Photo by Shane Stocks

The Use of Waterborne-Resistivity Profiling to Quantify Hydraulic Conductivity of 180 Kilometers of Streambed in the Mississippi River Alluvial Plain

Benjamin V. Miller[1], David S. Wallace[2], and Wade H. Kress[1]

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1. Hydrologist, Lower Mississippi-Gulf Water Science Center, U.S. Geological Survey, Nashville, TN, 2. Hydrologist, Texas Water Science Center, U.S. Geological Survey, Fort Worth, TX

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Abstract

In June of 2016, the US Geological Survey used waterborne-resistivity profiling to map the shallow (< 10m) subsurface distribution of electrical properties as a proxy for streambed hydraulic conductivity. Two-dimensional vertical profiles of resistivity were used to identify differences in geoelectrical structure of the streambed for reaches of the Tallahatchie (60 km), Quiver (50 km), and Sunflower (70 km) Rivers in central Mississippi. Inverse modeling was used to develop two-dimensional (2-D) vertical profiles of resistivity for each stream. Modeled streambed resistivities of the Tallahatchie River were 51 ohm-m higher than the Quiver River and 38 ohm-m higher than the Sunflower River. Differences in streambed lithology can be interpreted from the variation and distribution of resistivity values. Along the Sunflower, resistivity is highly variable, with a standard deviation of 64.6 ohm-m. This is about 49% greater than the variability in resistivity of the Tallahatchie, with a standard deviation of 33 ohm-m, and 25% greater than the Quiver at 49 ohm-m. In regional groundwater-flow models, the hydraulic conductivity of streambed materials is typically an estimated parameter because of difficulty in obtaining a data-supported value in real-world conditions. Modeled resistivities from this work will be used to scale streambed hydraulic conductivity within a regional groundwater-flow model used to assess water-management scenarios. Future studies will continue the application of geophysical methods to improve this model.

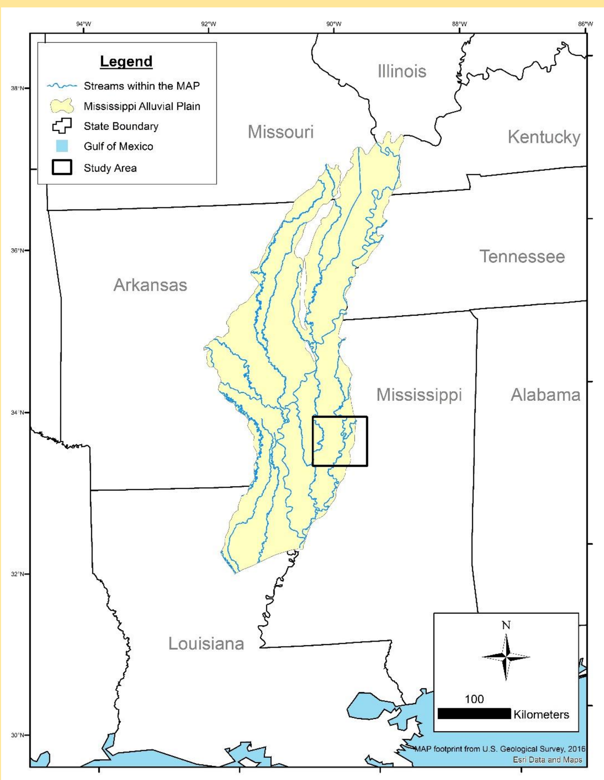


Figure 1: Overview map of Mississippi Alluvial Plain, map citation 1.

Introduction

- Hydraulic conductivity of streambed materials is typically an estimated parameter in regional groundwater-flow models. The electrical resistivity of earth materials in fresh water aquifers commonly has a positive correlation with hydraulic conductivity.
- In unconsolidated alluvial settings coarser-grained deposits such as gravel and sand typically have higher resistivities compared to silts and clays which have lower resistivities (Ball and others, 2006; Shah and others, 2007).
- Starting in June of 2016, the Mississippi Alluvial Plain (MAP) Regional Water Availability Project used waterborne-resistivity profiling to map the shallow (<10m) sub-surface distribution of electrical properties as a proxy for streambed hydraulic conductivity.
- The objective of this analysis is to determine the relationship between results of the waterborne-resistivity survey to general lithologic changes in mapped geomorphological units.

Setting

The Mississippi Alluvial Plain extends across portions of five states and comprises an area of 141,895 km^2 (Fig. 1).

- Within the MAP, the Delta region of northwestern Mississippi is an area where land use is dominated by agriculture, primarily row crop production. The region represents one of the most productive agricultural areas in the nation, producing more than $7 billion in agricultural products in 2012.
- This agriculture is possible through significant irrigation, primarily from groundwater drawn from unconsolidated alluvial aquifers.
  - These sediments, 60-80 meters-thick, represent a long and complex history of sedimentation from the nearby Mississippi River, that have been altered by down cutting and sedimentation from local streams.
- Mapped geomorphological units within the study area include Holocene and Pleistocene-aged sediments deposited by the Mississippi River and other smaller streams (Table1) (Saucier, 1994).
  - Variations in the extent, thickness, and lithology of these geomorphological units impact surface water-groundwater exchange in the study area, which can have implications for recharge into the alluvial aquifer.

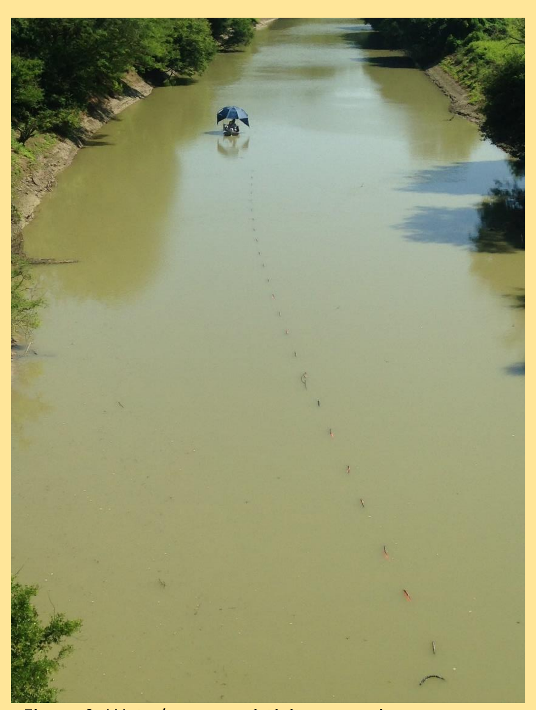


Figure 2: Waterborne -resistivity survey in-progress on Quiver River, Photo by author

Methods

For this survey a reciprocal Schlumberger array was used, which positions the transmitting pair of electrodes toward the center of the array and the receiving pairs radiating away from the transmitter.

The resistivity of the water in the river was measured at the beginning of each profile and at the end of the last profile each day using a field conductivity meter. Data collected within each river included: latitude, longitude (GPS system), injected current, voltage, resistance, apparent resistivity, electrode location (referenced to the position of the GPS), water depth (echo sounder), water temperature, water conductivity, and calculated water resistivity.

*Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Methods *

- Waterborne-resistivity profiling was done using a 10-channel Iris Instruments Syscal Pro resistivity meter. A 60 meter long floating reciprocal Schlumberger array with a 5-meter electrode spacing was used to conduct the survey (Figs 2 & 7).
  - Geospatial positioning and water depth were collected using a Garmin GPSmap 188 Sounder.
  - Stream temperature, conductivity, and specific conductivity were measured using an YSI Professional Plus water quality meter.
  - Data processing and visualization was done using Geosoft's Oasis Montaj geophysical software. The raw and processed data are available in Miller and others (2016).
- Apparent resistivity data were modeled using IX1D version 3.52 developed by Interpex Limited (2016)
  - Occam's inversion (Constable et al., 1987) was used to create a smooth model for each sounding
  - The water column was represented in the model as layer 1. Layers 2-4 (~4m) were analyzed to evaluate the near-surface geoelectrical properties of sediments near the streambed controlling surface water and groundwater exchange.

Table 1: Geomorphic units within the study area, modified from Saucier 1994

Age- Geomorphic Unit (Map symbol)	General Description	Sedimentary Structures	Grain size	Resistivity Properties
Holocene- Backswamp (Hb)	• Firm to stiff clays, abundant organic matter	• Thin silt laminations and frequent burrows	• Very fine-grained clay	Low resistivity
Holocene- Abandoned channels (Hchm)	• Composed of two units, first unit is a sand wedge which forms in the arms of the cutoff. • Second unit is a clay plug described as slightly organic silty clay.	• Sand wedges are cross-bedded • Clay plugs exhibit bedding	• Fine to medium-grained sand. • Fine-grained clay.	Low to medium resistivity
Holocene -Point bars from Mississippi River & small streams (Hpm 2-5, Hps)	• Ranges from stily or sandy clay to silty sand. • Beneath is a coarsening downward sequence of sandy sediments.	• Highly cross-bedded with fine ripples in upper portion • Coarser textured trough stratification below.	• Fine in upper portion, coarser in lower portion.	Medium to high resistivity
Holocene - Abandoned course of Mississippi River & trunk channel of major delta complexes (Hcom)	• Top strata can be very soft to soft organic clays and silts transitioning to sandy loams and silty sands. • Substratum is well-sorted sands with thin horizontal clay layer.	• In substratum, large scale migrating sand waves • Rip up clasts present throughout	• Very fine in upper portion. • Fine to medium-grains in substrate.	High resistivity

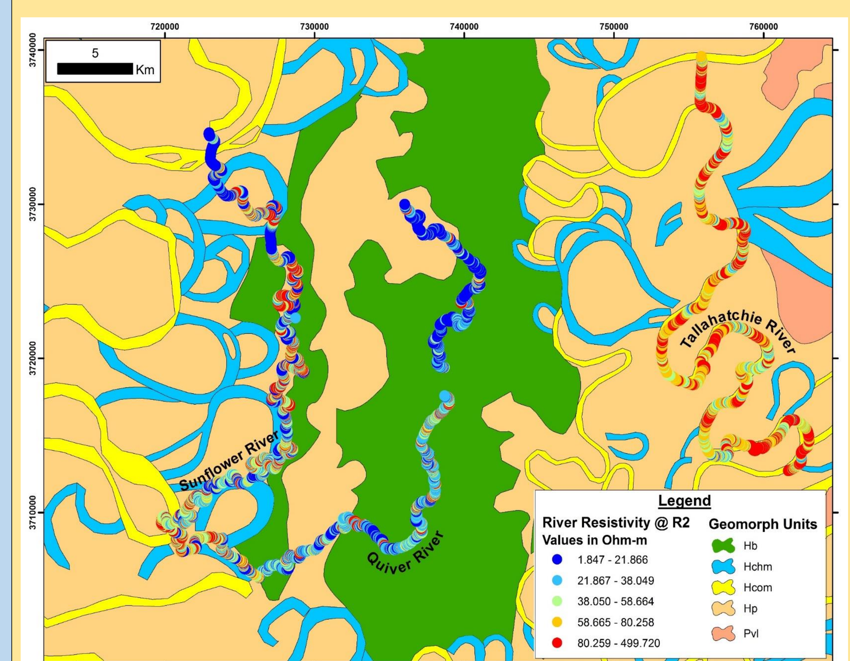


Figure 3: Qualitative estimate of streambed hydraulic conductivity from waterborne resistivity values for surveyed rivers overlain on geomorphology, map citation 2.

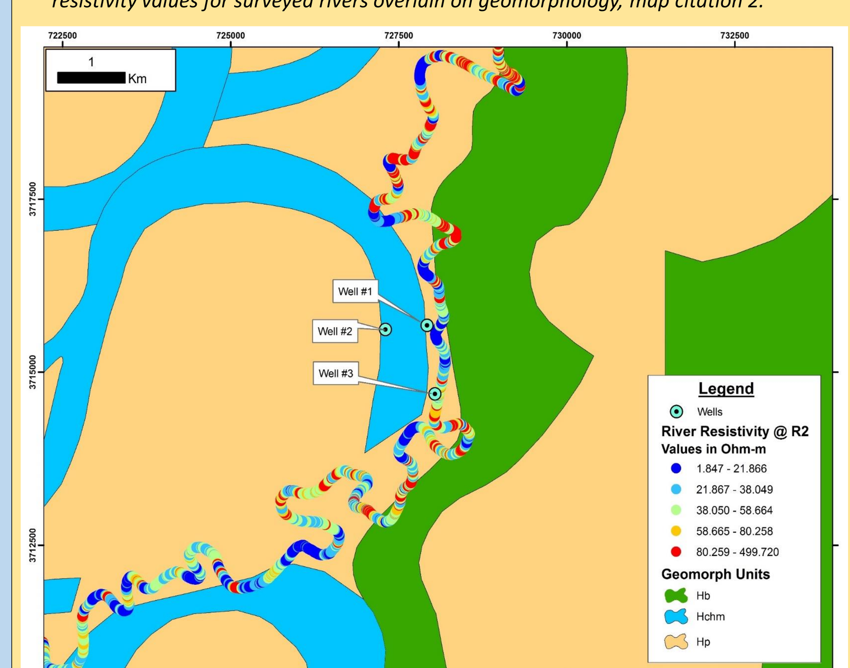


Figure 4: Detail of resistivity values for Sunflower River with well locations, map citation 3.

Results & Discussion

Overall, resistivity values from waterborne surveys for the Sunflower, Quiver, and Tallahatchie Rivers show major differences that correlate to large scale lithologic changes in each geomorphology unit (Figs. 3-5, Table 2 & 3).

- Sunflower River (Figure 4) : Resistivities were highly varied longitudinally along the main channel.
  - The Sunflower meanders through a mix of backswamp, point bar, and abandoned channel deposits, each with their own geophysical signatures (Table 2).
  - As the river meandered into the abandoned channel deposits the resistivity values decreased substantially, indicative of an increase in clay content found within the abandoned channels.
  - As the river meanders out of the abandoned channel deposits, into the increasingly sandier point bar deposits, the resistivity increases from values around 13 ohm-m up to 55 ohm-m.
  - Subsurface lithology data collected from the installation of three wells were used to evaluate the waterborne-resistivity surveys with the geomorphology. Along the western bank of the Sunflower River are three wells with documented borehole lithology (Figs. 4 & 6).
    - Well 1 has approximately 13.5 m of clay which correlates with the low resistivity feature in the resistivity profile.
    - Well 3 has a more sand-dominated lithology, with four meters of silt followed by eight meters of sand ending in clay. Resistivity data near this well show moderate resistivity values in the upper four meters of the profile corresponding to the silts and increased resistivity below representing the increased sand content with depth.
- Quiver River (Figure 3): Generally lower resistivities and less variation, indicative of clay-rich streambed and less surface water-groundwater exchange.
  - The Quiver flows through backswamp deposits which filled the Yazoo basin in the center of the study area.
  - The average resistivities for the northern portion of the Quiver River survey are 30 ohm-m less than the resistivities in the southern portion of the river. This is likely the result of thinning backswamp deposits along the southern edge of the basin.
- Tallahatchie River (Figure 3): Higher resistivity values, compared to other streams, indicate an increase in sand content and more potential for surface water-groundwater exchange and recharge.
  - The Tallahatchie flows almost exclusively over abandoned channels (Hcom) as characterized by Saucier (1994).
  - Resistivities along the Tallahatchie were typically higher than other surveyed streams resulting from the increased sand content of geomorphic unit Hcom (Table 3).

Table 2: Resistivity values for geomorphic units

Geomorphic Unit	Min Res (Ohm-m)	Max Res (Ohm-m)	Mean Res (Ohm-m)	Stan. Dev	# soundings	% of total
Hp : Point Bar	2.37	499.72	57.45	45.52	20110	55
Hcom : Abandoned Course	6.786	467.03	69.13	27.82	6939	19
Hb : Backswamp	1.847	491.64	38.97	42.13	8314	23
Hchm : Abandoned Channel	3.583	487.18	49.96	54.43	1433	4

Table 3: Resistivity values for surveyed rivers

River name	Min Res (Ohm-m)	Max Res (Ohm-m)	Mean Res (Ohm-m)	Stan. Dev	# soundings	Thickness - avg (m)	Thickness - max (m)	Thickness -min (m)	Thickness - st dev
Quiver	1.85	491.64	34.06	37.37	9930	1.88	3.2	1	0.32
Tallahatchie	7.225	498.1	73.58	26.77	13177	3.05	6.2	1.3	0.51
Sunflower	2.37	499.72	53.36	52.06	13957	1.66	3.9	0.6	0.29

Abbreviations within Table 2 & 3 include:
Min. = Minimum Max. = Maximum Stan. Dev. = Standard Deviation Avg. = Average

Conclusion

Waterborne-resistivity profiling is a relatively quick, non-invasive method to map shallow, subsurface geoelectrical properties of rivers in the Mississippi River Alluvial Plain. The resistivity data in this study area has a good correlation with mapped geomorphological features and can be used to determine, qualitatively, streambed hydraulic conductivity. For example point bar and abandoned course deposits have relatively higher resistivity values due to the increase in sand content. Whereas backswamp and abandoned channel deposits which contain substantially more clay have lower resistivity values. Lithologic data from nearby boreholes confirmed the relation between resistivity and lithology at depth. The mapped geomorphological units and resistivity data can be used collectively to design a targeted drilling program to develop a quantitative estimate of streambed hydraulic conductivity from the resistivity data.

Figure 5: Perspective view from southwest of 3D modeled resistivity of all three rivers.

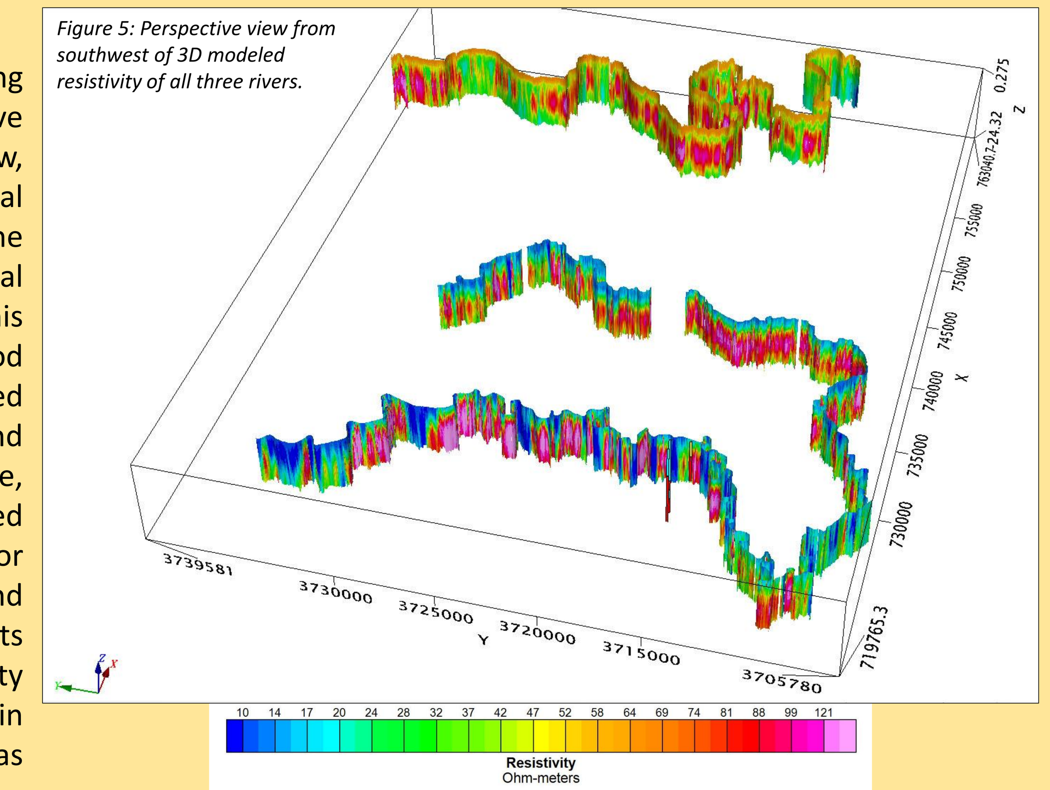
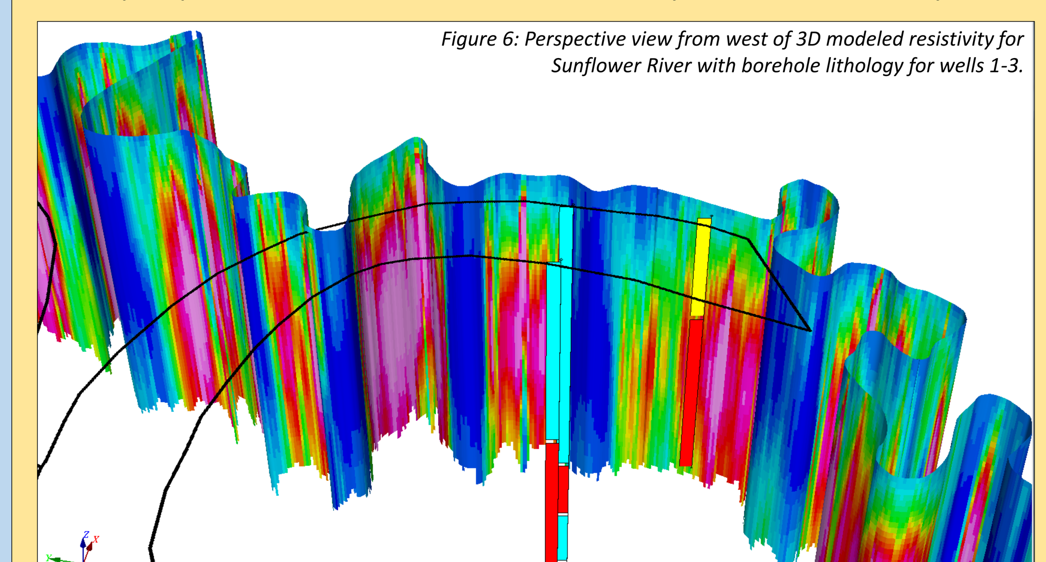


Figure 6: Perspective view from west of 3D modeled resistivity for Sunflower River with borehole lithology for wells 1-3.



Map Citations

1: Base map of United States and Gulf of Mexico from ESRI Online Data. MAP aquifer boundary and stream shapefile from U.S.G.S.. Datum is WGS 1984
2: Geomorphology units modified from Saucier, 1994. Resistivity data from USGS. Datum is UTM Zone 15N NAD 1983.
3: Geomorphology units modified from Saucier, 1994. Resistivity data and well locations from USGS. Datum is UTM Zone 15N NAD 1983.

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Acknowledgements

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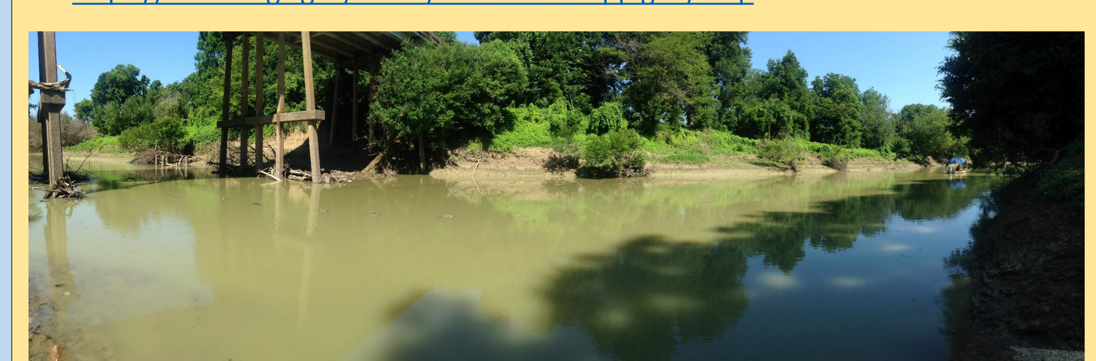

Figure 7: Side view of waterborne-resistivity survey on Quiver River, note boat on far right of photo. Photo by author