INTEGRATION OF BOREHOLE INFORMATION AND RESISTIVITY DATA FOR AQUIFER VULNERABILITY

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ABSTRACT

We present a concept that integrates geological borehole information with geophysical resistivity information to produce optimized clay thickness maps. Geostatistical estimation and non-linear inversion are used to optimize a function translating geophysical resistivity models to geophysical clay thickness. The concept minimizes the difference between reported clay thicknesses in boreholes and calculated clay thicknesses based on geophysical resistivity models. We call it geoStatistical estimation of Structural Vulnerability (SSV).

For sedimentary areas the cumulated clay thickness in the upper part of the subsurface is an important factor for the water infiltration speed and thereby the vulnerability of underlying aquifers to pesticides, nitrate etc.

Borehole information contains the most detailed information on the clay thickness, but most often borehole information is too sparse for the detail level required in actual mapping situations. However, the amounts of clay are also reflected in the resistivity of the sediments and thereby in geophysical data having resistivity as the physical measuring parameter. The geophysical data often has the desired spatial coverage (Christensen and Sørensen, 1998, Thomsen et al., 2004).

In short, the concept incorporates:

1. Clay thicknesses in boreholes cumulated for some interval with accompanying uncertainties.
2. Layered models obtained from inversion of geophysical data including parameter uncertainties.
3. A spatial interpolation (kriging) from the positions of the geophysical models to the positions of the boreholes. The uncertainties of the geophysical clay thicknesses, originating from the geophysical models, are carried through the interpolation together with the uncertainty on the interpolation itself.
4. A non-linear inversion scheme minimizing the difference between observed clay thicknesses and calculated clay thicknesses

The concept has been employed in a couple of vulnerability mapping campaigns in Denmark with promising results. We show an example in which SSV was used to produce an optimized geophysical clay thickness map. The optimized map greatly improved the overview of the data and it improved the basis for decisions regarding the area planning.

1. INTRODUCTION

The accumulated clay thickness in the upper part of the subsurface plays an important role for the infiltration speed of water. Often, the clay content is the dominating factor determining the infiltration speed in sedimentary areas because, roughly speaking, sand and silt formations are permeable while clayey formations are impermeable. Furthermore, the clay content of a formation has a considerable influence on the resistivity of the formation. Thus, with some caution, we can use the resistivity as an indicator of the clay content.

A simple weight function translating resistivities to clay thickness is shown in Figure 1a. All resistivities below 60 ohm-m are considered *clay* and all resistivities above 60 ohm-m are considered *not-clay*. This means that a 5 m thick layer with a resistivity of 40 ohm-m is equal to 5 m geophysical clay. Similarly, a 5 m layer with a resistivity of 70 ohm-m equals 0 m geophysical clay. More complex weight functions including a transition zone between *clay* and *not-clay* are shown in Figure 1b and c, but essentially they do the same. All weight functions are fully described by the two parameters called *Upper* and *Lower* in Figure 1, in which case the weight function in Figure 1a is a special case of that in Figure 1b. The smooth weight function in Figure 1c is based on the error function and in this case the lower and upper values are defined having weights of 0.975 and 0.025 respectively.

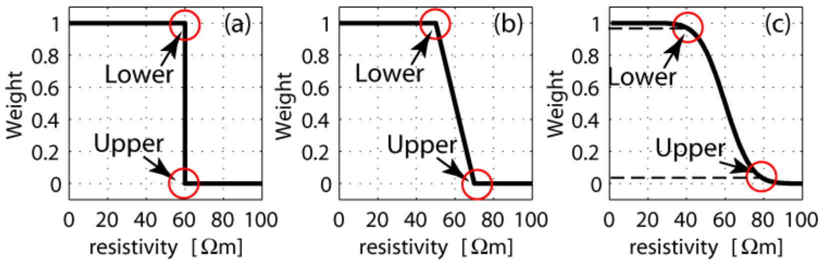

FIGURE 1. Weight functions translating resistivity to clay content. The function in (a) defines resistivities lower than 60 ohm-m as clay and resistivities above 60 ohm-m as not clay. The model in (b) includes a transition zone between clay and not clay. The model in (c) is a smooth version of the function in (b). The functions are in all cases defined by the *Lower* and *Upper* parameter marked with the red circles.

With a simple weight function as the ones above we can translate layered resistivity models to (geophysical-) clay thickness, GCT:

$$GCT = \sum_{i=1}^{N} W(\rho_i) \cdot t_i \qquad (1)$$

where $W(\rho_i)$ is the weight of the resistivity in layer i with thickness t_i. N is the number of layers. Often the clay thickness is calculated only down to some specific depth, e.g. 30 m, in which case only layers that are fully or partially in that interval are used.

Having defined the geophysical clay thickness we can make a sketch of the central principle of the SSV concept, as shown in Figure 2.

The concept consists of three main parts:

1. Clay thicknesses in boreholes cumulated for some interval and accompanying uncertainties. This is the circle to the right in Figure 2.
2. Resistivity models obtained from inversion of geophysical data including the parameter uncertainties. This is the left circle in Figure 2.
3. A weight function translating geophysical resistivity models to clay thicknesses. This is the central circle in Figure 2. The weight function is combined with a spatial

interpolation (kriging) taking the calculated geophysical clay thicknesses from the geophysical measurement locations to the locations of the boreholes for comparison.

The main target is to minimize the difference between geophysical clay thicknesses obtained from the geophysical resistivity models and the clay thicknesses reported in boreholes. This point of maximum consistency is obtained by updating the weight function in a non-linear inversion scheme to produce the Best Linear Unbiased Estimate (BLUE).

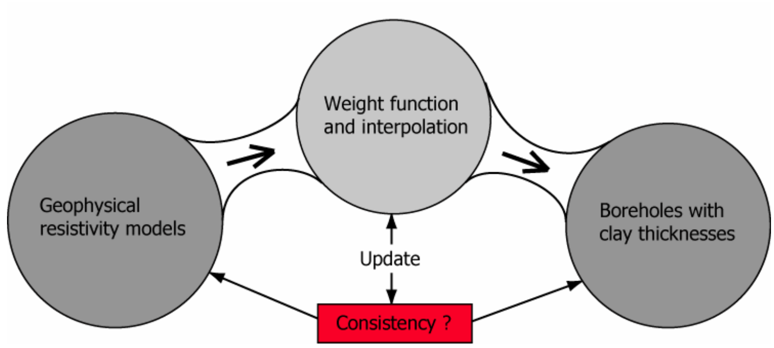

FIGURE 2. Principle of the SSV concept. The geophysical models are correlated with the clay thicknesses described in boreholes through a weight function and spatial interpolation. The main idea is to optimize the weight function in an inversion routine minimizing the difference between the borehole clay thicknesses and the geophysical clay thicknesses.

2. METHODOLOGY

The backbone of the SSV concept is an iterative non-linear inversion scheme developed for inversion of geophysical data (Auken and Christiansen, 2004) combined with the geostatistical interpolation method, kriging (Pebesma and Wesseling, 1998).

In short, we minimize the quality function, Q:

$$Q = \left(\frac{1}{\mathrm{Nd}} \sum_{i=1}^{\mathrm{Nd}} \frac{\left(\mathbf{d}_{\mathrm{obs},i} - \mathbf{d}_{\mathrm{for},i}\right)^2}{\mathrm{var}(\mathbf{d}_i)} \right)^{\frac{1}{2}} \tag{2}$$

where Nd is the number of boreholes, $\mathbf{d}_{obs}$ are observed data (reported clay thicknesses in boreholes), $\mathbf{d}_{for}$ are the geophysical clay thicknesess at the locations of the boreholes and var(**d**) holds the combined variances of:

1. the cummulated clay thicknesses reported in boreholes. This is estimated by the person describing the borehole
2. the geophysical clay thicknesses originating from the variance on the parameters in the geophysical resistivity models in turn originating from the data error.
3. the spatial interpolation taking the geophysical clay thicknesses from the geophysical locations to the locations of the boreholes.

The model parameters of the inversion procedure are the two parameters of the weight function translating geophysical models to geophysical clay thicknesses (Figure 1). In order to represent variations in the geology, the weight function parameters (the model parameters) are assigned to node points in a grid covering the survey area. The density of the grid is determined by the user reflecting the complexity of the desired solution. Model values between node points are obtained with bi-linear interpolation from surrounding node points. The model space is furthermore regularized with soft constraints between neighboring nodes.

The model update, δ**m,** at the n'th iteration can be written as:

$$\delta\mathbf{m}_{\text{BLUE}} = \left(\mathbf{G}^{\text{T}}\mathbf{C}^{-1}\mathbf{G}\right)^{-1}\mathbf{G}^{\text{T}}\mathbf{C}^{-1}\delta\mathbf{d} \tag{3}$$

where **C** is the covariance matrix holding variances as described above, and δ**d** is the difference between forward data and observed data.

In the end, the non-linear inversion outputs the model (weight function) that produces the smallest misfit between described clay thicknesses and geophysical clay thicknesses. This weight function can then be applied to the geophysical models to produce an optimized geophysical clay thickness map.

Uncertainties are handled throughout the system providing the end user with an uncertainty map for each parameter map produced. Obviously, a map of the uncertainty of the clay thickness is just as important as the clay thickness map itself. Thus, the uncertainty maps enable thorough evaluation of the results obtained from the SSV, strengthening the basis for decision-making in the survey area.

The suite of parameter maps combined with accompanying uncertainty maps provides an overview of hundreds of boreholes and tens of thousands of geophysical data sets and. Areas were boreholes are incongruent with the geophysical data are easily identified as well as areas were the borehole information are in agreement with the geophysical data.

3. FIELD EXAMPLE

This field example is from a 40 km^2 aquifer vulnerability survey in Denmark. The survey was carried out by the County of Vejle. The geophysical data considered is geoelectrical data obtained with the PACES system (Sørensen, 1996), having 8 electrode configurations, mapping resistivities to depths of 20-25 m. A total of 200 km PACES profiles were collected (approx. 20,000 soundings). The accumulated clay thicknesses to a depth of 20 m were described by a geologist in 137 bore holes.

Figure 3 presents the data and model setup of the field survey. The blue stars indicate node points in the model grid. In this case the model grid has 8x8 nodes each holding two model parameters (upper and lower cut-off parameters) giving a total of 128 model parameters. The model space is constrained using soft constraints between node points.

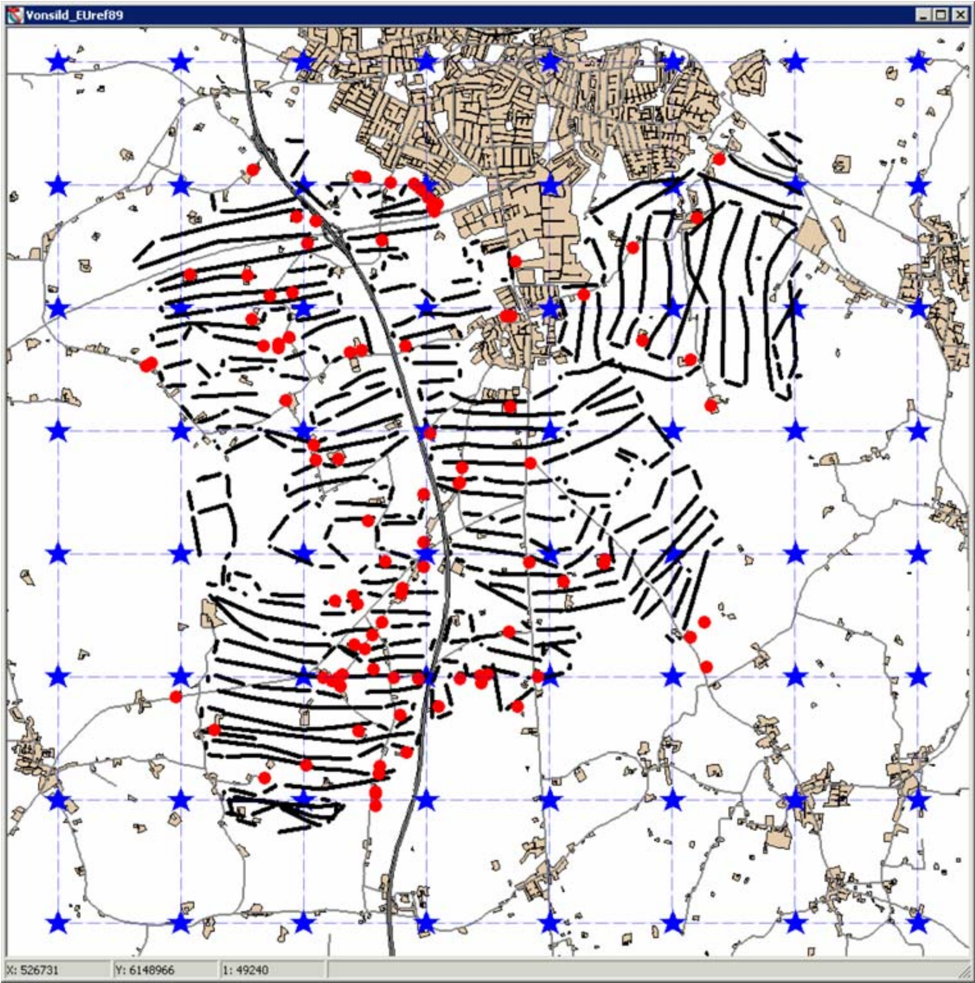

FIGURE 3. Survey area overview. Boreholes are marked with a red dot, the PACES soundings are marked with black dots (appear as lines), and the grid nodes are marked with a blue star. The distance between nodes in the grid is 1500 m. A small city is seen to the north in the survey area.

Figure 4 shows the value of the *upper* model parameter (as in Figure 1c) after application of SSV. The map shows that the cut-off value has been altered by the SSV to make a better fit between the geophysical models and the clay thickness described in drill holes. Furthermore, the northeastern part of the survey area has higher cut-off values for the weight function than the southwestern part.

Figure 5 shows a map of the geophysical clay thickness based on the optimized model parameters shown in Figure 4. The area reveals some very sharp boundaries between areas with a thick clay cover and areas with a thin clay cover.

The map has dominating areas of both very small geophysical clay thickness and clay thicknesses close to 20 m. The map of geophysical clay thickness will be used for establishing specific groundwater protection zones (Thomsen et al., 2004).

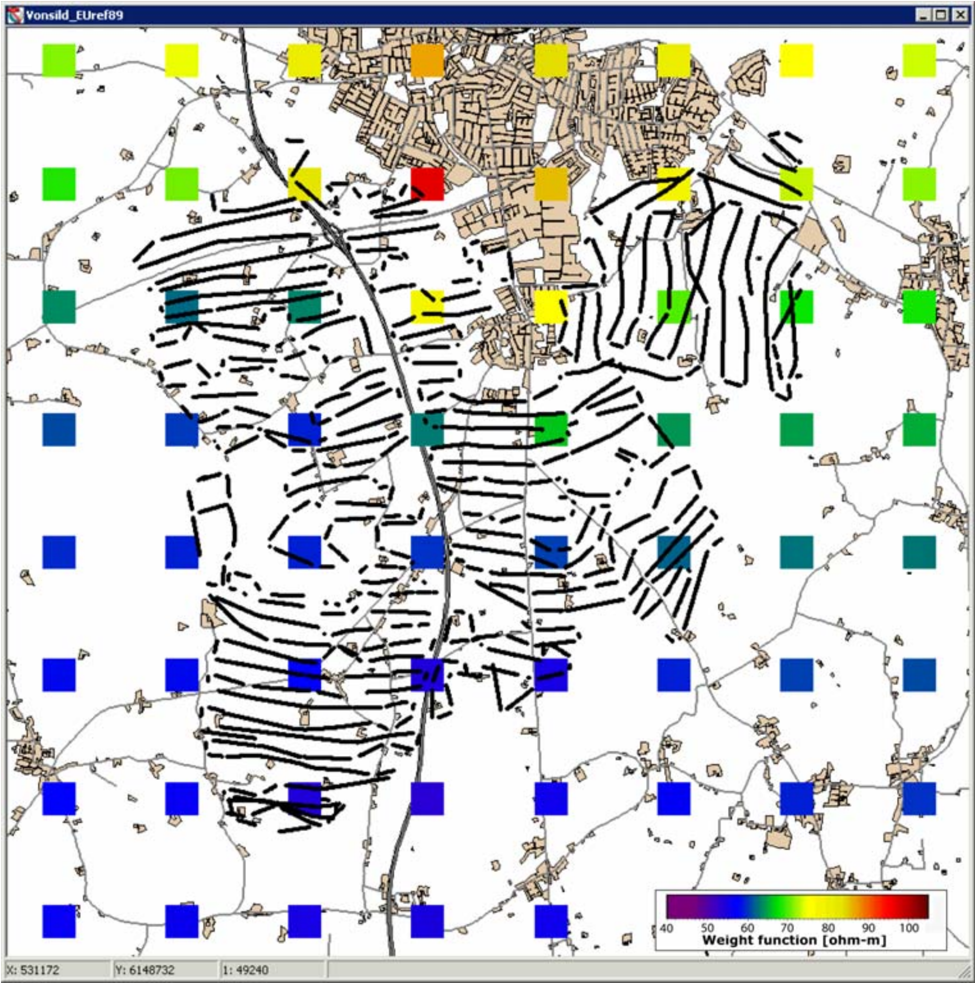

FIGURE 4. The upper cut-off model parameter of the weight function after application of SSV. The distance between nodes in the grid is 1500 m.

4. CONCLUSION

The SSV concept integrates geological borehole information with geophysical resistivity information to produce optimized clay thickness maps. The concept is based on a non-linear inversion scheme and the geostatistical interpolation method kriging.

The SSV can be seen as an objective interpolator between the geophysical and geological information available for a survey area.

On output the SSV produce an optimized clay thickness map that gives an overview of thousands of soundings and possibly hundreds of boreholes. Areas with a poor fit between the borehole information and the geophysical data are easily identified as well as areas were the data sets are in agreement with each other.

Uncertainties are handled throughout the system providing the end user with an uncertainty map for each parameter map produced. The uncertainty maps enable thorough evaluation of the results obtained from the SSV strengthening the basis for decision-making in the survey area.

REFERENCES

Auken, E. and Christiansen, A. V., 2004, Layered and laterally constrained 2D inversion of resistivity data: Geophysics, 69, 752-761.

Christensen, N. B. and Sørensen, K. I., 1998, Surface and borehole electric and electromagnetic methods for hydrogeological investigations: European journal of environmental and engineering geophysics, 3, 75-90.

Pebesma, E. J. and Wesseling, C. G., 1998, Gstat: A Program for geostatistical Modelling, Prediction and Simulation: Computers & Geosciences, 24, 17-31.

Sørensen, K., 1996, Pulled Array Continuous Electrical Profiling: First break, 14, 85-90.

Thomsen, R., Søndergaard, V. H., and Sørensen, K. I., 2004, Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark: Hydrogeology, 12, 550-562.

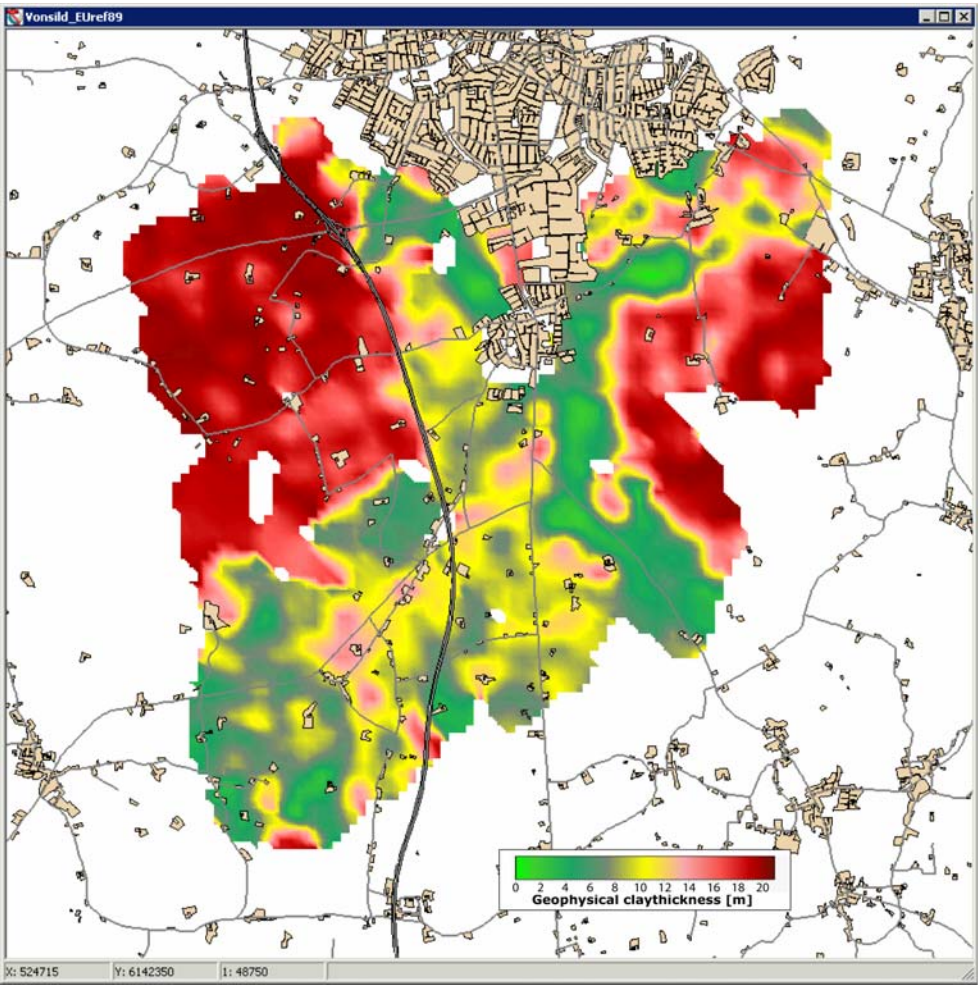

FIGURE 5. Optimized clay thickness map. Red colors indicate thick clay cover, whereas green colors indicate thin clay cover.