System-scale airborne electromagnetic surveys in the lower Mississippi River Valley support multidisciplinary applications

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SUMMARY

The lower Mississippi River Valley spans over 200,000 square kilometres in parts of seven states, encompassing areas of critical groundwater supplies, natural hazards, infrastructure, and low-lying coastal regions. From 2018 – 2022, the U.S. Geological Survey acquired over 82,000 line-kilometres of airborne electromagnetic, radiometric, and magnetic data over this region to provide comprehensive and systematic information about subsurface geologic and hydrologic properties that support multiple scientific and societal interests. Most of the data were acquired on a regional grid of west-east flight lines separated by 3 – 6 kilometres; however, several high-resolution inset grids with line spacing as close as 200 m were acquired in targeted areas of interest. Approximately 8,000 line-kilometres were acquired along streams and rivers to characterise the potential for surface water-groundwater connection, and another 6,000 line-kilometres were acquired along the Mississippi and Arkansas River levees to characterise this critical infrastructure. Here, we present a summary of the data along with several examples of how they are being used to inform regional groundwater model development, inferences of groundwater salinity, identification of faults in the New Madrid seismic zone, and levee infrastructure.

Key words: airborne electromagnetic, lower Mississippi River Valley, groundwater, hazards, levee infrastructure

INTRODUCTION

The Mississippi Alluvial Plain (MAP) hosts one of the most prolific shallow aquifer systems in the United States but is experiencing chronic groundwater decline over much of its spatial extent. The Mississippi River Valley alluvial aquifer (MRVA), the surficial aquifer within the MAP region, was among the most heavily withdrawn aquifers for irrigation in the United States in 2015 (Lovelace et al. 2020). Furthermore, the Reelfoot rift and New Madrid seismic zone underlie the region and represent an important and poorly understood seismic hazard (Frankel et al. 2009). Despite its societal and economic importance, the shallow subsurface architecture has not been mapped with the spatial resolution needed for detailed scientific studies and prudent resource management.

Here, we present airborne electromagnetic (AEM), magnetic, and radiometric observations, measured over 82,000 flight-line-kilometres, which collectively provide a system-scale snapshot of the entire region of more than 270,000 square kilometres (Figure 1). This work nearly doubles the extent of regional airborne geophysical coverage originally completed in 2019 (Minsley et al. 2021), extending coverage south to the gulf coast of Louisiana as well as expanding laterally to cover recharge areas of the Mississippi Embayment and the Chicot aquifer system. Additional cooperator funding was leveraged to investigate the confining unit in Shelby County, Tennessee as well as improve coverage of the entire Mississippi River and Arkansas River levees within the study area.

We developed detailed maps of aquifer connectivity and shallow geologic structure, inferred relations between structure and groundwater age, identified previously unseen palaeochannels and shallow fault structures, and characterised variability in the surficial fine-grained deposit on which the levee system is built. This work demonstrates how regional-scale airborne geophysics can close a scale gap in Earth observation by providing observational data at suitable scales and resolutions to improve our understanding of subsurface structures. In addition to supporting a range of applications today, comprehensive and foundational data collection efforts support a large 'decision-space' that will contribute to future studies with emergent sets of questions benefiting from expanded knowledge of regional geologic and hydrologic properties.

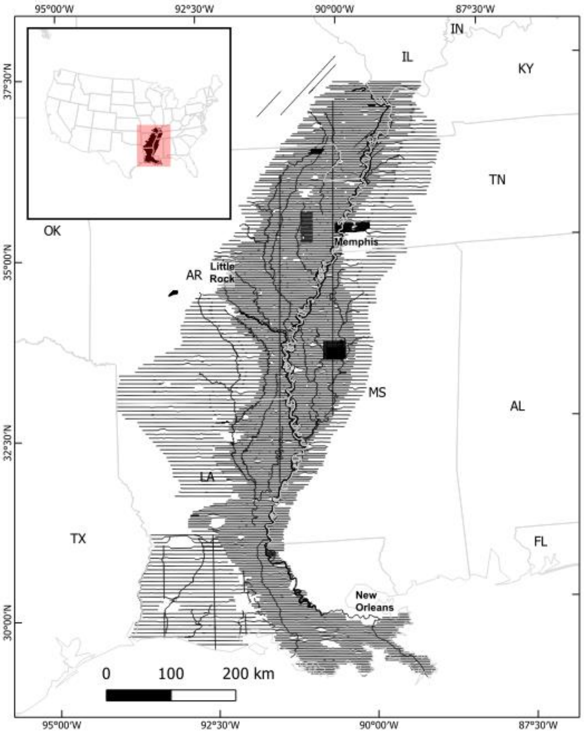

Figure 1. Airborne geophysical flight lines collected from 2018 - 2022.

METHOD AND RESULTS

Data acquisition and processing

Airborne geophysical data were collected over multiple phases from 2018–2022. Data were collected with both the helicopter frequency-domain Resolve AEM instrument and the fixed-wing Tempest time-domain system. One-dimensional electrical resistivity models were recovered for the Resolve data using Aarhus Workbench (Auken et al. 2015) and for the Tempest data using GALEI (Brodie 2017). Both radiometric and magnetic data were acquired together with the AEM surveys (Figure 2A,C).

Native-resolution models (~30 m spacing for Resolve and ~150 m spacing for Tempest) are investigated along flight lines in specific areas of interest. However, given the widely spaced (3–6 km) flight lines and regional nature of the investigation covering a large area, we also produced a coarse three-dimensional gridded resistivity grid that combines data from both sensors (Figure 2B, Figure 3). Resistivity models from each AEM instrument were kriged separately onto a common 1 km by 1 km grid with 5 m vertical intervals. The two grids were then combined using a depth-weighting function that favours the Resolve models at shallow depths, transitioning to Tempest models towards the maximum depth of investigation for Resolve (Minsley et al. 2021).

Hydrogeology

Regional-scale resistivity models agree with known hydrogeologic structures and areas of high groundwater salinity (Figure 2B, Figure 3), and provide additional detail needed to refine the geometry of hydrologic structures and variability within units. Binned resistivity classes were the basis for several interpretive products derived from the AEM data; these include thickness and extent of shallow confining materials, connectivity between the surficial aquifer and deeper geologic units, and connectivity between the aquifer and streams and rivers (Minsley et al. 2021).

The configuration of different resistivity classes, inferred to have different hydrologic properties, were used to inform both regional and inset groundwater models in the study area. Resistivity classes were used to inform layering of the groundwater models during model construction, then to assign initial values to the aquifer properties, streambed conductance, and recharge zonation in the calibration process.

Resistivity models and their derived interpretive products, together with the radiometric data and in situ measurements of groundwater chemistry and water quality have been incorporated into machine learning algorithms to predict distributions of manganese and arsenic (Knierim et al. 2022) and groundwater salinity in the surficial aquifer. A separate multi-method machine learning model incorporates geophysical information along with hydrologic and climatological variables to predict monthly groundwater levels with uncertainty bounds for the MRVA from 1980 through 2020 (Asquith and Killian 2022).

Hazards

In northeast Arkansas and southeast Missouri, west of the New Madrid Seismic zone, a previously undocumented fault was identified along multiple AEM profiles spanning an along-strike distance of more than 100 km. Fault offset of about 50–75 m is observed, clearly extending at least to the base of the shallow surficial aquifer (Minsley et al. 2021). Several shallow features attributed to sand boils caused during past earthquake liquefaction events are identified along several higher-resolution Resolve flight paths.

Infrastructure

Resistivity models from flight lines acquired along the Mississippi River and Arkansas River levees were classified into 10 groups using a k-means clustering algorithm. Individual clusters identify resistivity models that share similar layering structure and lithologic characteristics. Cluster numbers were mapped back to positions along the levees in order to identify regions of interest for follow-up investigation with drilling or other ground-based methods.

Outreach

We have focused on raising community awareness about airborne geophysical surveys and the value provided by these data throughout the project. Outreach efforts have included: multiple stakeholder and public events held during survey operations, presentation of data interpretations, and publication of online geonarratives that describe the results of the geophysical surveys for the general public. We developed a 3d-printed physical model interpreted from a subset of our AEM data for use as a communication tool and handout for cooperators and other officials (Figure 4).

CONCLUSIONS

Airborne geophysical data extend our view into the subsurface, transforming our ability to inform three-dimensional mapping from catchment to basin scales in a cost-effective and systematic approach. Here, we demonstrated that system-scale airborne geophysical data of the lower Mississippi River Valley provide a robust platform from which to address a host of subsurface questions with important scientific and societal applications.

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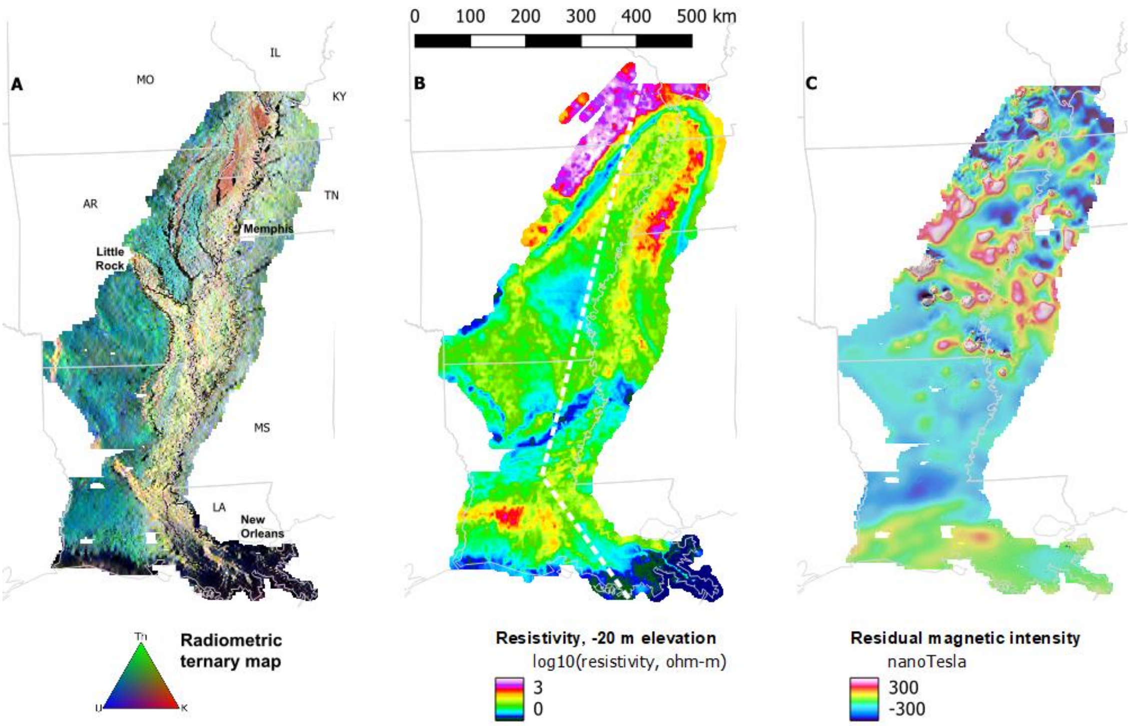

Figure 2. Gridded airborne geophysical results. (A) Ternary radiometric map showing relative abundance of Potassium (K), Thorium (Th), and Uranium (U). (B) Electrical resistivity at a constant elevation of 20 m below sea level. (C) Residual magnetic intensity.

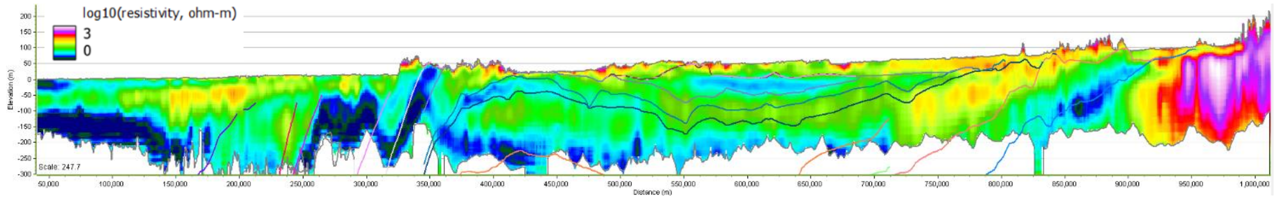

Figure 3. South-north resistivity cross-section. Gridded resistivity models are shown along a ~1,100 km cross-section from the Louisiana gulf coast on the left, where elevated groundwater salinity can be seen as a low-resistivity lens in the near surface, to the upland area outside the alluvial plain in southeast Missouri (white dotted line, Figure 2b). The subsurface resistivity architecture closely corresponds with the top surfaces of hydrogeologic units (colored lines, Mississippi Embayment Regional Aquifer Study (MERAS) model (Hart, Clark, and Bolyard 2008)).

Figure 4. Outreach and communication examples. (top-right) Open-house events were held during survey operations to provide opportunities for media and the public to view the AEM survey equipment and learn about the project. Follow-on meeting sessions were held with cooperators to review datasets and discuss interpretations. Photo credits: Roland Tollett (USGS) and Randy Hunt (USGS). (top-left) A physical 3d-printed model of three layers interpreted from the AEM data collected over one of the high-resolution survey blocks in Mississippi is a useful communications tool and handout for cooperators. Photo credit: Department of the Interior. (bottom) Online geonarratives were created to present both regional and high-resolution inset AEM datasets in a simplified format to showcase the survey results to public audiences. The geonarratives can be found at:
https://www2.usgs.gov/water/lowermississippigulf/map/regional_SM.html
https://www2.usgs.gov/water/lowermississippigulf/map/shellmound_SM.html