# Hydrostratigraphy Modeling of the Southern Hills Aquifer System

## Basic Information

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## Publications

1. • Elshall, A.S., F. T.-C. Tsai, and J.S. Hanor. (2013). Indicator Geostatistics for Reconstructing Baton Rouge Aquifer-Fault Hydrostratigraphy, Louisiana, USA. Hydrogeology Journal, 21, 1731-1747. doi:10.1007/s10040-013-1037-5
2. Frank Tsai and Jeffrey Hanor, 2013, Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach, Louisiana Water Resources Research Institute, Louisiana State University, Baton Rouge, Louisiana, 10 pages. (USGS 104G)
3. Frank Tsai, 2013, Hydrostratigraphy Modeling of the Southern Hills Aquifer System and Faults, Louisiana Water Resources Research Institute, Louisiana State University, Baton Rouge, Louisiana, 10 pages. (USGS 104B)
4. Elshall, A. S., F. T.-C. Tsai, and J. S. Hanor, Indicator geostatistical approach to reconstruct geological architecture of the Baton Rouge aquifer-fault system, Louisiana. Gulf Coast Association of Geological Societies Transactions. v. 63, p. 539-542, 2013

# SYNOPSIS

## Problem and Research Objectives

The Southern Hills aquifer system is located in southeastern Louisiana and southwestern Mississippi shown in Figure 1. The area covers 32,678 km$^2$, ranging from latitude 30.15 to 32.56 degree and longitude from -91.81 to -89.56 degree. It includes 14 counties of Mississippi and 10 parishes of Louisiana. The area has an average slope of 11% with an elevation varying from -2 m to 172 m above mean sea level.

**Figure 1:** The extent of the Southern Hills aquifer system.

The lithology of the Southern Hills aquifer system is comprised of a series of sandy gravel to clayey formations that generally dip south towards the Gulf of Mexico. The surficial geology shows formations from early Miocene at the north and northwest to Pleistocene and Holocene extending from northeast to south of the aquifer system (Dicken et al. 2005). The Miocene deposits consist of Catahoula, Pascagoula, and Hattiesburg formations, the Pleistocene deposits include Citronelle and Terraces formations, and the Holocene deposits account for Mississippi River and other major stream alluvium (Buono 1983). Southeastern Louisiana also contains several east-west trending listric geologic faults (McCulloh and Heinrich 2012), which limit southward groundwater flow through the faults.

Groundwater recharge through the outcrops in southwestern Mississippi provides an important freshwater source to the deep aquifers in southeastern Louisiana. The U.S. Environmental Protection Agency (USEPA) designates the Southern Hills aquifer system as one of the sole source aquifers (SSAs), which is the only source of potable water consumed in the area overlying the aquifers and has no substitute drinking water source(s). The SSA protection program secures the Southern Hills aquifer system in order to ensure the strictest protection of the local groundwater resources from contamination, under the section 1424 of Public Law 93-523, the Safe Drinking Water Act of 1974 (US Congress 1996).

Saltwater intrusion, droughts, climate change, groundwater shortage, and potential groundwater contamination by hydraulic fracturing activities in the Tuscaloosa Marine Shale (TMS) prompt the need to study the groundwater resource in the Southern Hills aquifer system in Louisiana. To do so, the objectives of this project are to develop techniques to construct the hydrostratigraphy for the Southern Hills aquifer system with a focus on the aquifer system in the Baton Rouge area and to convert the constructed hydrostratigraphy into the USGS MODFLOW computational grid for future groundwater flow simulation.

## Methodology

### (1) Hydrostratigraphy modeling

This study applies the indicator geostatistical method (Elshall et al. 2013) to the wireline well logs to construct three-dimensional geological architectures. Consider that the indicator function $\left\{I\left(\mathbf{x},v\right):\mathbf{x}\in\text{study area}\right\}$ is a random function with the indicator random variable $v$ describing the spatial extent of sand or clay facies. For a given sand-clay cutoff $\alpha$ , the random function of the indicator random variable $v$ for sand facies and clay facies is defined as

$$I\left(\mathbf{x},v\right)=\begin{cases}1 & v\in\text{Sand}\ ,\ v\left(\mathbf{x}\right)\geq\alpha \\ 0 & v\in\text{Clay},\ v\left(\mathbf{x}\right)<\alpha\end{cases} \tag{1}$$

From equation (1) the indicator outcome (one or zero) indicates the presence of sand facies or clay facies, respectively. The indicator variogram has the same definition as the normal variogram except that the real random function is replaced by the indicator random function $I\left(\mathbf{x},v\right)$. To calculate the expected value $v^{*}(\mathbf{x}_0)$ at location $\mathbf{x}_0$, the generalized parameterization (GP) method (Tsai and Yeh 2004, Tsai 2006) is adopted as

$$v^{*}\left(\mathbf{x}_0\right)=I\left(\mathbf{x}_k\right)+\sum_{i=1}^{N}\lambda_i\left[I\left(\mathbf{x}_i\right)-I(\mathbf{x}_k)\right]\beta_i \tag{2}$$

where $N$ is the number of wireline well logs, $I\left(\mathbf{x}_i\right)$ is the indicator data, $\lambda_i$ is the indicator kriging weight, and $\beta_i$ is the data weighting coefficient for a data point of a well log at location $\mathbf{x}_i$. $I\left(\mathbf{x}_k\right)$ is indicator data for a zone defined by a well log at location $\mathbf{x}_k$. Equation (2) shows that the GP estimate is the same as the indicator kriging (IK) estimate $v^{*}\left(\mathbf{x}_0\right)=\sum_{i=1}^{N}\lambda_i I\left(\mathbf{x}_i\right)$ if $\forall\beta_i=1$ and is the same as the indicator zonation (IZ) estimate $v^{*}\left(\mathbf{x}_0\right)=I\left(\mathbf{x}_k\right)$ if $\forall\beta_i=0$. For $0<\beta_i<1$, the GP estimate is between the IK estimate and IZ estimate. Elshall et al. (2013) suggests an inverse method to estimate the $\beta_i$ values.

### (2) MODFLOW grid generation

The USGS MODFLOW (Harbaugh 2005) is widely used in the hydrogeological and groundwater communities, in which the groundwater flow is simulated using a block-centered finite-difference method. Using the structured grid, a MODFLOW grid requires that all computational layers must be continuous throughout the model domain. This requirement creates difficulties in generating MODFLOW grids for complex hydrostratigraphic architectures including unconformed sand and clay sequences, isolated sands, discontinuity, varying thicknesses, complex interconnections, pinch-outs and geological faults. An accurate conversion of hydrostratigraphic architectures into the MODFLOW grids is an important step to reduce model structure errors in groundwater models and improve model prediction results.

Due to a lack of better grid generation techniques, complex hydrostratigraphic architectures are often overly simplified into several MODFLOW layers or into a uniform layer thickness. These simplifications significantly alter the original geological information. Unreasonable sediment thickness is often offset by adjusting hydraulic conductivity and other model parameters in the model calibration procedure. As a consequence, the groundwater flow regimes are inaccurately modeled by unrealistic aquifer parameters and structures.

In this study, we develop a technique through the following three steps to generate a MODFLOW grid that matches a complex faulted hydrostratigraphic architecture. The technique is applied to develop the MODFLOW grid for the Baton Rouge aquifer system, southeastern Louisiana. The aquifer system includes the Baton Rouge fault and the Denham Springs-Scotlandville fault. Using the hydrostratigraphic modeling technique in Elshall et al. (2013), the complex faulted hydrostratigraphic architecture is constructed by more than 500 well logs. Specifically, we generate a MODFLOW grid for the sequence of the “1,200-foot” sand, the “1,500-foot” sand, the “1,700-foot” sand, and the “2,000-foot” sand for the saltwater intrusion study in this area.

### Step 1: Eliminate thin sand and thin clay

To avoid an overwhelming number of computation layers in MODFLOW, it is recommended to eliminate thin sand and thin clay in each vertical column of the hydrostratigraphic grid before generating the MODFLOW grid. Given a criterion of the minimum thickness to define thin sand and thin clay, thin sand in thick clay or thin clay in thick sand are eliminated. For a sequence of thin sand and thin clay, eliminate sand or clay, whichever has total thickness less than 50% in the sequence. After cleaning up thin sand and thin clay, bed boundaries of each vertical column are assigned indices as basic information to form MODFLOW layer boundaries. A bed boundary is an interface where sediment material changes. Bed boundaries naturally form the boundaries of MODFLOW layers.

### Step 2: Project neighboring bed boundaries

To account for the continuity of MODFLOW layers from neighboring columns, additional bed boundaries are added to a vertical column by projecting the bed boundaries of its four adjacent vertical columns to the column. This is an important step in order to preserve the continuity of flow pathways, especially through geological faults, pinch-out areas, or narrow connections between thick sands. A new bed boundary may be deleted if the thickness between two consecutive bed boundaries is less than a thickness threshold. The smaller the thickness threshold is, the more the bed boundaries are added to vertical columns, which increases MODFLOW layers.

### Step 3: Generate MODFLOW grid

From Step 2 the minimum number of MODFLOW layers can be determined. Given a number of MODFLOW layers, this study introduces a “ruler” algorithm to assign MODFLOW layer indices to each vertical column. Again, the layer boundaries are required to match the bed boundaries. The start and the end of the ruler match the top and the bottom boundaries of a vertical column, respectively. The number of major ticks in the ruler represents the number of MODFLOW layers. The number of layers up to a bed boundary for a vertical column is obtained by comparing its bed boundary location to the ruler. For example, a bed boundary located between 0 and 1.5 in the ruler indicates one layer up to the bed boundary, between 1.5 and 2.5 indicates two layers up to the bed boundary, between 2.5 and 3.5 indicates three layers up to the bed boundary, and so forth. When the thickness between consecutive bed boundaries is small, the ruler algorithm is likely to assign two or more bed boundaries with the same number of layers up to their bed boundaries. In this case, the ruler algorithm will adjust the numbers to make sure that each bed boundary has a distinct layer index. In the last step, equal thickness of layers is given to segments that need to be divided into two or more layers based on the final assignment of the layer indices to the bed boundaries.

## Principal Findings and Significance

### (1) Geological architecture

We have collected and analyzed 1256 wireline well logs in southeastern Louisiana from the Louisiana Department of Natural Resources (LaDNR), the U.S. Geological Louisiana (USGS) Water Science Center, and the Louisiana Geological Survey (LGS). The location of the well logs is shown in Figure 2. Most of the well logs are in the East Baton Rouge Parish because groundwater is heavily pumped in this parish.

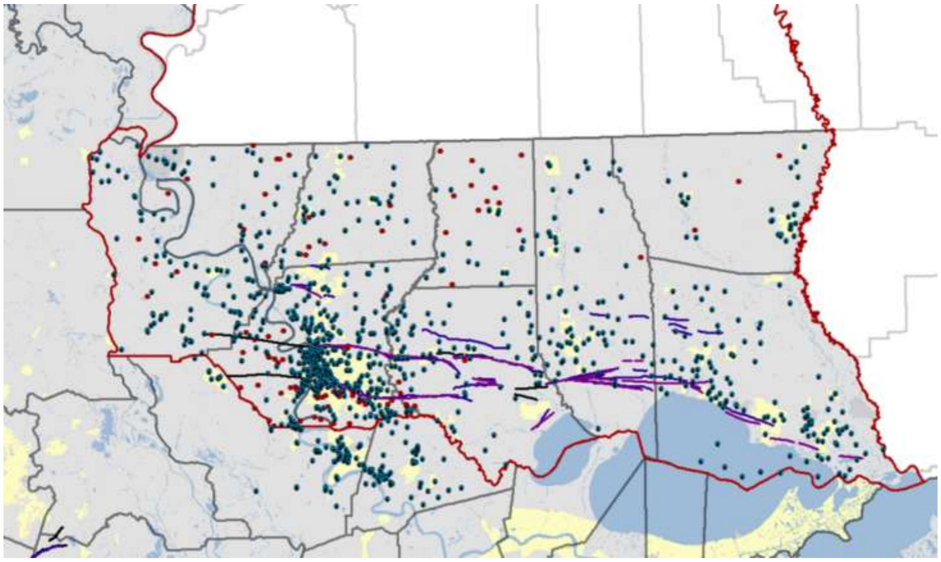

**Figure 2:** Location of the wireline well logs in southeastern Louisiana being analyzed for hydrostratigraphy construction. Blue circles are water well logs and red hexagons are oil/gas well logs. The blue lines are geological faults.

We analyze each well log to determine sand and clay. In general, shallow electrical resistivity (e.g., short-normal resistivity, medium induction resistivity, etc.) of 20 ohm-m is a good threshold for water-well logs to identify sand units for the freshwater formations in southeastern Louisiana. When salty water is present instead, the spontaneous-potential response helps to identify sand units. When available, the gamma ray response is used as a guide along with resistivity and spontaneous potential to identify sand units. For example, in Figure 3 the saline sands are identified in well log EB-783 located at the south of the Baton Rouge fault using SP and resistivity. For a saline sand, the SP response is pronounced and the long normal resistivity is less than the short normal resistivity. Also, the presence of salt water can be seen at the bottom of the sand in the depth of 2200 feet. Freshwater sands are identified in well log EB-1317 (south of the Baton Rouge fault) and WBR-128 (south of the Baton Rouge fault) based on resistivity. SP is not pronouncing in these two well logs. Low gamma ray in EB-1317 correlates sand units.

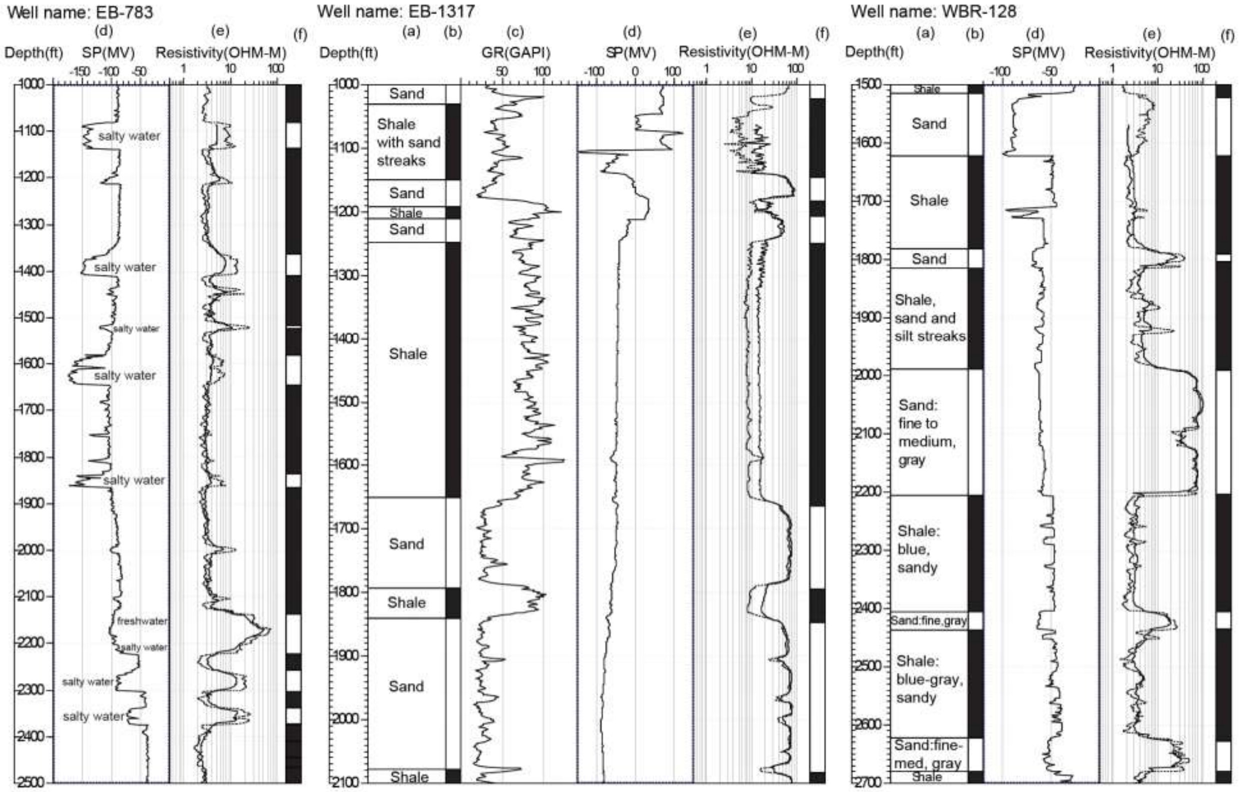

**Figure 3:** Wells logs for water well EB-1317, north of the Baton Rouge fault, and water wells EB-783 and WRB-128, south of the Baton Rouge fault. Column index is as follows: (a) drillers' log, (b) binary interpretation of drillers' log (white for sand and black for clay), (c) gamma ray (GR), (d) spontaneous potential (SP), (e) short normal resistivity (dotted line) and long normal resistivity (solid line), and (f) binary interpretation of electric log (white for sand and black for clay) (Elshall et al. 2013)

Using the technique in Elshall et al (2013), the geological architecture of the Southern Hills aquifer system in southeastern Louisiana was constructed as shown in Figure 4. There are many freshwater sands underneath southeastern Louisiana. Figure 5 shows the names of the sands and their depth in the Baton Rouge area.

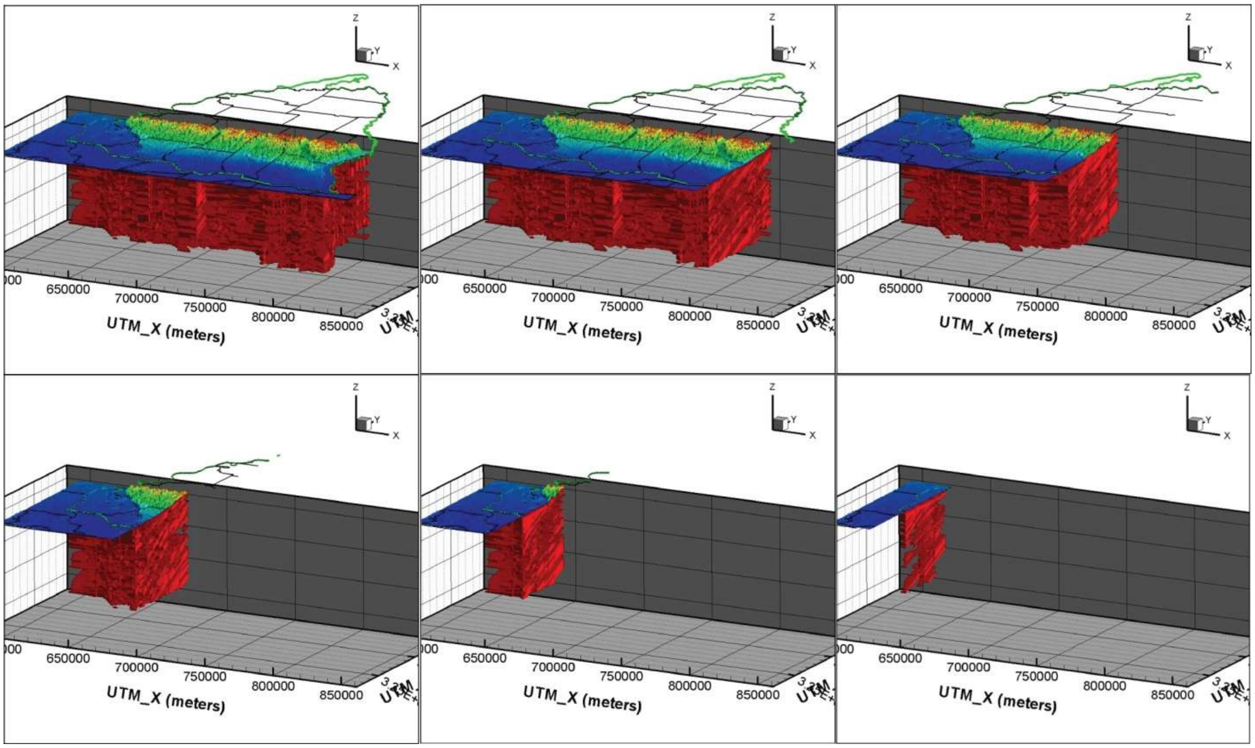

**Figure 4:** Geological architecture of the Southern Hills aquifer system in southeastern Louisiana

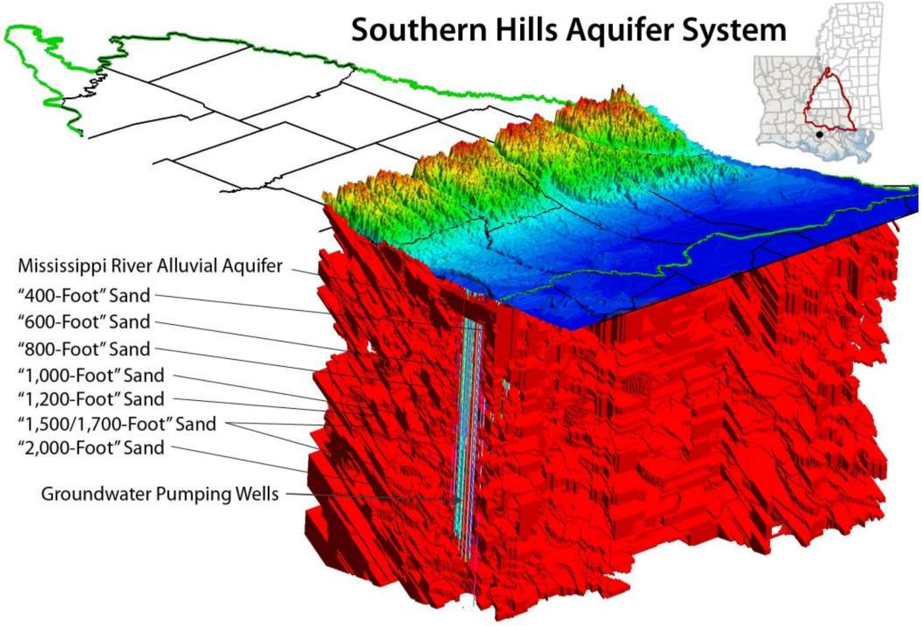

**Figure 5:** Geological architecture of the Southern Hills aquifer system in the Baton Rouge area

### (2) MODFLOW Grid Generation

Using the proposed methodology, we convert the geological architectures of the “1,200-foot” sand, the “1,500-foot” sand, the “1,700-foot” sand, and the “2,000-foot” sand in Figure 5 into a MODFLOW grid. Figure 6 shows the hydrostratigraphy model area.

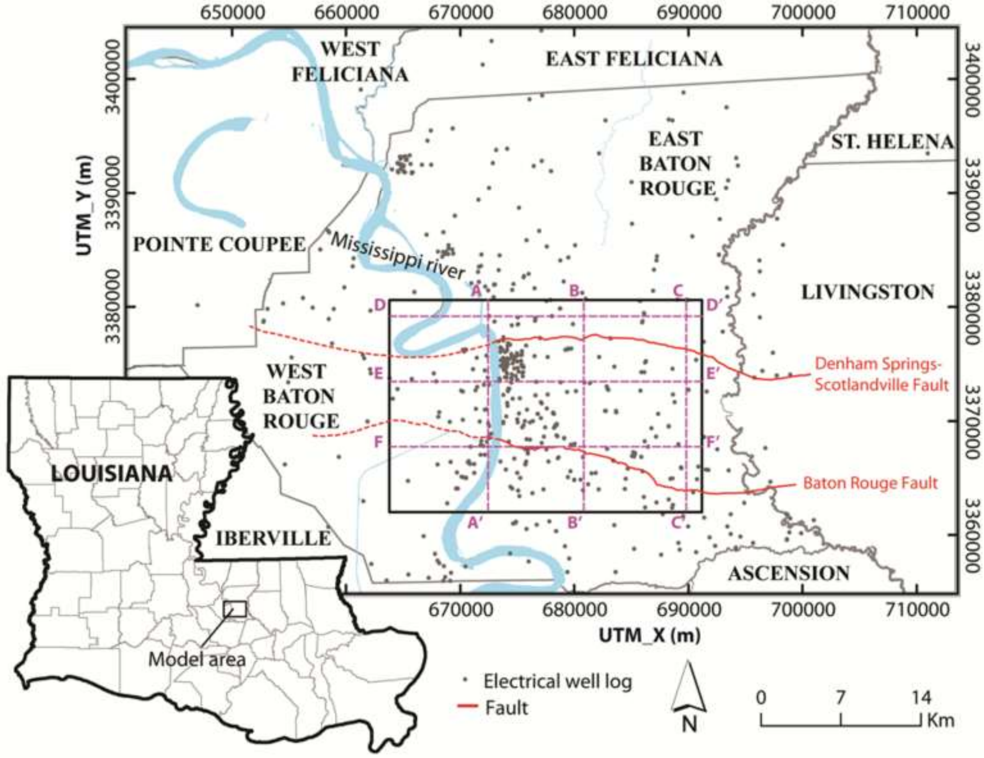

**Figure 6:** Map of the hydrostratigraphy model area (the box) and the location of the well logs. The solid red lines are the fault lines identified by the surface expression. The dashed red lines are the approximation surface locations of the faults.

Before eliminating thin sand and thin clay, the number of sand and clay segments in each vertical column ranges from 4 to 53, indicating at least 53 layers needed for constructing a MODFLOW grid. By eliminating sand and clay segments less than 10 ft (3.05 m) thick, the number of sand and clay segments in each vertical column is significantly reduced and ranges from 3 to 26. The second step is to consider continuity of layers by projecting the bed boundaries of four adjacent vertical columns to their respective column. After the bed boundary projection, the number of segments in vertical columns increases and ranges from 5 to 80.

In the final step, we use the processed hydrostratigraphic architecture to generate the MODFLOW grid. Figure 7 shows a grid of 76 layers, which accurately matches the complex hydrostratigraphic architecture and preserves the layer continuity. The layer thickness ranges from 3.05 m to 13.4 m. The average thickness of the layers is 5.2 meters. The “1,200-foot”, the “1,500-foot”, and the “1,700-foot” sands are from layer 6 to layer 46. The “2,000-foot” sand is from layer 47 to layer 76.

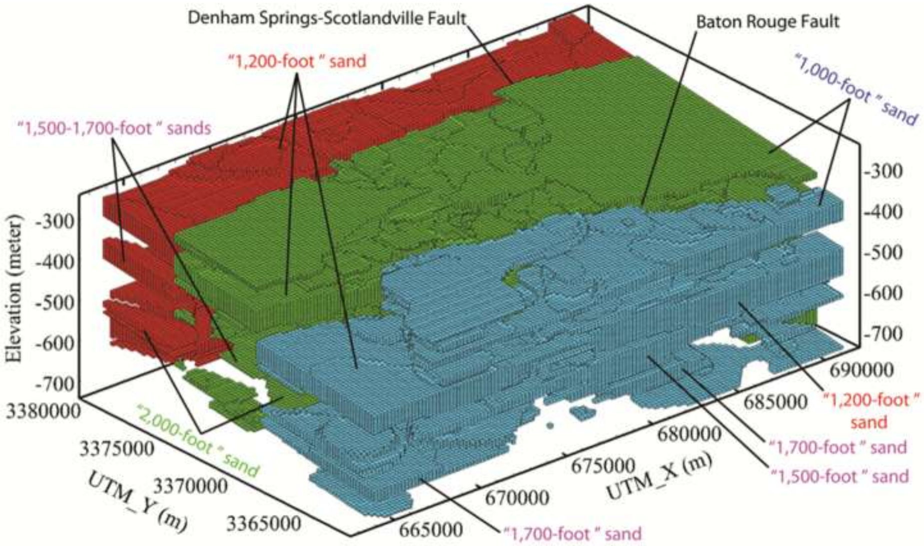

**Figure 7.** A three-dimensional MODFLOW grid for the "1,200-foot" sand, the "1,500-foot" sand, the "1,700-foot" sand, and the "2,000-foot" sand. Clay is blanked. The vertical exaggeration is 20 times.

## Flexibility of the grid generator

Different complex three-dimensional MODFLOW grids similar to Figure 8 can be automatically regenerated using: (1) different criteria to eliminate thin sand and thin clay, (2) different thickness thresholds to delete new bed boundaries, and (3) different number of layers. Since hydrostratigraphic architectures usually carry material indices (e.g., "1" for sand and "0 for clay in this study), the material properties will also be automatically assigned to new grids. The MODFLOW grids can also be easily updated when new well logs become available.

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