Uncertainty assessment of geological models – a qualitative approach

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Abstract Geological models are often used in assessments of groundwater resources and groundwater vulnerability and often in connection with numerical groundwater models. As the uncertainties of the geological models most likely will affect the results of the subsequent calculations and assessments it is important to describe the uncertainties related to the geological model. A comprehensive assessment of the uncertainties of the geological model is, however, a complicated task. The nature of the datasets included in the geological model is normally very heterogeneous and every dataset has uncertainties of its own. In addition to this, the geological interpretations performed during the geological modelling have a high degree of subjectivity. As quantification of the uncertainties of the geological model as a whole is complicated, a simple method for qualitative assessment of the uncertainty of the geological model is proposed. The method takes the uncertainties related to the datasets, the density of data points as well as the uncertainties related to the geological interpretations into consideration.
Keywords geological models; groundwater; qualitative uncertainty assessments; groundwater models

INTRODUCTION

The construction of geological models includes use of several different datasets, each with their own uncertainties. When combining these datasets, uncertainties related to the geological interpretations are introduced in addition to the uncertainties of the individual datasets. Furthermore the differences in data types and data density will consequently lead to a geological model with a very varied uncertainty within the model area. When geological models are used as basis for subsequent assessments and calculations, the uncertainties will consequently affect the results. In recent years, strategies for uncertainty assessments of data and model structure have been proposed for models used in connection with environmental and groundwater resources (Refsgaard *et al*., 2006; Nilsson *et al*., 2007). Geological models, however, need special attention because of the high degree of embedded subjectivity.

A quantification of the uncertainties may be carried out on the individual datasets. But a quantification of the uncertainties of the geological model as a whole requires an assessment of contributors to the uncertainty that can not necessarily be described numerically. Typically, the subjective aspect of the geological interpretations is so dominant, that it will overshadow the uncertainties related to the datasets. A quantification of the uncertainties would be preferable because we thereby get an opportunity to perform automated calculations of the uncertainties. A quantification of the uncertainties of each dataset can be performed objectively by determining the uncertainties related to equipment, sampling, data interpretation etc. But when interpreting the geology of the area, different data types are combined and a high degree of subjectivity is introduced by the geologist. In the interpretation process, the uncertainties of the individual datasets are not additive, creating a higher model uncertainty. On the contrary, as the datasets typically support each other, the uncertainty of the model as a whole will most likely attain a lower degree of uncertainty. The subjectivity of the geological interpretations is crucial when drawing the layer boundaries in the geological model. A quantification of the uncertainty of the geological model is therefore practically impossible to perform.

A METHOD FOR ASSESSMENT OF THE QUALITATIVE UNCERTAINTIES OF GEOLOGICAL MODELS

When performing geological interpretations decisions are made based on a combination of the data and knowledge of the geology of the area. The interpretation of a certain layer in a borehole has an uncertainty related to the quality of the borehole data from that particular borehole. But the most important part of the geological interpretation is the lateral correlation of the layers and layer boundaries between the boreholes along the profile. Should a specific layer be correlated with, for instance, an upper layer with a comparable lithology in the adjacent borehole or with a layer in the lower part of the borehole also showing a comparable lithology? These interpretations - these choices - are highly subjective.

Because of the difficulties related to quantification of the model uncertainties, it is proposed that assessments of uncertainties of geological models focus on a qualitative approach. The method described in the following is simple and is centred on a qualitative assessment and a visualisation of the uncertainty of the geological model along the individual geological profiles. In this way, the uncertainties are communicated to users of the geological model, providing for example the groundwater modeller with a geographical overview of the varying uncertainty of the geological model.

The method is in the following exemplified using a profile-based geological model with profiles arranged in a regular and evenly spaced network. This simplifies the method as no bias is introduced while placing the profiles.

Before performing the uncertainty assessments, all datasets should be thoroughly controlled in order to minimise the uncertainties related to the individual dataset. Erroneous data is deleted, poor quality data evaluated and a description of the general data quality is made.

The assessment of the uncertainties of the geological model is performed after the modelling is completed. The geological model normally comprises a network of profiles with geological interpretations, layers and layer boundaries applied to each profile. A qualitative assessment of the uncertainty of the geological interpretation as a whole is performed along each of the geological profiles. Accordingly, the assessment reflects the geologist's own evaluation of the reliability of the model interpretation along the profile.

The uncertainty assessment along every profile is visualised on a map and thus giving an overview of the area as a whole. In this way the uncertainty assessment comprises the data uncertainties as well as the uncertainty of the geological interpretations and the assessment is illustrated in direct association with the used data. The degree of uncertainty is split into a number of intervals and drawn onto the profiles as coloured or shaded bars above the profile:

- <u>Light grey/Low uncertainty:</u> Low uncertainty of the geological model interpretation. An adequate amount of reliable data ensures that a credible geological interpretation can be made. The data can stand alone and the interpretation is not dependent on data from adjacent areas.
- <u>Grey/Intermediate uncertainty:</u> Intermediate uncertainty of the geological model interpretation. A limited amount of data and/or lower data quality. The geological interpretation is to a certain degree made on the basis of information from adjacent areas and from indirect information such as topography or wellhead measurements.
- <u>Black/High uncertainty:</u> High uncertainty of the geological model interpretation. No or only a limited amount of data and/or poor data quality. The geological interpretation is primarily based on extrapolations from adjacent areas.

The uncertainty assessments are relative and the used intervals should be adjusted to the area in question in order to obtain a suitable description of the variations. Apart from varying geology the individual geological models will also vary in purpose, degree of detail, data types etc. Therefore it is not necessarily possible to compare uncertainty assessments of different geological models.

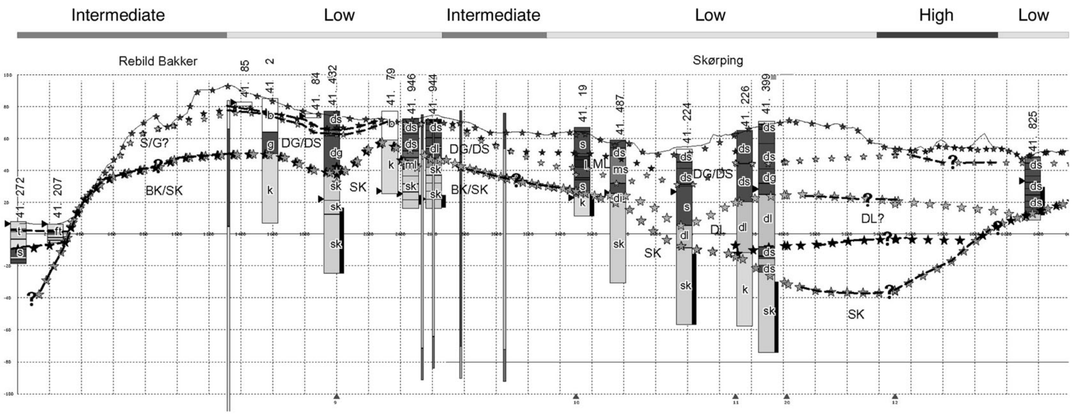

Fig. 1 Qualitative uncertainty assessment inserted as greyscale bars above profile the geological profile. Broad vertical bars=boreholes; narrow vertical bars=TEM soundings; stars=layer boundaries. Example from: Watertech (2006) Geological model of the Skørping-area. Performed for the County of Nordjylland.

An example of an uncertainty assessment of a geological model where the above mentioned uncertainty intervals have been used is shown in Fig. 1. The geological profile is one of a series of profiles where the uncertainty assessment is an expression of the geologists own evaluation of the uncertainties related to the geological model interpretation along the profile. The primary data sets in the geological model are borehole data (broad vertical bars) and geophysical TEM soundings (narrow vertical bars), whereas secondary information is obtained from topography and soil type maps. On the basis of these data a geological model consisting of a number of layers is constructed. The profile shows a 6 layer geological model interpreted using the data seen on the profile as well as geological interpretations from crossing profiles. The deepest layer (‘BK/SK’) is chalk/limestone and on top of this is a succession of quaternary sand and clay layers.

The uncertainty assessment of the geological model is visualised as grey scale bars above the profile on Fig. 1. In the middle of the profile the uncertainty is in two sections described as ‘low’ because an adequate amount of data ensures a reliable interpretation of layer boundaries and a reliable correlation between the boreholes. Between these two sections the uncertainty is described as ‘intermediate’ because the data density is lower and because the correlation of the layers above the chalk/limestone is uncertain. On the left side of the profile the uncertainty is ‘intermediate’ because the data density is limited and because the geological interpretations partly rely on geological interpretations from adjacent profiles, from topographical data and from other surface related information. In the right side of the profile there is a section with ‘high uncertainty’. In this section the depth to the depression in the chalk (‘SK’) as well as the thickness and lateral extension of the clay layer marked ‘DL’ are geological interpretations that have a high degree of uncertainty because the data density is low. As a consequence of this, the interpretation in this section is primarily based on extrapolation of interpretations from adjacent areas.

If uncertainty assessments, as shown in Fig. 1, are performed along all the profiles of the geological model an overview of the model area as a whole can be visualised on a map theme (see example in Fig. 2).

Using the same procedure, uncertainty assessments can be performed for e.g. specific layers, specific boundaries, the upper part or the lower part of the succession, depending on the purpose. The output is a series of individual uncertainty maps with varying focus. The qualitative uncertainty assessments can easily be visualised in GIS together with quantitative uncertainty assessments of specific datasets, map themes of spatial distribution of data, etc.

APPLICABILITY OF THE QUALITATIVE UNCERTAINTY ASSESSMENTS

The applicability of the qualitative uncertainty assessment is broad:

- Collection of supplementary data: As the uncertainty maps include an assessment of data density, it provides a basis for selecting areas where collection of supplementary data is required. Adding new data in areas with a high degree of uncertainty will increase the credibility of the geological model with every subsequent update.
- Ground water modelling: When the layers of the geological model are handed over to the groundwater modeller to be used in the groundwater model, they are accompanied by the uncertainty maps. The uncertainty assessments enable the groundwater modeller to get a geographical overview of the geologist's own evaluation of the geological interpretations. In this way, the groundwater modeller can more easily relate areas in the groundwater model with a poor fit between observations and predictions, to the uncertainty assessment of the geological model. This enables the geologist to put forth alternative geological models for specific sub areas pointed out by the groundwater modeller. In this iteration process the groundwater model most likely will contribute to a lowering of the uncertainty of the geological model and vice versa.
- Groundwater resource management: If assessments of groundwater vulnerability have been performed on the basis of the geological model and vulnerable areas have been delineated, the uncertainty assessments of the geological model can be used to evaluate the lateral extent of these areas. If, for example, a delineated vulnerable area coincides with an area of the geological model that has a low uncertainty, the boundary of the vulnerable area can be considered as well defined. If, on the other hand, a vulnerable area lies within parts of the geological model that has a high degree of uncertainty, the boundary of the vulnerable area will be less well defined. This is of great importance in connection with initiation of groundwater protection measures, as these tasks generally are very expensive. In this way, the use of the uncertainty assessments is not limited to quality assurance and documentation of the geological model, but can also be incorporated as a dynamic element in the administration of the groundwater resources.

CONCLUSIONS AND PERSPECTIVES

Even though the described method of qualitative assessment of geological models deals with a high degree of subjectivity, the method is directly useful in connection with groundwater modelling, groundwater resource evaluations and vulnerability assessments. The main reason for this is that it provides a geographically based visualisation of the geologists own assessment of the uncertainties and thus combines the varied types of uncertainties that are related to the geological model. The limitations of the method are primarily the subjective aspects. Therefore, it is crucial that a thorough documentation of the individual steps of the process is carried out. This documentation and the use of a profile-based assessment and visualisation make it easy for other workers to evaluate the model and perform later updates of both the uncertainty assessments and the geological interpretations.

If the total project comprising the construction of both the geological model and the groundwater model is handled as an iterative process with focus on obtaining the best correspondence between the models, the result will unquestionably be a lowering of the uncertainties of both model types.

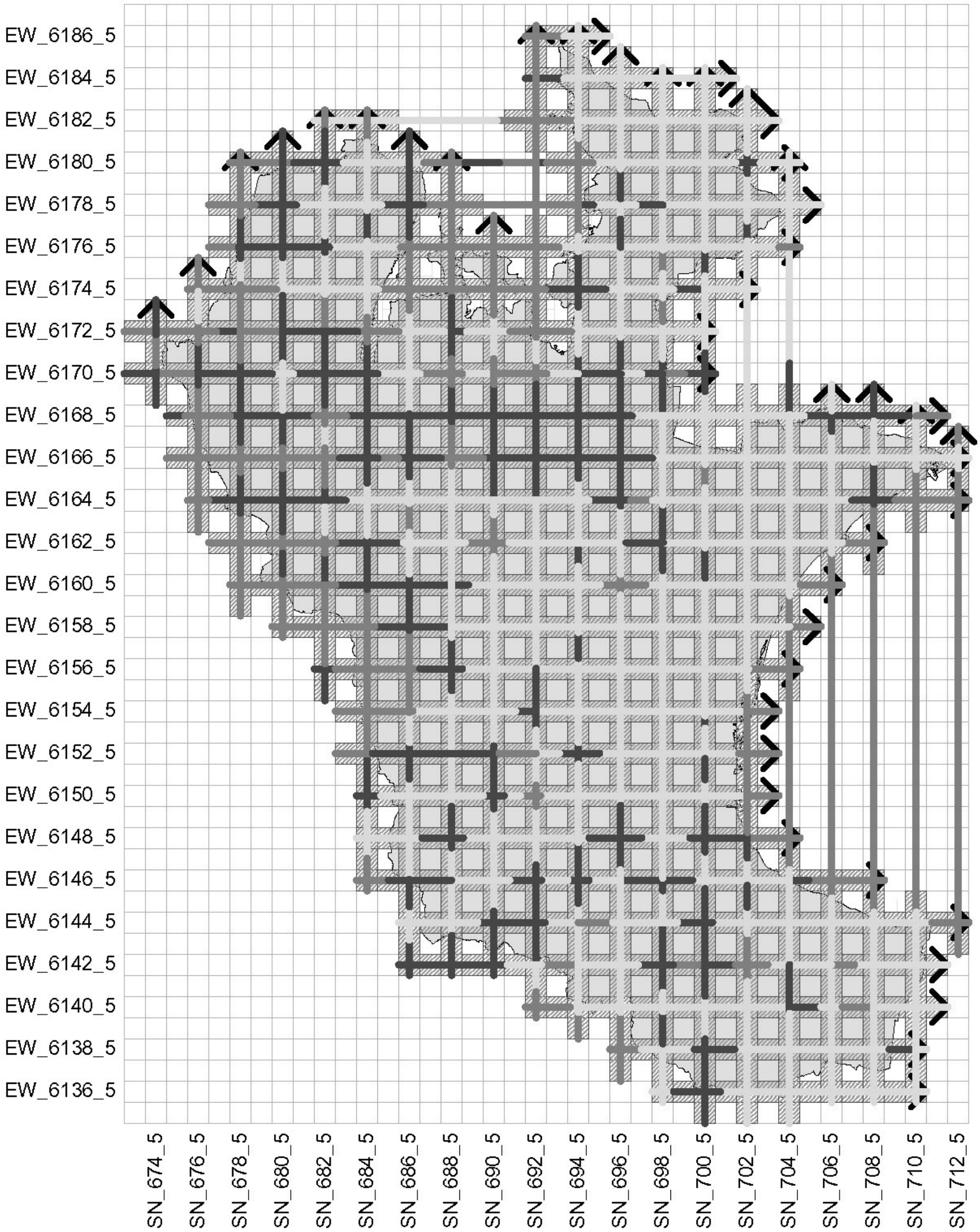

Fig. 2 Map theme of qualitative uncertainty assessments along geological profiles. (Please note that the grey scale of the uncertainty intervals deviate from the description in the text. The uncertainty intervals in this example are: Light grey=low, dark grey=intermediate, grey=high). Example from: Watertech (2006) Regional geological/hydrostratigraphical model of the County of Roskilde. Report 2. Performed for the County of Roskilde.

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