Mapping of sand deposition from 1993 midwest floods with electromagnetic induction measurements

N.R. Kitchen, K.A. Sudduth, and S.T. Drummond

ABSTRACT: Sand deposition on river-bottom farmland was extensive from the 1993 Midwest floods. A technique coupling electromagnetic induction (EM) ground conductivity sensing and Global Positioning System (GPS) location data was used to map sand deposition depth at four sites in Missouri along the Missouri River. A strong relationship between EM reading and probe-measured depth of sand deposition (r^2 values between 0.73-0.94) was found. This relationship differed significantly between sites, so calibration by ground-truthing was required for each sand deposition survey. An example of the sand deposition mapping using the EM/GPS system is shown for two 50-60 ha (125-150 ac) sites. Such maps can provide valuable detailed information for developing restoration plans for land affected by 1993 Midwest floods.

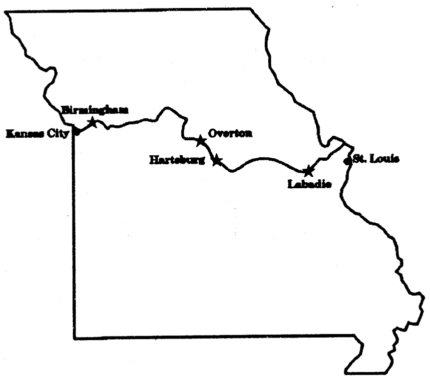

Figure 1. Sites for evaluation of sand deposition along the Missouri River in Missouri

During the flooding of 1993, sand was deposited onto thousands of acres of river-bottom farmland along the Missouri and Mississippi Rivers. The extent of this deposition was not realized until weeks later when flood waters receded. According to estimates from the USDA-Natural Resources Conservation Service (NRCS), 150,000 ha (371,000 ac) of cropland were damaged as a result of sand deposition along the Missouri River within the state of Missouri alone (USDA-NRCS 1993). Of that, 55,000 ha (136,000 ac) were covered with 15 cm (6 in) or more sand. In all, over 4.17×10^8 m^3 of sand were estimated to have been deposited onto Missouri farmland. The NRCS estimated the cost of recovering affected cropland by removing the sand and/or by deep plowing to mix the sand with the pre-flood soil would exceed a half billion dollars in Missouri alone. Other states along the Missouri and Mississippi Rivers were similarly impacted by sand deposition from 1993 flooding.

Development of restoration plans for individual fields covered with flood sands required a determination of sand deposition depths. The normal procedure has been to estimate sand depth over large areas from visual observations and a few soil cores. However in areas where deposition has been extreme, taking measurements by soil probing or by shovel has been laborious and impractical; this has resulted in only crude estimates of deposition over large areas. The lack of spatial detail obtained with this method of estimating sand deposition prompted the question of whether there was some noninvasive sensing technology which could be developed or adapted for measuring sand deposition quickly over large tracts of land.

Our previous work with electromagnetic induction (EM) methods of conductivity measurement on claypan soils (Doolittle et al. 1994; Kitchen et al. 1993; Sudduth and Kitchen 1993) led us to surmise that a similar EM-based approach could accurately estimate sand deposition, such as that found on fields after the 1993 flood. EM measurements have previously been shown to be an effective tool in assessing soil clay content (Williams and Hoey 1987) since, relative to sand and silt-sized particles, clay is very conductive. In sandy soils, electrical conductivity is low with large pore spaces between particles. The low conductivity of sand overlying a more conductive soil was hypothesized to make it possible to use EM methods for estimating sand deposition depth. Since the EM technique is noninvasive, rapid surveys of large areas for mapping purposes have been possible (Jaynes et al. 1993; Lesch et al. 1992; McNeil 1992; Sudduth and Kitchen 1993; Williams and Hoey 1987). In this project, a method of combining EM data with Global Positioning System (GPS) location data was evaluated as a means for surveying and mapping sand deposition following the 1993 floods along the Missouri River.

Methods

Four locations along the Missouri River were identified to evaluate the use of EM data for estimating sand deposition depth (Figure 1). Sites and evaluation dates are listed in Table 1 along with the general conditions at the time of data collection. At Hartsburg, two distinctive areas were observed based on sand size. These areas were independently evaluated. At most of the sites the lower portion of the sand was saturated in some areas of the field. Additionally, a 2-10 cm (1-4 in) layer of silty "muck" was present in some areas, directly on top of the old soil. Since this "muck" layer was generally thin and was not present everywhere, its thickness was included as part of the deposition depth measurement.

The EM instrument used in this study

Interpretive summary

From the 1993 Midwest flooding, large amounts of sand were deposited along some river-bottom cropland. This study was performed to determine whether soil conductivity measurements could be used to accurately estimate depth of sand deposition. Soil conductivity was determined with a commercial sensor based on the principle of electromagnetic induction (EM). A strong relationship between sensor readings and sand deposition was found. Linking EM sensor data with location data obtained from GPS, maps of sand deposition were obtained. These maps helped show the water flow patterns over crop land and would also be valuable in developing restoration plans.

Key words: sand deposition, electromagnetic induction, EM, ground conductivity, 1993 Midwest floods

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Table 1. Sites and dates for determining the relationship of EM38 conductivity measurements and sand deposition along the Missouri River following the 1993 flood

Location	Date	Sand	General sand conditions	Air temperature	Evaluation area
				— °C —	— ha–
Labadie (1st)	12/28/93	mostly fine, small areas of coarse	• sand wet, lower 5-20 cm of deposition saturated • top 15 cm frozen	-12	50
Labadie (2nd)	2/17/94	mostly fine, small areas of coarse	• sand moist, lower 5-20 cm of deposition saturated	18	50
Labadie (3rd)	5/31/94	mostly fine, small areas of coarse	• sand moist, lower 5-20 cm of deposition saturated • some areas rip-tilled and were drier	30	50
Hartsburg (coarse sand area)	7/21/94	mostly coarse	• surface very dry, moist else where, lower 0-10 cm of deposition saturated	29	30
Hartsburg (fine sand area)	7/21/94	mostly fine	• surface very dry, moist elsewhere, lower 0-30 cm of deposition saturated	29	10
Overton	7/27/94	mostly fine	• sand moist, lower 0-8 cm of deposition saturated	26	40
Birmingham (1st)	7/26/94	mostly fine, small areas of coarse	• sand moist, lower 0-5 cm of deposition saturated	24	60
Birmingham (2nd)	8/03/94	mostly fine, small areas of coarse	• sand moist, lower 0-5 cm of deposition saturated	30	60

was the EM38 manufactured by Geonics Limited, Mississauga, Ontario, Canada.[1] The EM38 is a lightweight bar approximately 1 m (3 ft) in length, and includes calibration controls and a digital readout of apparent conductivity in milliSiemens per meter (mS/m). An analog output port is provided to allow data to be recorded on a data logger or computer. In this study, the instrument was operated in the vertical dipole mode, providing an effective measurement depth of approximately 1.5 m (5 ft) (McNeil 1992).

The instrument response to soil conductivity varies as a nonlinear function of depth. Sensitivity in the vertical mode is highest at about 0.4 m (1.3 ft) from the instrument. The apparent conductivity measured by the instrument is determined by the soil conductivity with depth, as weighted by the instrument response functions (McNeil 1992). Procedures have been developed to infer the soil conductivity profile with depth by means of multiple readings obtained with the instrument held at varying heights above the ground (Cook and Walker 1992; Rhoades and Corwin 1981). However, since our previous work (Doolittle et al. 1994; Kitchen et al. 1993; Sudduth and Kitchen 1993) showed that depth of topsoil over a claypan could be successfully estimated from single-height EM readings, we applied the same approach to measure sand deposition depths. Eliminating the need to take measurements at multiple heights quickened the data collection process since it was then possible to collect EM data on-the-go.

In investigating the relationship of conductivity to sand depth at the four sites (Table 1), we used the standard method of measuring apparent conductivity with the EM38 where the instrument was placed on the ground surface and the reading recorded. Depth of deposition was then determined at each measurement location by soil coring with a bucket auger soil-corer to the pre-flood soil surface and measuring the resulting depth. At most locations, the pre-flood soil boundary was easily determined based upon crop residues and soil structure. The EM readings were inverted (i.e., 1/EM) and the resulting data were correlated with depth of sand. The inverse transformation was chosen because it had provided the best correlations between EM reading and depth of topsoil over a claypan horizon in previous studies (Doolittle et al. 1994; Sudduth and Kitchen 1993).

For mapping of depositional areas, a mobile EM measurement system was developed. The EM38 was mounted on a 3 m (10 ft) long cart consisting of a wooden beam supported at the rear by two spoke-wheeled pneumatic tires (Figure 2). Use of the wooden beam was necessary because the EM38 will respond strongly in the presence of metallic objects within approximately 1 m (3 ft). The tongue of this cart was attached to the rear of a second, similar cart, which was in turn attached to the rear hitch of a four-wheel all-terrain vehicle (ATV). The second cart was necessary to increase the distance between the EM38 and ATV, for eliminating the effects of ATV engine noise on the EM readings. With this configuration, the EM38 was suspended 20 to 22 cm (8 to 9 in) above the ground surface during data collection.

Figure 2. Mobile system for collecting EM38 and GPS data used for developing maps of sand deposition depth

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[1] Mention of trade names or specific products is made only to provide information to the reader and does not constitute an endorsement by the University of Missouri or the USDA Agricultural Research Service.

Table 2. Relationship of EM38 conductivity measurements to sand deposition for seven site-dates along the Missouri River

Site	N	Regression model		r^2	Root MSE	CV
	deposition	(cm) = b + m (EM reading)*†				
		— intercept —	—slope—		— cm —	
Labadie 1st	12	-30.7 a	3019 ad	0.79	20	27
Labadie 2nd	23	-32.3 a	2527 a	0.89	18	22
Hartsburg coarse	8	-72.7 a	3494 acd	0.73	22	33
Hartsburg fine	12	-25.7 a	1574 b	0.91	10	19
Overton	16	-35.5 a	4964 cd	0.94	8	15
Birmingham 1st	17	13.4 b	1896 b	0.79	21	26
Birmingham 2nd	11	-21.8 a	3737 d	0.87	21	21
all data	99	12.6	1664	0.47	31	43

* Intercepts and slopes suffixed by a common letter are not significantly different by a F-test protected LSD (p=.05).

† Actual EM38 meter conductivity readings transformed by 1/EM38 reading before regression (see methods for explanation).

EM conductivity data were read into an IBM laptop computer mounted in front of the ATV operator, through an IOtech Daqbook data acquisition interface. Data obtained from an Ashtech M-XII GPS receiver were integrated with the EM data to provide the coordinates of each measurement point. The GPS data were differentially corrected by post-processing to obtain absolute position accuracies of 3 m (9 ft) or better. EM and GPS data were collected on transects approximately 30 m (98 ft) apart over the study areas. Data were recorded on a 1 s interval, which corresponded to a measurement every 2 to 5 m (6 to 16 ft) along the measurement transects. Calibration data were obtained at 15 or more points in each mapped area as described previously, except that the EM readings were obtained with the instrument mounted on the wheeled cart. After calibration, EM-determined sand depths were interpolated to a 10 m (33 ft) grid spacing and mapped.

Results and discussion

Relationship of EM measurements with sand deposition. When readings were taken with the EM38 placed directly on the ground surface, a strong relationship between EM data and depth of sand deposition (r^2 values ranged between 0.73-0.94) was found for each of the data sets (Table 2, Figure 3). Two factors contributed to obtaining a good relationship between EM values and deposition depth without taking EM38 readings at various heights above the soil surface. One, soil conductivity differed greatly between the pre-flood soil and the deposited sand. Two, the EM38 response is affected by depth to each soil layer as well as the conductivity of each layer (McNeil 1992). Thus only one EM reading at or near the ground surface was needed to develop the relationship between EM and sand depth.

Deposition depth varied from 2 cm (1 in) to more than 1.9 m (6 ft) within the survey areas. At a few locations where EM readings were taken, deposition measurements exceeded 1.5 m (5 ft), the manufacturer's stated effective sensing depth (McNeil 1992). We found that measurements up to a depth of about 1.9 m (6 ft) followed the same relationship as $\leq$ 1.5 m (5 ft) and were therefore included in the regression analysis. Locations with deposition over 1.9 m (6 ft) were excluded.

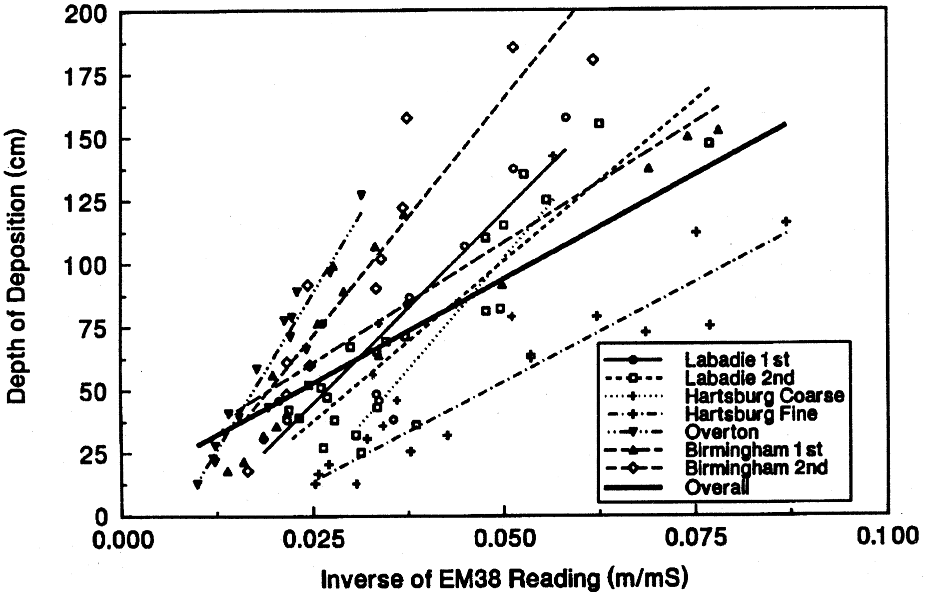

Figure 3. Regression relationship of EM38 readings and depth of sand deposition

For site calibration regressions, y axis intercepts were not significantly different between sites (except for Birmingham 1st test), but slopes between sites generally varied (Table 2, Figure 3). Calibration data were collected on multiple dates at Labadie and Birmingham. For the latter site the slope for the 2nd regression calibration was significantly different than that for the 1st (Table 2). Differences between sites were attributed to differences in sand size (see difference between Hartsburg coarse and Hartsburg fine), clay (Williams and Hoey 1987) and silt content, soil water content (Kachanoski et al. 1988) and climate (i.e., air temperature and humidity). Differences between dates at a given site were attributed to soil water content and climate conditions at the time of calibration. A single regression including all data yielded poorer estimates of deposition depth ($r^2 = 0.47$) (Table 2). Correcting EM data for temperature would likely improve the single-regression depth prediction (McKenzie et al. 1989). Based upon the variations in climate conditions, soil water, and soil texture for these data sets, we concluded that ground truthing by soil probing was necessary for each site and date in order to ensure an accurate survey.

Mapping of sand deposition. Detailed field surveys of sand deposition were conducted on two fields with the mobile EM data collection system (Figure 2). Instrumentation setup, data collection, and ground truthing took approximately 6 hours for each site. About 5,600 EM readings were obtained at Labadie and 7,500 EM readings at Birmingham using the mobile EM system, or an average of approximately 110 and 125 EM readings ha^{-1}, respectively. From these data, maps showing differences in deposition depth at the sub-ha scale were obtained with much more detail than would be practical by using visual observations or soil-probe methods.

As expected, we noticed a general pattern of decreasing sand deposition with increasing distance away from the river. At Labadie and Birmingham, flood waters continued inland 2 to 4 km (1.2 to 2.5 mi) beyond the areas that were surveyed. At Labadie, the Missouri River runs

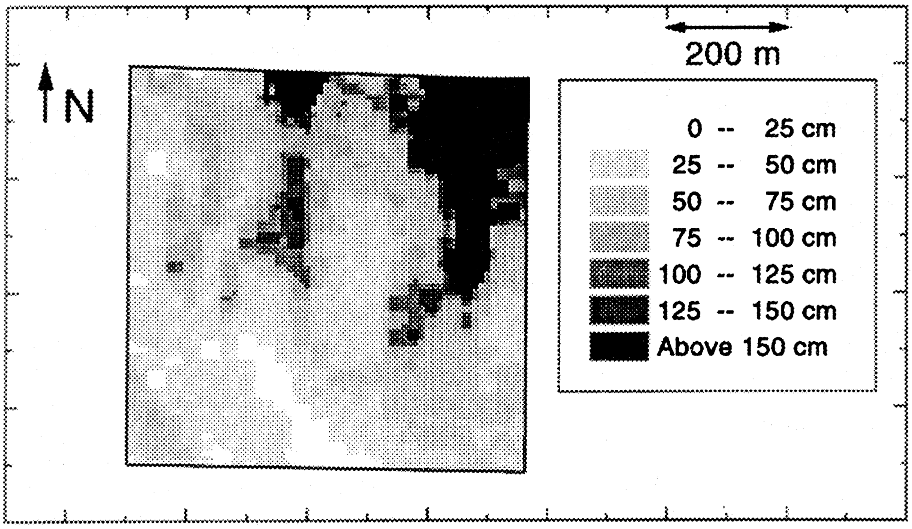

Figure 4. EM38-estimated sand deposition at Labadie, Missouri

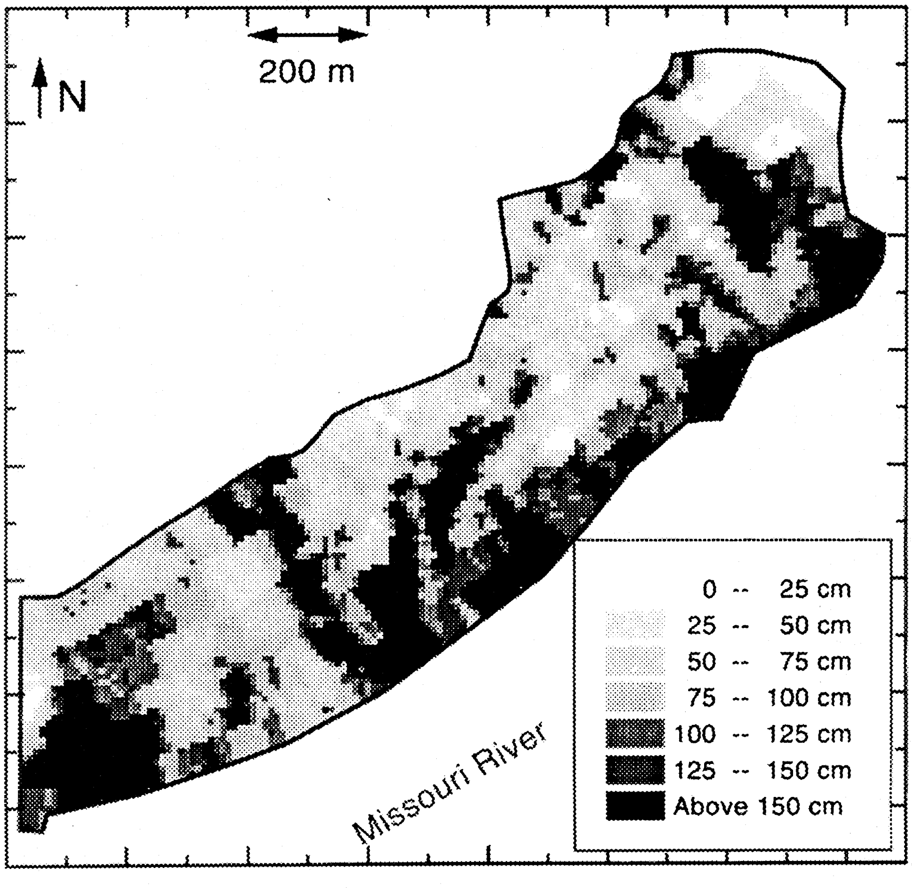

Figure 5. EM38-estimated sand deposition at Birmingham, Missouri

roughly in a northeast direction several hundred meters to the north of the surveyed area. The deepest depositional areas in the north east corner of the surveyed area (Figure 4) corresponded to a location of low elevation in an east-west secondary levee located along the northern edge of the surveyed area. Evidence of concentrated flow at these low levee points included some localized large and deep eroded holes (5-20 m [16-66 ft] diameter), large fallen trees, and coarse sand. While the levee did not erode away, deposition in this area was affected more by it than by distance from the river.

At Birmingham, the southeastern boundary of the deposition survey area (Figure 5) ran parallel to and about 50 m (160 ft) from the Missouri River. Most of the cropland inland from the surveyed area had less than 30 cm (12 in) of deposition, and by the time of the survey, deposited sand had been tilled to mix with the underlying soil and returned to crop production. Within the surveyed area, sand deposition generally decreased away from the river, but this decrease was not uniform and varied along the river. The deepest sand deposits were found in narrow strips running perpendicular from the river. From visual observations of large fallen trees and other flood debris these strips appeared to be associated with the primary floodwater flow pathways.

Calibration of EM readings at the Birmingham site revealed a limitation to use of the EM for estimation of sand deposition depth. Several large areas in the southwestern portion of the surveyed field were estimated to have ≥ 140 cm (55 in) of sand deposition (Figure 4). However, ground truthing by soil coring indicated that these areas were predominantly sandy soils prior to the 1993 floods, and the true depth of deposition in this area was generally less than 50% of the EM-estimated depth. Thus, deposition in 1993 was with material similar in texture (and thus conductivity) to the pre-flood soils, and the EM technique did not accurately estimate sand deposition from the 1993 floods. Only if significant conductivity differences exist between the sand deposition and the pre-flood soil profile will suitable conditions exist for using EM methods to predict sand deposition depth.

Summary

The relationship between EM readings and sand deposition after the 1993 floods was found to be sufficiently strong to use the EM meter as a noninvasive tool for estimating depositional depth. When EM data were linked with GPS location data, we could quickly survey large fields and synthesize the resulting data to develop detailed sand deposition maps. Such maps can provide valuable information to land-owners for developing restoration plans. In the case of the Birmingham location, the area had been previously developed with an underground pipe system (at a depth below EM38 signal penetration) for land disposal of secondary-treated municipal biosolids. In order to preserve this investment, recovery of the land to pre-1993 conditions by removing the sand is planned.

This study shows that linking EM sensing with GPS location data can be extremely valuable for quickly obtaining detailed spatial information about soils within a landscape that differ in bulk soil conductivity. A necessary step in the method is being able to establish with ground truthing the cause(s) of the changes in EM conductivity measurements. To measure the depth to an interface between two soil layers, a significant difference in conductivity between those two layers must exist. For these data, the depth of sand deposition on top of loamy soil was determined to be the primary factor causing differences in EM conductivity measurements within the study area. To what extent this method can be used to evaluate and predict soil differences within landscapes and the effect those differences have on plant production has had limited attention (Jaynes et al. 1993; Kitchen et al. 1993; McBride et al. 1990), and needs additional research.

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