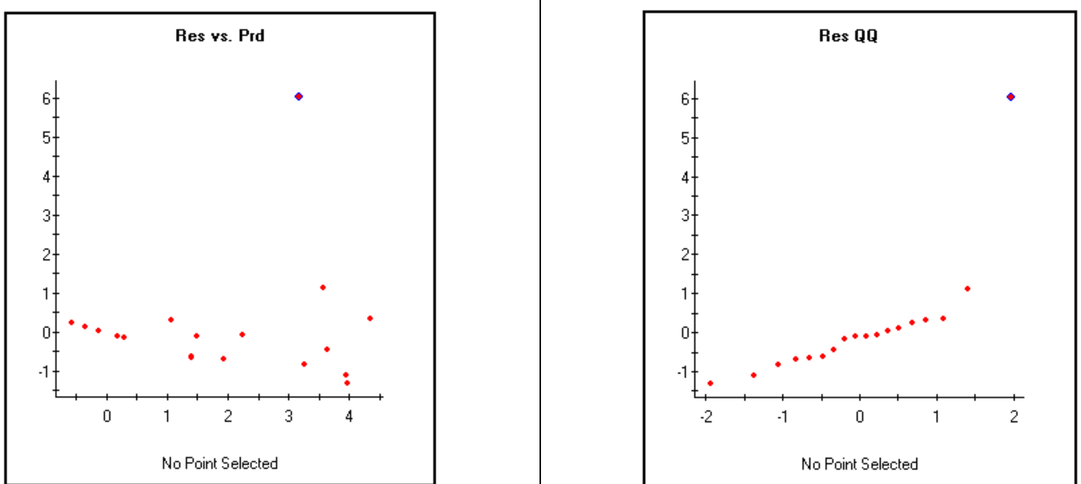
Predicting Flow Depth with Apparent Electrical Conductivity Measurements

The twenty RSSD sites were used to develop a MLR model predicting flow depth based on EC_a data. However, due to the modification of the VTA (the addition of the earthen berms) these original twenty sites from the 2007 EC_a data could not be used for calibrating the MLR model using data collected after VTA modification in 2008. Therefore, the GPS coordinates for each 2007 site were matched with EC_a data corresponding locations from the 2008 EC_a data. These sites were not optimized but gave a good range of values so that a model could be generated and correlations between the EC_a and water depth could be evaluated. Spatial independence of the sites were checked and verified. The coordinates from 2008 survey were not exact matches to those in 2007 because of the slight variations in the survey. Usually there were three or four acceptable survey points to choose from with the exception of two data points that did not have adequate coordinate matches to be used in this analysis. Thus only eighteen points were available for creating the predicted flow depth map. The MLR model used for this analysis was of the form:

$$Water\ Depth = b_0 + b_1(z) + b_2(x) \qquad (1)$$

Where b_0 is the intercept, b_1 is determined by ESAP based on the association between apparent electrical conductivity and flow depth data, and b_2 is determined by ESAP based on the trends in the north/south direction.

A MLR analysis with all eighteen data points was then conducted and produced an overall model fit of R^2= 0.336. The low quality of the model fit did not warrant further predictive analysis. A plot of the residuals versus the predicted values was then analyzed. This plot is shown in Figure 6a. Based on this plot is appears that one of the points is an outlier (This point is highlighted as a larger diamond). This point was located before the first earthen berm in the VTA where deeper effluent flow, but little to no increase in EC_a was seen. As discussed earlier, this could have been caused by rain water accumulating at this location. A residual normal QQ plot is also shown in Figure 6b. In this plot the residuals should appear linear with a mean of zero. In this case the proposed outlier lies far from the line, indicating again that this point is an outlier. Grubbs' test for outliers was performed on the residuals. Based on this test it was determined that the point was an outlier. The analysis was run again after removing the outlier.

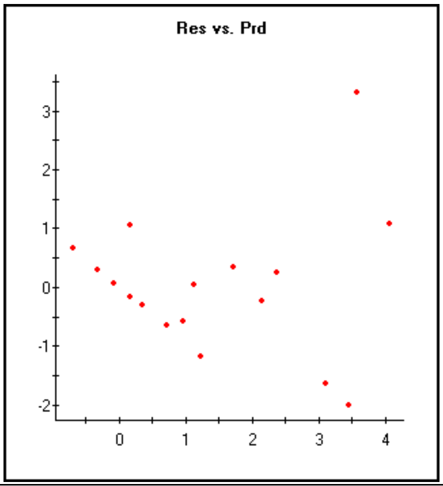


(a) (b)

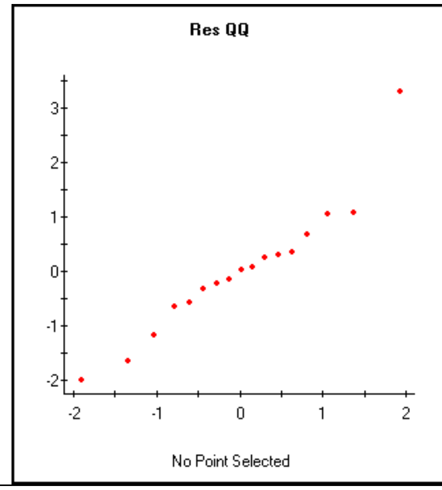
Figure 6. Residuals versus predicted values from the ESAP model generated using eighteen data points (a) and a normal residual QQ plot (b).

A plot of the residuals versus the predicted values from the analysis with seventeen data points is shown in Figure 7a. In this case the residuals appear to be random and approximately normally distributed. Also a residual normal QQ plot is shown in Figure 7b. In this case the points form an approximately straight line with a mean of zero, indicating that the data are approximately normal. After removing the outlier the MLR model fit improved to R^2 = 0.656 which was sufficient for further predictive analysis.

Figure 8 shows the predicted flow depths from the ESAP model. Also included on this map are dots to represent the seventeen sampling locations used in creating the ESAP model. In general the predicted flow depths are similar to those monitored with the exception of the ponded area near the first earthen spreader in VTA. Water tended to pond for extended periods (approximately one week) of time after a rainfall in this location. During SSB release events, effluent from the settling basin would mix with this rainwater before infiltrating. Also, there were very few flow depth readings taken in and around this area. It is believed that more sampling locations, specifically near this area, would have increased the accuracy in modeling flow depth.



(a)



(b)

Figure 7. Residuals versus predicted values from the ESAP model generated using eighteen data points (left) and a normal residual QQ plot (right).

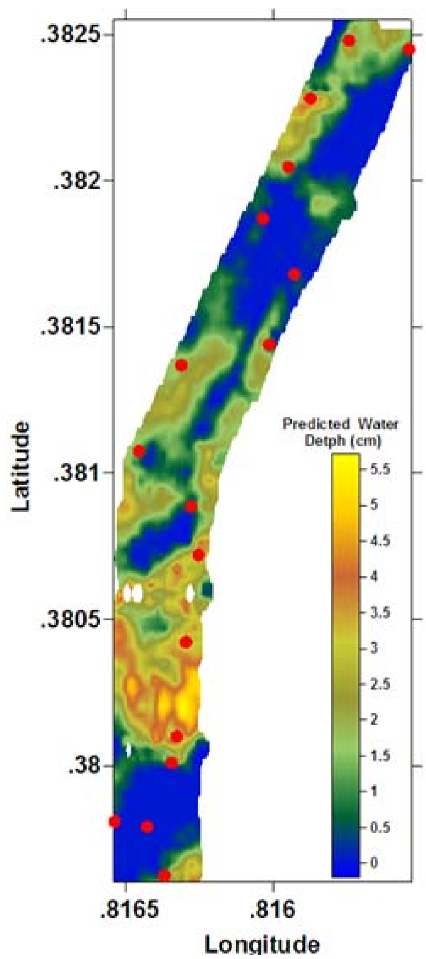


Figure 8. Predicated flow depths generated using the apparent electrical conductivity data and the measured flow depths. Areas in blue predict where no flow occurred, areas in orange and yellow represent where the deepest flow areas occurred.

Conclusions

In this study a flow path map generated based on changes in apparent electrical conductivity of the soil was compared to monitored flow depths within the VTA. In general the flow depths measured and those seen based on the change in apparent electrical conductivity appeared similar, indicating that change in apparent electrical conductivity could be used to provide an indication of where flow was channelizing in the VTA. A MLR model was then used to generate a map of flow depth occurring in the VTA. The generated model did a reasonable job of predicting flow depths in the VTA with the exception of around the first earthen berm in the VTA. As discussed previously, this can be attributed to the lack of calibration points in this area. This study indicated that high density apparent electrical conductivity data provided a quick and easy method to identify flow paths within the vegetative treatment area. Therefore, it appears that these maps provide a method to show producers where flow is channelizing within the VTA, can be used by engineers and producers to make system modifications to improve flow distribution and system performance, and can be used by regulators to monitor VTA performance.

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