Guidelines for Airborne Electromagnetic (AEM) Surveys, Data Integration, and Hydrostratigraphic Modeling in Nebraska

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Jesse T. Korus[1], Kathleen Cameron[1], Chris Hobza[2]

[1]Conservation and Survey Division–School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska-Lincoln

[2]Nebraska Water Science Center
U.S. Geological Survey

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INTRODUCTION

This document contains guidelines for the collection, reporting, and use of hydrogeological data in Nebraska, with particular emphasis on airborne electromagnetic (AEM) surveys. The intended audience for this document is the community of hydrogeologists, geophysicists, and related professionals involved in the planning, collection, and use of AEM and related hydrogeological data. This community is collectively referred to as "model builders" (Fig. 1). The professionals in this community have specialized skills to handle large volumes of data from multiple sources, develop hydrogeological models, and deliver products to "model users"—the decision makers who require simplified maps and models to make water-management decisions.

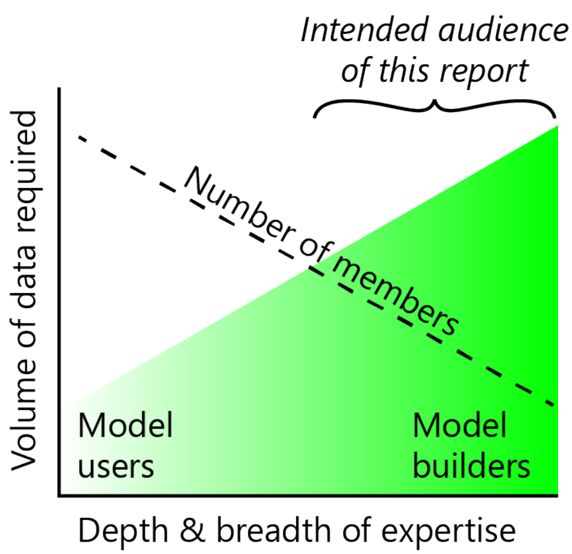

Figure 1. The concept of model builder versus model user. Builders are fewer, but have more breadth and depth of knowledge of the subject matter. Users are the decision makers who are manage water resources.

AEM surveys and related modeling procedures are complex and highly technical. Model builders are increasingly making use of AEM in hydrogeological studies, and this trend is expected to continue. Consequently, it is necessary that data and models be made available to geologists and hydrogeologists and that experience and information be transferred to the broader community. In addition, it is necessary that guidelines be established to maintain consistency and reliability of data and products. These guidelines are henceforth contained in this document, which will be updated and maintained as technology, software, and applications of the data change through time.

To assist in creating freely available, standardized data and models, a team of geoscientists have created the Nebraska GeoCloud (NGC), a web-based digital infrastructure for geophysical, geological, and groundwater information. The purpose of the NGC is to archive AEM data and related datasets and models, make these data available to users, and to provide guidance on the best scientific approaches to mapping hydrogeologic units using AEM. Standards for NGC are described in the companion document, **Standards for Data and Model Reporting in the Nebraska GeoCloud.**

The NGC project involved targeted hydrogeologic studies to investigate best practices and to serve as template examples for future projects. Based on these investigations and the collective experience of geoscientists conducting AEM surveys in Nebraska since 2006, the following chapters have been developed to provide model builders with the information necessary to achieve consistency and quality of hydrogeologic products from AEM surveys.

This document is organized into three chapters: Airborne Electromagnetic Surveys, Hydrogeologic Data Integration and Visualization, and Hydrostratigraphic Modeling. These chapters summarize recommended procedures for survey planning, data collection, and model building.

GUIDELINES FOR AIRBORNE ELECTROMAGNETIC (AEM) SURVEYS

Airborne electromagnetics (AEM) are proven geophysical survey methods that greatly advance hydrogeologic mapping and groundwater management efforts (Fountain 1998; Paine and Minty 2005; Christiansen et al. 2006; Siemon et al. 2009; Auken et al. 2017). Compared to traditional, invasive techniques such as drilling and boring, AEM is noninvasive, cost-effective, and it provides high-resolution subsurface information across large areas in a relative short amount of time. It is expected that AEM will be the primary tool for large-scale hydrogeological mapping into the foreseeable future. Therefore, the guidelines in this chapter are aimed at assisting future

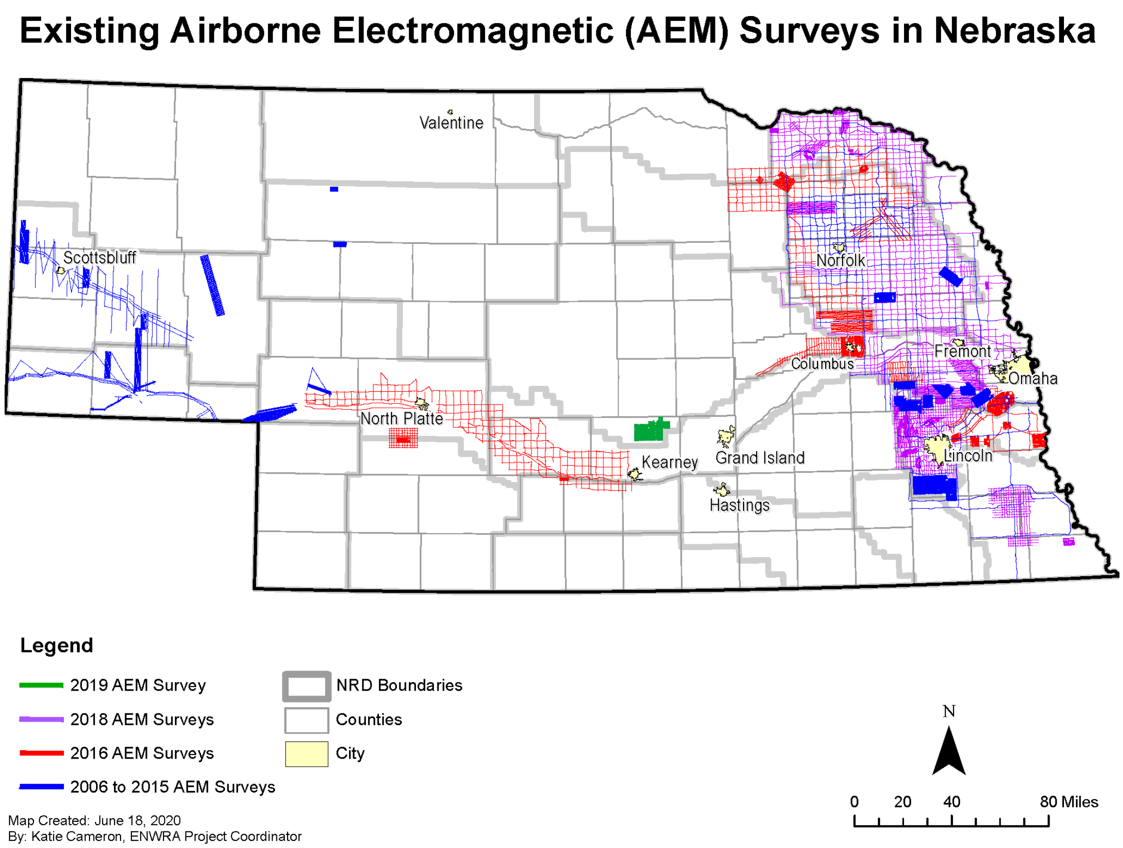

Figure 2. Map showing AEM flight lines from 2006 – 2019.

researchers and consultants in planning, conducting, and reporting AEM surveys. The guidelines will also help those using AEM data for mapping and modeling. The guidelines build on the collective experience of the geologists and geophysicists involved in the planning, implementation, and use of these surveys in Nebraska since 2006.

Over 32,000 line-km (20,000 line-mi) of AEM surveys have been flown in Nebraska (Fig. 2). The first AEM surveys in Nebraska were conducted in 2006 and 2007 by Fugro Airborne using the RESOLVE© frequency-domain electromagnetic (FDEM) system under contract by the USGS for the Eastern Nebraska Water Resources Assessment (ENWRA) (Smith et al. 2008). Fugro RESOLVE© was used again in western Nebraska in 2008 and 2009 by the North Platte and South Platte Natural Resources Districts (NRDs) (Hobza et al. 2014), in eastern Nebraska in 2009 by ENWRA NRDs (Smith et al. 2011), and at Mead, Nebraska in 2012 for a U.S. Army Corps of Engineers project. In 2010, SkyTEM's time-domain electromagnetic (TDEM) system, Aeroquest's AeroTEM IV system, and Geotech's VTEM™ systems were tested in western Nebraska (Bedrosian et al. 2016). Ground-based TDEM tests were conducted in eastern Nebraska the same year (Abraham et al. 2011). The TDEM system has emerged as an effective tool for achieving mapping objectives, and thus it has been the only system used since 2013 in eastern and central Nebraska, including campaigns in 2013, 2014-2015, 2016, 2018, and 2019. These surveys have used several variations of the SkyTEM system which was developed in Denmark.

The Hydrogeophysics Group at Aarhus University led the development of this system along with a detailed set of guidelines for SkyTEM surveys in Denmark. Because SkyTEM has been used extensively in Nebraska, the SkyTEM guidelines and standards are included with this document as **Appendix A**. It is suggested that users of the Nebraska document also review and refer to the SkyTEM guidelines for details about SkyTEM systems. However, keep in mind that the material is specifically related to the Danish experience and is specific to SkyTEM, and so the content may not be applicable in every situation.

Survey Planning

Planning an AEM survey begins with defining clear goals, objectives, and expectations. The plan should be focused on answering one or more basic questions. Examples of such questions are:

- What are the investigation objectives?
- What are the geological characteristics of the survey area?
- What are the volumes, thicknesses, and depths of saturated and unsaturated aquifer materials in the area?
- Where are the volumes, thicknesses, and depths of confining units in the area?
- Where are the aquifer boundaries and do hydrogeologic connections exist between aquifers and between groundwater and surface water?
- Is there potential for managed aquifer recharge in this area?
- What are the potential contaminant migration paths?
- How shall the hydrogeologic properties of an area be defined for a groundwater model?
- Is brackish or saline water present within an aquifer?

- What is the depth and extent of the saline/fresh water interface?

The specific objectives, goals, and geology within the project area will determine the type of system, its configuration and settings, including flight paths of the survey. Some surveys are flown for regional reconnaissance and others are flown for detailed characterization of a local area (i.e. wellhead protection area or recharge area).

Site Characterization

Physical and geologic setting is a fundamental consideration in the planning stage and should be characterized prior to the survey activities. Providing detailed geologic background information for the project area along with survey objectives and outcomes from the detailed planning discussions at the survey proposal stage will ensure that the final survey deliverables are most effective as possible. Clients may provide the characterization information to the selected survey contractors or have the contractors gather the information; however, survey proposals should consider the following:

Terrain

Exceedingly uneven topography and tall vegetation presents a challenge for AEM data collection. Altitude greatly affects the amplitude of the response at the receiver, which can affect data usability. The aircraft should try to maintain a constant altitude over the ground surface, if possible. Over hilly or high relief terrain, aircraft operators may find it difficult to maintain altitude tolerance thresholds at typical survey speeds of around 80 km/hr (50 mi/hr).

It is important to consider the geographic coordinate system and digital elevation model (DEM) that will be used to plan the survey. Is the resolution of the DEM appropriate given the scale and detail of the project area and its topography? Is the resolution of the DEM matched with the planned deliverables? An accurate land surface elevation is a fundamental part of creating an accurate geophysical inversion and geological interpretation.

All AEM systems use the WGS84 GPS system and geoid height for navigation and data acquisition. A DEM can be created from the laser and radar altimeters on board the AEM system. However, it is often much better to use a standard datum such as the NGVD88 from the USGS national map (USGS 2019a). Nevertheless, problems can occur in areas of active quarries or areas of drastic stream erosion. Data from the helicopter or LiDAR may be needed to create an adequate DEM for these areas of rapidly changing topography.

Season and Weather

During which season do you plan to conduct the survey? What are the expected weather patterns during this season? What are the hours of daylight available? What will be the temperature highs? Questions such as these are critical to proper planning. Lengthy precipitation trends or sustained variable winds or very high temperatures will ground the survey crews resulting in costly delays. Overcast skies and a low ceiling will limit or ground flight crews. Careful planning won't completely eliminate these weather factors, but scheduling surveys with these considerations in mind can help manage expectations and reduce the risk of delays.

Infrastructure and Land Use

Where are the buildings, roads, confined feeding operations, airports, military installations, major pipelines and actively pumping wells, rail lines, and above-ground and buried power transmission lines and stations in the survey area? Failure to account for this infrastructure can cause failure to collect data in some areas and affect large portions of the data such that they will become unusable, creating unnecessary costs. Although coupling and noise will always be present to some degree, retention of good data can be maximized through careful flight planning. The flight-line routing efforts (optimization) should strive to avoid sources of electromagnetic coupling to retain the most usable data possible. However, sharp turns should be avoided, as this can cause undesirable effects on the pitch and roll of the instrument. AEM systems cannot be flown over buildings and must obey Federal Aviation Administration (FAA) rules. Many areas in Nebraska have confined feeding operations and other obstructions such as radio towers and wind turbines that needed to be avoided during flight. A high density of infrastructure can result in substantial data loss along flight lines, but this should not be used as an argument against using AEM. Even in areas of high infrastructure, data retention percentages of ~50 – 60% can still provide useful information for hydrogeological characterization (Viezzoli et al. 2013).

To obtain GIS files of major infrastructure paths and locations, contractors may need clients or local government partners to make requests to utility companies due to security concerns. Some sources of data are fee based and may add to survey cost.

Depth of Investigation

What range of depths below the ground surface will you target? Is there a considerable thickness of conductive clay, shale, or salt waters overlying the units you are targeting that could mask resolution at the desired depths? Provide shallow, medial, and deep threshold depths for proposal objectives and potential contractors as necessary.

Review of existing geologic data

Existing reports and boreholes are a good starting point for gathering background information. Provide a map of the proposed survey area depicting nearby boreholes (CSD test holes, DNR registered wells, Nebraska Oil and Gas Commission holes) and existing AEM flight lines. Require a Professional Geologist (PG) or qualified hydrogeologist on the interpretation and geologic log summary work. Cite other known geologic reports or unpublished data sources (if available or deemed critical) and the client's local working knowledge about specific aquifers or local formations pertinent to the mapping goals. Break up the project area into subareas if you have multiple geologic settings or different survey goals and objectives in one survey area.

Flight Line Planning

In Nebraska, reconnaissance surveys have been flown in a grid pattern with flight lines generally spaced ~1.6 to ~4.8 km (~1 to ~3 mi) apart. Experience has shown that flight spacing of around

200 m (650 ft) is ideal for block flights where 3D volumes are required to characterize heterogeneous glacial geology or other areas that need fine detail for volume estimates and assessment of boundary conditions. Planning the flight lines to intersect or come near the existing wells or test holes will help during the data processing, inversion, and interpretation process.

Flight line orientation is another important consideration. Generally, the flight lines should intersect geologic bodies of interest in a manner that will provide the most useful profile views. This would typically be perpendicular if access and infrastructure allows. If the units of interest are unmapped or unknown, then regional geologic knowledge can be used to inform the flight plan. Infrastructure may also dictate flight line orientation in some areas of heavy development such as along highway corridors, railroads, pipelines, and major transmission lines.

Contractor Selection

Contractor selection is a primary step that will determine the quality of your deliverables at the end of the project. Contractors will need to be hired to perform several key tasks.

1. *Survey planning and coordination*—A geophysicist specializing in AEM will be needed to plan survey logistics and coordinate field surveys. These tasks are not trivial: proper planning is essential for selecting an appropriate AEM system. Field coordination is necessary for quality control and quality assurance and will result in higher data retention.
2. *Data acquisition*—A geophysical surveying company will conduct the AEM survey. This company will operate the system, conduct the flights, acquire the data, and deliver it to the client. This is recommended to be done under the supervision of a qualified geophysicist or a licensed PG.
3. *Data processing and inversion*—Specialized software and training are required to carry out data processing, inversion, and upload to NGC. Typically, the geophysicists that plan and coordinate the survey also process and invert the data after the survey.

To date in Nebraska, survey planning and geophysical inversion has been carried out by a group of geophysicists not affiliated with the AEM surveying companies. Although AEM companies employ their own geophysicists, the focus of these companies is on the survey itself, and less on the pre- or post-processing. Therefore, an independent geophysicist will typically provide a higher level of detail and quality for the important tasks involved with delivering a product useful for hydrogeologists.

Based on the terms of the consultant-client agreement, proposals for survey subcontractors may be useful for keeping costs down (see Cost Considerations below). Whether or not bids are required, a request for proposals or similar document (in the case of no required bids) outlining the project plan and specifying how the contractor will meet NGC requirements should be prepared. If bids are required, scoring criteria should be prepared for evaluation of bid acceptance. Contractor and subcontractor proposals should specify the following:

- Project personnel credentials including professional registration in Nebraska
- Experience (including examples and references)

- Potential subcontractors involved (qualifications of pilots and operators)
- A statement of how the contractor will address the requirements in this guidance document.
- How well will the proposed system address the project objectives and goals? Provide examples. This can be done with the use of forward modeling of target geology.

It is recommended that the bids be reviewed by qualified professionals representing the client's best interests.

Selection of AEM System

The selected survey contractor will need to illustrate how their recommended system responds to the geologic setting of the general project area. The contractor should be able to provide examples of successful AEM surveys that have been flown in similar settings. The contractor should demonstrate the sensitivity responses of their systems to (i.e. show simulations of potential system response model results and sensitivities for each geologic setting in the project area). These models should include comparison to any borehole geophysical logs in the project area. If recommendations outlined herein are inapplicable or cannot be met, the contractor should explain how the deficiencies affect the quality of the data that will be delivered to NGC.

The geophysical survey company should be able to describe how and why the system's specifications will adequately meet the goals and objectives of the project. Details on the system should be provided, including the following:

- System geometry
- Time gates or frequencies, and bandwidth
- Current waveform(s), current waveform monitoring
- Any filters used in acquisition and processing
- Calibration procedures including data calibration and earth response calibration
- Typical noise levels
- Forward and inverse response models based on site geology
- Flight speeds
- Various sensors required (AEM receivers, Total Field magnetometers, tilt meters, accelerometers, altimeters)
- Height tolerances
- Tilt and pitch tolerances
- Data recording rates
- Horizontal and vertical datums
- Units of measurement

AEM surveys, particularly the TDEM method, have proven successful in mapping Nebraska's varied geology for water resources management purposes. The SkyTEM 304, 304M, 312, and 508 system configurations have been able to map subtle changes between sand, clay, silt, gravel, and glacial tills and shales in the sediments present from the near surface [top ~0.6 to ~5 m (~2 to ~16 ft] to depths approaching ~200 to ~500 m (~600 to ~1,600 ft) depending on the geologic target, area of the survey, and system type selected. Since 2006, the Nebraska AEM surveys have been used in combination with Aarhus Workbench, a Danish software produced by Aarhus Geosoftware (https://www.aarhusgeosoftware.dk/) for processing, inversion, and visualization of geophysical and geological data handling the workflow from handling the raw data, processing, and inversion to the final visualization and interpretation of the inversion models. Additionally, the initial concept for the NGC was modeled after the Danish Ministry of Environment's example which applied SkyTEM to map all of the country's aquifers and used I-GIS (the firm used to develop the NGC) to compile the data into an accessible country-wide, cloud-based platform. Based on the above discussions and anticipated future Nebraska AEM surveys and investments made into the NGC, the continued use of TDEM in conjunction with Aarhus Workbench is recommended for seamless data integration of new and old survey areas, maximizing future successful utilization of the NGC by Nebraskans.

Although SkyTEM systems have proven successful for many projects in Nebraska, other geophysical systems should be considered when developing new projects based on project objectives and site characteristics. For shallow resolution of the geologic system for geotechnical data needs, airborne frequency-domain electromagnetic (FDEM) systems should also be considered for data collection. These systems have proven more successful than TDEM at resolving highly heterogeneous geology in the near subsurface of parts of western and southeastern Nebraska, but they are generally limited to depths ranging from 55 – 75 m (Bedrosian et al. 2016; Korus et al. 2017). In the presence of a thick, conductive unit in the near subsurface, the depth of investigation of FDEM can be severely restricted (Abraham et al. 2011).

The recommendations of SkyTEM and Aarhus Workbench are of course loose guidelines based on recent successful results. Other survey systems or software may be appropriate for certain projects or changing industry conditions. If AEM systems other than SkyTEM are used in the future, the guidelines herein should be used to ensure that the data quality is similar to that of previous recent projects.

Cost Considerations

Experience has shown that many factors can affect cost of an AEM survey. Some of these costs can be managed through careful planning. As a note of caution, although the bid process helps keep costs down, going with the lowest bid could end up being the most expensive option, especially if the data do not match existing geologic logs or if results do not agree with geologic knowledge of the project area. If the survey results are unusable and unable to meet the project goals, the cost cannot be justified.

In the case of bidding, it may be best to prepare a baseline estimate of expected flight line distance and a separate set of optional flight lines just in case your bid comes in lower than expected. In this manner, clients can avoid over-promising on grant applications. Generally speaking, $500 per line km has been a used as a maximum cost target for surveys in recent years (2014 to 2020). This cost typically includes planning, acquisition, processing, inversion, interpretation, and hydrogeological framework development.

Mobilization (and demobilization) of an AEM survey crew and aircraft operators are a substantial factor in the cost of a survey. To save on mobilization, it may be worth coordinating efforts between multiple surveys. Are there other entities considering or planning AEM that could share in crew and system mobilization costs? Can the timelines be coordinated such that multiple surveys can be flown during one mobilization event? In the past several years of AEM surveys in Nebraska, careful coordination of surveys has resulted in more of the cost going toward data collection and less of the cost going toward mobilization.

The economy of scale should also be considered. It has been experienced in previous surveys that larger surveys result in a lower cost per distance unit. Be sure to mention if any potential add-on lines will be interspersed throughout the planned survey area footprint, adjacent to the planned flight lines, or in a separate area. The add-on amount can be negotiated at the time of contract award based on the base bid price.

Data Acquisition and Reporting

The geophysical surveying company is responsible for supplying calibrated, error-free data and detailed documentation of system parameters and survey conditions. The contractor should deliver a full data suite that gives precise system parameters (i.e. filters, current waveforms, geometry, other system setup parameters), raw (unprocessed) voltage and instrument data, final delivered processed data and a report of system calibration and survey conditions. In general, the contractor should be as transparent as possible as to system specifications and measured data. Acquisition specifications and documentation should meet or exceed expectations from past Nebraska surveys and ensure that the deliverables contain the required information for NGC upload. This will support proper data archiving and allow optimal processing and interpretation by independent parties beyond the life of the project.

The geophysical survey contractor should have a quality control (QC) program that is agreed upon by the geophysicists involved in the project. The QC program should be part of any contract between consultant and subcontractor.

For SkyTEM surveys, details on data acquisition and reporting should closely follow the document in **Appendix A**.

The following sections are guides to the data and information that should be provided by the airborne geophysics surveying contractor.

System Parameters

The system parameters should be described in a geometry file (.gex file for SkyTEM). The geometry file contains all the necessary information to accurately model the system in the inversion. It describes the frame geometry and the placement of instruments relative to the frame. The contractor should provide a diagram showing the system design and as well as the point of reference for all measurements (origin, or 0, 0 node). The geometry file also contains time and amplitude values describing the current waveforms (low and high moment for SkyTEM), time positions of the gates used to measure voltage responses, and any delays, filters, and calibration factors that are to be applied to the data. For FDEM data this would include in-phase and quadrature calibrations and offsets for each frequency.

In summary, a geometry file should contain the following elements:

- Description and origin of all instrument positions
- Transmitter and receiver loop geometries and number of turns of coils
- Positions of altimeter(s), inclinometer(s), GPS, TX and Rx coil(s)
- Gate positions and specification of unusable gates
- Frequencies used in frequency domain systems
- Current waveforms including current monitoring
- Filters, delays, and calibration definitions

Measured Data

The raw data file contains all the flight line data measured during the production survey flights. These data are used to create maps showing the GPS positions of each sounding, the flight speed, altitude, tilt, pitch, and roll. SkyTEM systems will produce a .sps file for GPS, altitude, pitch and roll data, and a binary .skb file with receiver voltage data. Other systems will use .xyz files or other formats. The raw data should also specify the position and numbering of every flight line and the time intervals for production data. For SkyTEM systems, these data are provided as part of the line number file (.lin).

In summary, the raw data should contain the following as part of a full data suite:

- Raw voltage stacks
- Raw altitude, pitch, and roll, ground speed
- Navigation (Differential GPS)
- Transmitter current
- Line numbers and positions
- Power line (60 H) monitoring
- Total Field magnetometer data with IGRF and diurnal corrections
- Total distance over which data was collected (total line km)

Calibration & Validation

Calibration and validation of the measurement equipment is performed by the geophysical surveying company and verified by the geophysicist overseeing the survey. SkyTEM systems are calibrated to a ground test site in Lyngby, Denmark. High altitude test flights are also performed to ensure appropriate levels of acquisition system noise. Past Nebraska surveys have also been calibrated at local test sites to ensure that equipment is operating within technical specifications. The procedures will vary by AEM system. The raw data report from the contractors should contain a comprehensive data calibration statement specifying the procedures used to calibrate and validate the data. This statement is documentation that the equipment was fully functional during the entire production survey. Calibrations of the system to the earth response is also desirable.

Additional Information

The raw report shall include any additional information pertinent to the survey and that is necessary for processing and inversion. Such information may include:

- A report of specific conditions and problems which may affect data quality, processing or interpretation (e.g. increased flight altitude and/or speed and any temporary component malfunction);
- A description of the overall weather conditions, especially the wind speed and direction, and any rain shall be specified for the altitude test and for every production flight;
- The GPS positions and description of reference and landing localities;
- Onboard recording system and flight path recovery (digital camera record of terrain passing beneath the helicopter) are required.

Before the final delivery of the raw data and report, it is recommended that all files be checked for discrepancies or errors. Ensure that the data can be successfully loaded into the processing software.

Data Processing and Inversion

AEM processing and inversion requires highly specialized training. Proper processing is essential to avoid flaws and misinterpretation of the results (Viezzoli et al. 2013). Therefore, only experienced professionals with training in AEM methods should perform these tasks. The consultant who performs these tasks shall ensure that the software settings, parameters, and decisions made during each processing step are adapted to the specific circumstances of the data and the characteristics of the study area.

From 2006 to 2009 the University of British Colombia Geophysical Inversion Facility EM1DFM program was used for the inversion of frequency domain data (https://www.eoas.ubc.ca/ubcgif/iag/sftwrdocs/em1dfm/em1dfm-descrip.htm). The data processing and inversion of the Nebraska AEM datasets since 2010 was accomplished with the Aarhus Workbench (https://www.aarhusgeosoftware.dk/). Therefore, it is recommended that the contractor reports available at http://enwra.org/ and https://geocloud.live be reviewed and closely followed in future proposals and deliverables. Aarhus Workbench is recommended as the preferred software for SkyTEM data. Additional recommendations for data processing and inversion in Workbench are given in **Appendix B**. Training for the latest software version can be obtained from Aarhus Geosoftware.

Data processing begins with a review of all the raw data deliverables. Then, the geophysicist will make multiple iterations of automatic and manual processing steps to prepare the data for inversion. For proper archiving of data in NGC, it is critical to document all the procedures and parameters used so that the results are reproducible after the life of the project. The following subsections outline the information that should be delivered in reports on geophysical processing and modeling of AEM data.

Automatic Processing

Geophysical processing software typically contains several automatic processing routines such as GPS position corrections, altitude correction, voltage data averaging, removal of biased data, and noise filtering. The report should specify which software program and version was used for processing. If default settings were used, these should be explained in the report.

The following information on automatic processing should be reported:

- Software program and version;
- Used and unused time gates;
- Settings and parameters used for corrections, averaging, and filters;
- Trapezoidal filter averaging widths;
- Sounding density and distance in relation to the selected averaging filter width;
- Selected data profiles showing examples of results (e.g. raw vs. corrected altitude).

Manual Processing

Manual processing is required to make additional altitude adjustments and to remove electromagnetic couplings and noise from the voltage data. The changes and edits made to the data during this stage should be explained in a report. Manual processing is subjective, so it may not be feasible to explain every decision made by the geophysicist. However, the consultant should describe the overall strategy for making these edits and supply a data file containing the fully processed data that was used in the final inversion (e.g. a Workspace file with processing nodes for Aarhus Workbench).

In general, documentation of manual processing should consist of the following:

- An explanation of the general procedures and reasoning for making manual edits to the data;
- Selected data profiles showing examples of manual edits applied to the data;
- Maps showing retained and removed soundings;
- Percent data retained for each survey block or subset of data;
- Software files containing final processed data.

Geophysical Inversion

The solution to a geophysical inversion problem is non-unique: there are many possible models that fit the data. Therefore, the final model presented to the client should be accompanied by documentation describing the model choices, discretization, assumptions, starting parameters, and data residuals so that results can be reproduced beyond the life of the project.

At a minimum, the consultant report should contain:

- Model choice (i.e. smooth, layered, blocky, sharp);
- A-priori constraints;
- Lateral and vertical constraints;

- Type of inversion run (each inversion should have its own unique identifier)
- Number of layers;
- Thickness of starting layer and factor by which thickness of successive layers increase;
- Table of layer depths and thicknesses;
- Data residuals;
- Depth of investigation (DOI) estimates and what factors were used to calculate the DOI's;
- Summary of quality control findings;
- Resistivity maps and description of interpolation methods;
- Resistivity profiles.

GUIDELINES FOR HYDROGEOLOGIC DATA INTEGRATION AND VISUALIZATION

Communicating and displaying complex three-dimensional geologic data to resource managers and the general public has long been a challenge to geologists. Traditionally, geologic data products, such as surficial maps, cross-sections, and isopach maps synthesize and communicate complicated three-dimensional geologic structures in two dimensions. Complex subsurface geology such as folded or faulted layers, unconformities, and changes in surface topography are challenging for many resource managers to visualize, understand, and interpret.

The collection of AEM data for groundwater mapping and resource evaluation has increasingly become common practice among resource managers in Nebraska (Korus 2018) and other parts of the world (Møller et al. 2009; Chandra et al. 2016). Realizing the potential and need for 3D visualization with geologic and geophysical data, several software companies have developed programs for data processing, management, interpretation, and geologic modeling. This chapter provides guidelines on data sources and integration in 3D visualization software programs.

Software Programs

A variety of commercial software programs can be used to view geologic, geophysical, and hydrogeologic data within a three-dimensional (3D) environment. These programs can provide an integrated 3D geological modeling environment by displaying geographic information system (GIS) maps and data, test-hole information, and AEM or other geophysical data. Listed below are some examples of software programs used by hydrogeologists.

- GeoScene3D (http://www.geoscene3d.com/software/geoscene3d)
- Leapfrog (https://www.leapfrog3d.com/)
- Rockworks (https://www.rockware.com/product/rockworks/)
- Oasis Montaj (https://www.geosoft.com/products/oasis-montaj)
- Petrel (https://www.software.slb.com/products/petrel)
- EarthVision (https://www.dgi.com/earthvision/evmain.html)
- GOCAD (https://www.pdgm.com/products/gocad/#)
- GeoModeller (https://www.intrepid-geophysics.com/product/geomodeller/)

Each software program has different strengths, and not all are suited for handling AEM data. It is recommended that model builders investigate the software programs thoroughly before purchasing to explore geophysical data handling and compatibility with NGC file formats.

Although software preference will vary between users, we recommend the use of GeoScene3D for its ability to directly access the Nebraska GeoCloud through an interconnected web server and because it handles AEM data with ease. Users of GeoScene3D can display geophysical and hydrogeologic data from a web portal. The Nebraska GeoCloud, in combination with GeoScene3D is intended to permit the seamless data integration and sharing of data and geologic models between water managers, scientists, and the general public. There are several license types available.

- GeoScene3D Viewer—A free viewer is available for download which will enable access to the Nebraska GeoCloud data and products. The free viewer was created primarily for non-scientist general users, such as land owners, community planners, or well drillers.
- GeoScene3D Nebraska Viewer—A viewer with enhanced options for NGC partners. This version of the software has a web portal for access to NGC, options for creating and manipulating profiles, and the ability to change some settings. Access to this viewer is provided for partnering agencies in the NGC collaboration.
- GeoScene3D Builder—A comprehensive version of GeoScene3D, which requires purchase of an individual license and annual renewal of the license. The program has various optional extensions that can be purchased. The Layer Builder allows for the creation of projects, importing of AEM and test hole data, and geological modeling. The intended end users of the full version of GeoScene3D are model builders: geologists, hydrologists, and engineers.

The use of other software programs does not prevent model builders and model users from accessing data in Nebraska GeoCloud. Data can be downloaded for a project area and imported into the preferred software program. Model builders should be aware, however, of which file formats are supported to ensure compatibility.

Supporting Data

The inclusion of supporting data, such as test holes, water-level, and water quality data are essential to constrain interpretation of AEM data and enhance the geologic framework for a given project area. This section describes common sources of supporting data for Nebraska, with emphasis on publicly available and quality-assured datasets. Unless otherwise noted, metadata are available for these data sets. The user may include project specific data sources not discussed here, such as unregistered well logs from a private driller or groundwater sampling results. Inclusion of these data sources in projects within the Nebraska GeoCloud requires unique metadata, so the user understands the purpose, quality, and limitations of the specific data source. More information regarding metadata requirements can be found in the companion document **Standards for Data and Model Reporting in Nebraska GeoCloud.**

Spatial reference system is an important consideration. Most supporting datasets, including test-hole, water-level, or water-quality data, are associated with a well or test-hole location with unique horizontal coordinates. Some software programs re-project these coordinates on the fly, allowing data with different coordinate systems to be used simultaneously. Within the GeoScene3D program, however, all datasets are required to be in the same spatial reference system. All data served on the Nebraska GeoCloud are projected to the Nebraska State Plane meters coordinate system referenced to the North American Datum of 1983 (European Petroleum Survey Group [EPSG] 32104). The Nebraska State Plane coordinate system was chosen for all data served through the Nebraska GeoCloud because it is a single system for the entire state, unlike Universal Transverse Mercator (UTM), which has three zones in Nebraska. Furthermore, the State Plane system is a projected coordinate system, so it minimizes scale distortions (ESRI 2019). Minimizing scale distortions is particularly important if the user wishes to calculate aquifer or formation volumes from regional 3D geologic models. The native coordinate systems for many datasets described herein are given in latitude and longitude. Spatial coordinates of supporting data sets must be re-projected to the Nebraska State Plane meters (EPSG 32104) coordinate system if the they are to be uploaded to NGC.

Land surface elevation data are critical for the construction of geological models; however, the source of elevation data and the associated accuracy can vary greatly. For any GeoScene3D project, a terrain surface or digital elevation model (DEM)(ESRI 2019) is used from which all AEM and supporting subsurface data are referenced. The horizontal coordinates associated with supporting data are used to extract an elevation from the project terrain surface. The NGC contains a reference DEM for Nebraska, which has been down-sampled to 90 m resolution from a 10 m DEM. But for most projects, a high-resolution terrain model will be necessary. DEMs can be created for any project area by downloading an Esri raster (ESRI 2019) from the National Elevation Dataset (NED) USGS National Map web page (USGS 2019a). High-resolution LiDAR is also available for many areas of Nebraska through the USGS National Map.

Data processing may be required to prepare data for use in visualization software: for example, converting well screen depths from feet to meters below land surface or removing unnecessary columns from native datasets. These types of basic data manipulations can be done in Microsoft Excel™ or Python™ environment. Final datasets can be saved as a comma delimited text file for import into the GeoScene3D program.

Test-Hole and Well Data

The integration and inclusion of ground-truth information, in the form of test holes and driller's logs, is essential to constrain geophysical models and interpret AEM data. All geophysical methods, including TDEM, exhibit a degree of non-uniqueness where, in the absence of ground-truth information, multiple models or interpretations can fit or honor the measured geophysical data. Within the state of Nebraska, ground-truth information is available from two primary sources; Conservation and Survey Division (CSD) test holes (CSD 2019b) and drillers logs from the Nebraska Department of Natural Resources registered well database (NDNR 2019).

CSD test holes contain detailed lithologic information recorded and quality assured by trained professional geologists and are regarded as the most reliable and consistent source for geologic information in Nebraska. CSD test-hole data are available online from a continuously updated online database (http://snr.unl.edu/csd/geology/testholes.aspx) and is stored on the Nebraska GeoCloud. CSD test holes contain lithologic descriptions recorded in the field for specified depth intervals. Often the lithologic descriptions are aggregated and given a more generalized lithologic unit. For some test holes, described intervals are assigned the stratigraphic unit. Test-hole drilling is often done in support of hydrogeologic investigations and the test hole penetrates through the primary aquifer to the base of the aquifer or the regional confining unit.

Borehole geophysical logs, including long- and short-normal resistivity, gamma, and caliper are available for many test holes in the CSD database (CSD 2019b) as well as for deep oil and gas wells in the Nebraska Oil and Gas Conservation Commission database (NOGCC 2020). Borehole geophysical logs are collected to improve the depth control of geologic contacts and are essential to interpretation of AEM data. Further information regarding borehole geophysics can be found in reports such as Keys (1990).

Additional lithologic information is available statewide through the NDNR registered well database (NDNR 2019). An advantage of the NDNR registered well database over the CSD test-hole database is the density and availability of data for a given project area. There are over 200,000 registered wells and drillers logs publicly available. Driller's logs from the Nebraska Department of Natural Resources database provide valuable information but are generally considered to be a less reliable source of lithologic information compared to CSD test-hole logs. Depending on the driller, level of experience, and geologic expertise, lithologic descriptions can often vary greatly for a given geologic material. Recently, the NDNR has established a uniform set of terms for drillers to use—via a drop-down selection list—when uploading new well registrations to the database. Furthermore, the CSD published an education circular (Divine et al. 2015) to introduce some standardization of lithologic descriptions for commonly encountered geologic materials within Nebraska. Nevertheless, a wide variety of descriptive terms are contained in the registered wells database. In most cases the user will need to distill lithologic descriptions into a manageable number of standardized lithologic descriptions to categorize all geologic materials encountered within a given project area.

The standardization and integration of geologic logs from water well drillers has long been a challenge for geologists (Allen et al. 2008; Bayless et al. 2017; Korus et al. 2018). The CSD has developed the Lithology Keyword Automation Tool (LithoKAT) to help automate, streamline, and standardize the conversion of driller's terms to standardized terms. LithoKAT is described and available in the companion document titled **Standards for Data and Model Reporting in Nebraska GeoCloud.**

Water-level Data

Discrete and continuous water-level data are an integral part of groundwater monitoring activities for local, State, and Federal agencies within the state of Nebraska. The CSD and USGS have worked cooperatively since the 1950s developing, maintaining, and operating observation well networks across the state. Both agencies are also responsible for collection, aggregation, storage, and disseminating water-level data to the general public. CSD's statewide discrete water level database contains water levels from approximately 24,000 wells dating back to 1920 (CSD 2019a). The USGS NWIS database contains water-level data from over 21,000 wells dating back to 1905 (USGS 2019b). Nebraska's 23 NRDs collect much of the water-level data contained within both databases.

Substantial duplication exists within both databases and efforts are ongoing within the CSD and USGS to serve the groundwater-level datasets on the National Groundwater Monitoring Network (NGWMN; https://cida.usgs.gov/ngwmn/index.jsp). The NGWMN is a collection of selected groundwater monitoring wells from Federal, state, and local groundwater monitoring networks across the nation. The NGWMA data portal provides access to historical groundwater level data as well as water-quality data, and well construction information. Currently (2019), there are approximately 265 wells for Nebraska; however, approximately 4,000 more wells will be added by the end of 2020 (Aaron Young, Conservation and Survey Division, written comm., 2019).

Discrete water-level data can be displayed within visualization software such as GeoScene3D in two different ways; as point data or as a surface. Individual water-levels are displayed as a discrete point or dot in 3D space or in profile view. Often individual water level points are not sufficient to interpret groundwater flow direction, gradient, and assess groundwater/surface-water connectivity. Within the GeoScene3D program, or in another geospatial program such as ArcGIS, a set of water-level data can be used to create a water-level surface that spans the entire project area. Creating a water-level surface allows the user to view a water-level surface projected onto AEM profiles or user-defined profiles.

Water-Quality Data

Characterizing groundwater quality and assessing the vulnerability of aquifers to contamination is often a primary motivation for AEM surveys. Incorporation of water-quality results from monitoring wells can complement and enhance a project. Water-quality data are routinely collected by several Federal, State, and local agencies within the state of Nebraska to support regulatory and management decisions and advance scientific understanding of groundwater systems. The two primary sources of quality-assured statewide groundwater quality data in Nebraska are the quality-assessed agrichemical contaminant database for Nebraska groundwater (UNL 2019), commonly known as the agrichemical clearinghouse, and the USGS NWIS database (USGS 2019b).

The agrichemical clearinghouse is focused on providing sampling results for selected agricultural contaminants including nutrients and pesticides. At the time these standards and guidelines were written (2019), approximately 455,302 individual results have been reported. Of those results, approximately 127,000 report nitrate concentration. Often results stored within the clearinghouse are wells sampled annually by NRDs as part of the routine groundwater quality monitoring. The data stored in the clearinghouse document concentrations of specific nutrients and pesticides. Supporting geochemical information, however, such as dissolved oxygen, water temperature, specific conductance, and water levels, are not reported with the sample result. The USGS NWIS database (U.S. Geological Survey, 2019b) also contains quality-assured groundwater-quality data from nearly 15,000 groundwater samples collected across the state of Nebraska. Much of the water-quality data reported in NWIS was collected for focused studies with different purposes. Typically, these wells are not resampled annually and results only represent a snapshot of groundwater-quality conditions; however, supporting information such as field parameters, including dissolved oxygen, provide a more complete picture of the geochemical conditions.

Displaying and interpreting water-quality data within 3D software programs such as GeoScene3D is possible, but it is generally limited to one sample for each data point. However, this can be a powerful way to explore and evaluate water-quality data in complex geologic areas where the sampled formation or geologic unknown may be previously unknown. Hobza and others (in press) created a project examining nitrate concentrations within the Bazile Groundwater Management Area in northeastern Nebraska. Points were color-coded based on the nitrate concentration for a sampled monitoring well. An example is given in Figure 3. The display of water-quality and geochemical information is an ongoing area of software development in GeoScene3D (Tom Martlev Pallesen, I-GIS, personal comm., 2019). At this time, groundwater quality data are represented in 3D space as points at a user-defined depth.

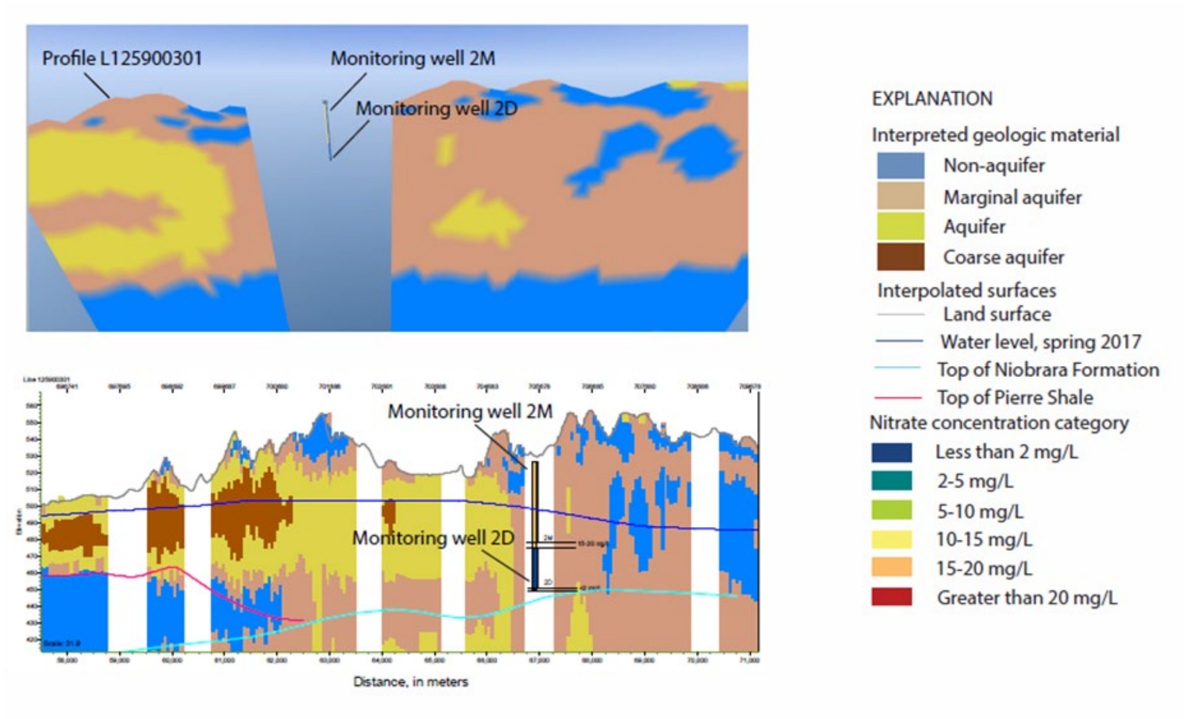

Figure 3. Nitrate concentration shown from two monitoring wells within the Lower Elkhorn Natural Resources District, June 2007 displayed in 3D space *A* and profile file *B*.

Geologic maps and cross-sections

The incorporation of other interpretive geologic products, such as cross-sections and maps or lithological logs is a key feature of GeoScene3D and other software programs. These traditional geological products can be integrated and utilized for visual interpretation or geologic modeling. Surficial geologic maps are published as part of the STATEMAP program and are available at online through the Conservation and Survey Division at https://snr.unl.edu/csd/geology/statemap.aspx (CSD 2020). Typically, these maps are produced at the 1:24,000 scale. These maps are also available at the USGS National Geologic Map Database at https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html (USGS 2020) as well as geologic maps produced at other scales. Shapefiles are typically available for surficial maps, which can be imported into GeoScene3D. Cross-sections, which are often provided as supplemental products in peer-reviewed reports or geologic maps, can be visually integrated to the 3D project. Cross-sections require the user to scan and save the image as a compatible image file. Within the GeoScene3D program the user specifies horizontal coordinates and an elevation at specified control points to georeference the image within the project.

GUIDELINES FOR HYDROSTRATIGRAPHIC MODELING

Introduction

The aim of many hydrogeologic studies is to map aquifers or numerically simulate the flow of groundwater and transport of contaminants. To perform any of these tasks, we must first obtain estimates of the true physical properties of the subsurface at any location in the volume of interest. It is not possible to measure these properties at every location in space, so instead we make informed estimates on the basis of geological knowledge and observations. These approximations of geological reality are contained in computer representations called geomodels (Mallet 2002). AEM is particularly useful for creating geomodels.

There are many different types of geomodels, but often in hydrogeology the aim is to construct a hydrostratigraphic model. Hydrostratigraphic models define layers, volumes, or grid elements with similar hydrogeologic properties and can be input directly to groundwater flow models (i.e. MODFLOW). To build a hydrostratigraphic model, geologists must use other models in the workflow. These include conceptual models, interface (layer) models, and geophysical (e.g. resistivity-depth) models. The focus of this chapter is on the workflow and methods involved in constructing a hydrostratigraphic model.

Many excellent textbooks, review papers, and case studies have been published on the subjects contained in this chapter. Therefore, the aim here is to present some of the basics of geomodeling as a guide to geologists working with AEM in Nebraska. Detailed treatment of the methods and procedures can be obtained from the publications given in the references, or from attending training and workshops offered by academics, software companies, or hydrogeological consulting firms.

Workflow

The modeling workflow describes the inputs, processes, and outputs involved in transforming geological and geophysical data into a computer representation of the geological or hydrogeological subject of interest (Fig. 4)(Jerome 2020). The workflow does not always progress in a linear fashion. Many iterations of the workflow may be required as new data and knowledge are generated during an investigation.

For each of the processes of the workflow, a geologist will need to make important choices about the methodology. These choices are informed by geological knowledge and principles, and they should depend on the objectives of the study and the complexity of the volume of interest. Prior to engaging in geomodeling, the geologist should answer some basic questions:

- What resolution (vertical and horizontal) is needed to achieve the objectives of the study?

- Is the density of data and observations appropriate for the desired level of resolution?

Figure 4. Basic geomodeling workflow. Modified from Jerome (2020).

Model Elements

Earth's subsurface contains volumes of rock or sediment which can be subdivided into distinct layers, bodies, or inclusions on the basis of age, lithology, or other physical characteristics. Hydrostratigraphic units are defined on the basis of hydrogeological properties. A hydrostratigraphic model is a numerical description of the boundaries between units as well as the property distributions within these units. Thus, a model will consist of two basic elements: a framework model defining boundaries, and a volume model defining property distributions. These elements are further described below.

Framework models

A framework model is a representation of geological interfaces, or boundaries between separate geological volumes of rock. The model should describe all the structural and stratigraphic attributes of interest: layer contacts, disconformities and angular unconformities, faults, or the bounding surfaces of intrusive bodies. Framework models are also known as geometry, structural, interface, surface, boundary, or layer models.

Geological interfaces vary from simple to complex. Simple interfaces are continuous and sub-horizontal: every *x, y* location has one and only one corresponding *z* value. These interfaces can be represented in 2D maps as contoured surfaces. Complex interfaces have 3D geometrical attributes: any *x, y* location may have multiple *z* values. Examples of geological bodies with these surfaces include recumbent (overturned) folds, doubled layers across reverse faults, intrusive domes, pipes, or dikes, and buried channels. Only 3D models can adequately represent the geometry of such surfaces.

For framework models to be geologically realistic, relationships between surfaces must be considered (Fig. 5). Several rules apply: 1) a single interface cannot intersect itself, 2) stratigraphic succession must be preserved (older interfaces cannot cross younger interfaces), and 3) interfaces that are offset by a fault must preserve geological continuity (the interface must double across a reverse fault and must have a discontinuity across a normal fault). Model validity depends on whether or not geological surfaces meet these conditions (Caumon et al. 2009).

Most geomodeling software programs provide tutorials on interface modeling. Furthermore, most incorporate tools for generating interfaces from point data and for dealing with the basic rules of geological realism listed above.

The reader is referred to Turner (2006) for a basic treatment of framework modeling. For a detailed treatment of the theory behind framework modeling, the reader is referred to (Mallet 2002) and Wellmann and Caumon (2018).

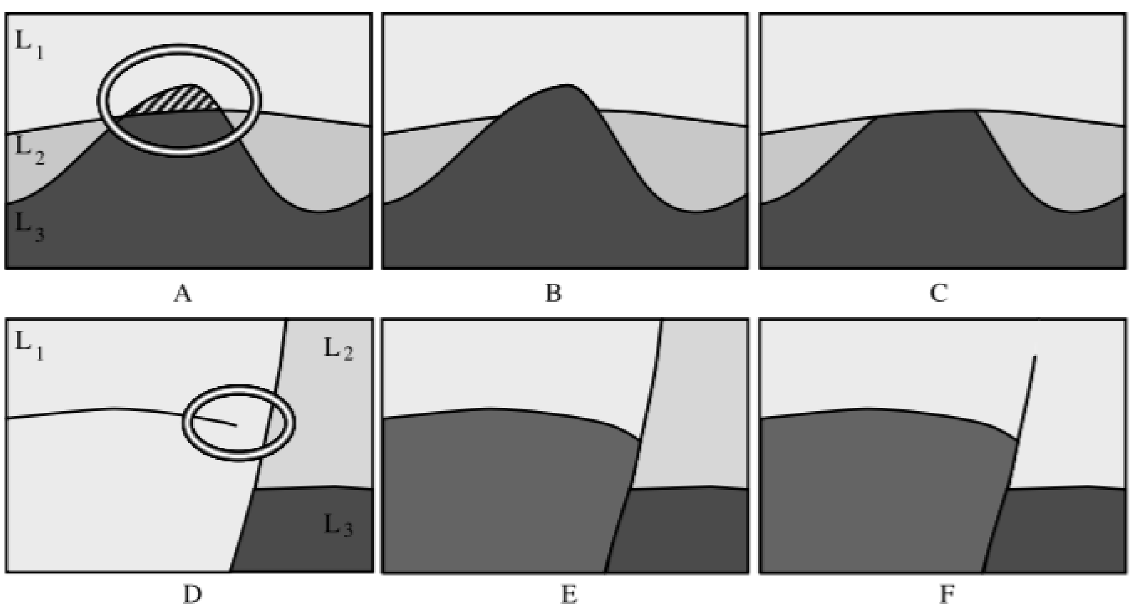

Figure 5. Basic rules for surface relationships. Overlapping layers and leaking layers as in A and D are invalid. The geological relationships in B, C, E, and F are valid. From Figure 2 of Caumon et al. (2009).

Volumetric models

For hydrogeological applications, it is often desirable to represent the variations in physical or chemical properties within a volume of rock or sediment. This is known as volumetric modeling. As the framework model defines the boundaries of the volumes, the volumetric model describes the spatial distribution of one or more properties within these volumes. Volumetric models are also known as voxel (volumetric pixel), 3D grid, discretized, geocellular, and mesh models.

In order to assign properties to the model, the volume must first be discretized into a mesh (grid). There are a variety of methods for discretizing the model domain, but these fall into two basic categories: 1) structured meshes and 2) unstructured meshes.

Structured meshes divide the model into regular cubes. Each interior node of the cube is related to exactly four other nodes. In voxel (volumetric pixel) modeling, cubes are defined by constant node spacing and face dimensions, resembling a stacked volume of identical boxes. In an octree mesh, the node spacing and face dimensions of the boxes are allowed to change. The model resembles a stacked volume of boxes with different sizes. This accommodates grid refinement in areas of the model requiring greater detail.

Unstructured meshes are not constrained by node spacing and face geometry. The numbers of connections between nodes is allowed to vary. The fundamental element of an unstructured mesh is a polyhedron (tetrahedron, hexahedron, dodecahedron, etc.). These meshes allow greater flexibility in aligning the grid to irregular or 3D layer boundaries.

Most software programs can easily handle the generation and manipulation of structured meshes, as well as methods to assign property values to cells. Unstructured meshes, however, are not available in all 3D modeling software.

Volumetric meshes are described in more detail in Gable et al. (1996) and Turner (2006).

Combining Framework and Volumetric Models

Although framework and volumetric models are considered separately from a modeling standpoint, together they form a comprehensive representation of the subsurface useful for most geological and hydrogeological modeling purposes. A hydrostratigraphic model will typically be a combination of the framework and volumetric models. For example, if the bedrock surface defines the base of an unconfined sand and gravel aquifer, the framework model can be used to define the upper and lower bounding surfaces of the model. The upper surface is defined by the water table and the lower surface is the bedrock surface. The hydrogeological properties of unconsolidated sediments between these two surfaces can be represented by a volumetric model describing the spatial distribution of lithological facies and hydrogeological properties.

Geomodeling Methods

A variety of methods exist for automatically generating surfaces for framework models and populating volume models with property distributions. A model builder will make many important decisions about which modeling methods to use. No one method is superior to others in every situation. Model choice depends on many factors, including the complexity of the system and availability and density of data.

One important distinction to make regarding geomodeling is the difference between deterministic and stochastic models. With a given set of circumstances, a deterministic model will predict a single outcome whereas a stochastic model will predict a suite of many possible outcomes. It should be noted that geological processes and products are not in and of themselves inherently deterministic or stochastic (Pinsky and Karlin 2010). Rather, it is the choice of the geologist which type of model to use for the geologic domain of interest. This choice depends on the usefulness of either type of model to achieving the objectives of the work.

It is difficult to place these methods into clearly defined categories because they often overlap or are used in combination. Nevertheless, some of the main groups of methods are outlined here to assist model builders in this decision-making process. The following guidelines offer brief overviews of the main techniques in use by hydrogeologists. For a more detailed treatment of these methods, the reader is referred to Koltermann and Gorelick (1996), Coburn et al. (2006), and MacCormack et al. (2019).

Cognitive

Cognitive (i.e. descriptive, explicit, or classical) methods transfer a geologist's interpretation and knowledge directly to a geologic model. Geological boundaries are interpreted from data and then points and polylines are digitized directly onto a series of maps or cross sections. Substantial manual work is necessary.

The cognitive modeling approach is the most direct way of incorporating geologic experience and understanding into the model. However, because geologists are subject to human biases and opinions, the method is subjective, and it may be difficult to determine if any given model is credible. It is also time-consuming and difficult to reproduce. Nevertheless, the cognitive method is relatively straightforward and can be implemented by most geologists without specialized training.

Typically, the cognitive method is combined with other approaches to develop gridded layer boundaries from point data or cross sections. Point data can be interpolated into 2D layer boundaries using geostatistical methods. For models of complex 3D interfaces such as overturned folds or isolated geologic bodies, triangulation is used transform manually interpreted cross sections into 3D surfaces (Wellmann and Caumon 2018).

There are numerous examples of cognitive models in the literature. The examples selected here demonstrate application to some common hydrogeological problems (Sharpe et al. 2003; Scharling et al. 2009; Royse 2010; Jorgensen et al. 2013).

Geostatistical Methods

Geostatistics is a set of methods aimed at estimating (interpolating) the quantities of interest at all locations within a model domain. The statistical parameters (mean, variance, standard deviation, etc.) that determine the spatial distribution are derived from measured values (data). These parameters are then used to interpolate the variables at locations where no measurements are available. In this manner, continuous surfaces and volumes can be constructed from a set of sparse measurements. It should be noted, however, that complex interfaces such as overturned folds cannot be modeled using geostatistics.

Geostatistics are useful for estimating structural patterns in a given geological environment. Moreover, these methods provide a means by which to quantify uncertainty, an inherent and unavoidable part of geoscientific inquiry. Knowledge of statistical theory is not prerequisite for using geostatistics in geomodeling. Geostatistical methods have become standard tools in software programs and are widely applied across a variety of disciplines. Interpolation procedures have become so routine that they can be carried out by almost anyone with access to the software, with very little knowledge of the theoretical basics of geostatistics. Unfortunately, this can lead to misuse and abuse. Results can be made to appear believable even if model parameters are unrealistic or unverified.

It is therefore recommended that geomodelers have a basic understanding of the limitations of geostatistics and that the results of interpolation procedures and errors be included as part of a geomodeling report. There are numerous literature resources on geostatistics. The reader is referred to review papers by De Marsily et al. (2005) and Koltermann and Gorelick (1996) for overviews of geostatistical methods in hydrogeological modeling. Oliver and Webster (2014) provide a concise, informative summary of the kriging method.

Multiple-Point Geostatistics

Traditional geostatistics deals with smoothly varying properties. In reality, these variables are typically discontinuous and they conform to predictable geological patterns. It is desirable in some situations to develop geostatistical models that have realistic geometrical attributes. One way to deal with this challenge is with the use of multiple-point geostatistics (MPS). This technique reproduces geological features using statistically derived attributes from a training image (TI). The selection of a training image is a critical choice for the geologist as it determines the structural patterns from which the multiple-point statistics are derived, thereby influencing the patterns in the realizations. The MPS method also has the ability to condition the model realizations to hard data (i.e. boreholes, layer boundaries) and soft data (i.e. AEM resistivity).

Example applications of MPS where AEM was used in the modeling workflow are Høyer et al. (2017) and Barfod et al. (2018). Model builders are also referred to the textbook by Mariethoz and Caers (2014) for a detailed treatment of MPS methods.

Genetic (process-imitating) Methods

Whereas geostatistical methods produce models that imitate geological patterns, genetic models imitate geological processes. These processes can be numerically simulated to model sedimentary basin evolution, producing grids representing subsurface heterogeneity. The processes include mechanisms of fluid flow, sediment transport, erosion, and deposition. Genetic models give insight to how geologic processes control aquifer geometry and heterogeneity patterns; however, such models have been used primarily as research tools and therefore are not commonly available in commercial hydrostratigraphic modeling software. For a detailed discussion of genetic models, readers are referred to Koltermann and Gorelick (1996)

Machine Learning

Machine learning tools offer a relatively new and exciting opportunity for geomodelers. Machine learning lends itself readily to large data volumes. Thus, AEM data seems a natural fit for such methods. Friedel (2016) and Friedel et al. (2016) provide example applications of machine learning to an AEM dataset from the Nebraska Panhandle.

Machine learning tools are beginning to show up in commercial geomodeling software. For example, GeoScene3D contains a Smart Interpretation tool that uses machine learning to assist in the picking of geological contacts from AEM resistivity models. This tool can greatly reduce the amount of time it takes to map and model geological interfaces. However, if the surface of interest does not follow a consistent resistivity contrast, the tool can have limited applicability.

Hybrid Approaches

Model builders may find it useful to combine several different methods in a study area to suit different data types and densities (e.g. Jørgensen et al. 2015). Hybrid approaches can also be useful where the geology is particularly complex or where the degree of complexity varies with depth. The advantage of using multiple modeling methods is that it gives modelers more options and allows them to make choices that improve the quality of the model and increase the efficiency of the modelling process.

Modelling with AEM

AEM has proven successful in providing spatially dense data that can be built into hydrostratigraphic models. An AEM resistivity-depth model contains estimates of the resistivity values at certain depths in the volume of interest. This model is informed by the conceptual model and can be combined with the layer model to improve the resolution of the hydrostratigraphic model. The critical part of using AEM to populate a volume model with hydrogeological property estimates is defining a resistivity-lithology transformation. Example approaches include bootstrapping (Knight et al. 2018), clay-fraction modeling (Christiansen et al. 2014; Foged et al. 2014), and Bayesian sequential simulation geostatistics (Ruggeri et al. 2014).

AEM is particularly suited to volumetric modeling, but under certain conditions, it can be used to define surfaces for framework modeling. For volumetric modeling, the challenge is to convert resistivity to lithology or hydrogeological properties. For framework modeling, a consistent resistivity contrast must exist along the boundary of interest. This requires that the two volumes separated by the boundary have differing resistivities and that the boundary can be resolved.

There are generally two approaches to mapping geological surfaces with an AEM resistivity-depth model: (1) steepest gradient approach, and (2) threshold approach. The steepest gradient approach finds the elevation at which the rate of change in resistivity with depth is at its maximum. The threshold approach defines a cutoff resistivity (threshold) value and draws a contour along this value to map the interface.

Bedrock Surface Mapping

The bedrock surface is important in Nebraska because it commonly defines the base of the regional aquifer system. Therefore, this surface has been used historically in defining groundwater model boundaries. The experience of geologists working on Nebraska AEM has shown that mapping the bedrock surface can be challenging. These challenges relate to (1) low resolution of AEM resistivity models at depth, and (2) the variable nature of resistivity gradients and thresholds at the bedrock surface.

To overcome the challenges of using AEM to map the bedrock surface, it is strongly recommended that good-quality borehole logs be used as an initial starting point for mapping. The following procedure should be used as a guideline.

1. Assemble borehole lithology logs from data sources given in **Guidelines for Hydrogeologic Data Integration and Visualization.**
2. Exclude borehole data for which x,y coordinates were not derived from GPS or calculated from measurements (wells with coordinates derived from legal locations should not be used).
3. Exclude boreholes that contain obvious errors or poor-quality lithological descriptions.
4. Extract an elevation for the land surface at the location of each borehole using a high-resolution Digital Elevation Model (DEM).
5. Determine the depth to bedrock in each borehole, then calculate the elevation of this point. Do not remove partially penetrating boreholes from the dataset. Save them for later.
6. Interpolate a preliminary bedrock surface model using the borehole picks.
7. Construct a 3D project (using GeoScene3D or similar software program) combining the boreholes, AEM resistivity-depth models, and the preliminary bedrock surface.
8. If the AEM line spacing allows, construct a 3D grid of resistivity. [As a rule of thumb, maximum AEM line spacing suitable for 3D resistivity gridding is ~400 m is heterogeneous aquifers (i.e. glacial aquifers) and ~1000 m in laterally continuous aquifers (i.e. alluvial aquifers and the Ogallala Aquifer).]
9. Visualize the boreholes (including fully penetrating and partially penetrating types), bedrock picks, bedrock surface, and AEM resistivity (either a 3D grid or soundings along a flight line) on a series of profiles through the model area.
10. Edit the borehole picks if necessary, using visual inspection of the data in each profile. For partially penetrating wells, it may be appropriate to add a bedrock pick at the total depth of the well (Drillers sometimes stop drilling as soon as they encounter bedrock without

penetrating it, resulting in no log entry for that depth. Thus, the depth of the well in some cases defines the bedrock surface).

11. Pick bedrock surface in AEM using resistivity contrasts (steepest gradient or threshold approach). The borehole picks and preliminary bedrock surface grid should be used as a guide to interpreting AEM between boreholes. The borehole data will also help the geologist determine which resistivity threshold or gradient, if any, represents the bedrock surface.
12. Combine the borehole picks with the AEM picks and interpolate a final bedrock surface.

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