Geophysics as an Integral Part of the ASR Process

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Purpose

Develop a rationale for electrical resistivity surveying as a means for mapping ASR (Aquifer Storage and Recovery) bubble morphology during an ASR injection/withdrawl cycle.

Background

Bubble morphology is often assumed to have radial symmetry when the ASR process is modeled. While density variation and its effect on cross-sectional shape is sometimes included, too little attention is given to radial asymmetry due to fracture-dominated permeability, lateral variations in limestone mineralogy, or regional groundwater flow. The net combination of these could influence bubble growth such that the 'real' bubble shape could depart significantly from radial symmetry. We propose that electrical resistivity surveying is a tenable means of mapping bubble morphology/growth characteristics from the ground surface without impacting the ASR process itself.

Why Electrical Resistivity?

Kwader[1] has established the following empirical relationship from his study of water wells (Floridan aquifer) in Seminole County, Florida:

$$\mathbf{Cl = (3500/Rw) - 153} \qquad \mathbf{(1)}$$

or, alternatively,

$$\mathbf{R_0 = (32{,}163)/(Cl + 153)} \qquad \mathbf{(2)}$$

where Cl is the equivalent chloride concentration (mg/l), R_w is the resistivity of pore water (ohm-meters), and R_0 is the electrical resistivity of the limestone formation @ 100% water saturation. The second formulation utilizes Archie's equation and assumed values for porosity (25%) and empirical constants in Archie's equation.

Equation (2) allows us to estimate the bulk electrical resistivity of the Floridan aquifer based on the chloride concentration of the pore water.

[1] Kwader, Thomas, 1982, Interpretation of bore geophysical logs and their applications to water resource investigations: Florida State University, Tallahassee, Florida (Ph.D. dissertation).

The USGS[2] has published statistics from cycle test data taken from numerous ASR well fields in Florida. The average (typical) ambient or native water chloride concentration is approximately 2,937 mg/l while the average injected water chloride concentration is approximately 76 mg/l. Inserting these into equation (2) yields formation resistivity contrast (bubble versus aquifer) of 140 ohm-meters (bubble) versus 10 ohm-meters (aquifer). Therefore, there is, theoretically, a 14:1 resistivity ratio between the bubble and the brackish aquifer. No other physical parameter (density or seismic velocity, for example) comes close to this – which pushes electrical resistivity mapping to the forefront for geophysical (remote) mapping of bubble morphology.

Preferred Methodologies – CSAMT

Classical electrical resistivity techniques employing series of steel stakes driven into the ground are at a disadvantage when it comes to mapping detail at depth. To see deeply into the subsurface, the spacing of such stakes is required to be extremely large (on the order of the objective depth). To counter such a large footprint requirement, we propose using an electromagnetic (EM) technique for mapping the two- and three-dimensional distribution of electrical resistivity. The method is Controlled Source Audiofrequency MagnetoTellurics (CSAMT).

With this method, depth of investigation is not dependent on the station spacing at the surface. A dense grid of stations could provide the necessary lateral and vertical resolution required to accurately map the ASR bubble morphology in depth ranges approaching 1000 ft or more, depending on bubble size and resistivity contrast. The technique determines the subsurface distribution of electrical resistivity by pulsing the ground with electromagnetic waves and recording earth response at various wave frequencies after a pulse is initiated. The physics and mathematics are beyond the scope of this paper.

Further, by repeating surveys at various time intervals, we can track small changes and growth tendencies in the ASR process. Time-lapse models can be generated that accentuate the developing ASR-related changes in the subsurface, while minimizing anomalies from natural variations that do not change, or change little, with time.

As with electrical techniques, EM techniques are still susceptible to surface cultural noise (powerlines, pipelines, grounded structures) so additional site characterization will need to be conducted to determine the nature and extent of cultural noise.

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[2] USGS, 2002, Inventory and review of aquifer storage and recovery in southern Florida (Table 5), WRI Report 02-4036.

Model Predictions

Using the resistivity parameters predicted by empirical studies and typical depths and volumes for an ASR cycle, we have modeled the theoretical response of a CSAMT survey over an ASR cycle test. These 2-D models evaluate the effects of depth, length/radius of bubble, and thickness of bubble.

The models were generated by simulating the CSAMT response at surface stations spaced 100 ft apart for a bubble vs. background resistivity contrast of 140 vs. 10 ohm-meters. The resistivity contrast was kept constant, and bubble morphology or depth was varied (the target, or 'bubble', is represented by white rectangles shown on the plots). An inversion model was then calculated (color-contoured resistivity plots below) that estimates the subsurface resistivity based on the simulated data.

Results from the three test cases investigated in this study are shown below. The cases include a theoretical ASR bubble morphology with:

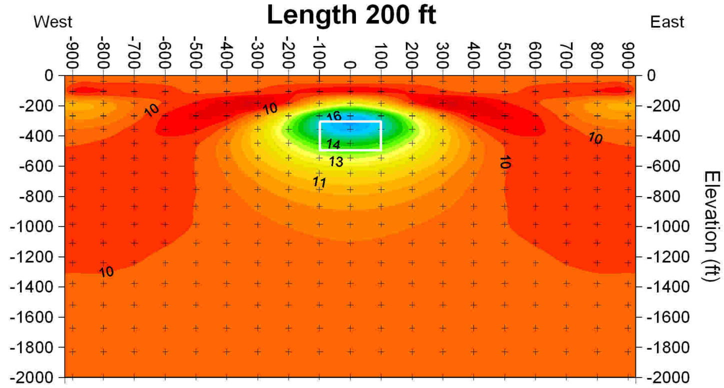
- Case 1- Constant Depth/Thickness, Variable Length
- Case 2- Constant Depth/Length, Variable Thickness
- Case 3- Constant Length/Thickness, Variable Depth

In summary, the models show that the ASR target bubble can be resolved given reasonable dimensions and resistivity contrast. For small to moderate size target scenarios (>200 ft length, > 100 ft in thickness) and depths on the order of 500 ft or less, the modeled target resistivity is about 2 times that of background. Deeper ASR scenarios can probably be resolved, given larger bubble dimensions or greater resistivity contrast.

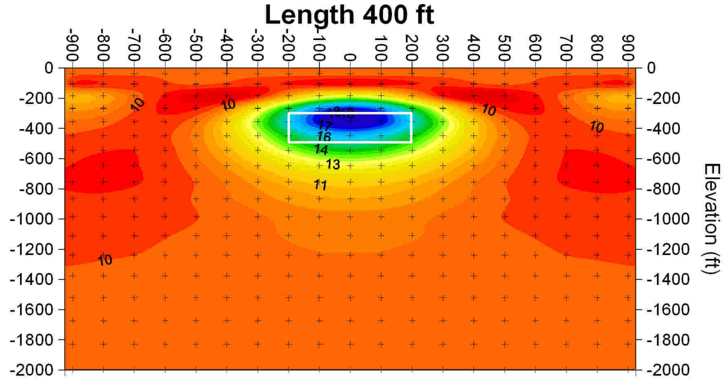
ASR Modeling Case 1: Variable Length

300 ft to 500 ft Depth 140 ohm-m Target in 10 ohm-m Background

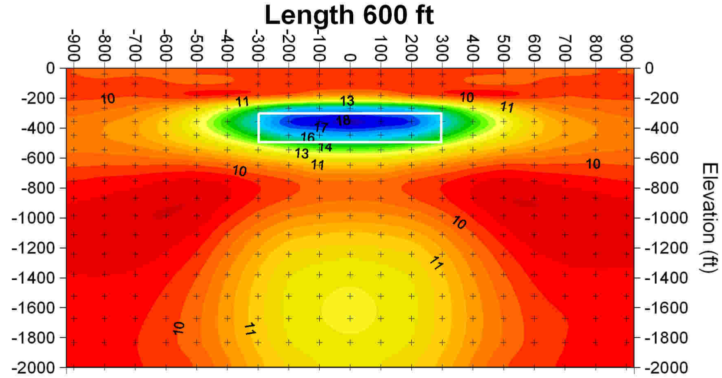
Length 200 ft



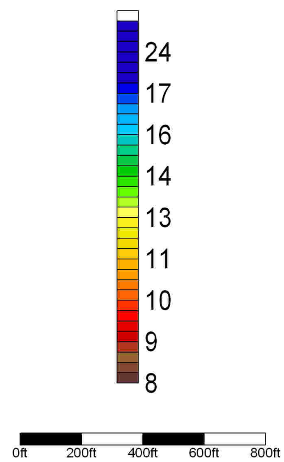
Length 400 ft



Length 600 ft



Model Resistivity (ohm-m)



Natural Source Data
Receiver Data:
Length = 100 ft
Orient. = N90E
Inversion control parameters:
ResSmth=0.32, dpW=0.1, dxW=0.32, dzW=0.3

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EM2D Modeling for Florida ASR

2D Smooth-Model Inversion
Scalar AMT Data

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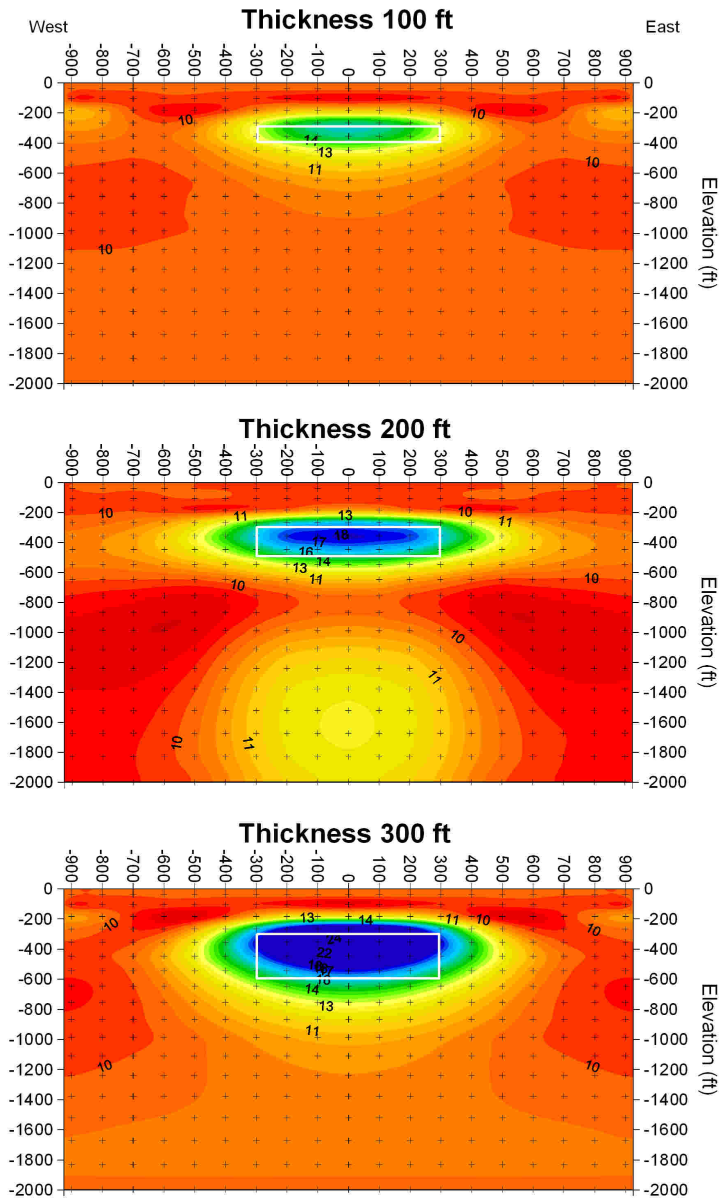
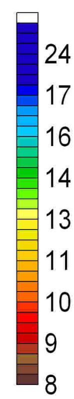
REF:mod3a.mtm				

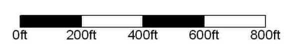


ASR Modeling Case 2: Variable Thickness

Top Depth 300
140 ohm-m Target in
10 ohm-m Background

Model Resistivity
(ohm-m)





Natural Source Data
Receiver Data:
Length = 100 ft
Orient. = N90E
Inversion control parameters:
ResSmth=0.32, dpW=0.1, dxW=0.32, dzW=0.3

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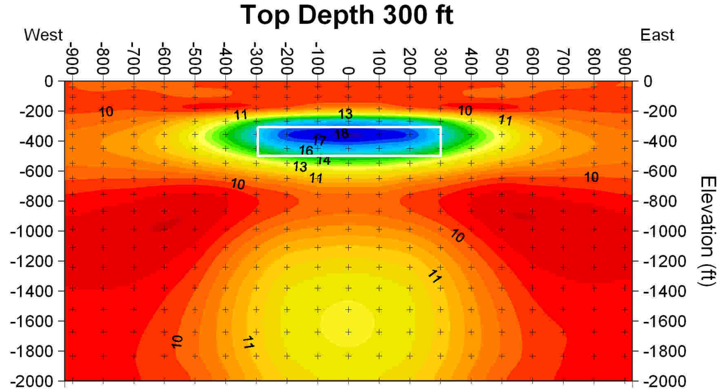
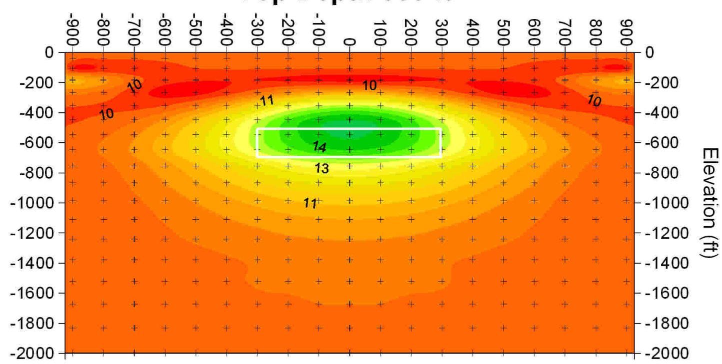
ASR Modeling Case 3: Variable Depth

600 ft Long x 200 ft Thick 140 ohm-m Target in 10 ohm-m Background

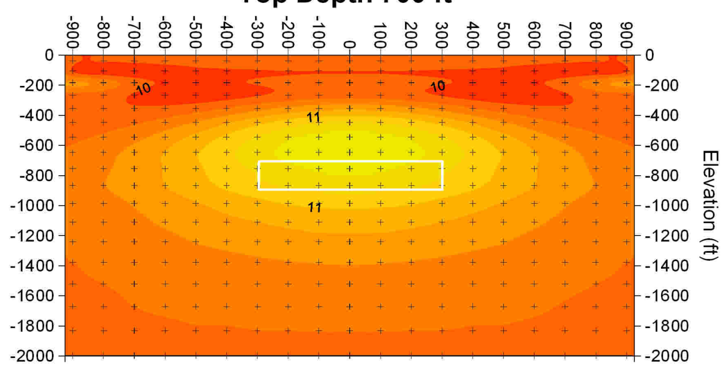
Top Depth 300 ft

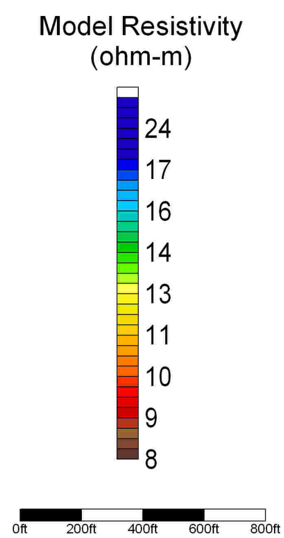


Top Depth 500 ft



Top Depth 700 ft





Natural Source Data
Receiver Data:
Length = 100 ft
Orient. = N90E
Inversion control parameters:
ResSmth=0.32, dpW=0.1, dxW=0.32, dzW=0.3

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