Prepared in cooperation with the City of Cedar Rapids

Delineation of Selected Lithologic Units Using Airborne Electromagnetic Data near Cedar Rapids, Iowa

Pamphlet to accompany
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U.S. Department of the Interior
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Front cover. Helicopter and the RESOLVE frequency-domain "bird" lifting off from airport to begin data collection survey (Photograph taken by J. Valder, U.S. Geological Survey).

Back cover. Helicopter used in airborne electromagnetic study (Photograph taken by Bruce Jacobs, City of Cedar Rapids).

Delineation of Selected Lithologic Units Using Airborne Electromagnetic Data near Cedar Rapids, Iowa

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U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Vertical coordinate information is referenced to the Geodetic Reference System 1980 (GRS 80).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AEM airborne electromagnetic

USGS U.S. Geological Survey

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Abstract

The U.S. Geological Survey, in cooperation with the City of Cedar Rapids, began a study in 2013 to better understand the effects of drought stress on the Cedar River alluvial aquifer. After an evaluation of the existing groundwater-flow models for the alluvial aquifer, a plan was begun to construct an updated groundwater-flow model capable of evaluating the effect of prolonged drought and increased demand. As part of the effort to update the existing groundwater-flow model, data were collected during an airborne electromagnetic (AEM) survey in May 2017. The study area for the AEM survey encompasses about 53 square kilometers of the Cedar River Basin, west of Cedar Rapids, Iowa, and includes a 19-kilometer reach of the Cedar River. The AEM survey of the Cedar River alluvial aquifer and adjacent areas was completed to characterize the subsurface geology of the area to refine a lithologic framework. The collected AEM data were postprocessed by numerical inversion using the program EM1DFM to produce subsurface apparent resistivity cross sections. Changes observed in resistivity profile values with depth were used to infer lithologic changes and delineate three of the four lithologic units designated in the lithologic framework for this area: alluvial deposits, glacial till, and bedrock; hereafter referred to as the “lithologic framework.” The fourth unit, composed of surficial eolian sediments, was not delineated in these profiles because these units are thin and discontinuous and are not reliably distinguishable from flood plain alluvial deposits. For the purposes of delineating lithologic units using the AEM data, bedrock was assumed to be the lowest unit in a profile, glacial till was deposited on a bedrock surface, and alluvium was deposited on erosional till or bedrock surfaces.

A three-dimensional fence diagram was created as part of the lithologic framework to further define the extent and thickness of the lithologic units near the Cedar River alluvial aquifer. The fence diagram shows a three-dimensional perspective of unit thickness, extent, and orientation of the delineated lithologic framework. A lithologic framework, by design, is intended to represent a simplification of a more complex natural system through data interpolation between known points, which usually are lithologic logs. The resistivity profiles produced from the AEM survey allow for continuous mapping and accurate interpolation of lithology between lithologic logs; however, the apparent resistivity value may reflect several characteristics of subsurface materials including variations in lithology, porosity, water quality, grain sorting, and degree of saturation. In this study, the only variables considered were those related to changes in the subsurface material.

Introduction

The Cedar River alluvial aquifer is the principal source of municipal water supply for the city of Cedar Rapids, Iowa. The alluvial aquifer, hereafter defined in this report as “alluvial deposits,” is generally composed of sands and gravels with spatially discontinuous overlying eolian sediments near valley margins where wind has reworked the older surficial alluvial deposits (Schulmeyer and Schnoebelen, 1998; Quade and others, 1998). Historically, the aquifer has been capable of supporting the water supply needs of the city of Cedar Rapids and the surrounding area, which has an estimated population of about 126,000 as of 2010 (U.S. Census Bureau, 2018). Between July 2011 and February 2013, Iowa experienced severe drought conditions (generally referred to as the “2012 drought”) that affected water availability throughout Iowa for those communities that rely on alluvial aquifers to supply their water needs (Hillaker, 2012). During this time, the city of Cedar Rapids observed water-level declines in their production wells (B. Jacobs, City of Cedar Rapids, written commun., 2018), raising concern about the reliability of the alluvial aquifer. Riverbed leakage accounts for an estimated 74 percent of recharge to the alluvial aquifer (Schulmeyer and Schnoebelen, 1998). As the streamflow in the Cedar Rapids area decreases, riverbed leakage to the underlying alluvial aquifer decreases and water levels in the alluvial aquifer decline (Schulmeyer and Schnoebelen, 1998). As a result, the underlying carbonate bedrock, hereafter referred to as “bedrock,” may have become the primary source of recharge to the alluvial aquifer. The bedrock is generally composed of 22 lithologic formations ranging from Silurian to Devonian in age (University of Iowa, 2013; Tucci and McKay, 2006; Iowa Department of Natural Resources, 2004).

The U.S. Geological Survey (USGS), in cooperation with the City of Cedar Rapids, began a study in 2013 to better understand the effects of drought stress on the Cedar River alluvial aquifer. Previously published groundwater-flow models provided flow analysis based on the existing understanding of the physical properties of the alluvial aquifer and the effects of pumping on source waters (Schulmeyer and Schnoebelen, 1998; Turco and Buchmiller, 2004). After an evaluation of the existing groundwater-flow models for the alluvial aquifer (Schulmeyer and Schnoebelen, 1998; Turco and Buchmiller, 2004), a plan was begun to construct an updated groundwater-flow model capable of evaluating the effects of prolonged drought and increased demand. As part of the effort to update the existing groundwater-flow models, data were collected during an airborne electromagnetic (AEM) survey in May 2017 (Deszcz-Pan and others, 2018; fig. 1) to better characterize subsurface materials and more accurately define the extent of the alluvial aquifer near Cedar Rapids. A total of 25 lithologic logs available from the Iowa Geological Survey (2018) were used for interpretation and validation of the AEM data collection (fig. 1).

An AEM survey can overcome some of the time and land-access constraints of ground-based geophysics and can be used to produce a comprehensive and continuous dataset for delineating horizontal extents and vertical depths of the aquifers and characterizing landscape-scale geologic structures (Valseth and others, 2018). In the AEM method, electromagnetic signals transmitted from an airborne device induce currents in the subsurface that are then measured by receivers in the device. In the RESOLVE frequency-domain AEM system used for this survey, the transmitters and receivers are housed in an apparatus, referred to as a “bird,” suspended by a tow line about 30 meters (m) below a helicopter and about 30 m above the ground (Valseth and others, 2018; fig. 2). The data collected by the AEM system indicate apparent electrical resistivity of the subsurface, and these data can be interpreted to delineate lithologic boundaries when processed (Valder and others, 2016; Valseth and others, 2018).

The City of Cedar Rapids contracted with CGG Canada Services Ltd. to collect the AEM data in May 2017. CGG Canada Services Ltd. provided the final AEM dataset to the City of Cedar Rapids and the USGS, who inverted the data using the program EM1DFM (Farquharson, 2000) to produce resistivity depth sections for three-dimensional visualization of subsurface electrical variations. Data generated during this study are available as a USGS data release (Deszcz-Pan and others, 2018).

Purpose and Scope

The purpose of this report is to present the delineation of selected lithologic units (alluvial deposits, glacial till, and bedrock) using AEM data collected in May 2017 near Cedar Rapids, Iowa (fig. 1). Data collected during the 2017 AEM survey are presented in a separate data release (Deszcz-Pan and others, 2018). This report describes (1) the lithologic setting near Cedar Rapids, Iowa; (2) AEM investigation methods; (3) delineation of selected lithologic units; and (4) data and interpretive limitations of the methods used.

Location and Description of Study Area

The study area for the AEM survey encompasses about 53 square kilometers (km^2) of the Cedar River Basin, west of Cedar Rapids, Iowa (fig. 1), and includes a 19-kilometer (km) reach of the Cedar River. The area includes a flat alluvial valley underlain by fluvial and glaciofluvial sands and gravels and uplands generally underlain by glacial tills and eolian sediments (Quade and others, 1998). The location and extent of the AEM survey area were planned with several considerations: gathering data near the Cedar River alluvial deposits; avoiding electromagnetic interference and built structures; and targeting representative alluvial deposits, glacial till, and eolian sediments that are in the study area (fig. 1). A total of two USGS streamgages, Cedar River at Blairs Ferry Road at Palo, Iowa (USGS streamgage 05464420), and Cedar River at Edgewood Road at Cedar Rapids, Iowa (USGS streamgage 05464480), are near the study area (fig. 1); streamflow data for these streamgages are available from U.S. Geological Survey (2018). The locations of 25 wells with lithologic logs (table 1) that were used for interpreting AEM data also are shown in figure 1 (Iowa Geological Survey, 2018).

Lithologic Setting

For the interpretation of AEM survey results, the regional lithologic system was simplified to four main units. Of these units, three consist of surficial deposits: glacial tills, eolian sediments (windblown), and alluvial (stream) deposits; the fourth is the underlying carbonate bedrock composed of 22 formations ranging from Silurian to Devonian in age (University of Iowa, 2013; Tucci and McKay, 2006; Iowa Department of Natural Resources, 2004). These lithologic units are components of the Southern Iowa Drift Plain and Iowan Surface landform regions in the study area and include sediment deposits and weathering zones formed during several glacial and interglacial intervals over the past 2.2 million years (fig. 1; Hallberg, 1986; Prior, 1991; Bettis and others, 2005).

The Southern Iowa Drift Plain is a region that was glaciated several times from 2.2 million to 500,000 calendar years before present, referenced to calendar year 1950 (Hallberg, 1986). These glaciations deposited predominantly basal tills on an irregular bedrock surface. These tills were assigned to the Pleistocene-age Alburnett Formation and younger Wolf Creek Formation by Hallberg (1980). Both formations consist of multiple depositional till units and paleosols (weathering surfaces with soil formation) and include deposits of several glacial and interglacial intervals. These tills are primarily silty

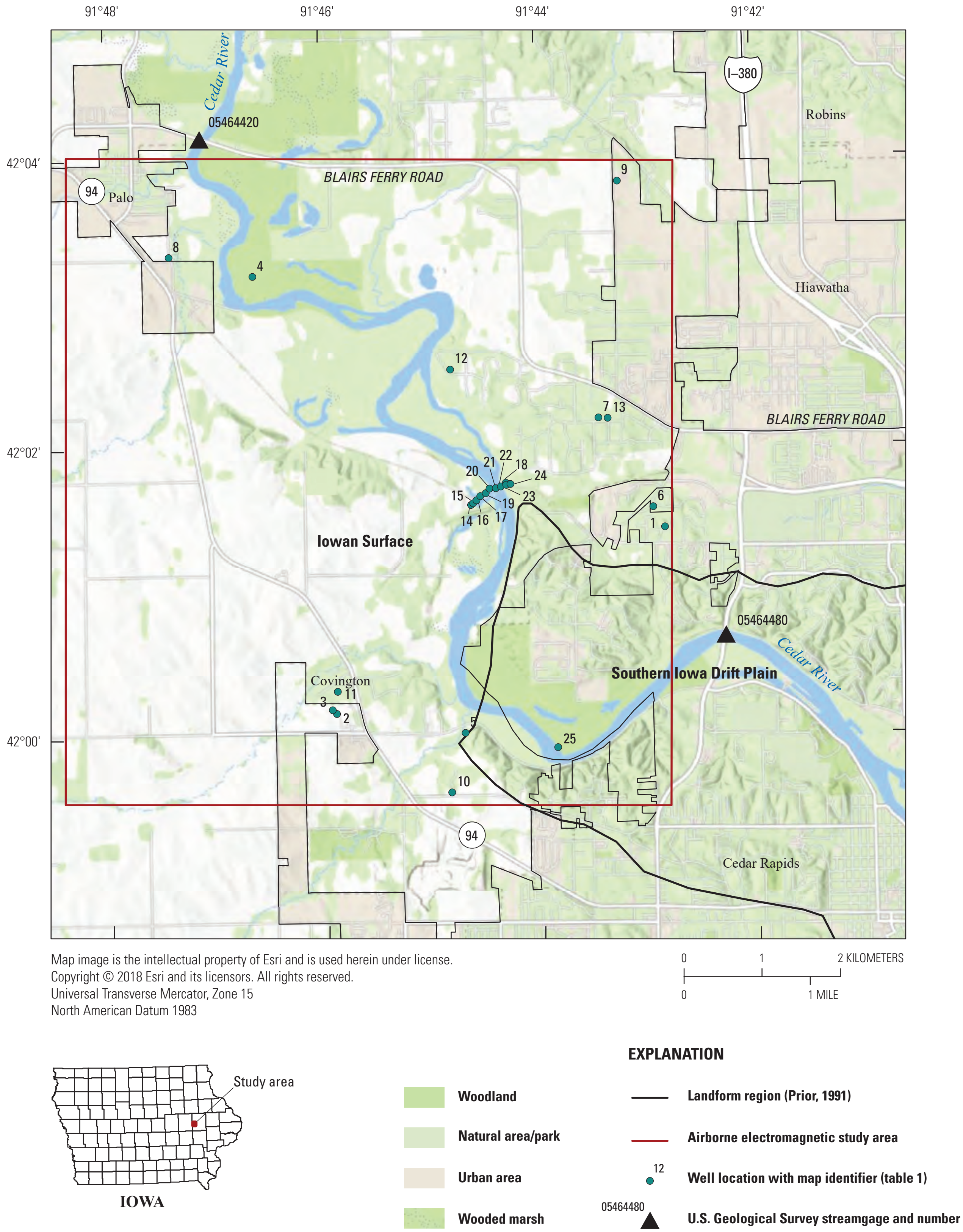

Figure 1. Study area for airborne electromagnetic survey, location of wells with lithologic information, and location of streamgages.

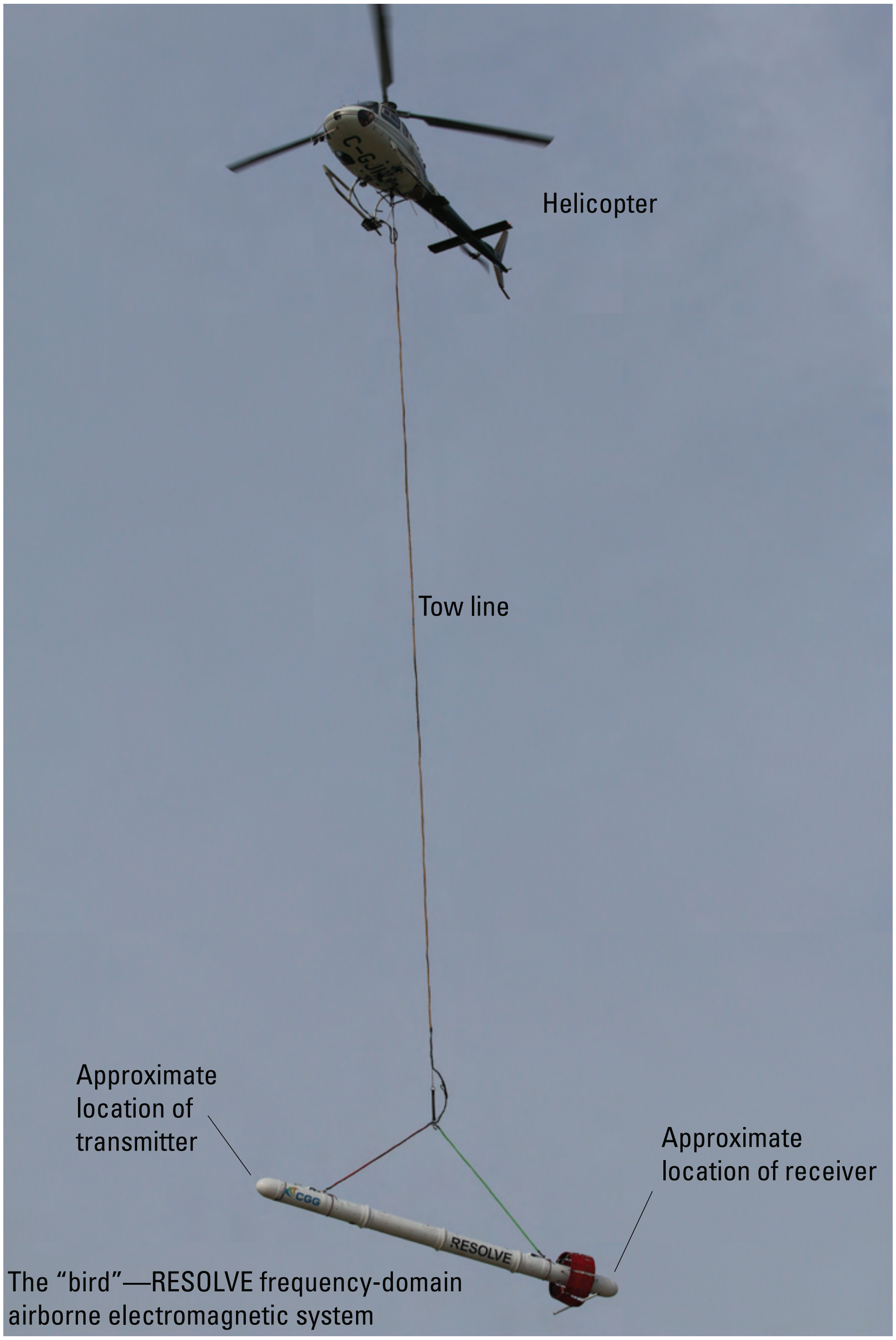

Figure 2. The RESOLVE frequency-domain airborne electromagnetic system (the “bird”) used to transmit and receive electromagnetic energy to characterize the Cedar River alluvial aquifer, suspended from the helicopter (photograph by Joshua Valder, U.S. Geological Survey).

Table 1. Well identification for 25 wells with lithologic logs in the study area. The well identification number is the unique number identifying each well in the GeoSam database (Iowa Geological Survey, 2018).

Map identifier (fig. 1)	Iowa Geological Survey well identification number
1	4975
2	5082
3	5084
4	12660
5	17042
6	22775
7	22783
8	23575
9	80616
10	81091
11	81096
12	81301
13	81309
14	83011
15	83012
16	83013
17	83014
18	83015
19	83016
20	83017
21	83018
22	83019
23	83020
24	83021
25	84479

clay and sandy clay loams with interbedded, discontinuous sand and gravel bodies that range in thickness from 1 to 3 m.

After the last pre-Illinoian glaciation, a drainage network formed, similar to the one observed on the modern landscape, as represented by the Iowan Surface. On the uplands, deep weathering profiles and erosional surfaces developed, removing till entirely in places; in the lowlands, stream channels incised, in some areas to bedrock, and, over the millennia (during the 500,000 calendar years before present), many cut-and-fill episodes left behind sand and gravel deposits (Hallberg, 1980). During the Wisconsinan glaciation, the last advance of continental ice in North America was between 23,000 and 11,000 calendar years before present. Although ice did not reach the study area during this last advance, two episodes of eolian sediment (loess) deposition (Prior, 1991) were on high alluvial terraces and upland surfaces near the Cedar River valley.

In the study area, the Cedar River alluvial aquifer is generally composed of 13–22 m of sand and gravel deposits that are Pleistocene to Holocene in age and eolian sand deposits in areas of the valley where wind has reworked older alluvial deposits (Schulmeyer and Schnoebelen, 1998; Quade and others, 1998). Other surficial deposits in the study area are primarily glacial till overlain by discontinuous sand and silt (eolian sediment) deposits (Quade and others, 1998). Tills in the study area contain interbedded sand and gravel bodies, but these interbedded bodies are typically too deep or too thin for the AEM survey RESOLVE system to distinguish the resistant material from surrounding till (David Smith, U.S. Geological Survey, oral commun., 2017). This geologic interpretation of subsurface materials was used to guide the lithologic interpretations of AEM data in the section “Delineation of Selected Lithologic Units Using Airborne Electromagnetic Data.”

Airborne Electromagnetic Investigation Methods

The AEM survey of the Cedar River alluvial aquifer and adjacent areas was completed to characterize the subsurface geology of the area to refine a lithologic framework. Using the AEM method provided a more detailed characterization of the aquifer that could not be otherwise achieved using traditional methods; for example, lithologic log characterization or surface observation of geology (Valseth and others, 2018). Initial ground-based resistivity surveys were used to characterize the lithologic targets (depth) and frequencies and to demonstrate electrical resistivity contrasts in the subsurface that made AEM a suitable method for the area. The shallow depth of the Cedar River alluvial aquifer supported the use of the RESOLVE frequency-domain AEM system for the survey.

The AEM survey was completed in May 2017 and consisted of 66 flight lines for a total of about 600 survey line-kilometers, including a grid of east-west flight lines (“primary flight lines”) with a spacing of 200 m and several north-south “tie” lines (fig. 3). Several free-flight, curving flight lines along the Cedar River channel also were surveyed. These “free-flight” lines were flown over other areas of interest that were too small or isolated to be captured by the survey grid (fig. 3); however, these data are not included in the delineation of lithologic units described in this report but are available as part of a USGS data release (Deszcz-Pan and others, 2018).

Horizontal spacing of the apparent resistivity measurements averaged around 2.5 m and varied based on the 10-hertz sampling frequency and the speed of the RESOLVE frequency-domain AEM system as it moved over the land surface. The collected AEM data were postprocessed by numerical inversion using the program EM1DFM (Farquharson, 2000) to produce subsurface apparent resistivity cross sections, hereafter referred to as “resistivity profiles,” below all flight lines and are available in a USGS data release (Deszcz-Pan and others, 2018).

Delineation of Selected Lithologic Units Using Airborne Electromagnetic Data

Changes observed in resistivity profile values with depth derived from the AEM data were used to infer lithologic changes and delineate three of the four lithologic units designated in the lithologic framework for this area: alluvial deposits, glacial till, and bedrock, hereafter referred to as the "lithologic framework" (fig. 4, sheet 1, available at https://doi.org/10.3133/sim3423). The fourth unit, composed of surficial eolian sediments, was not delineated in these profiles because these units are thin and discontinuous and are not reliably distinguishable from flood plain alluvial deposits. Lithologic logs from the Iowa Geological Survey were used to verify and modify the lithologic framework (table 1; Iowa Geological Survey, 2018). Finally, delineated resistivity profiles were used to interpolate maps of the glacial till surface elevation, the bedrock surface elevation, alluvial deposit thickness, and depth to bedrock (figs. 5*A–D*, respectively, sheet 2, available at https://doi.org/10.3133/sim3423) using similar techniques described in Valseth and others (2018).

Delineation of Lithologic Units in Resistivity Profiles

Resistivity profiles created from the AEM survey flight lines provided the foundation for building the lithologic framework (fig. 4, sheet 1). Each profile created by Deszcz-Pan and others (2018) was used to delineate three lithologic units: alluvial deposits, glacial till, and bedrock. Generally, lithologic unit boundaries were placed on profiles based on resistivity values and relative changes in values with depth. Land-surface elevation, geomorphology, and resistivity values of overlying material also were considered in lithologic unit boundary placement. Previously published investigations have documented that changes in electrical resistivity can be correlated to changes in bulk material properties in the subsurface and used for conceptualization in a lithologic framework (Valseth and others, 2018; Valder and others, 2016; Ball and others, 2011; Reynolds, 2011). Expected ranges in resistivity values for geologic materials were developed from published literature (Valseth and others, 2018), from measured resistivity values in geophysical logs of wells available from the Iowa Geological Survey (2018), and from comparison of resistivity values in the postprocessed AEM data with lithologic logs (Deszcz-Pan and others, 2018).

Some overlap in the expected resistivity value ranges for the three lithologic units made interpretation of contacts based upon resistivity values alone difficult. Some alluvial deposits in the study area have a range of resistivity values similar to the range of the underlying bedrock. In resistivity profiles where alluvial deposits overlie bedrock, the boundary between these units may not be clearly defined; for example, as shown in figure 4*B*. Interpretation of the resistivity profiles in these areas was informed by well lithologic logs that consistently indicated the contact between the alluvial deposits and the bedrock to be deeper than the area of resistivity contrast in the AEM data. Eolian sediments and alluvial deposits in the study area also have similar ranges of resistivity values and, in some profiles, are indistinguishable from one another; for example, eolian sediments were mapped adjacent to alluvial deposits by Quade and others (1998), yet a distinct boundary between these units cannot be observed in the resistivity values as shown in figure 4*B*. Eolian sediments were also mapped by Quade and others (1998) on the upland surfaces near the valley margin. The resistivity values of these eolian sediments contrast sharply with the values of the underlying glacial till (fig. 4*A*). Although this boundary is apparent, eolian sediments were not delineated as a separate lithologic unit. Other examples of potential undelineated eolian sediments are shown in figures 4*A* and *B*.

Subsurface delineation of lithologic units was informed by comparison of lithologic logs (Iowa Geological Survey, 2018) to resistivity profiles created from the AEM survey data (Deszcz-Pan and others, 2018). For the purposes of delineating lithologic units using the AEM data, bedrock was assumed to be the lowest unit in a profile, glacial till was deposited on a bedrock surface, and alluvium was deposited on erosional till or bedrock surfaces. This is illustrated in figure 4*A*, where a wedge of high-resistivity material was interpreted as a paleochannel alluvial sand and gravel deposit, not as bedrock. This interpretation is made on the premise that the alluvial deposit overlies and crosscuts a conductive unit interpreted as glacial till, which, in turn, overlies the lowest resistant unit, interpreted as bedrock.

Finally, the thickness of conductive material can alter the resolution and values of underlying resistant materials (Reynolds, 2011). This effect is illustrated in figure 4*B*, where resistivity values used to delineate the bedrock surface beneath till differ from values used beneath alluvial deposits. This effect was considered when delineating unit boundaries within each of the 66 profiles (1 for each flight line). An example from the 66 profiles illustrating a typical resistivity profile within the study is shown in figure 4*C*.

In some parts of the resistivity profiles, data seemed to be affected by interference from conductive or electrified structures such as roadways, power lines, and railroads, hereafter referred to as "cultural interference." Cultural interference can cause sharp and abrupt contrasting values in the resistivity profile that expand laterally with increasing depth (fig. 4*D*). Cultural interference suspected from such data irregularities was verified for this study using aerial imagery from Google Earth Pro (© 2016 Google), which shows power lines, railroads, and other anthropogenic structures, and location data provided by local utilities and the City of Cedar Rapids.

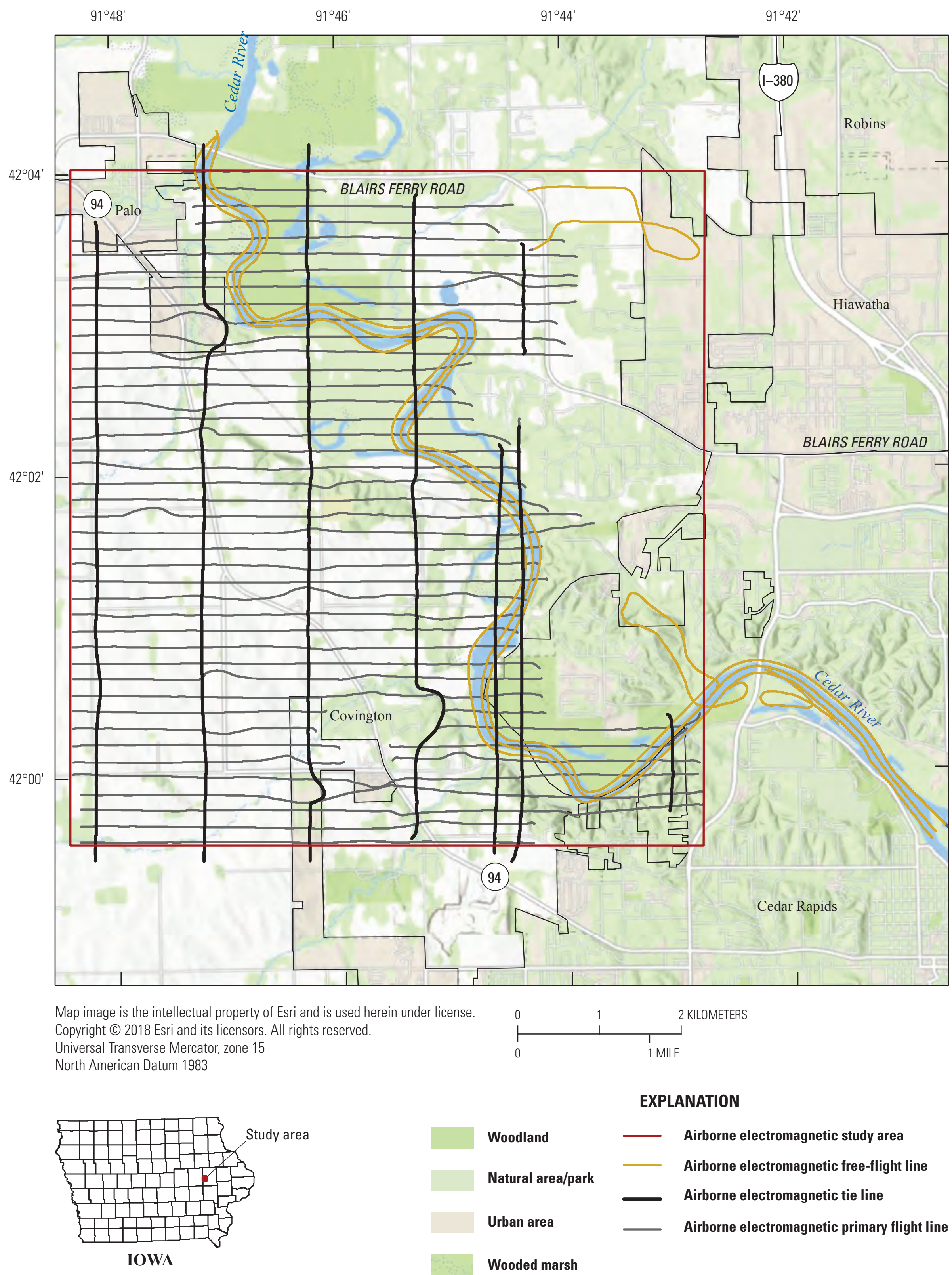

Figure 3. Airborne electromagnetic survey lines.

Map Interpolation from Lithologic Units

Each of the 66 resistivity profiles (Deszcz-Pan and others, 2018) with interpreted lithologic unit boundaries were imported into a geographic information system (Esri, 2018) using python scripts to georeference and analyze each resistivity profile and to interpolate each line spatially within the study area. The methods described in Valseth and others (2018) were used for all the processing of the data, except for the binning of existing wells based on perpendicular distance from the flight line. For this study, each well was used to validate the interpolation between lines. This validation was done to support the lithologic interpretations from interpolated resistivity values in areas between flight lines. Lithologic units were delineated in areas not flown (outside of the flight area) using the same interpolation methods but were designated as low-confidence areas (figs. 5*A*–*D*, sheet 2) because no resistivity profiles were available. The AEM flight data, resistivity profiles, interpolated maps, and delineation of the lithologic units are illustrated in the fence diagram in figure 5*E* and document the relative thicknesses of the three mapped lithologic units in the study area: alluvial deposits, glacial till, and bedrock. This three-dimensional fence diagram was created as part of the lithologic framework to further define the extent and thickness of the selected lithologic units in the area near Cedar Rapids. The fence diagram shows a three-dimensional perspective of unit thickness, extent, and orientation of the delineated lithologic framework (fig. 5*E*).

The thickness of the alluvial deposits was determined using the difference between the elevation of the glacial till surface and the land-surface elevation using a 3-m digital elevation model available through the Iowa Geodata website (https://geodata.iowa.gov/dataset/three-meter-digital-elevation-model-iowa-derived-lidar). The approximate thickness range of alluvial deposits is from 0 to 54 m, and the thickest alluvial deposits are in the northwest part of the study area (fig. 5*C*) where a paleochannel in the bedrock surface has been mapped (fig. 5*B*). The glacial till unit thickness was determined using the difference between the glacial till surface elevation (fig. 5*A*) and the bedrock surface elevation (fig. 5*B*). The approximate thickness range of the glacial till unit is from 0 to 72 m, and the thickest areas are in the southwestern part of the study area coinciding with low elevation of the bedrock surface and high elevation of the glacial till surface. The bedrock unit elevation does not have a delineated bottom because of the limitation of the AEM investigation depth, so no thickness was calculated. The depth to bedrock was calculated using the difference of the land-surface elevation (digital elevation model) and the bedrock surface elevation (fig. 5*B*). The approximate depth to bedrock range is from 0 to 72 m (fig. 5*D*).

Data and Interpretive Limitations

Interpolations made between data points inherently contain some uncertainty. A lithologic framework, by design, is intended to represent a simplification of a more complex natural system through data interpolation between known points, which usually are lithologic logs. The resistivity profiles produced from the AEM survey allow for continuous mapping and accurate interpolation of lithology between lithologic logs; however, the apparent resistivity value may reflect several characteristics of subsurface materials including variations in lithology, porosity, water quality, grain sorting, and degree of saturation (Reynolds, 2011). In this study, the only variables considered were those related to changes in the subsurface material. Those factors—variations in lithology, porosity, and sorting—were considered when delineating lithologic units in the resistivity profiles by comparing values to characteristics described in lithologic logs. Given the few lithologic logs available in the Cedar Rapids area, some uncertainty in exact placement of lithologic boundaries may exist. Delineating the different lithologic units provides an estimate of aquifer geometry, horizontal extents, and aquifer thicknesses, which are useful for future groundwater and hydrologic investigations.

References Cited

Ball, L.B., Smith, B.D., Minsley, B.J., Abraham, J.D., Voss, C.I., Astley, B.N., Deszcz-Pan, M., and Cannia, J.C., 2011, Airborne electromagnetic and magnetic geophysical survey data of the Yukon Flats and Fort Wainwright areas, central Alaska, June 2010: U.S. Geological Survey Open-File Report 2011–1304, 21 p. [Also available at https://doi.org/10.3133/ofr20111304.]

Bettis, A.E., Tassier-Surine, S., and Haj, A., 2005, Overview of the Quaternary geology of Martin Marietta's Cedar Rapids quarry, *in* Anderson, R.R., and Langel, R.J., eds., Quaternary and Silurian geology at the Martin Marietta Cedar Rapids quarry, Linn County, Iowa: Geological Society of Iowa, Guidebook 77, p. 5–18. [Also available at https://www.iihr.uiowa.edu/igs/publications/uploads/GSI-077.pdf.]

Deszcz-Pan, M., Smith, D.V., Smith, B.D., Haj, A.E., and Johnson, M.R., 2018, Airborne electromagnetic and magnetic survey data and inverted resistivity models, Cedar Rapids, Iowa, May 2017: U.S. Geological Survey data release, https://doi.org/10.5066/P9BS882S.

Esri, 2018, ArcGIS Desktop—ArcMap: Esri web page, accessed October 23, 2018, at http://desktop.arcgis.com/en/arcmap/.

Farquharson, C.G., 2000, Background for program "EM1DFM": Vancouver, Canada, University of British Columbia Geophysical Inversion Facility, 20 p.

Hallberg, G.R., 1980, Pleistocene stratigraphy in east-central Iowa: Iowa City, Iowa Geological Survey Technical Information Series no. 10, 168 p. [Also available at https://ir.uiowa.edu/igs_tis/10.]

Hallberg, G.R., 1986, Pre-Wisconsin glacial stratigraphy of the central plains region in Iowa, Nebraska, Kansas, and Missouri: Quaternary Science Reviews, v. 5, p. 11–15. [Also available at https://doi.org/10.1016/0277-3791(86)90169-1.]

Hillaker, H.J., 2012, Historical report—The drought of 2012 in Iowa: Department of Agriculture and Land Stewardship web page, accessed September 19, 2018, at https://www.iowaagriculture.gov/climatology/weatherSummaries/2012/DroughtIowa2012Revised.pdf.

Iowa Department of Natural Resources, 2004, Stratigraphic column of Iowa: Iowa City, Geological Survey Iowa Department of Natural Resources, 1 p., accessed October 23, 2018, at http://publications.iowa.gov/4862/1/EM-40.pdf.

Iowa Geological Survey, 2018, GeoSam—Iowa Geological Survey: Iowa Geological Survey web page, accessed August 6, 2018, at https://www.iihr.uiowa.edu/igs/geosam/home.

Prior, J.C., 1991, Landforms of Iowa: Iowa City, University of Iowa Press, 153 p.

Quade, D.J., Bettis, E.A., III, Ludvigson, G.A., Giglierano, J.P., and Slaughter, M.K., 1998, Surficial geologic materials of Linn County, Iowa: Iowa Department of Natural Resources, Geological Survey Bureau Open File Map Series 98–2, scale 1:100,000, accessed August 6, 2018, at https://www.iihr.uiowa.edu/igs/publications/uploads/ofm-1998-2.pdf.

Reynolds, J.M., 2011, An introduction to applied and environmental geophysics (2d ed.): Chichester, United Kingdom, Wiley-Blackwell, 710 p.

Schulmeyer, P.M., and Schnoebelen, D.J., 1998, Hydrogeology and water quality in the Cedar Rapids area, Iowa, 1992–96: U.S. Geological Survey Water-Resources Investigations Report 97–4261, 77 p. [Also available at https://doi.org/10.3133/wri974261.]

Tucci, P., and McKay, R.M., 2006, Hydrogeology and simulation of ground-water flow in the Silurian-Devonian aquifer system, Johnson County, Iowa: U.S. Geological Survey Scientific Investigations Report 2005–5266, 73 p. [Also available at https://doi.org/10.3133/sir20055266.]

Turco, M.J., and Buchmiller, R.C., 2004, Simulation of ground-water flow in the Cedar River alluvial aquifer flow system, Cedar Rapids, Iowa: U.S. Geological Survey Scientific Investigations Report 2004–5130, 39 p. [Also available at https://doi.org/10.3133/sir20045130.]

University of Iowa, 2013, Iowa stratigraphic column: University of Iowa, IIHR—Hydroscience & Engineering, accessed October 29, 2018, at https://www.iihr.uiowa.edu/igs/files/2014/04/Text-stratographic-coloumn-of-Iowa.pdf.

U.S. Census Bureau, 2018, 2010 demographic profile—IA-Cedar Rapids city: U.S. Census Bureau web page, accessed October 23, 2018, at https://www.census.gov/popfinder/.

U.S. Geological Survey, 2018, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed September 17, 2018, at https://doi.org/10.5066/F7P55KJN.

Valder, J.F., Delzer, G.C., Carter, J.M., Smith, B.D., and Smith, D.V., 2016, Construction of a groundwater-flow model for the Big Sioux aquifer using airborne electromagnetic methods, Sioux Falls, South Dakota: U.S. Geological Survey Fact Sheet 2016–3075, 4 p. [Also available at https://doi.org/10.3133/fs20163075.]

Valseth, K.J., Delzer, G.C., and Price, C.V., 2018, Delineation of the hydrogeologic framework of the Big Sioux aquifer near Sioux Falls, South Dakota, using airborne electromagnetic data: U.S. Geological Survey Scientific Investigations Map 3393, 2 sheets, accessed October 23, 2018, at https://doi.org/10.3133/sim3393.

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