Historical and Conceptual Synopsis of Hydrogeophysics

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**The Hydrogeophysics Mandate**

Rational, rigorous, groundwater resource exploration and assessment programs, which utilize hydrogeophysics in support of general basin-wide and localized hydrogeological investigations and optimization of resources, are essential to the survival of our species and its institutions.

If this sounds overly dramatic, it is—and is intended to be! Adaptation to greatly diminished fresh water sources may be possible to some extent, but is not a sufficient solution.
Global Water Supply Shortages Threaten People, Livestock, Crops, and Industry
Unequal Distribution of Water Supply Leads to Conflicts ("haves and have-nots")
Climate Change will Continue to Exacerbate the Problems
Must Consider both Intergenerational Equity AND Environmental Sustainability

* Renewable vs. Non-Renewable

WATER SUPPLY SOURCES

Development of new sources
- NEW RESERVOIRS
- DESALINATION PLANTS
- INNOVATIVE WATER/MOISTURE RECOVERY

Importation of water

Exploitation and enhancement of existing sources
- WELLS, QANATS, CISTERNS, SPRINGS
- Surface water
  - LAKES/RESERVOIRS
  - RIVERS/STREAMS
  - DRAINAGE ANALYSIS
  - BASINS AND GROUNDWATER RECHARGE AREAS

Groundwater

EXPLORATION/DETECTION

RESOURCE ASSESSMENT

Current and future roles for Hydrogeophysics
**Historical Considerations**

“History” abounds with charlatans and pseudo-science practitioners peddling tools and expertise for potable groundwater detection and exploration!

**Dowsing for potable water**

**Basic Y-Rod or Willow Stick**

**Universal Pro "L" rods**
(professional)

SOLD OUT
Not Available Until July 10

**THE DIAMOND PENDULUM**
for dowsing results you can trust

**Drill Here!**
Historical Considerations

- Considerable variations in **terminology and conceptual understanding of hydrogeology** between disciplines and practitioners:
  - Geologists and hydrogeologists and
  - Civil engineers and hydrologists and
  - Geophysicists and petroleum engineers and
  - Soil scientists and environmental scientists and ........

- Terminology and conceptual understanding of hydrogeology has evolved with time and with capabilities for investigating the subsurface

- There has been growth and maturation of **hydrogeophysics** as an area of study and practice that has helped bridge the gap between:
  - the *old* “engineering and groundwater geophysics” practice
  - and the other disciplines invested in understanding subsurface water (groundwater) occurrence and movement

- Hydrogeophysics is now an firmly established branch of Near-Surface Geophysics
Conceptual Models of Groundwater Occurrence

Simplest Model of Unconfined Aquifer in Soil/Granular Media

Water Table

<table>
<thead>
<tr>
<th>Unsaturated</th>
<th>Saturated</th>
</tr>
</thead>
</table>

**Corresponding Geophysical Model**

\[
\begin{align*}
V_p & \sim 300 - 1,000 \text{ m/s} \\
\rho_b & \sim \rho_H \\
V_p & \sim 1500 \text{ m/s} \\
\rho_b & \sim \rho_L \\
\rho_H & > \rho_L
\end{align*}
\]

More Detailed, Regional-Scale Hydrogeological Model

Model of Unconfined Aquifer With Transition Zone

<table>
<thead>
<tr>
<th>Unsaturated</th>
<th>Capillary Zone</th>
<th>Saturated</th>
</tr>
</thead>
</table>

**Corresponding Geophysical Model**

\[
\begin{align*}
V_p & \sim 300 - 1,000 \text{ m/s} \\
\rho_b & \sim \rho_H \\
V_p & \sim 1500 \text{ m/s} \\
\rho_b & \sim \rho_L \\
\rho_H & > \rho_L \succ \rho_I
\end{align*}
\]

Perched Water Table Model

**Ground Surface**

**Perched Water Table**

**Impermeable Stratum**

**Water Table**

**Unconfined Aquifer**
## Qualitative “Hydrogeophysical” Interpretations From Complementary Geophysical Surveys

<table>
<thead>
<tr>
<th>$V_p$</th>
<th>$\rho_b$</th>
<th>Qualitative Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Impermeable rock.</td>
</tr>
<tr>
<td>High</td>
<td>Int.</td>
<td>Rock. Possible aquifer.</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>Rock. Possible aquifer; probably brackish.</td>
</tr>
<tr>
<td>Int.</td>
<td>High</td>
<td>Dry, unconsolidated sediments at depth; dry, weathered, or fractured rock.</td>
</tr>
<tr>
<td>Int.</td>
<td>Int.</td>
<td>Possible aquifer in unconsolidated sediments ($V_{pS}$ ?) or in weathered rock.</td>
</tr>
<tr>
<td>Int.</td>
<td>Low</td>
<td>Clay or brackish water($V_{pS}$ ?)</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Dry unconsolidated sediments; no clay.</td>
</tr>
<tr>
<td>Low</td>
<td>Int.</td>
<td>Clayey, unconsolidated sediments; wet sediments.</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Wet, clayey sediments.</td>
</tr>
</tbody>
</table>

$V_p$—High (>3,000 m/s); $V_{pS} \geq 1,500$ m/s; Low (<1,000 m/s)

$\rho_b$—High (>300 ohm-m); Low (<10 ohm-m); *Int.*—Intermediate Values
Qualitative “Hydrogeophysical” Interpretations

Recommended New Well Site

Existing Wells

Drilling zone recommendation

Seismic refraction and electrical resistivity soundings located at 30-m intervals

(Butler 2000)
Familiar Correlations of Geophysical and Hydrogeological Properties to Soil/Rock Fundamental Properties

Perhaps the most familiar representations of geophysical parameters $V_p$ and $V_s$ to “fundamental” properties of the geological medium, are the elastic wave equations

To the extent that the geologic medium can be approximated as elastic, these relations are valid and have been used successfully for soil, silts/sands/gravels, and rocks.

Empirical Relations

Faust’s Equations:

\[ V_p = c (z T)^{1/6} \] (1951),

where $c = 125.3$, for $V_p$ [ft/s], $z$ = depth [ft], $T$ = geologic time since deposition [yr];

\[ V_p = c (z T L)^{1/6} \] (1953),

where $c = 1948$, for $z$ and $T$ as above, $L = \text{the lithology factor} = < \rho_b > / T$, and $< \rho_b >$ is the average bulk formation resistivity [ohm-ft].

➢ From Archie’s Equation, considered later, we have the remarkable result that: $V_p = f(\Phi, \rho_w, T, m)$
Familiar Correlations of Geophysical and Hydrogeological Properties to Soil/Rock Fundamental Properties

**Empirical Relations (Cont’d)**

**Pickett Equation:**

\[
\frac{1}{V_p} = A + B \Phi
\]

where \( A \) and \( B \) depend on lithology and depth of burial; \( A \) [\( \mu \text{sec} / \text{ft} \)], \( B \) [\( \mu \text{sec} / \text{ft} \)], and \( \Phi \) [%];

\( 0 < \Phi \leq 30 \%; S = 100\% \).

**Mixture Theories**

**Wylie’s Time-Average Equation:**

\[
\frac{1}{V_p} = \left( \frac{\Phi}{V_f} \right) + \left[ \frac{(1 - \Phi)}{V_m} \right]
\]

where \( V_f = \text{fluid velocity} \), \( V_m = \text{matrix velocity} \), \( 0 \leq \Phi \leq 1.0 \), and \( S = 100\% \).

- More complete mixture theories include more features of an air-fluid saturated particulate medium.
- For example, the Gassmann Equations and its descendants include realistic properties of the medium and replicates the \( Z^{1/6} \) depth dependence of Faust’s empirical equations (e.g., Russell 2013).
Illustration of the effects water-air pore fluid mixtures on bulk modulus (left) and P-wave velocity (right) as a function of degree of saturation (Fratta et al. 2005).

Starting from the theoretical elastic equations for $V_p$ and $V_s$ it is possible, using mixture theory relations for $K$, $G$, and $\rho$, to develop equations for $V_p$ and $V_s$ that include properties of an air-fluid saturated particulate geologic media (e.g., Fratta et al. 2005).
Archie’s Equation

Perhaps the most familiar of all empirical equations in geophysics is Archie’s equation (Archie 1942) for “clean” sands/gravels/sandstones

\[ \rho_b = a \rho_w \phi^{-m} S_w^{-n} \]

where \( \rho_b \) is the bulk resistivity of the material

\( \rho_w \) is the pore water/fluid resistivity,

\( \phi \) is the porosity, \( S_w \) is the pore water/fluid saturation (0 to 1.0)

\( a, m, \) and \( n \) are empirical material-dependent constants determined from laboratory measurements or field measurement correlations

\( m \) and \( n \) are thought to represent the “connectedness” of the pore space and the pore fluid, respectively (e.g., Knight and Endres 2005).

Considerable effort has been devoted to developing typical values of \( a, m, \) and \( n \) for soils and rocks, and Archie’s Equation has been used extensively to make predictions.
Use of Archie’s Equation to calculate bulk resistivity for a series of “clean” sands and gravels in the shallow subsurface (Sharp et al. 1999).

<table>
<thead>
<tr>
<th>Pore water resistivity, Ohm-m</th>
<th>Bulk resistivity (S = 100%), Ohm-m</th>
<th>Bulk resistivity (S = 50%), Ohm-m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Porosity</td>
<td>Porosity</td>
</tr>
<tr>
<td>Low-17</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>1,700</td>
</tr>
<tr>
<td>Mean-50</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>280</td>
</tr>
<tr>
<td>High-250</td>
<td>1,250</td>
<td>5,000</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>6,250</td>
<td>Very High</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>4,000</td>
</tr>
</tbody>
</table>

- Modified Archie’s Law: additive term for particle conduction -- \( \sigma_{\text{eff}} = a \sigma_w \phi^m S^n + \sigma_{\text{eff surface}} \)
- The Waxman-Smits Model (Equation) is an empirical effort, using mixture concepts, to include the effects of clays (shaly sands) on the bulk resistivity.
Conceptual States of Unsaturated, Partially Saturated, and (Fully) Saturated Conditions for a Granular Media (where the fluid resistivity is much lower than the resistivity of the granular media)

1. $S_f = 0$ – Extreme state, dry, highest in situ bulk resistivity ($\rho_b = \rho_H$); ($V_p \sim V_L$)
2. $S_f = 1$ – Extreme state, saturated, lowest in situ bulk resistivity ($\rho_b = \rho_L$); and $V_p \sim 1500$ m/s
3. $S_f << 1$ – Intermediate states, grains coated with fluid, $\rho_b > \rho_L$;
   For state 4, some pore fluid menisci begin to form.
4. $S_f < 1$ – “Critical” state, all pore fluid menisci touch, forming complete (tortuous) electrical conduction paths, $\rho_b \gtrsim \rho_L$
5. $S_f < 1$ – Intermediate state, air “bubbles” in pore spaces, but complete electrical conduction paths, $\rho_b \approx \rho_L$
The “Water Table” Complex

Defined in terms of Pressure, Saturation, Electrical Resistivity, and/or Seismic Velocity—Thickness of the Complex Varies Greatly—Dependent on Soil/Rock Type, Particulate Gradation, Porosity, Pore-space Interconnectedness, Clay Content.

-in coarse granular materials, these interfaces may nearly coincide; while in fine-grained materials, the complex can be several meters in vertical extent

(Butler 1990)
A Conceptual Model of the Water Table Complex

Water Table/Phreatic Complex – Entry point of water and of contaminants into the groundwater system; extremely dynamic.

The Hydrogeophysics Agenda:
Measure and model soil constitutive properties to directly support flow and transport modeling for assessment and prediction

Geophysical Methods – used to map and characterize the water table complex

- Electrical and electromagnetic methods; seismic methods.
- What is the relation of the geophysically-determined “water table” to the level measured in monitoring wells and to the actual in situ water table?
- What can we deduce/determine about in situ soil properties?
- Convert hydrogeophysical properties to hydraulic properties

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Additional Hydrogeophysics Challenges

• Depth limitations (or differences) of geophysical methods, e.g.
  • GPR versus electrical resistivity (ERT), TDEM, NMR, seismic refraction
  • Seismic refraction tomography (SRT) versus MASW
  • Etc., problematic for resolution and standard joint inversion approaches

• Characterizing heterogeneity
  • Hydrogeological characterization with limited boreholes complemented with “continuous” hydrogeophysics 2D / 3D datasets
  • Direct construction of geostatistical representation of hydrogeological properties from multiple, complementary hydrogeophysics datasets

• Establishing validated correlations (empirical, analytical) to water content, saturation, porosity, flow and transport properties
  • Existing but rapidly evolving methods: \textit{ERT}, \textit{SRT}, \textit{GPR}, \textit{MASW}, \textit{SP}, ....
  • Newly introduced and innovative adaptations to “older” methods: \textit{NMR}, \textit{automated time-lapse (4D) methods}, \textit{new joint inversion approaches}, \textit{cross-coupled parameters and flows} ....
Examples:
- Different Sites (2D)
- High Resolution
- Heterogeneity
- Complementary Methods
  - Also GPR, MASW, TDEM
- 2D and 3D

(Personal Communication, Ronald Kaufmann, 2008)
Broad Goals of Hydrogeology: Hydrogeophysics can Contribute to each Goal

• Define hydrogeologic regimes and Determine aquifer geometries: Micro- to Macro-Scale
• Determine fractured rock characteristics— faults/fissures and fluid circulation characteristics
• Gain knowledge of an aquifer's hydraulic properties— transmissivity, porosity, and permeability
• Determine water quality
• Monitor dynamic processes- seepage through the vadose zone, contaminant transport, drawdown of water table and piezometric surface due to pumping and drought conditions