Characterization of Siliciclastic Aquifer-Fault System for Southeastern Louisiana

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- Louisiana State University High Performance Computing
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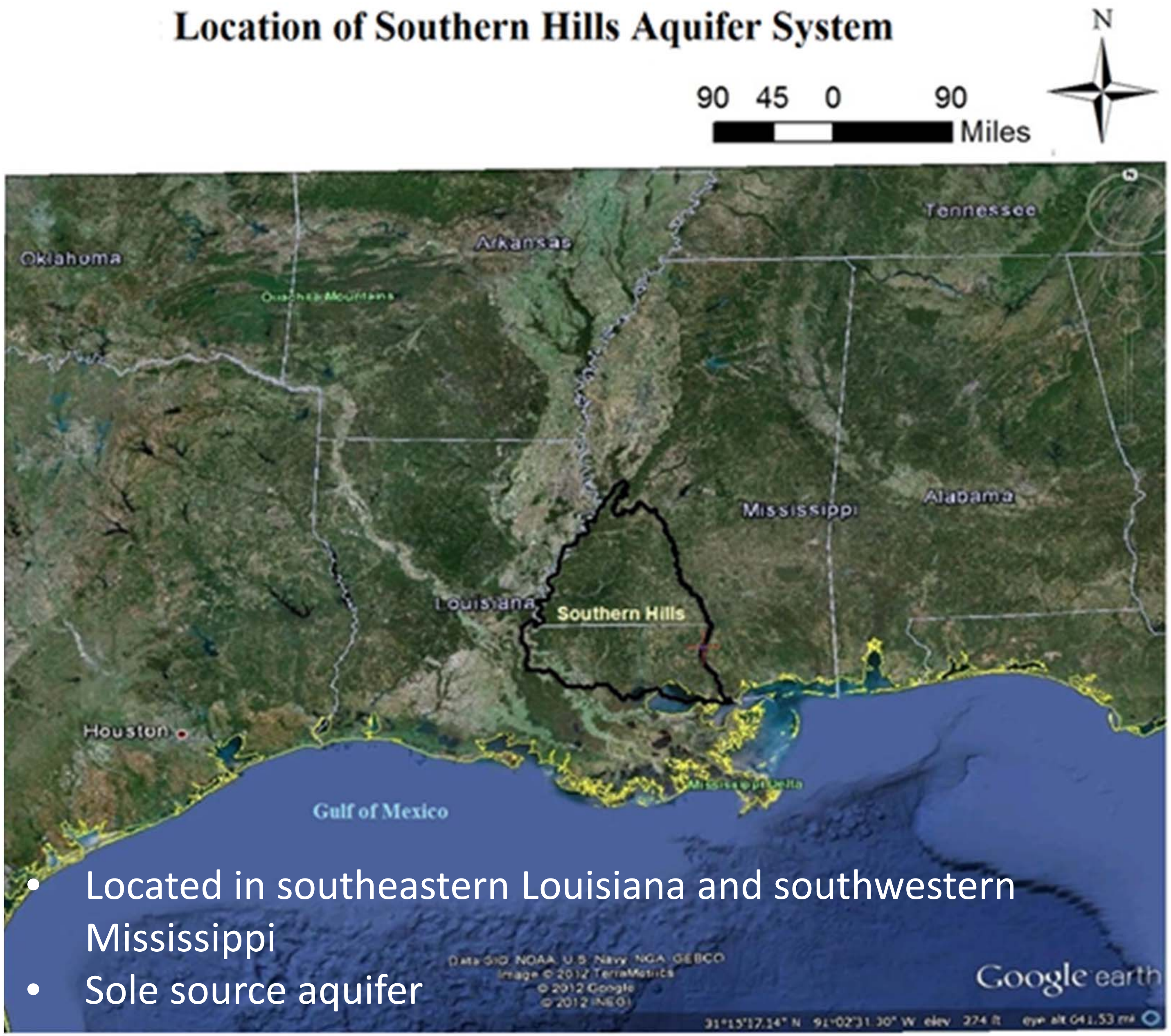
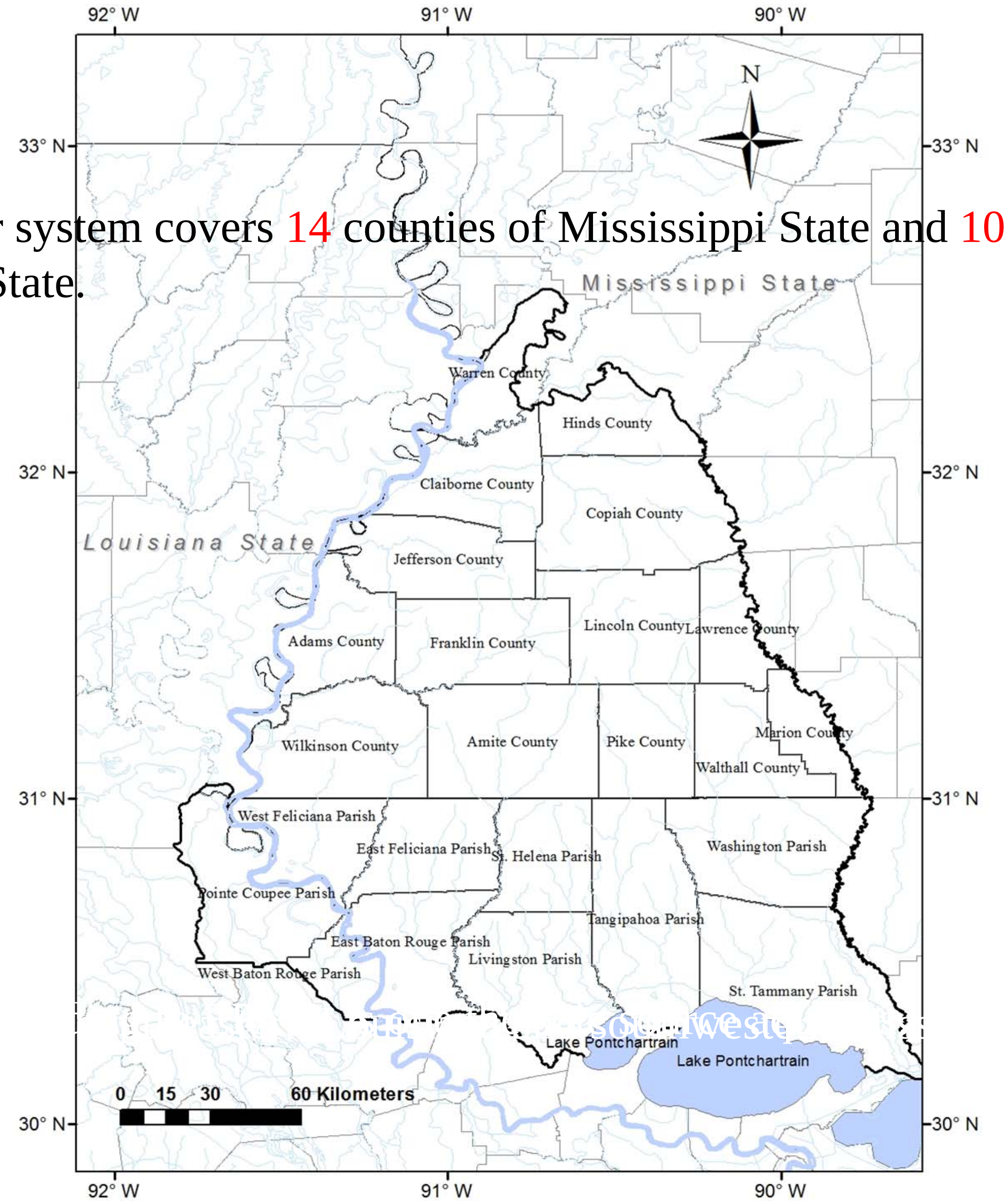
Southern Hills Aquifer System



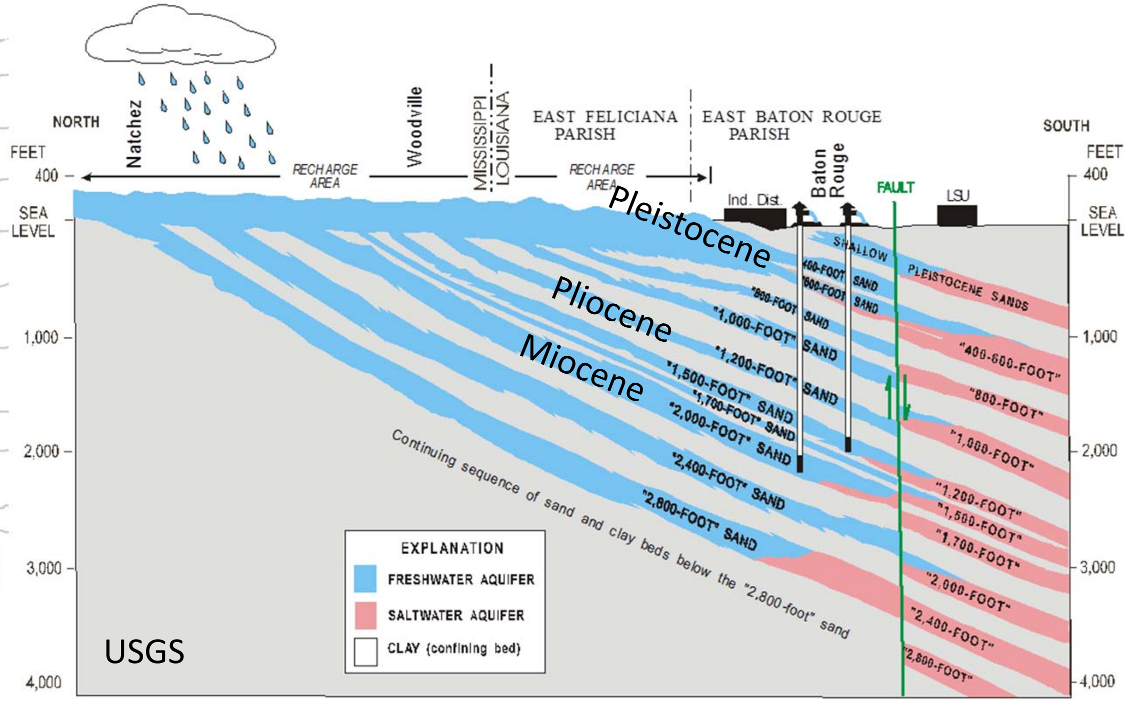
- Located in southeastern Louisiana and southwestern Mississippi
- Sole source aquifer

Southern Hills Aquifer System

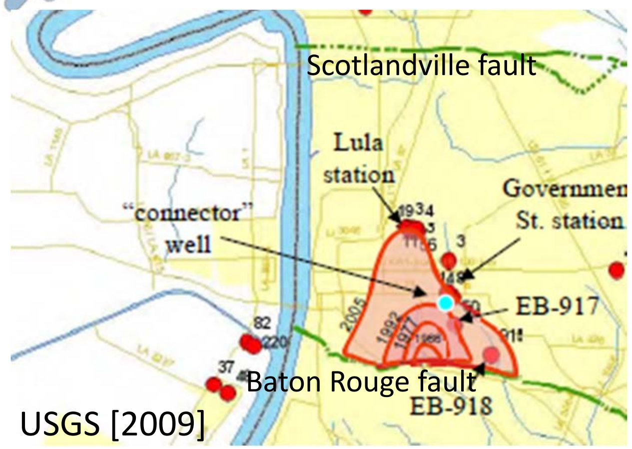
The aquifer system covers 14 counties of Mississippi State and 10 parishes of Louisiana State.



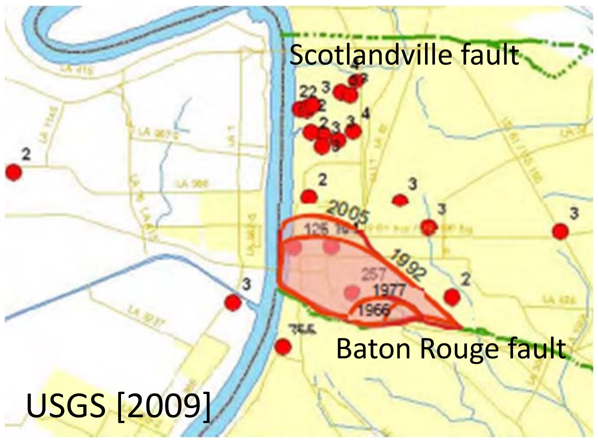
Motivation: Baton Rouge Salt Water Intrusion



USGS 2009: Municipal and Industrial well supply are under salinization threat



Brackish water plume "1500-foot" Sand



Brackish water plume "2000-foot" Sand

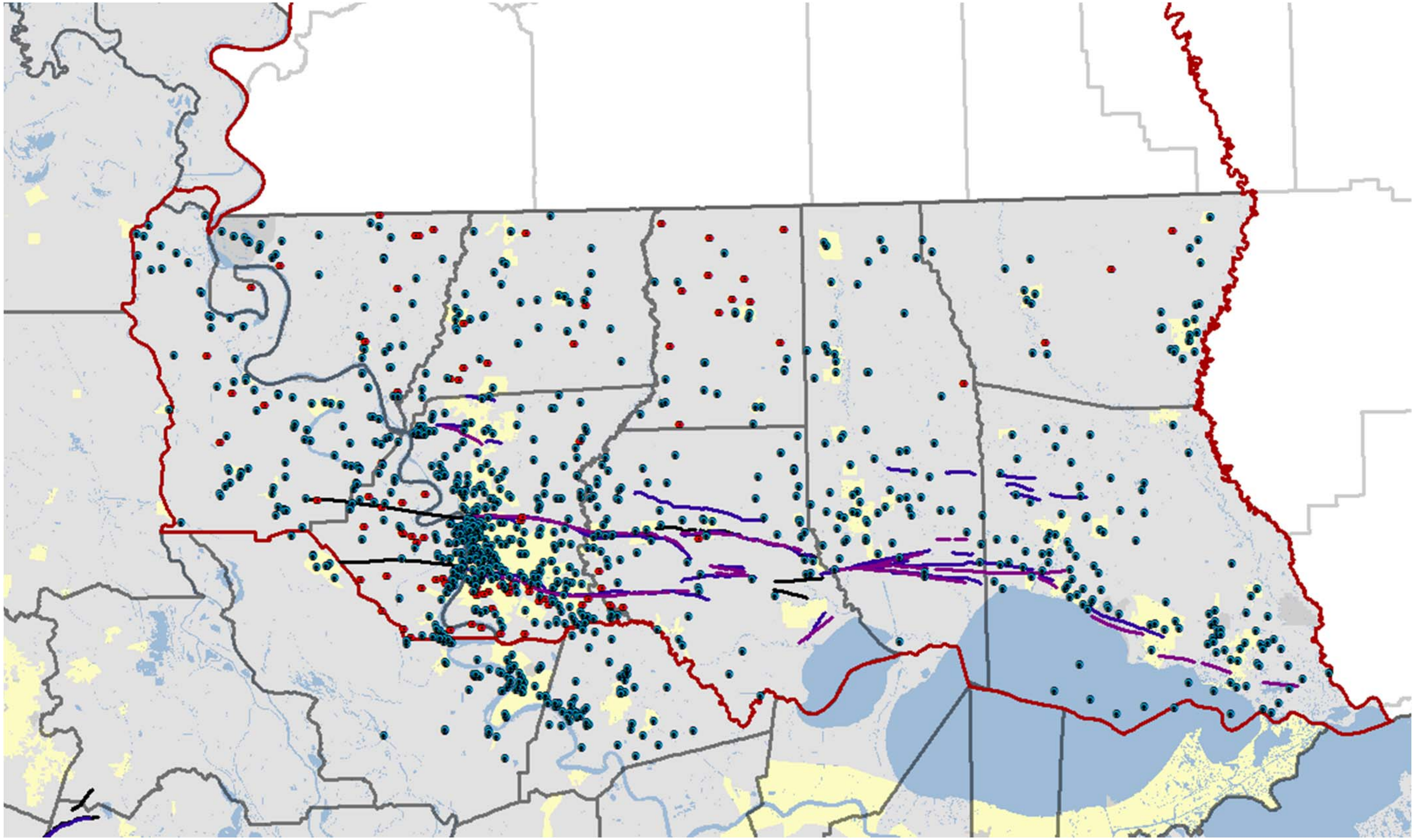
Saltwater Intrusion Evidence from Recent Studies

- Municipal and industrial water wells are under salinization threat (USGS, 2009)
- High salinity south and low salinity north (Wendeborn and Hanor, 2008)
- Lateral migration of saline waters across the Baton Rouge fault (Anderson, 2012).
- Complex geological architecture (Wendeborn and Hanor, 2008)
- Morphologically complex fluvial sand units with highly variable erosional unconformities (Chamberlain, 2012)

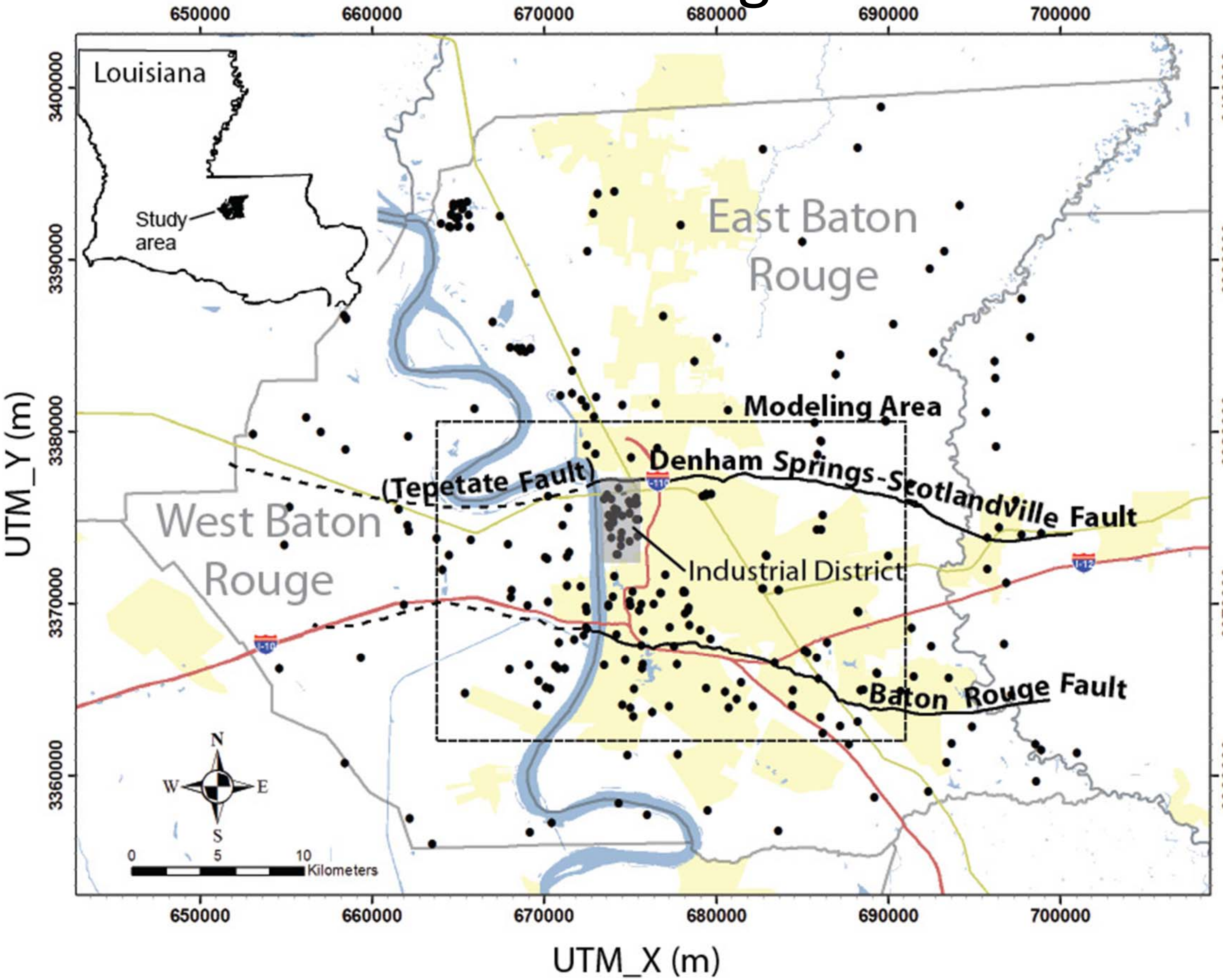
Outline

1. Methodology of geological architecture characterization
2. Fault architecture
3. Aquifer architecture
4. Quantify geological structure parameters of aquifer
5. Geological architecture for groundwater flow modeling
6. Groundwater flow modeling

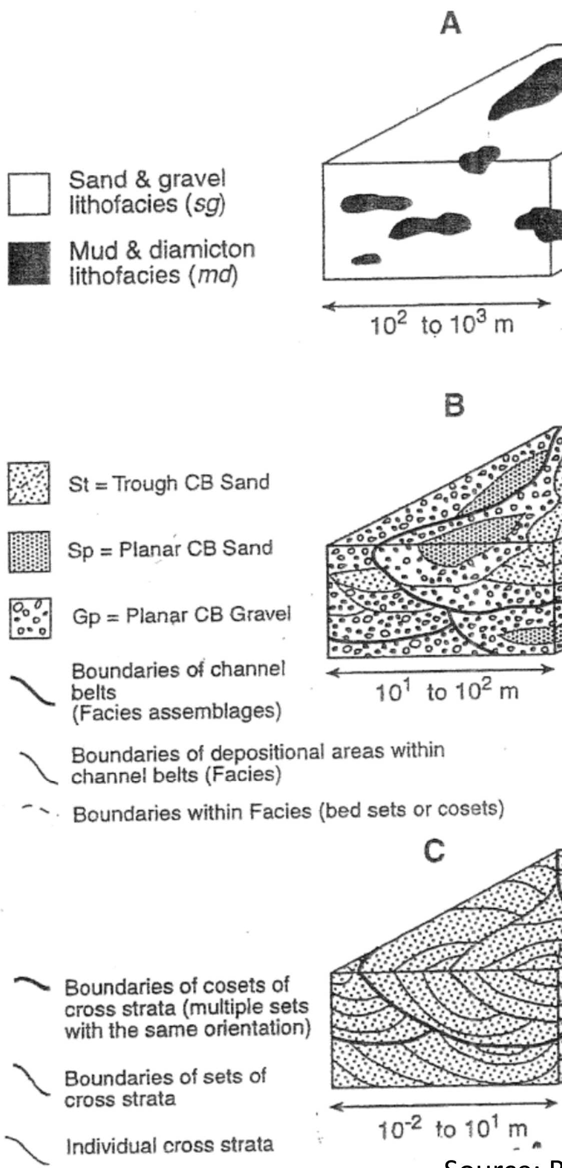
Southeastern Louisiana
200 km x 85 km
1256 well log location and several geologic faults

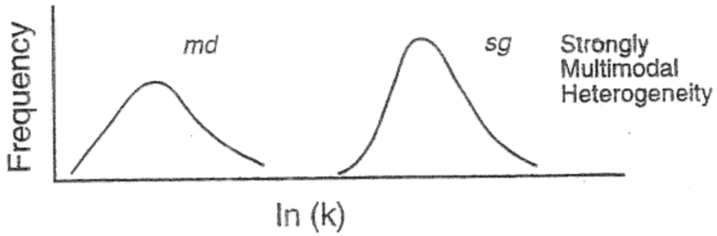


Baton Rouge Area (27 km x 19 km)
288 well logs

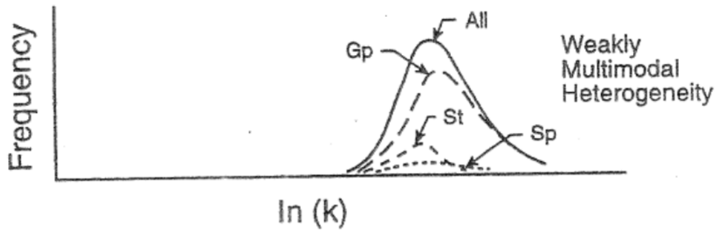


Hierarchical Scales of Hydrofacies Characterization

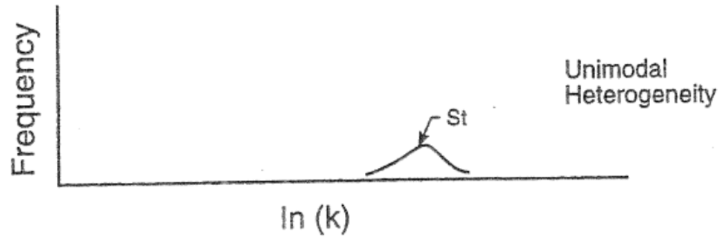




Depositional environment scale



Channel Scale

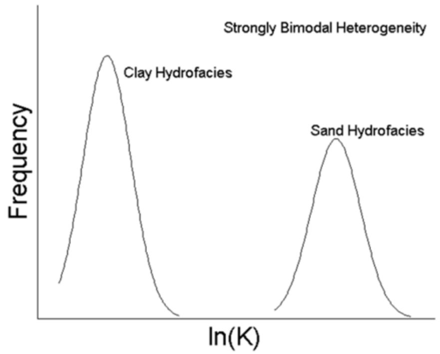


Stratigraphic features scale

Source: Rubin, 2003, Applied Stochastic Hydrogeology

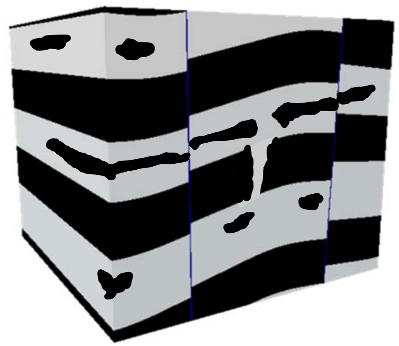
Advantages of the Depositional Environment Scale of Characterization

Depositional environment scale for the analysis of binary siliciclastic aquifer-fault system provides several informative and useful outcomes:



<u>(1) Binary fault architecture depicts:</u>
- Hydraulic continuity across faults
- Leaky areas for saltwater intrusion across faults

<u>(2) Binary aquifer architecture depicts:</u>
- Spatial extent of major aquifer units
- Interconnections of major aquifer units
- Preferential flow paths in each aquifer unit



<u>(3) Quantify geological structure parameters through postprocessing techniques:</u>
- Depositional dip of each aquifer unit
- Fault throw offset of each aquifer unit
- Volumetric spatial proportion of each aquifer unit

<u>(4) Geological architecture for groundwater flow modeling</u>

Scheme of Hydrofacies Characterization

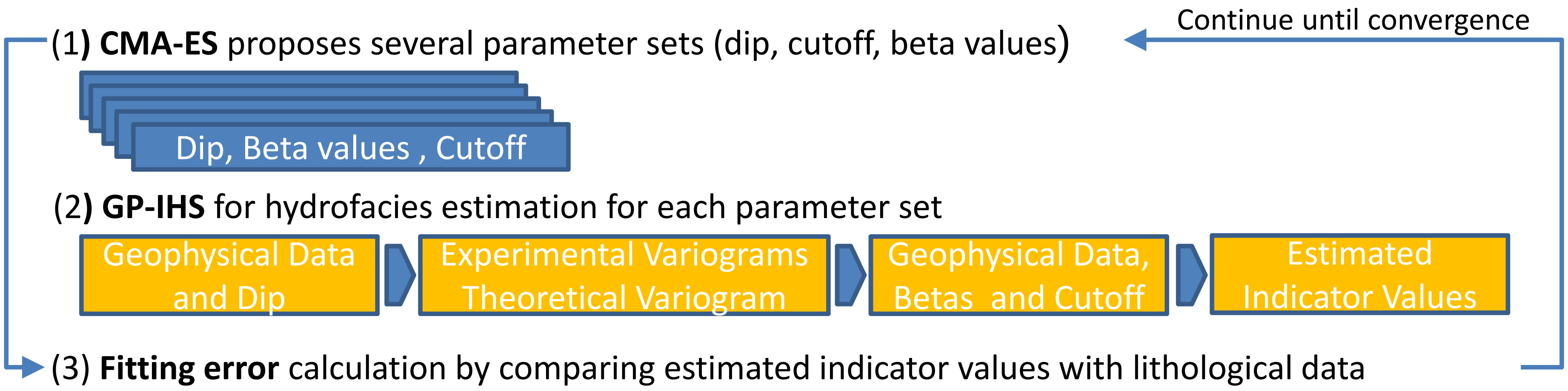
Method: Generalized Parameterization Indicator Hydrostratigraphy (**GP-IHS**) for hydrofacies estimation with Covariance Matrix Adaptation-Evolution Strategy (**CMA-ES**) for inverse modeling using **Geophysical and Lithological Data**

Hydrofacies estimation: GP-IHS using **geophysical logs** having two indicators (0 Clay and 1 Sand)

Inverse modeling: CMA-ES using **drillers' logs** for calibration having two indicators (0 Clay and 1 Sand)

Inverse model parameters: formation dip (1 unknown) , beta values for zonation-kriging weighting (48 unknowns), and sand-clay cutoff probability (1 unknown)

Steps of the inversion scheme:



Inverse modeling outcome: maximum-likelihood parameter set **(dip, cutoff, and beta values)**, which is used to generate any 2D cross-section or 3D diagram

Geophysical and Lithological Data

<u>Geophysical data:</u>

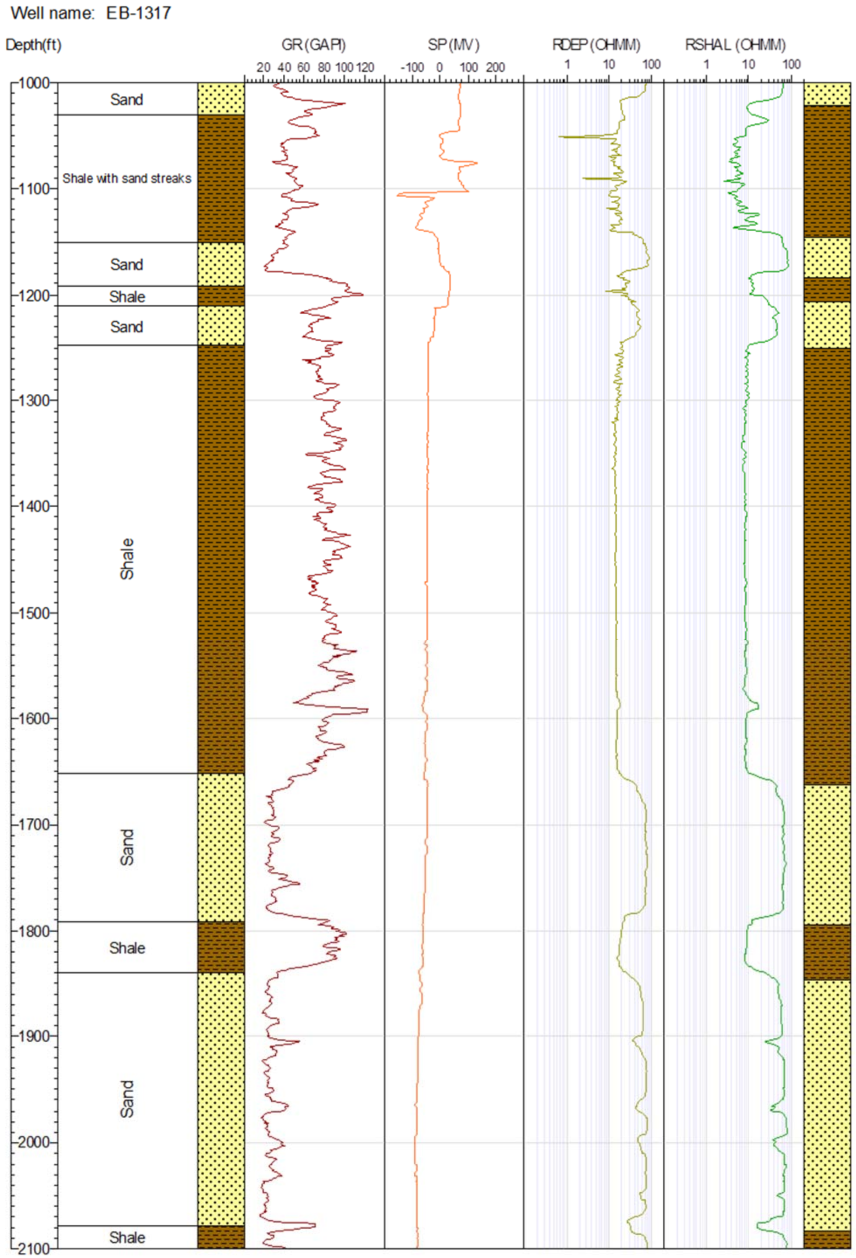
- 1256 geophysical logs (SN, LN, SP, and gamma ray) (288 logs in Baton Rouge area)
- Shale baseline 20 Ω-m
- Vertical discretization is every 1 foot

$$I(\mathbf{x},v)=\begin{cases}1? \quad v\in \text{Sand}?? \quad v(\mathbf{x})> \text{ lay Baseline}\\ 0? \quad v\in \text{ lay,}?????\ \mathbf{x})<?\text{Clay Baseline}\end{cases}$$

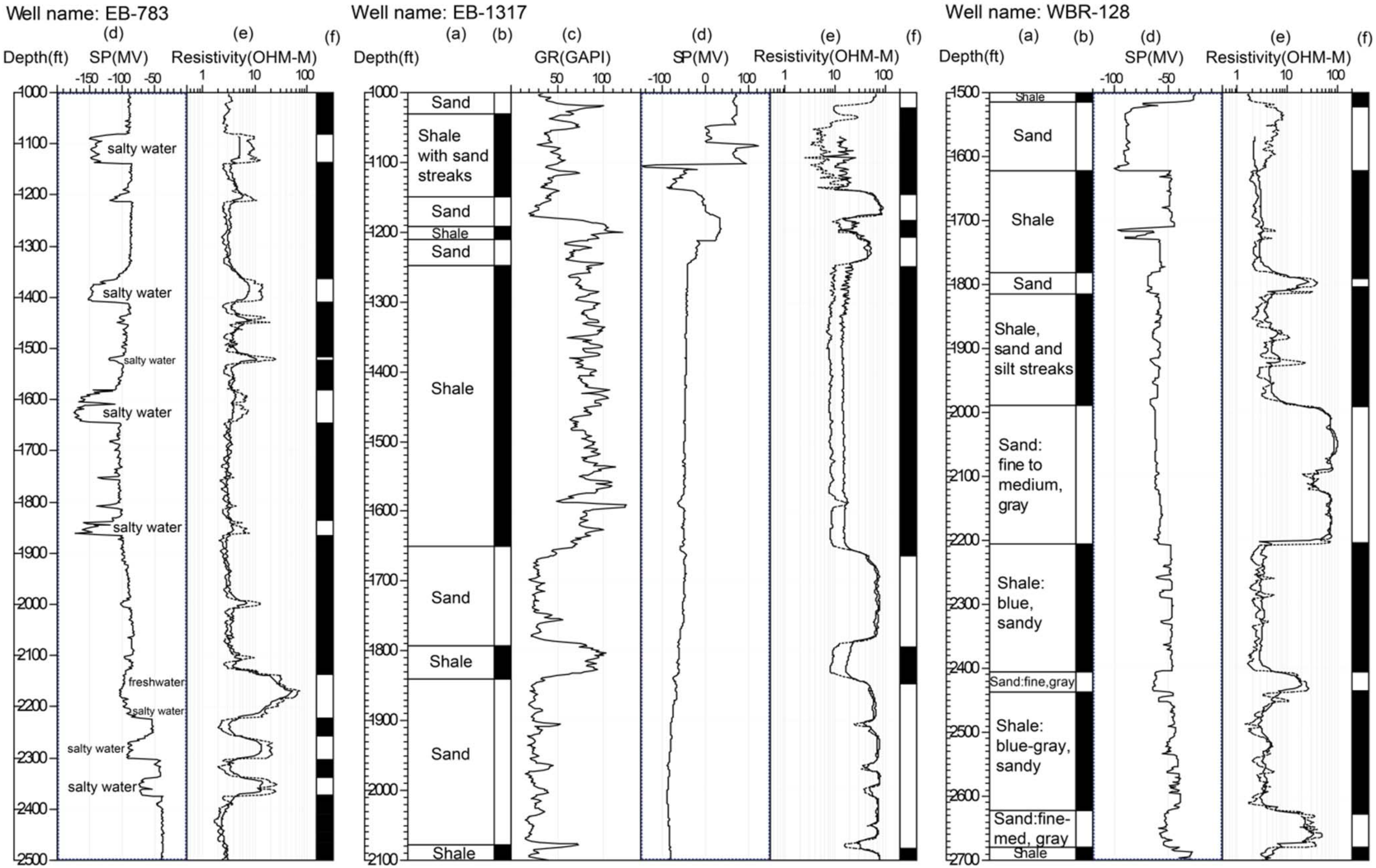
<u>Lithological data</u>

- 97 drillers' logs for calibration in the BR area
- Two indicators: 1 Sand 0 Clay/Undetermined

Sand (1)	Clay (0)	Undetermined(0)
Sand: fine, fine, packed, very fine, good, medium, coarse, loose, yellow, hard packed, packed, pay, sandstone, gray, lightly gray, tight , with shell fragments, with wood, gray-white, blue-gray, with gravel	Clay: blue, hard, soft, graygreen, brown, dark brown highly organic, tan, red-brown, green, with sand strings Shale: heavy, sandy, hard, red, brown , sticky, yellow, with mixed gravel, with streaks of sand, with some sand breaks	Clay and sand, shale and sand, streaks of sand and shale, shalely sand, , poor sand and streaks of shale, sand and hard sandy shale



Electrical Log Interpretation



GP-IHS for Hydrofacies Estimation

Combination of Indicator Kriging and Zonation to provide non-smooth estimate

Zonation Estimate $$v^*_{IZ}\left(\mathbf{x}_o \mid \mathbf{x}_k\right) = \{I_{IZ}\left(\mathbf{x}_k\right) \mid \mathbf{x}_o \in D_k\}$$

Indicator Kriging Estimate $$v^*_{IK}\left(\mathbf{x}_0 \mid \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\right) = \sum_{i=1}^{N} \lambda_i I_{IK}\left(\mathbf{x}_i\right)$$

$$v^*_{ZK}\left(\mathbf{x}_o \mid \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\right) = I_Z\left(\mathbf{x}_k\right) + \sum_{i=1}^{N} \lambda_i \left[I_{IK}\left(x_i\right) - I_{IK}\left(x_k\right) \right] \beta_i ????$$

$I_Z\left(\mathbf{x}_k\right) \quad k \in N$

$I_{IK}\left(x_i\right) \quad i \in N$

N Number of data points

λ_i Kriging weighting coefficient

β_i Data weighting coefficinet

Such that:

$\beta_i = 0$ Indicator zonation estimate (IZ)

$0 \le \beta_i \le 1$ Generalized parameterization estimate (GP)

$\beta_i = 1$ Indicator Kriging estimate (IK)

Inverse Modeling Formulation

Unknown model parameters

- Dip $0.1\ \% < \emptyset < 1\%$
- Sand-clay cutoff $0.3 < \propto < 0.7$
- Weighting coefficients 0 < $\boldsymbol{\beta} < 1$
- Selectivity analysis for weighting coefficients (48 unknowns out of 288 logs)

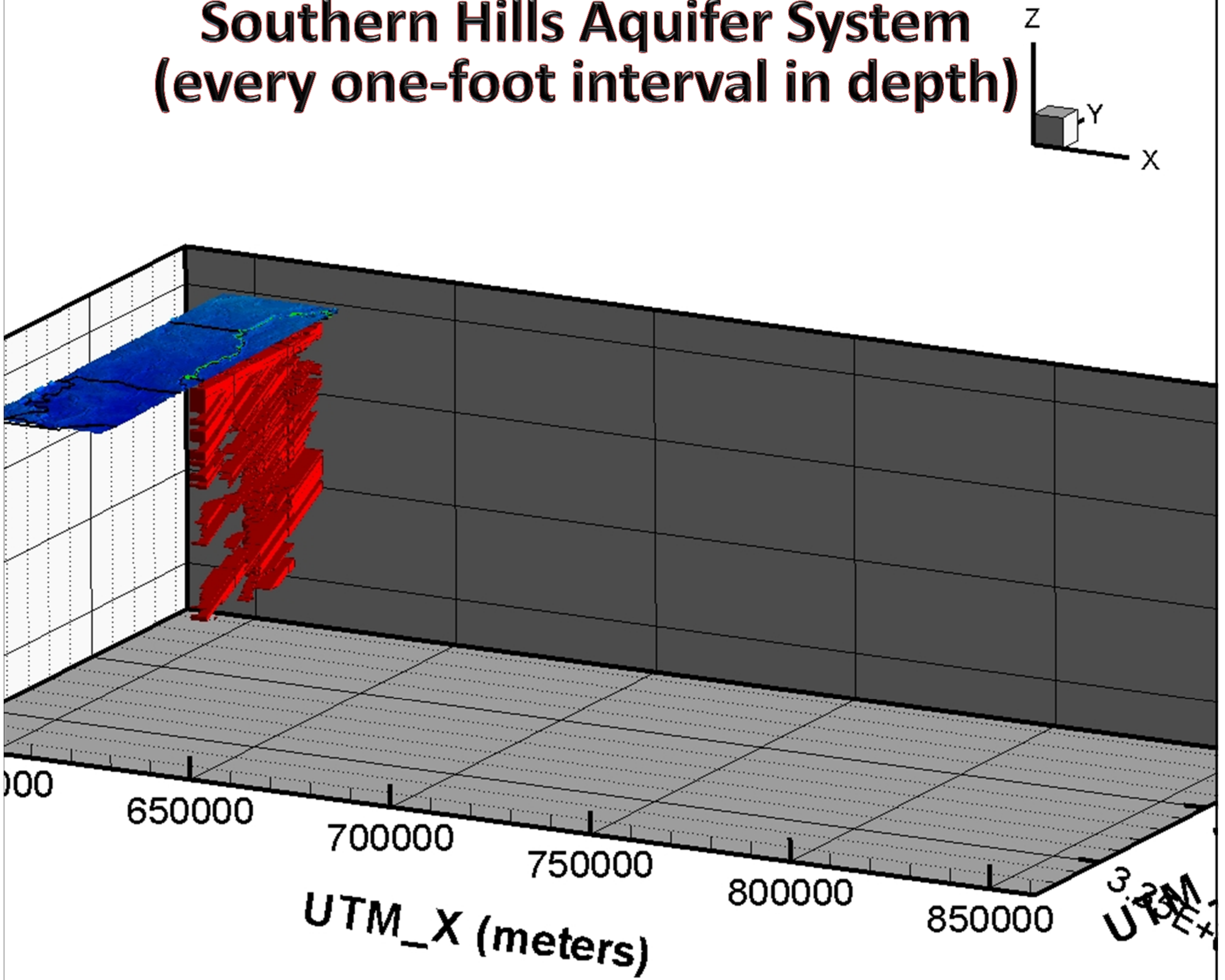
Minimize mean squared error

$$\min_{\mathbf{z}\in\Omega_{\mathbf{z}}} \quad \frac{1}{2}\left\{\frac{1}{M_{sand}}\sum_{i=1}^{M_{sand}}\left[I_{sand}^{i,est}\left(\mathbf{x}\right)-I_{sand}^{i,obs}\left(\mathbf{x}\right)\right]^{2}+\frac{1}{M_{clay}}\sum_{i=1}^{M_{clay}}?\left[I_{clay}^{i,est}\left(\mathbf{x}\right)-I_{clay}^{i,obs}\left(\mathbf{x}\right)\right]^{2}\ ??\right\}$$

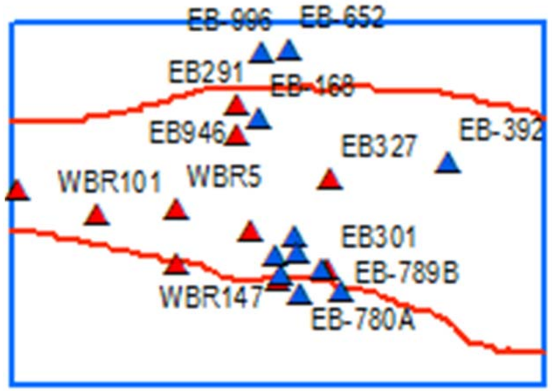
Inverse modeling algorithm

- CMA-ES to find the maximum likelihood estimate
- Maximum likelihood estimate and covariance matrix to generate realizations for model parameters sensitivity

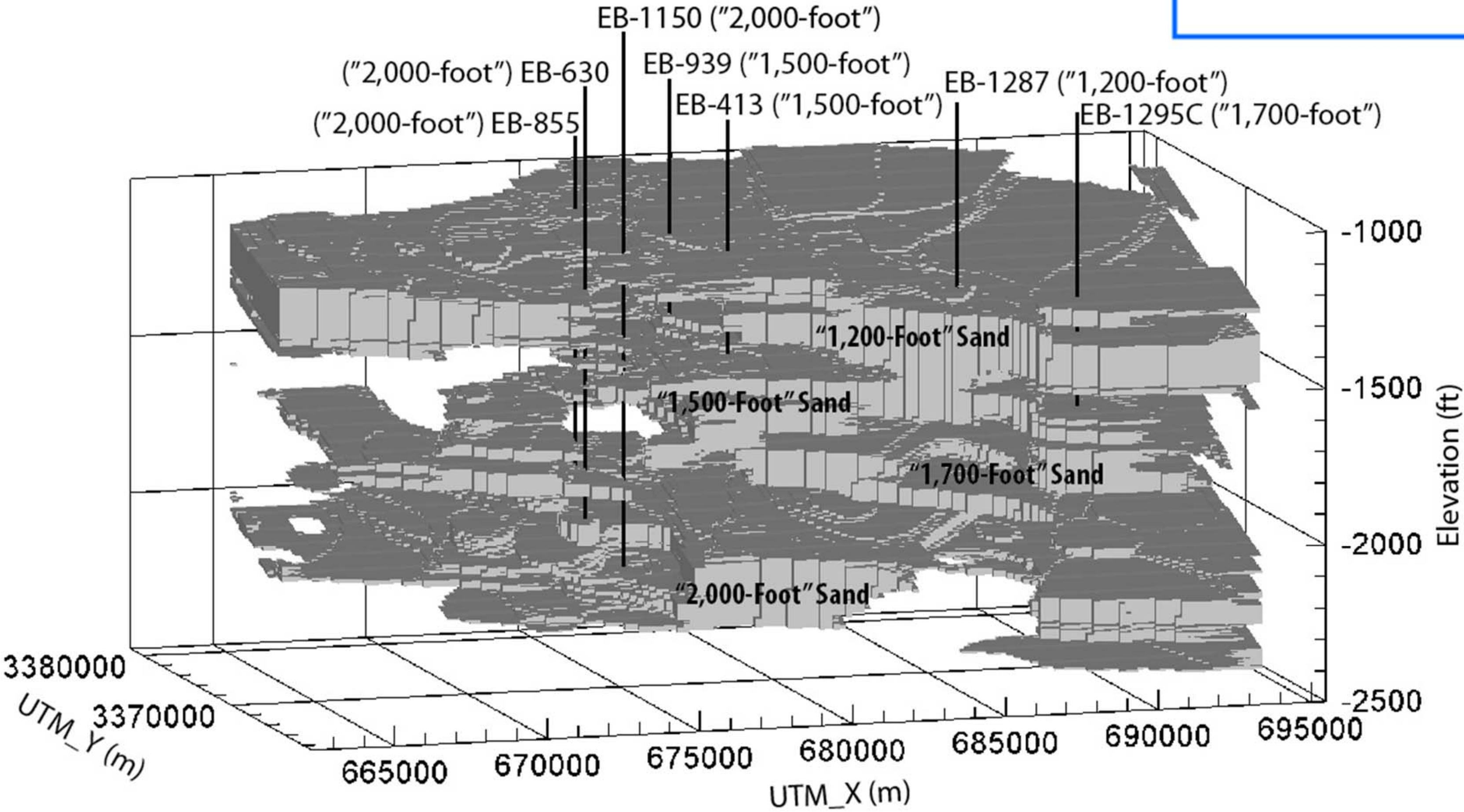
Southern Hills Aquifer System (every one-foot interval in depth)



Binary Aquifer Architecture for Baton Rouge Aquifer System (1500 layers)



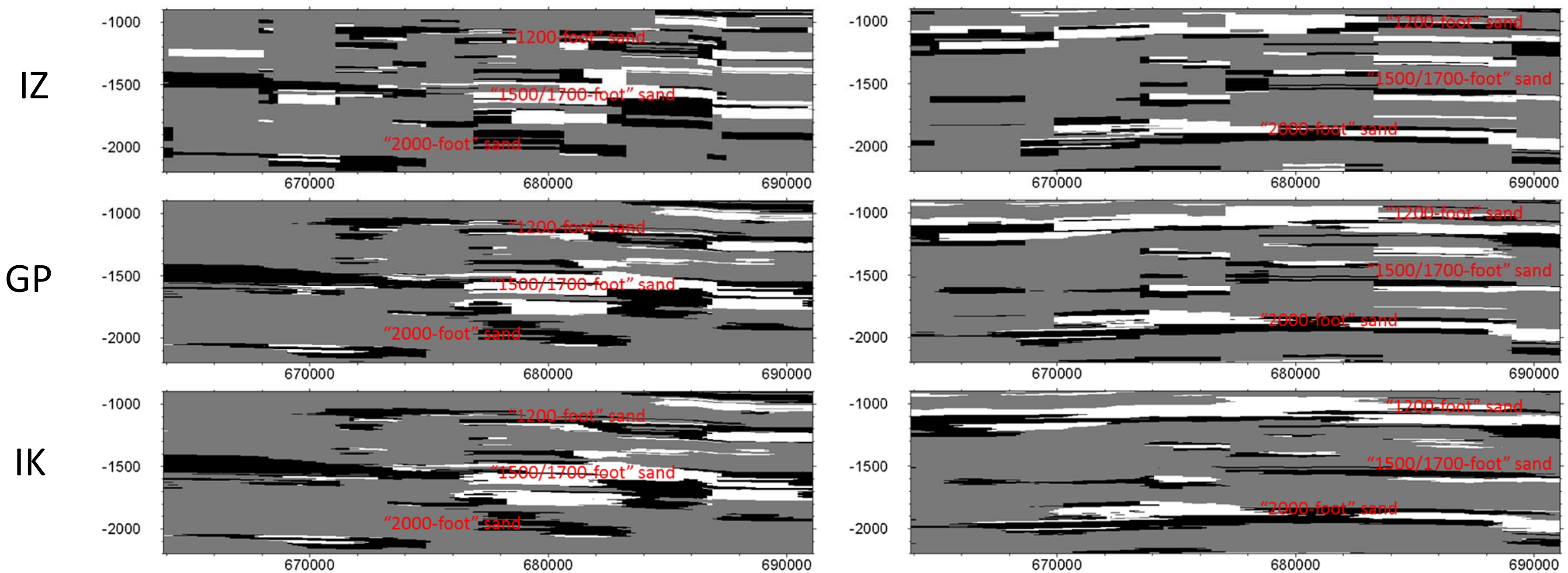
- Spatial extent of major aquifer units
- Interconnections of major aquifer units
- Flow paths in each aquifer unit



Inverse Modeling Results

Method	Nugget	Sill	Range [m]	Dip [%]	Cutoff [-]	Sand Ratio	Sand Error[%]	Clay Error[%]	Total Error[%]
IZ	-	-	-	0.498	-	0.340	13.02	12.79	12.91
GP	0.083	0.139	8400	0.504	0.404	0.347	11.96	12.90	12.43
IK	0.084	0.139	8600	0.500	0.404	0.347	12.04	12.96	12.50

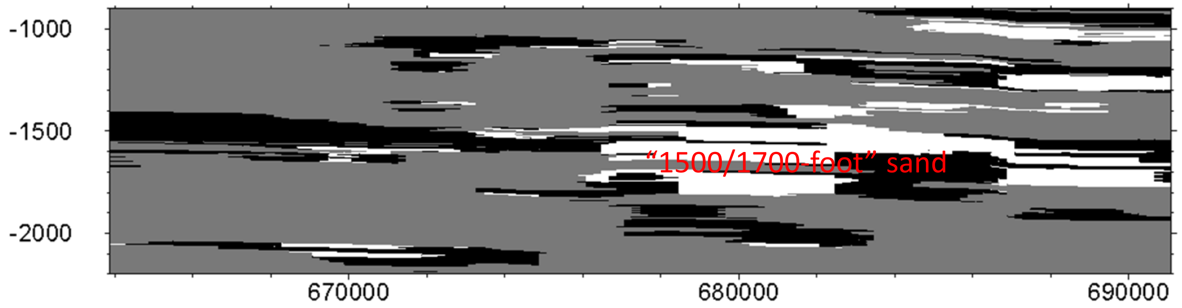
Reliability of the solution under different estimation methods

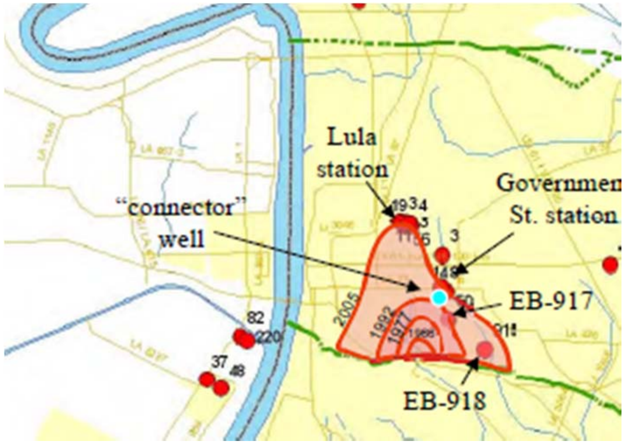


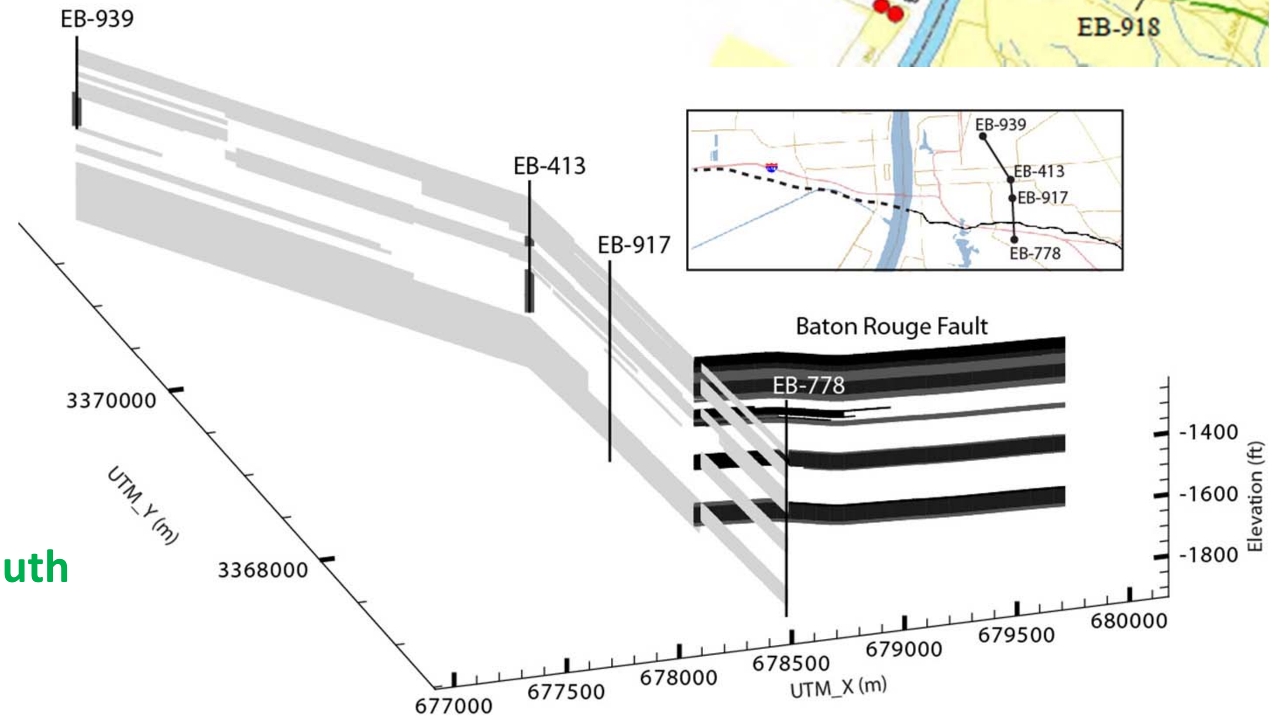
Baton Rouge Fault

Denham Springs-Scotlandville Fault

Leaky Areas of Baton Rouge Fault
“1,500-foot” Sand

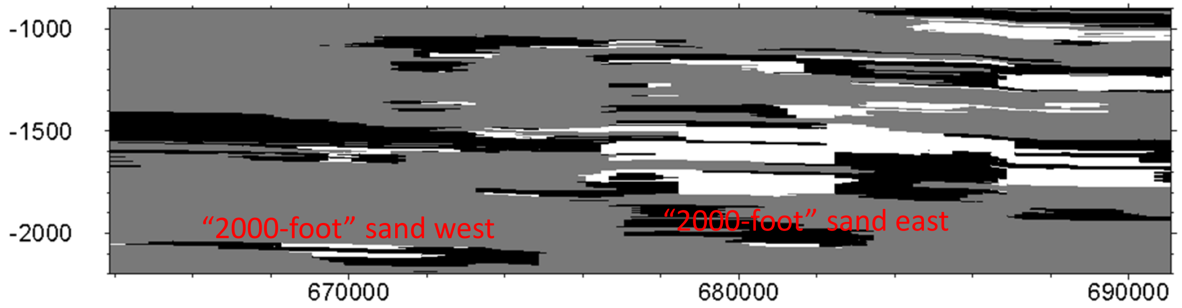






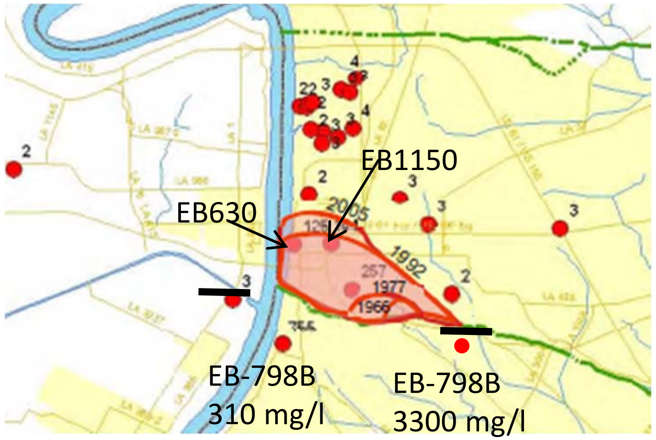
Connections from the south to the pumping wells

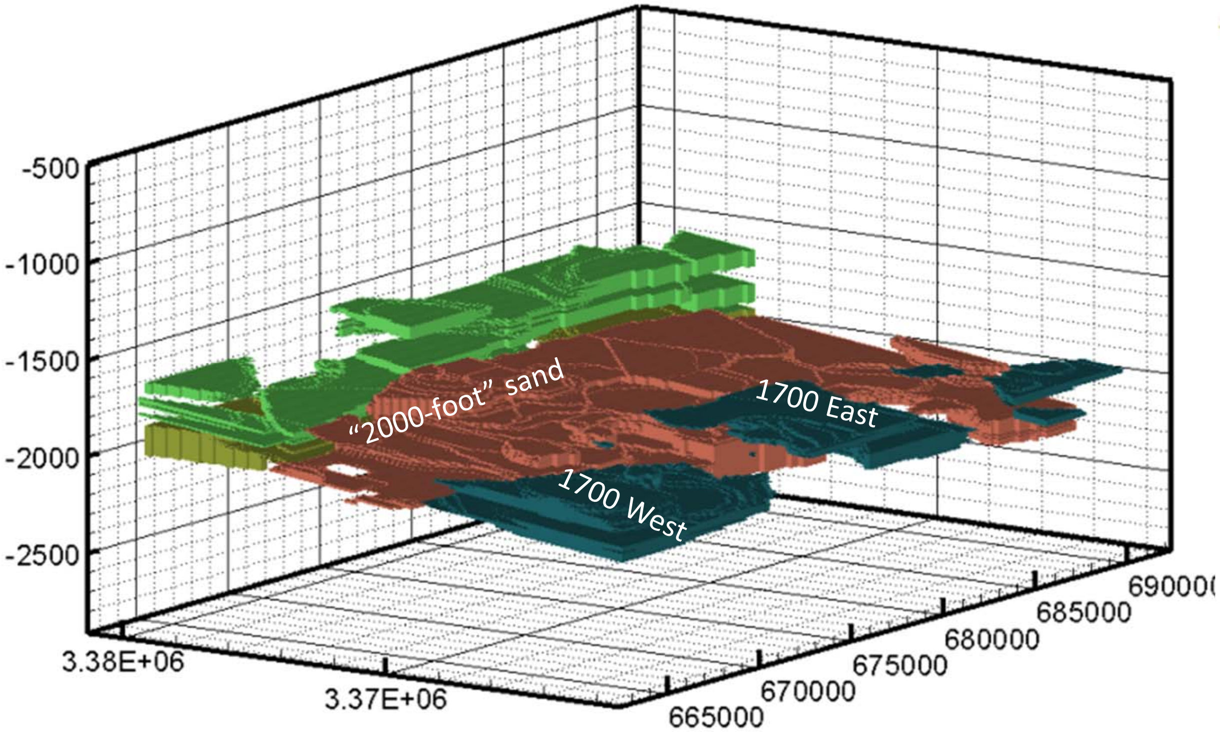
Leaky Areas of Baton Rouge Fault
"2,000-foot" Sand



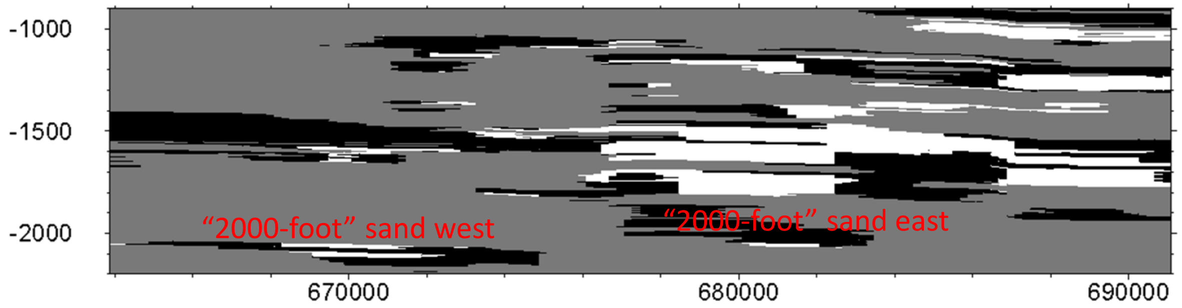
EB-798B 310 mg/l (1998)

EB-798B 3300 mg/l (1998)





Leaky Areas of Baton Rouge Fault
"2,000-foot" Sand



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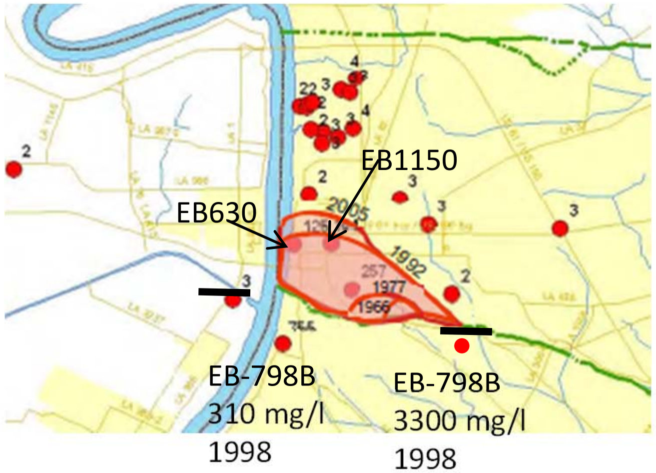
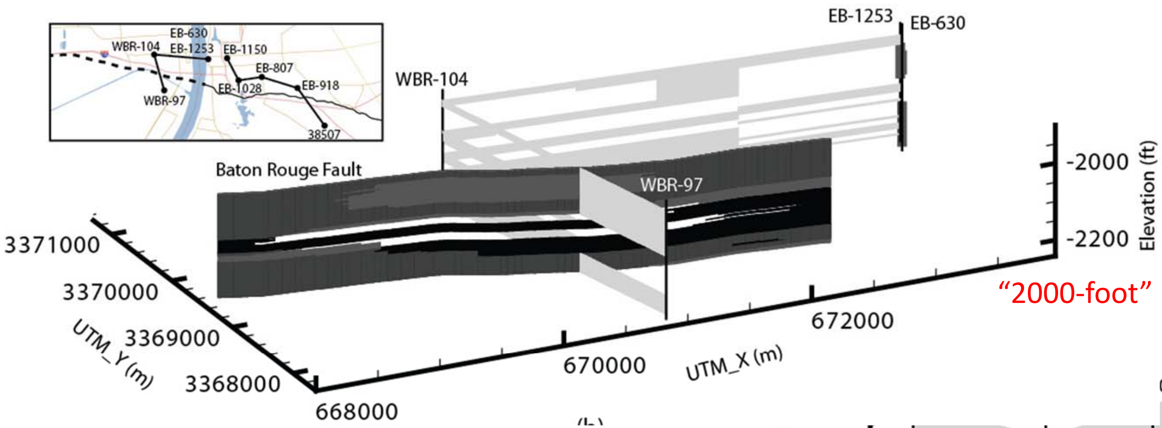
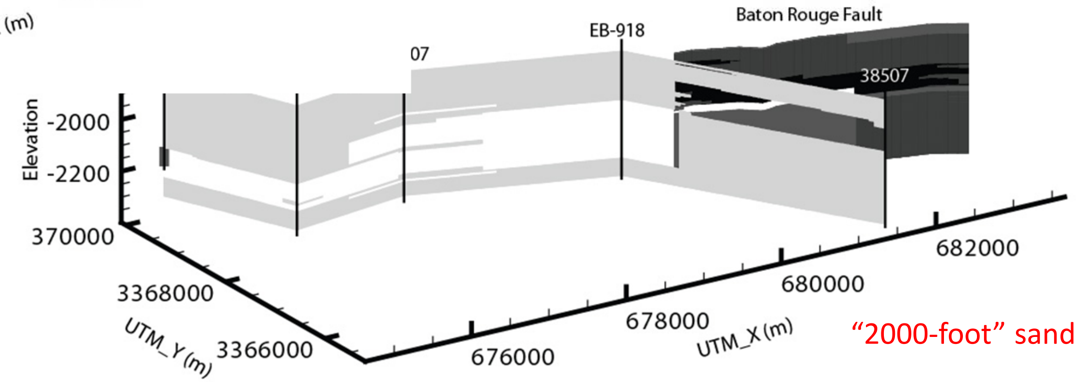




"2000-foot" sand east

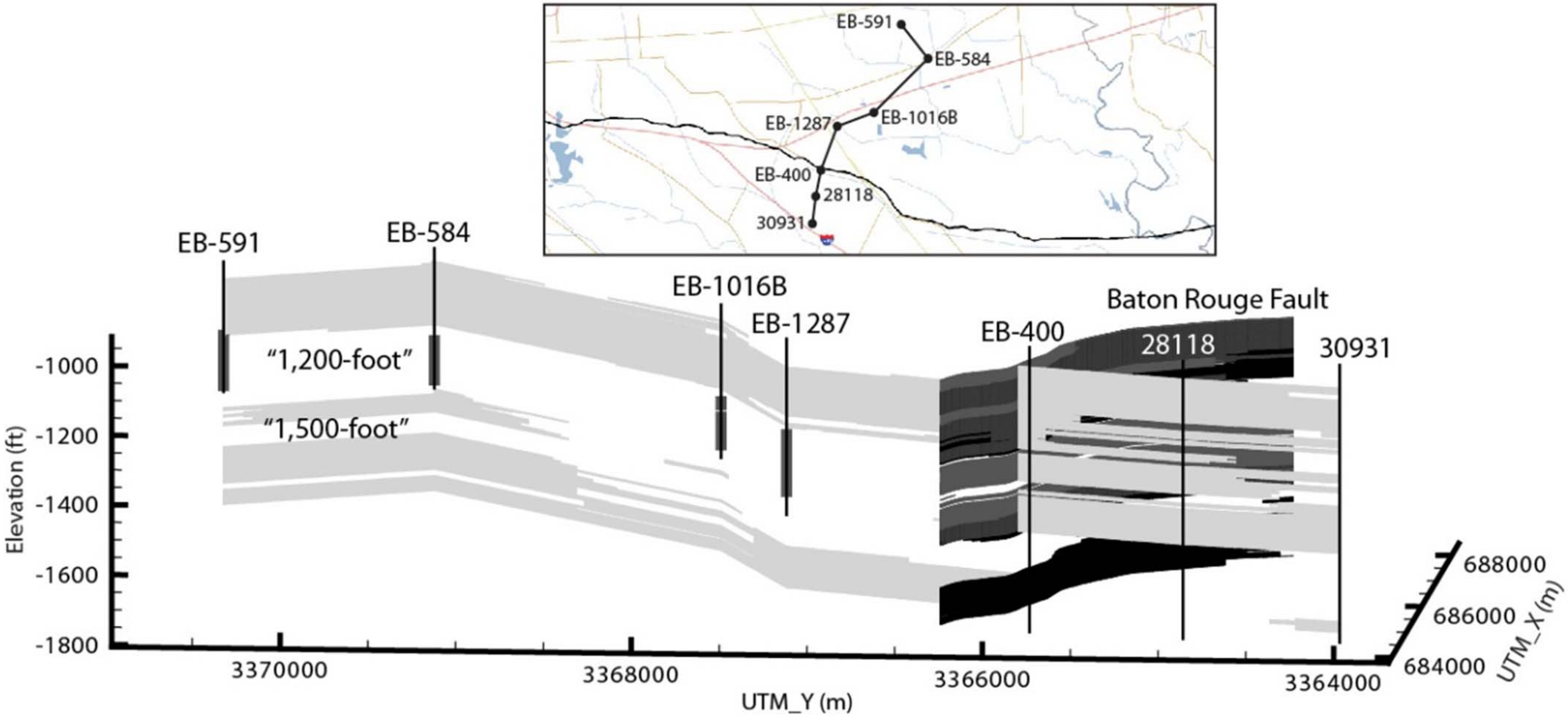


"2000-foot" sand west

Very narrow leaky area allows major leakage from the south to the pumping wells at north

Binary Aquifer Architecture

- Spatial extent of major aquifer units
- Interconnections of major aquifer units
- Flow paths within each aquifer unit

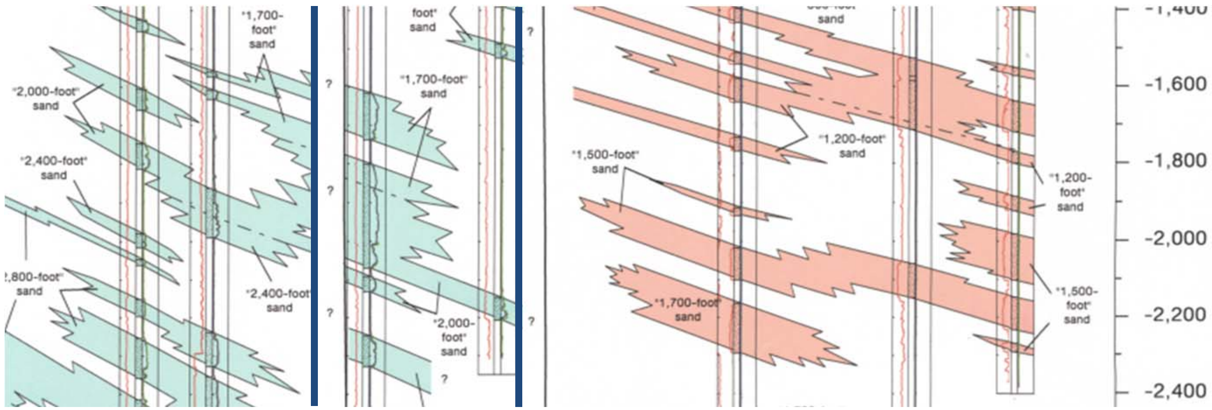


Binary Aquifer Architecture

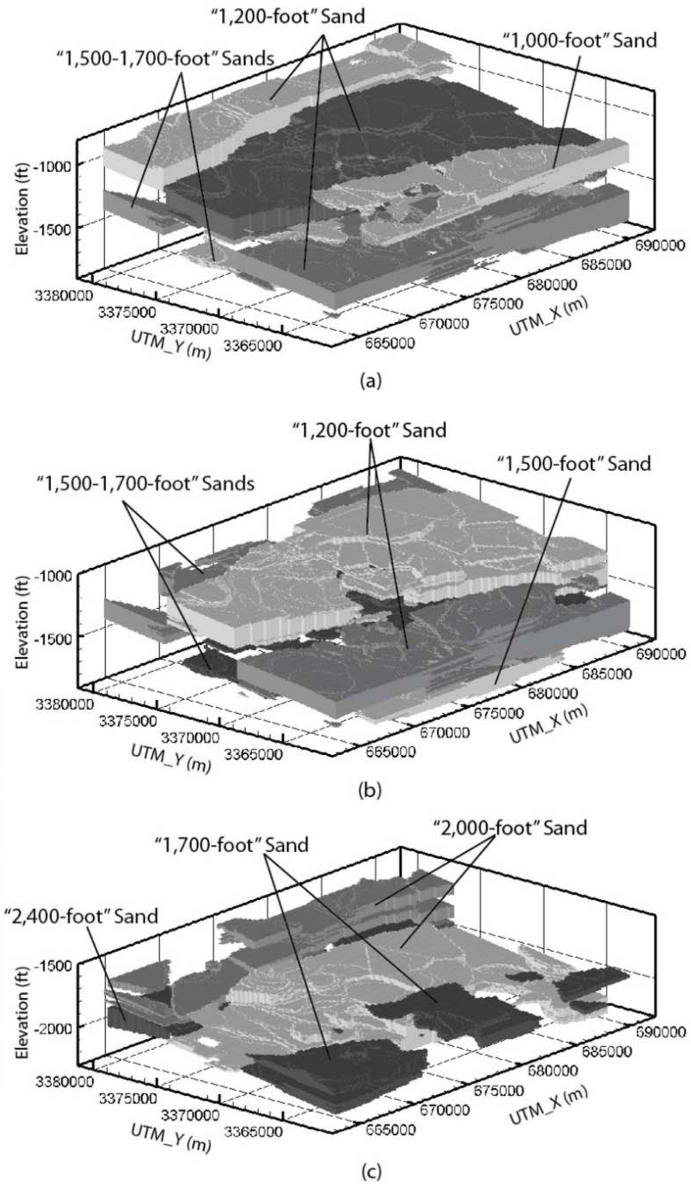
- Spatial extent of major aquifer units
- Interconnections of major aquifer units
- Flow paths in each aquifer unit

"1,200-foot" sand and "1,500-1,700-foot" sands are connected
A distinct confining layer to separate the "2,000-foot" sand

DSS Fault **BR Fault**



Griffith [2003]



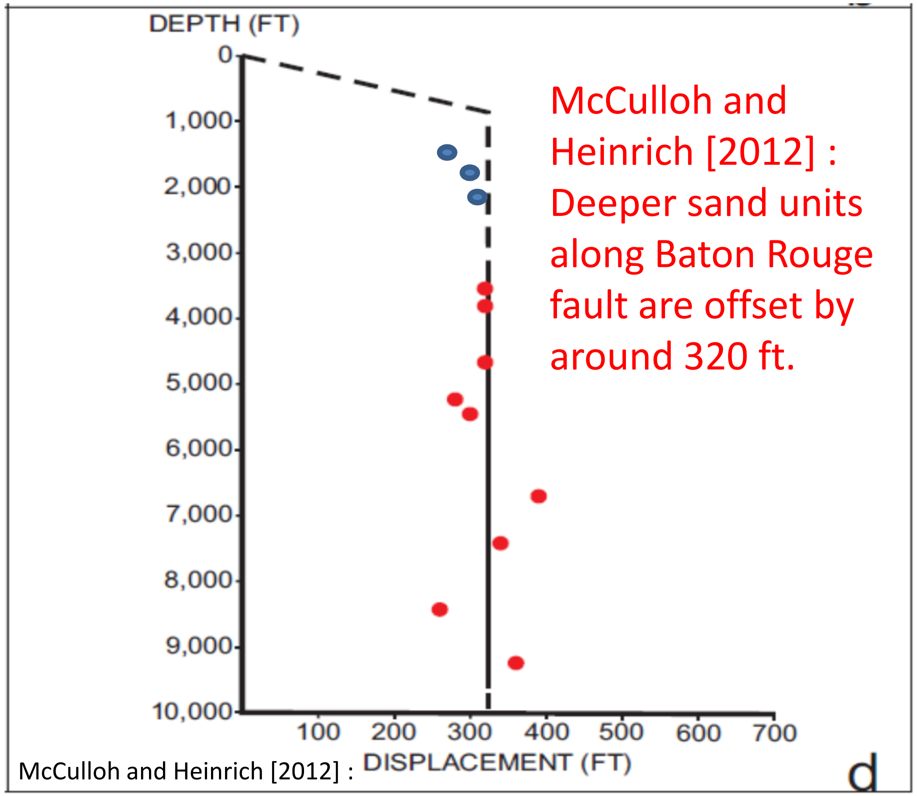
Geological Parameters Quantification: Sand Units Dip

	Technique	Regression Analysis			Clustering Analysis		
Parameter	Domain	South	Middle	North	South	Middle	North
Dip “1200-foot” sand [%]		0.49±0.05	0.56±0.01	0.51±0.05	-	0. 57±0.11	-
Dip “1500/1700-foot” sand [%]		0.49±0.03	0.55±0.05	0.54±0.05	-	0. 59±0.11	-
Dip “2000-foot” sand [%]		0.71±0.38	0.67±0.11	0.60±0.25	-	0. 61±0.12	-

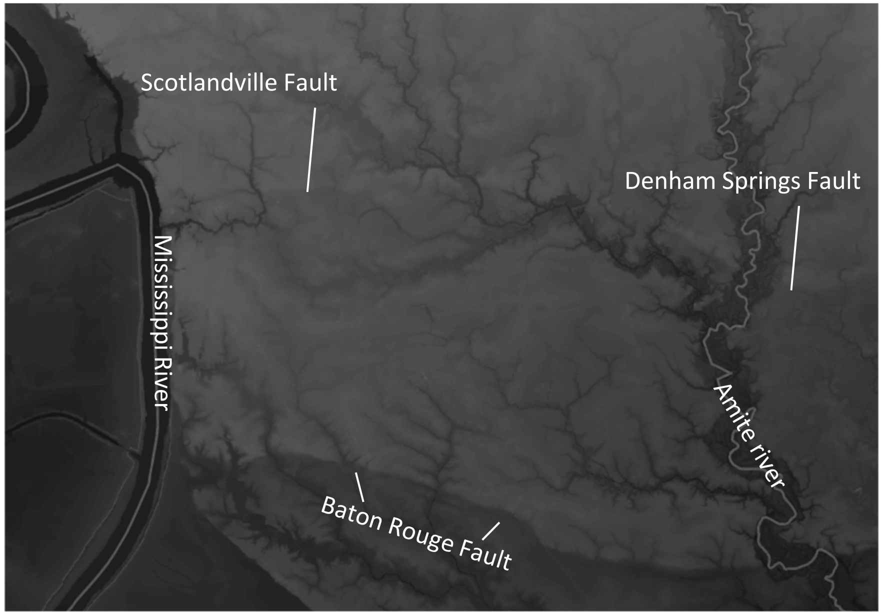
- Average dip calculated from all unit is 0.58%±0.15
- Dip estimated from [Griffith, 2003]= 0.52%±0.1
- Dip estimated from inverse problem = 0.50%
- Miocene formation (older) slightly more dipping than the Pliocene formations (newer)

Geological Parameters Quantification: Fault Throw Offset

		Baton Rouge Fault		Denham Springs-Scotlandville fault	
Parameter	Analysis Technique	Regression	Clustering	Regression	Clustering
Offset “1200-foot” sand [ft.]		241±62	262	114±54	120
Offset “1500/1700-foot” sand [ft.]		290±59	311	173±50	179
Offset “2000-foot” sand [ft.]		307±38	337	187±57	239



McCulloh and Heinrich [2012] :



Surface expressions from DEM imply that vertical displacement in Denham-Springs Scotlandville fault is less than from Baton Rouge fault

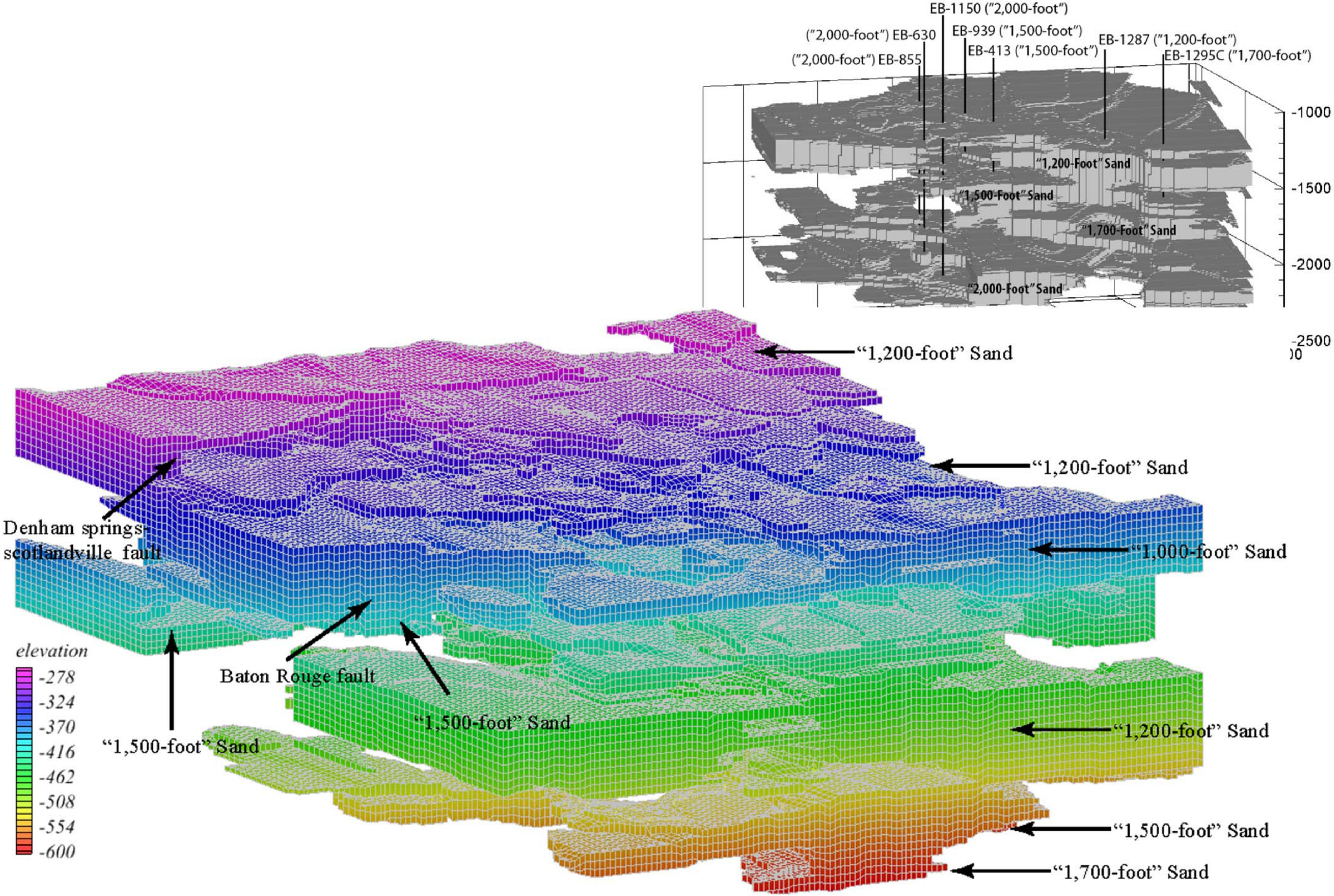
Geological Parameters Quantification: Sand Proportion

	Technique	Regression Analysis			Clustering Analysis		
Sand proportion		South	Middle	North	South	Middle	North
“1200-foot” sand [-]		0.44	0.51	0.64	0.52	0.49	0.64
“1500/1700-foot” sand [-]		0.25	0.27	0.29	0.19	0.24	0.32
“2000-foot” sand [-]		0.19	0.4	0.34	0.23	0.37	0.32
Three aquifers [-]		0.30	0.37	0.39	0.28	0.34	0.40

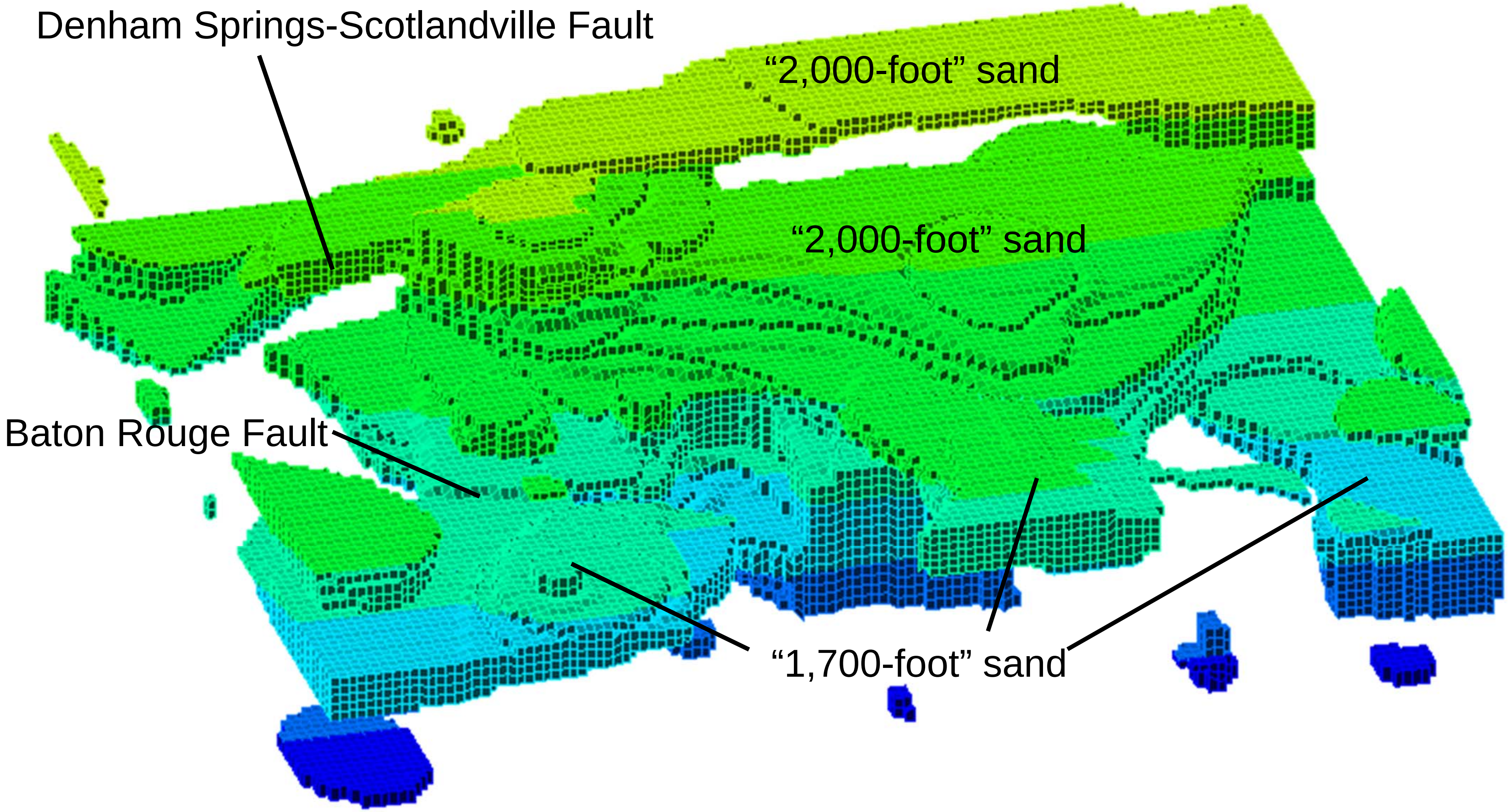
Method	Entire Domain	South Domain	Middle Domain	North Domain
Geophysical Logs	0.34	0.30	0.34	0.35
Physical Logs	0.34	0.32	0.33	0.37
Regression Analysis	0.35±0.05	0.30	0.37	0.39
Clustering Analysis	0.34±0.14	0.28	0.34	0.40
Mean	0.34±0.01	0.3±0.02	0.34±0.02	0.38±0.02

- “1,200-foot’ sand bulky and “1,500-1,700-foot” sand eroded
- 1/3 sand and 2/3 clay for the considered volume
- Less sand at the south for the considered volume

MODFLOW Grid for the “1,200-foot”, “1,500-foot”, and “1,700-foot” Sands (45 Layers)

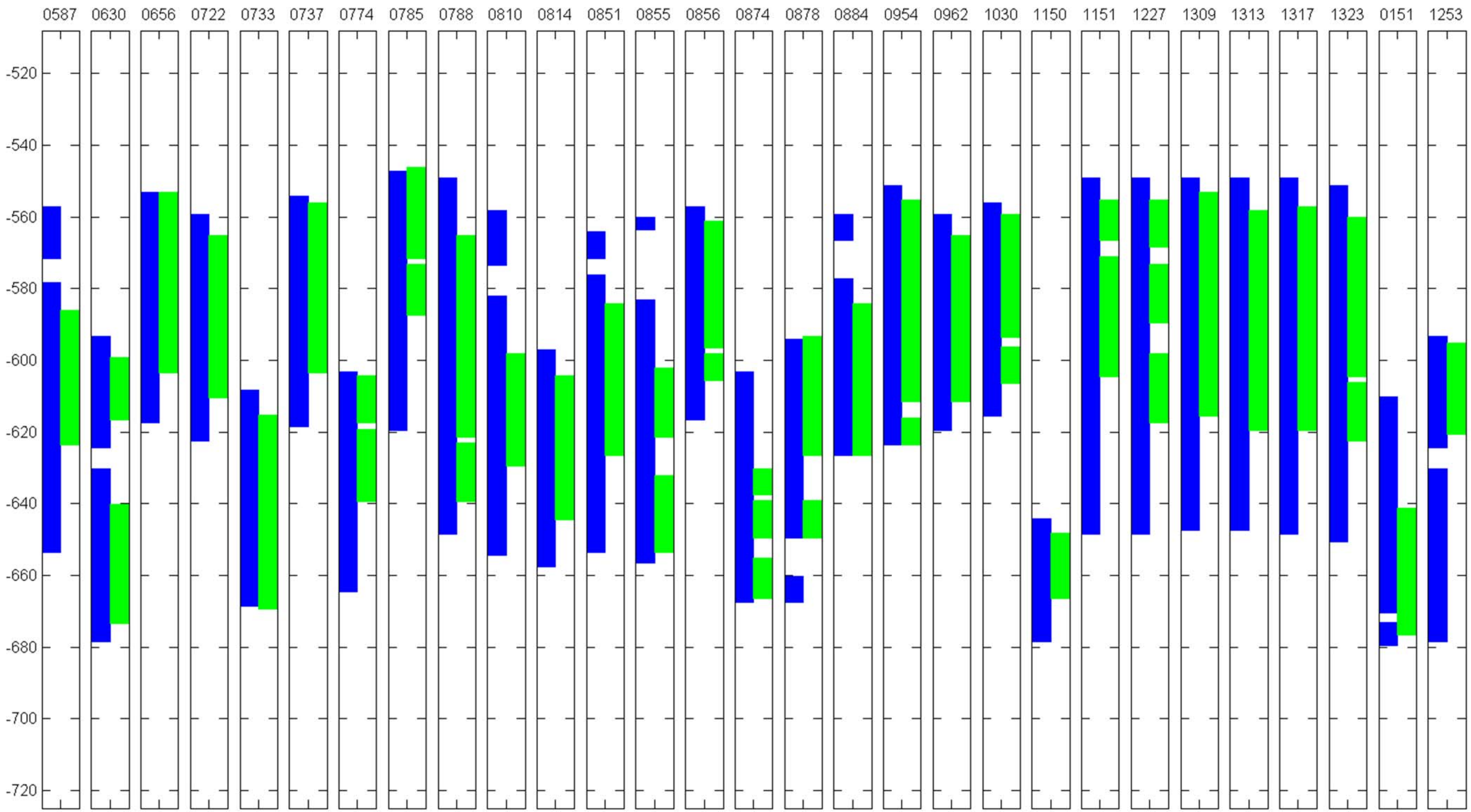


MODFLOW Grid for the “2,000-foot” Sand (28 Layers)



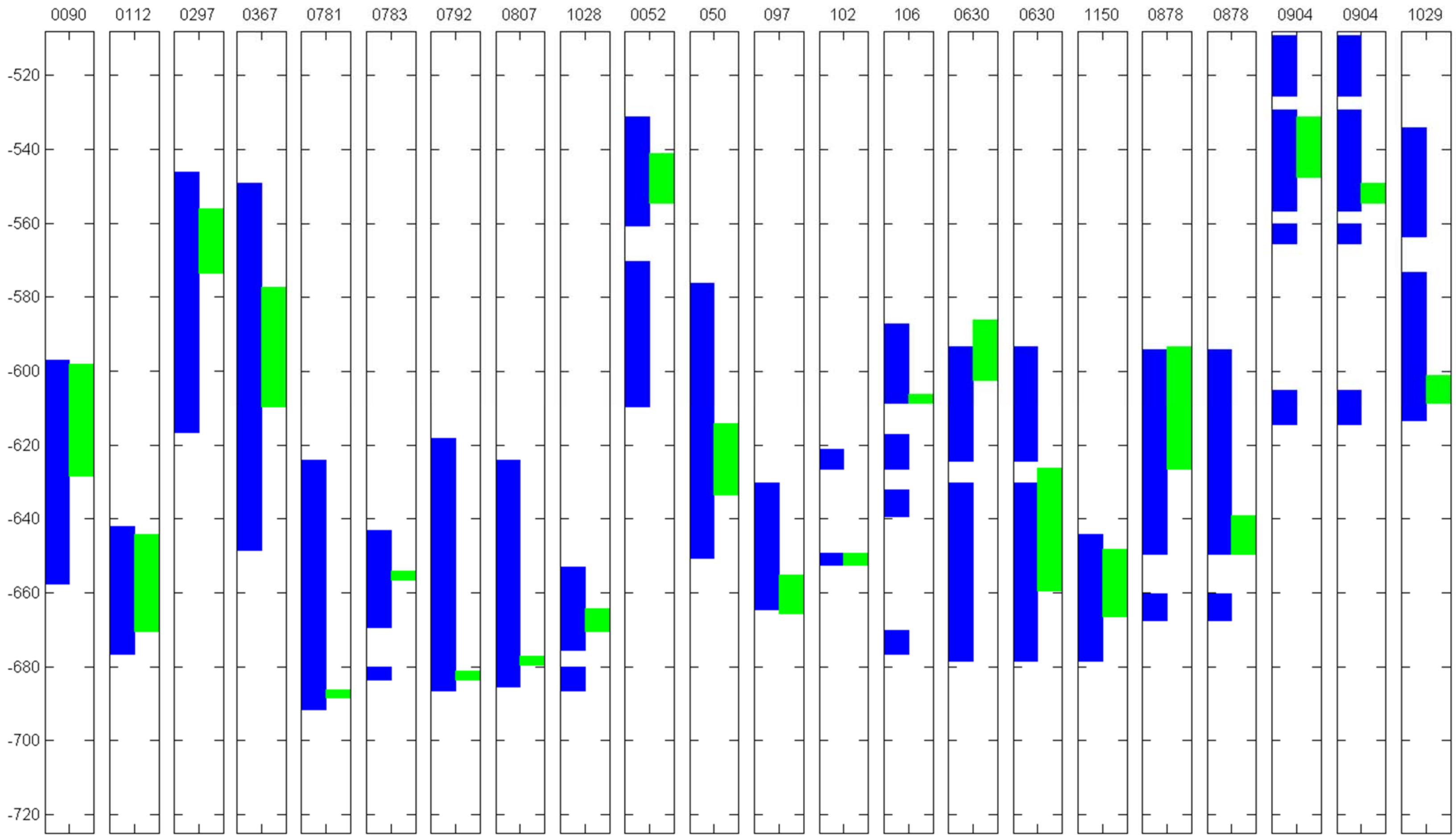
Pumping Wells:
Screen Depth vs. Model Estimation

How good is the aquifer geological architecture with respect to flow modeling?



Groundwater Observation Wells: Screen Depth vs. Model Estimation

How good is the aquifer geological architecture with respect to flow modeling?



Water Use

East Baton Rouge

Population: 440,171
Population served by public supply: 436,650
Per capita withdrawals (gal/d): 389
Acres irrigated: 0
Hydroelectric power instream use (Mgal/d): 0

West Baton Rouge

Population: 23,788
Population served by public supply: 23,265
Per capita withdrawals (gal/d): 460
Acres irrigated: 1,341
Hydroelectric power instream use (Mgal/d): 0

In "1,200-1,500-1,700-foot" sands by December 2010 = 112,556 m^3/day (~30 mgd), about 19%

East Baton Rouge — Withdrawals, in million gallons per day (Mgal/d)

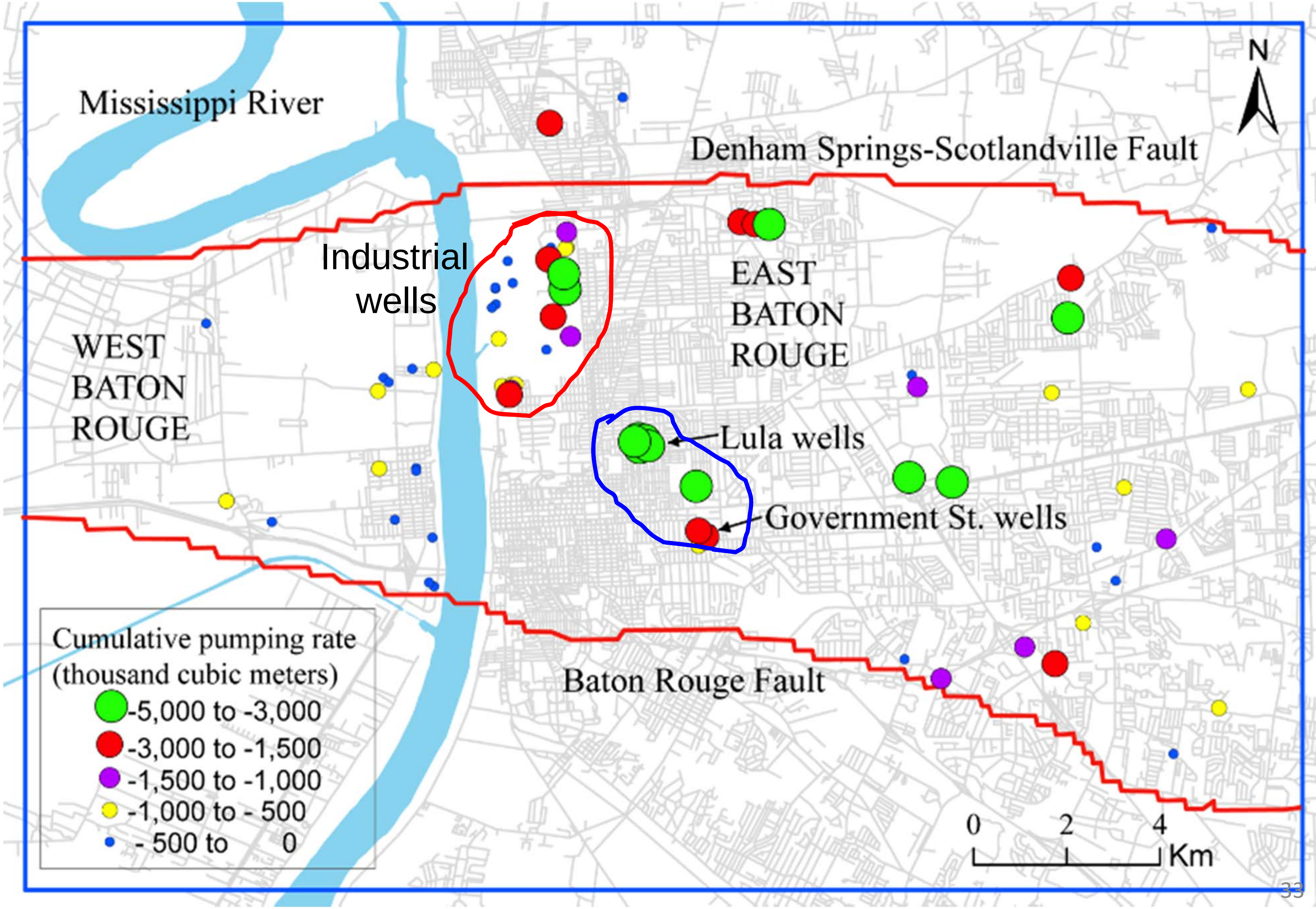
	Groundwater (GW)	Surface Water (SW)	Total
Public supply	75.12		75.12
Industrial	66.22	21.51	87.73
Power generation	7.79		7.79
Rural domestic	.28		.28
Livestock	.19	.01	.21
Rice irrigation			.00
General irrigation	.25		.25
Aquaculture	.04		.04
Total	**149.89**	**21.52**	**171.41**

West Baton Rouge — Withdrawals, in million gallons per day (Mgal/d)

	Groundwater (GW)	Surface Water (SW)	Total
Public supply	7.21		7.21
Industrial	1.50		1.50
Power generation			.00
Rural domestic	.05		.05
Livestock	.03	.01	.04
Rice irrigation			.00
General irrigation	.35	.18	.53
Aquaculture	1.07	.54	1.61
Total	**10.20**	**.73**	**10.93**

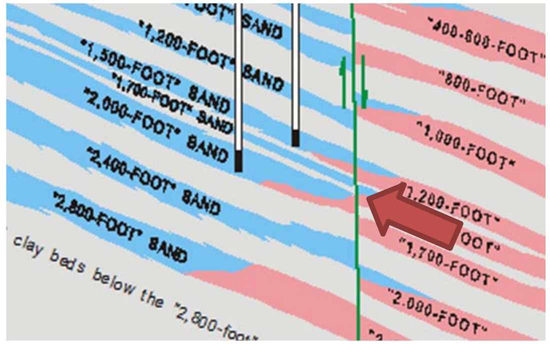
Sargent, B. P. (2011), *Water use in Louisiana, 2010*, Water Resources Special Report No. 17, Louisiana Department of Transportation and Development, Louisiana.

Cumulative Pumping Rates 1975 - 2010

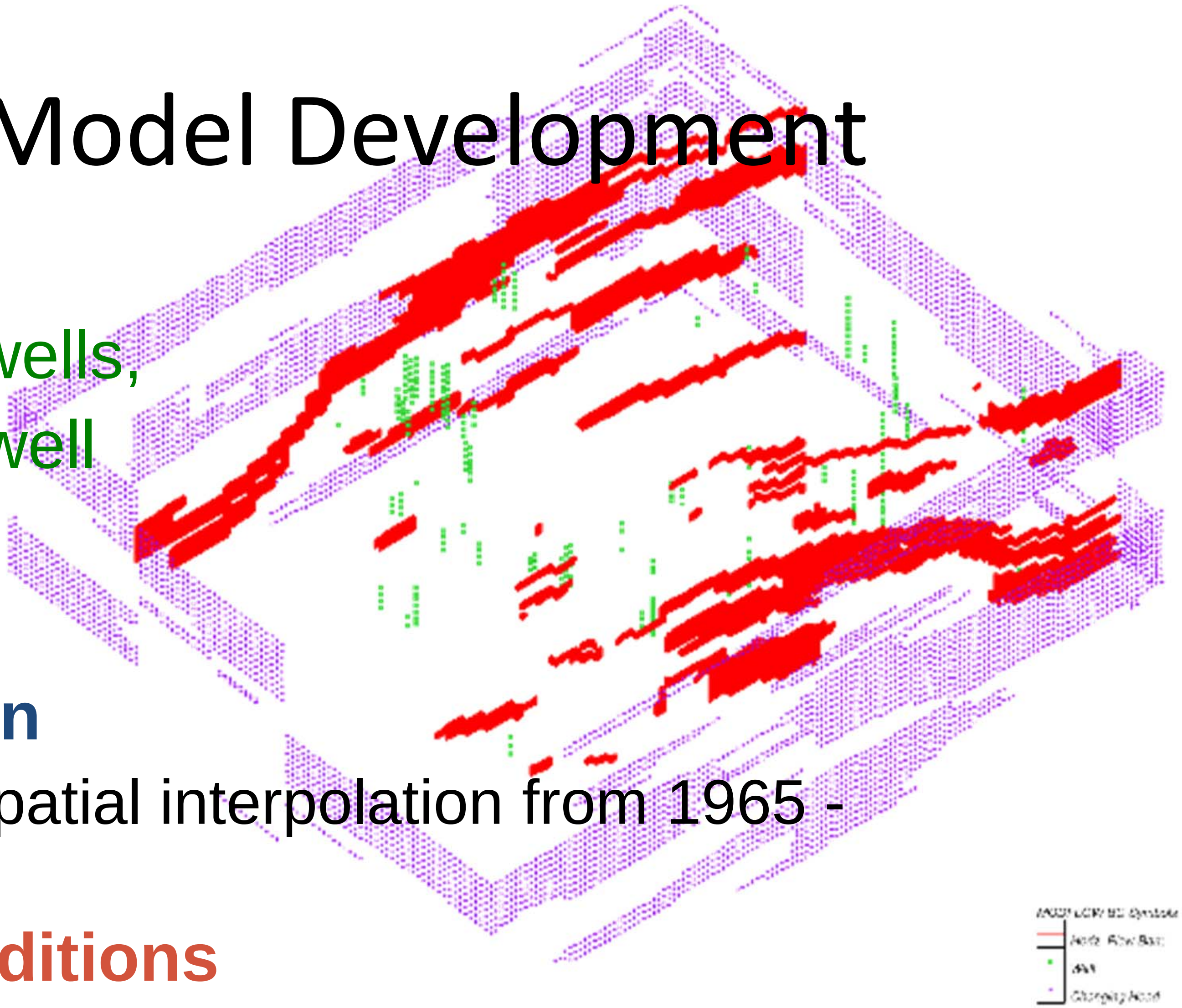


Current Issues in the Study Area

- **Key issues due to excessive groundwater withdrawals [*Meyer and Turcan, 1955; Tomaszewski, 1996; Tsai and Li, 2008; Li and Tsai, 2009; Tsai, 2010; Sargent, 2011; LAGWRC, 2012*]:**
  - The decline of groundwater heads: USGS monitoring data shows a decline of 53.34 m (175 feet) from 1945 to 2010 in the “1,500-foot” sand
  - Saltwater intrusion from south of the Baton Rouge fault moving north toward the Government Street and Lula pumping stations



Flow Model Development



- Two faults
- 87 pumping wells,
- 1 connector well

Initial condition

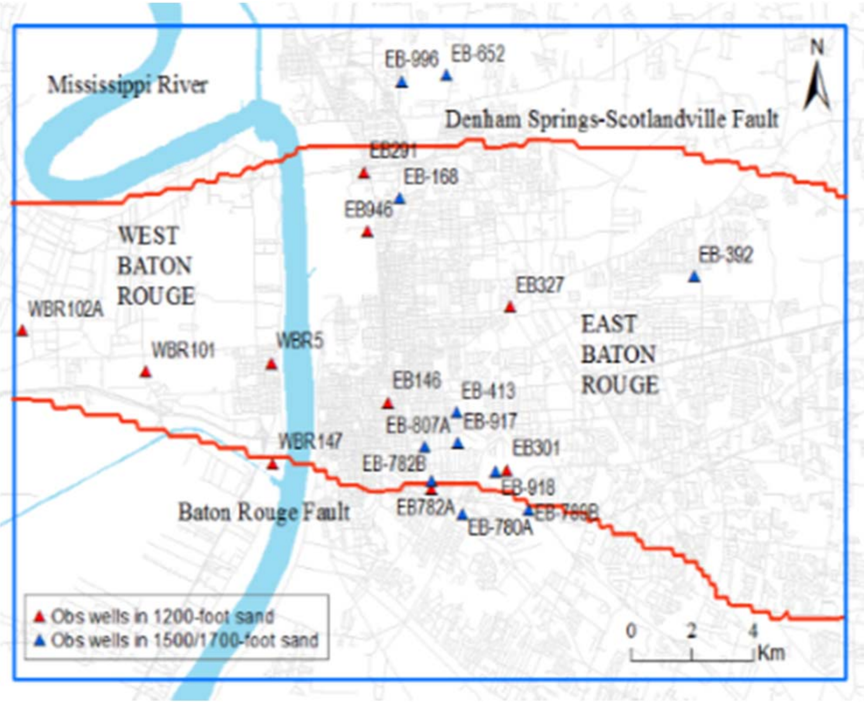
– Time and spatial interpolation from 1965 - 1978

Boundary conditions

– Transient boundary conditions were assigned for 4 active cells belong to north, south, east and west faces

Model Calibration

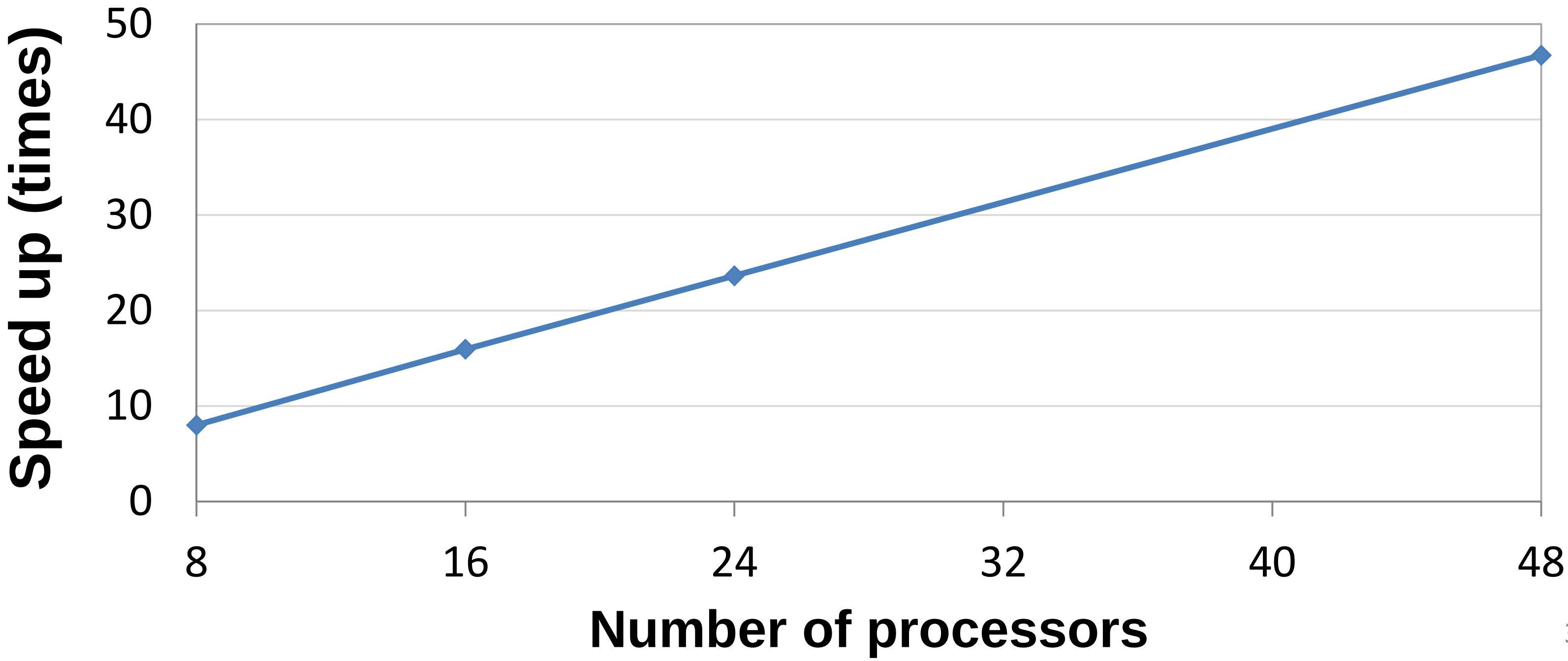
- 36 years simulation from 1975 to 2010 (432 time steps)
- 2,805 head records from 21 USGS observation wells to calibrate the model
- CAGWCC monthly pumpage data
- Estimated parameters: hydraulic conductivity, specific storage, and fault permeability.
- 48 processors were used to calibrate the model
- RMSE is used as objective function



The USGS groundwater levels monitoring networks in "1,200-1,500-1,700-foot" sands

Efficiency of Parallel CMA-ES

- CMA-ES scales up with increasing the number of processors.
- Using 48 processors and population of 48, model converges after 87 iterations (5.5 days)

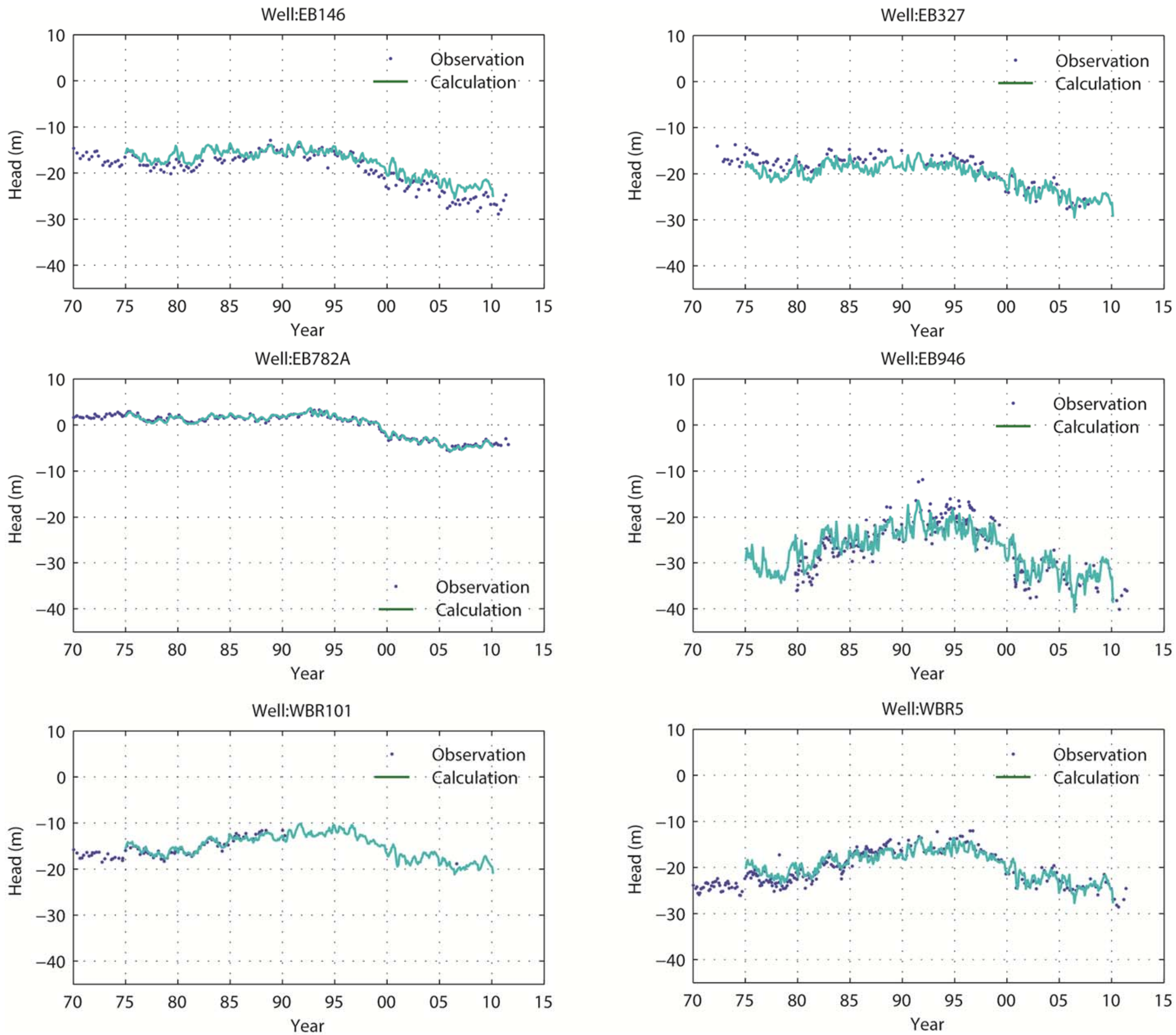


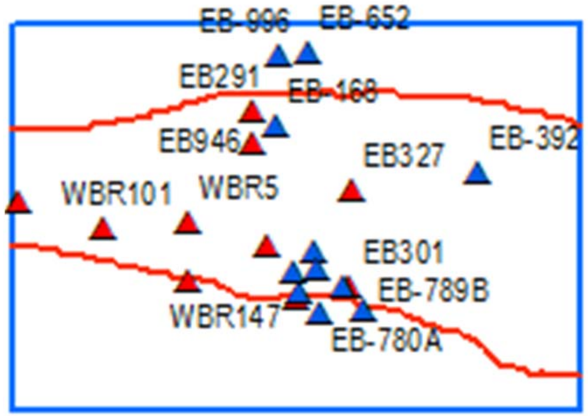
Estimated Parameters

- **Fitting error: RMSE ~ 1.46 m**
- **Model converges after 87 iterations (5.5 days)**

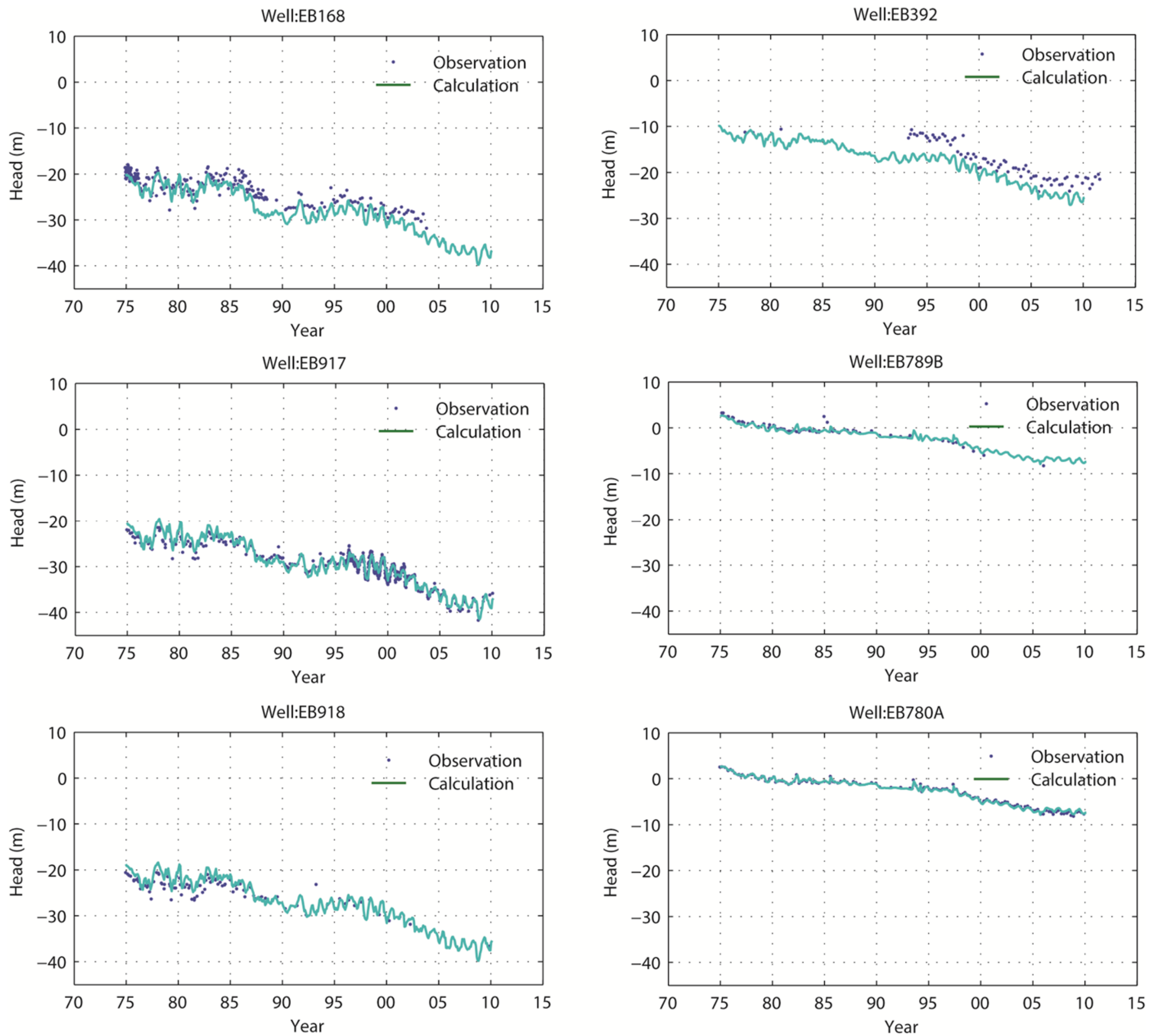
Parameters	"1,200-foot" sand	"1,500-1,700-foot" sands
Hydraulic characteristics (1/d)		
Baton Rouge Fault	3.38E-03	2.98E-04
Denham Springs-Scotlandville fault	5.11E-03	2.96E-02
Storage coefficient (1/m)	6.61E-06	7.65E-06
Hydraulic conductivity (m/d)	24.6	24.1

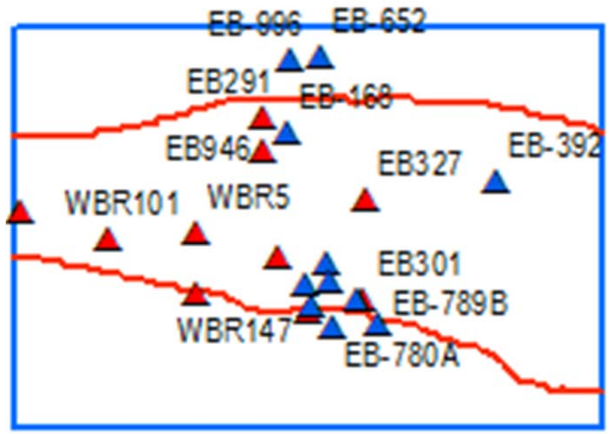
Matching of Calculated Head and Observed Head for the “1,200-foot” Sand



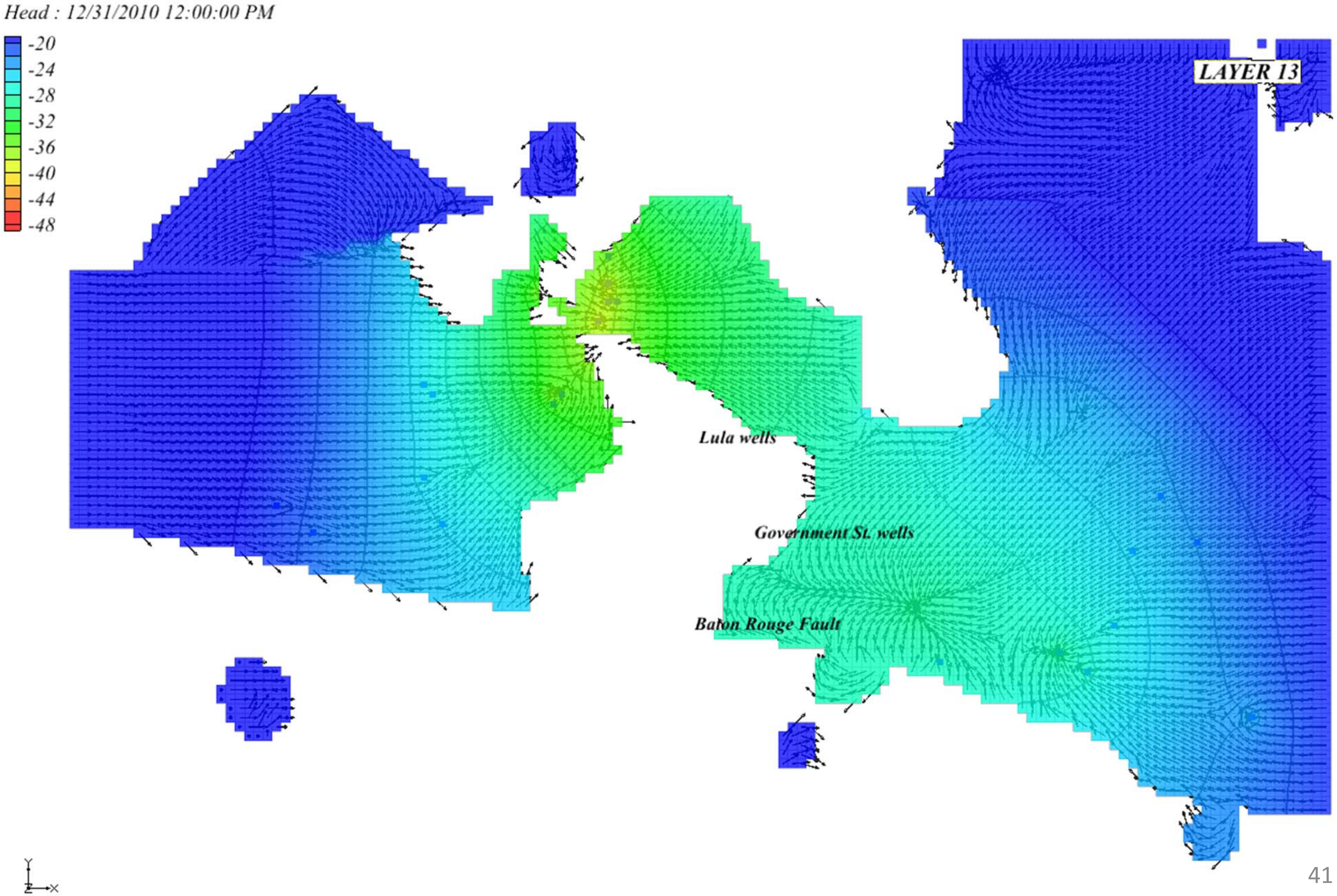


Matching of Calculated Head and Observed Head for the "1,500-1,700-foot" Sands

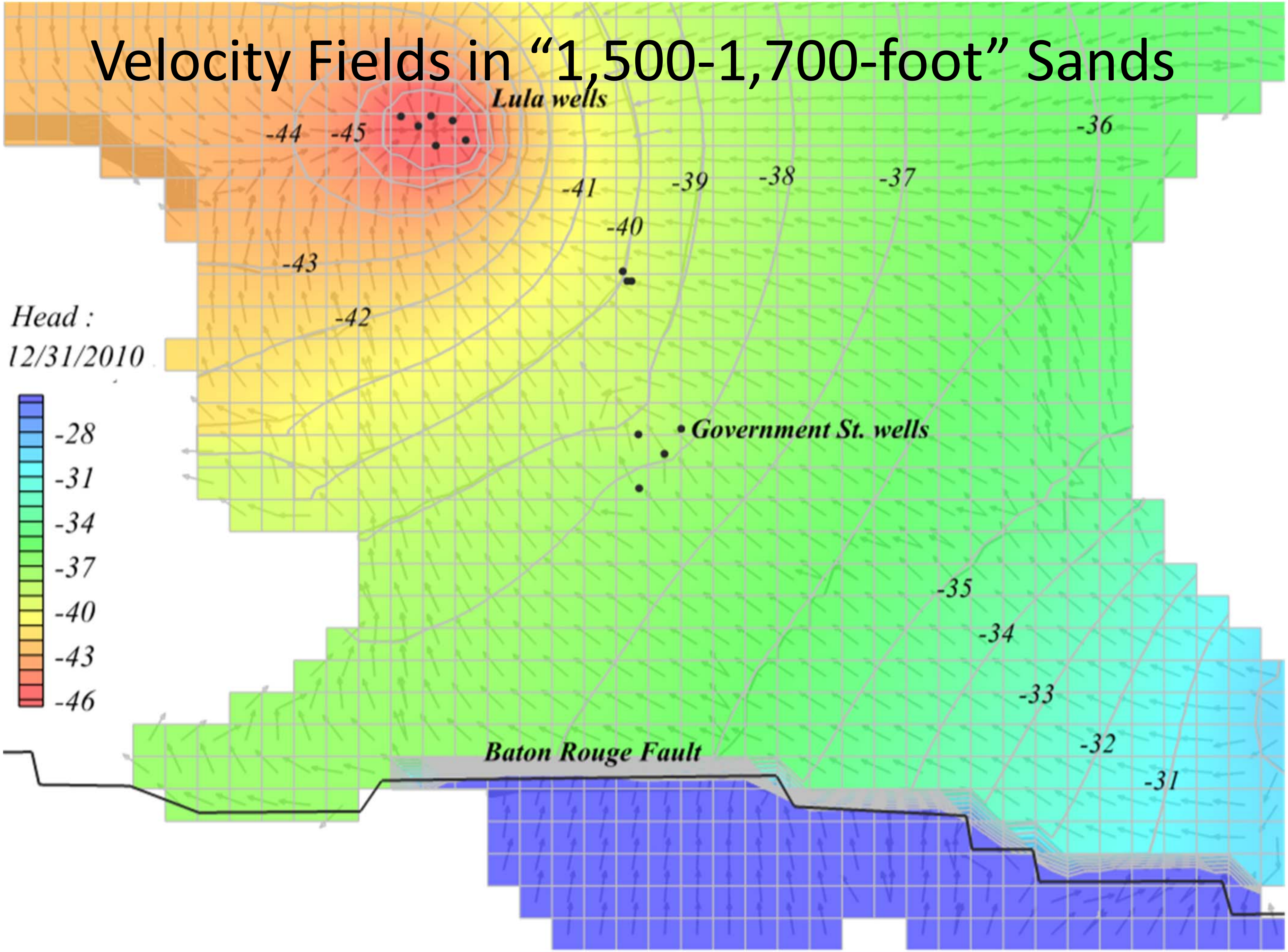




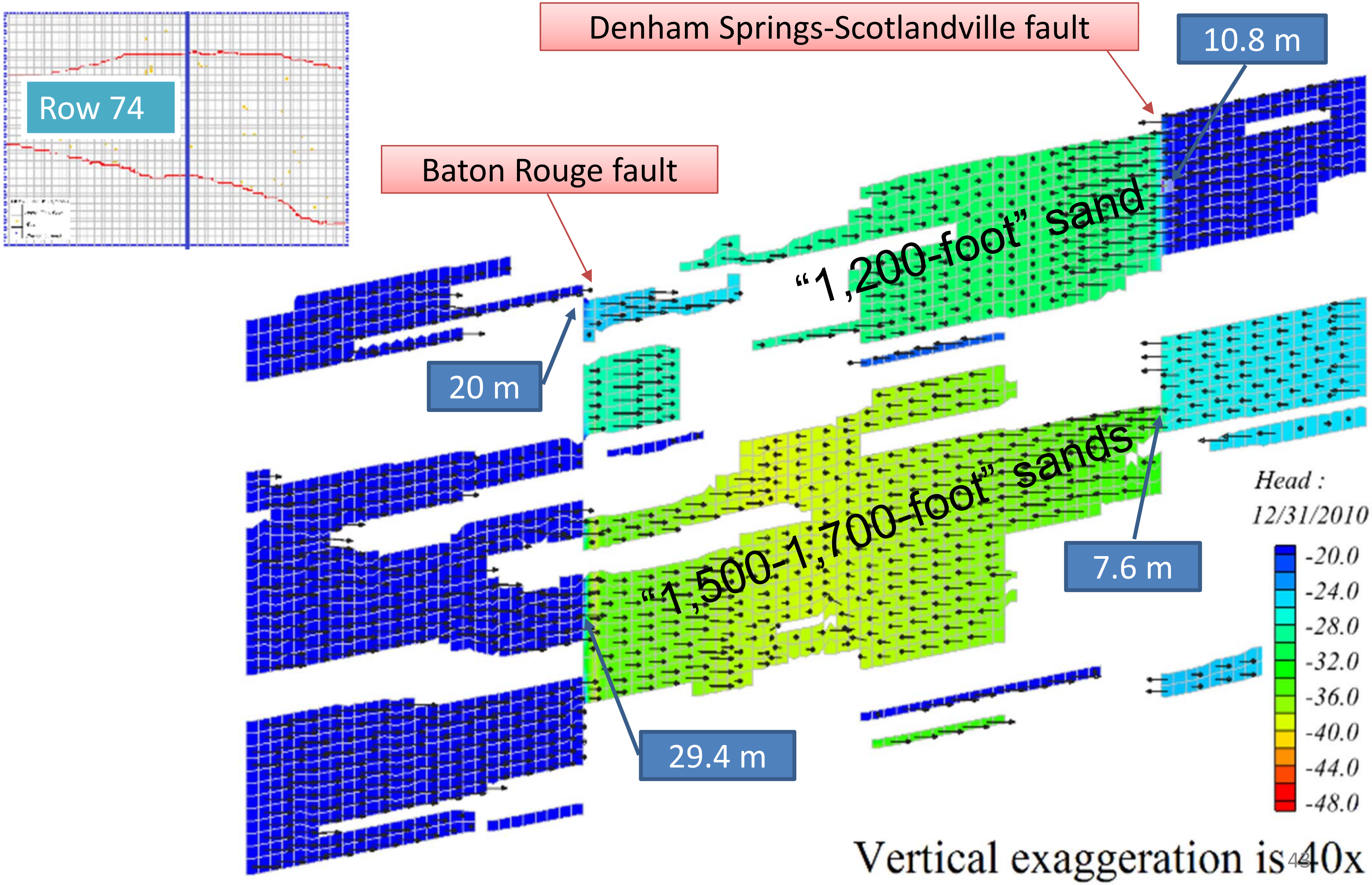
Velocity Fields in “1,200-foot” Sand



Velocity Fields in “1,500-1,700-foot” Sands

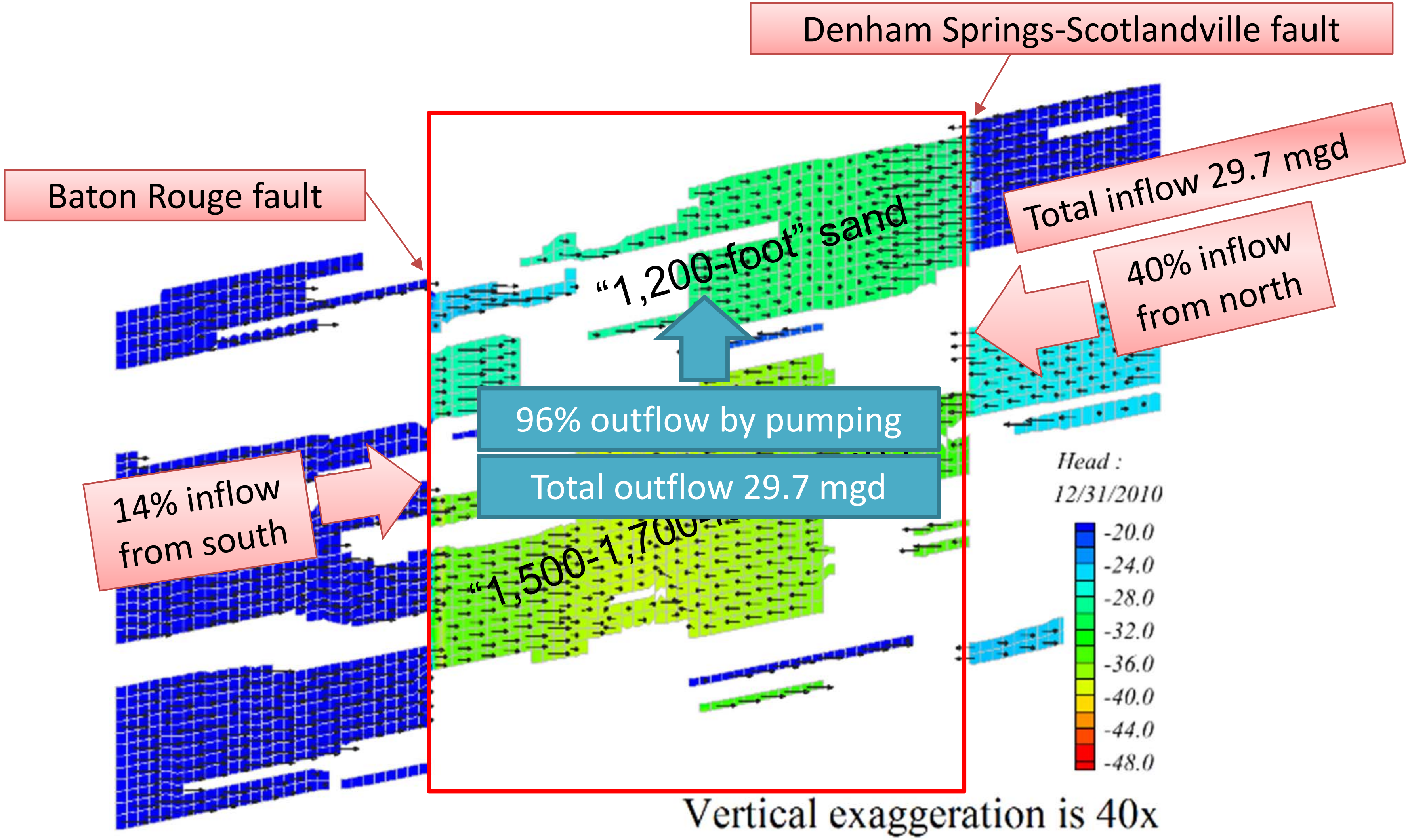


Head Differences across the Fault

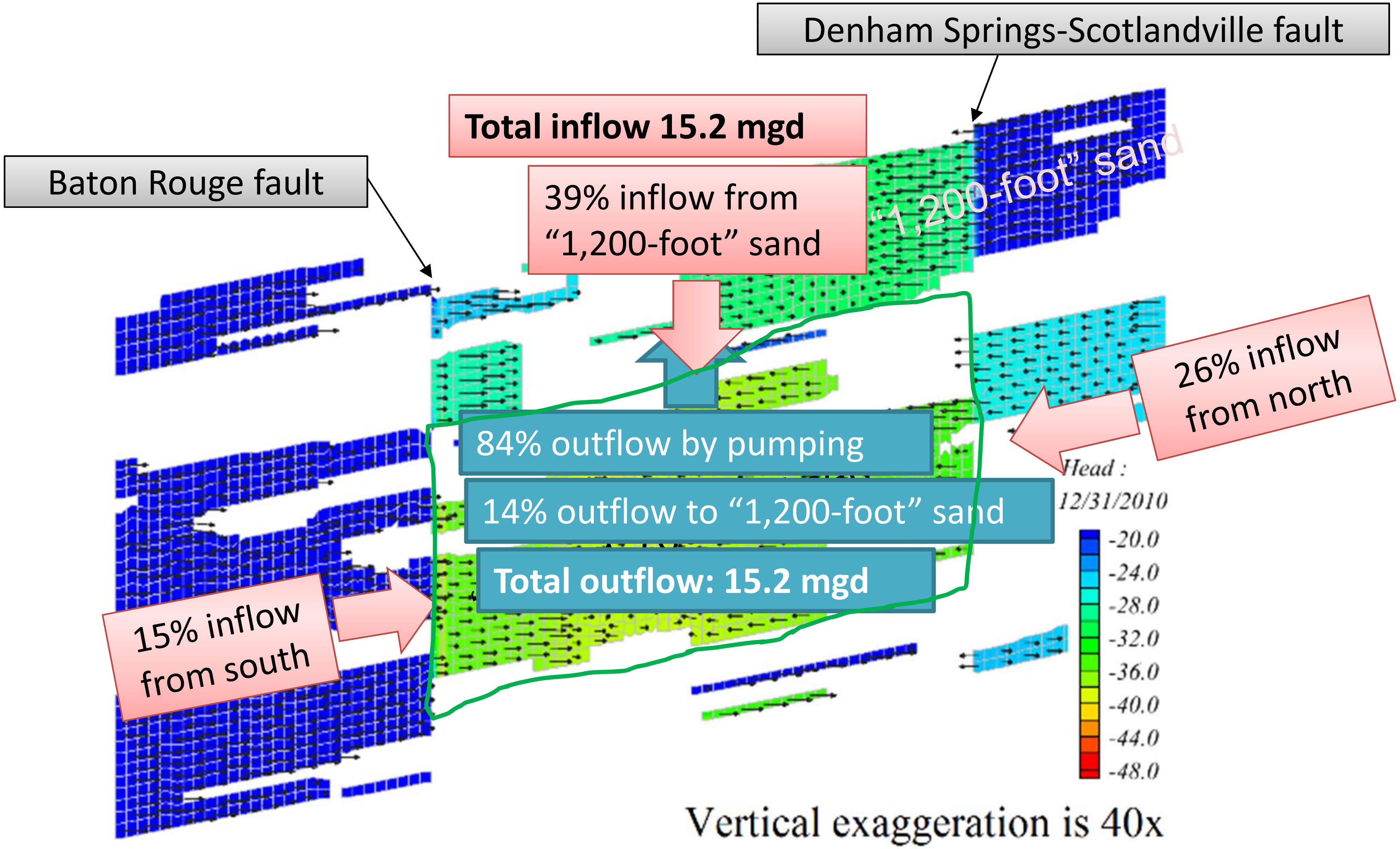


Vertical exaggeration is 40x

Flow budget for the area between two faults in "1,200-1,500-1,700-foot" sands



Flow budget for the area between two faults in "1,500-1,700-foot" sands



Conclusion

1. Methodology provided invaluable information on aquifer architecture and potential flow pathways through the faults.
2. Results show that the “1,200-foot” sand and “1,500-foot” sand are connected in the middle zone
3. Results show that there is a distinct confining layer between the “1,500-1700-foot” sands and the “2,000-foot” sand in the middle zone
4. Due to abundant well log data, a good geological architecture significantly reduce structure error in flow models
5. Calibration of geological architecture models is much less computationally expensive than flow models. Parallel algorithm is needed for flow model calibration.
6. Calibration of the 3D groundwater flow model for the “1,200-1,500-1,700-foot” sands in Baton Rouge area show:
   - The Baton Rouge fault and the Denham Springs-Scotlandville fault are low-permeability faults that restrict horizontal groundwater flow.
   - The head differences across BR fault is larger than those across the DSS fault.
   - The model shows strong groundwater flow interactions between the "1,200-foot" sand and the "1,500-1700- foot" sands for the area between two faults.

What we have learnt?

- Geological structure is a precursor of a groundwater model.
- The better the geology is understood, the better the groundwater model.

LSU

Thank You

Questions?