Risk Mapping of Groundwater Salinization Using Geographic Information Systems

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Abstract

Due to the increased withdrawal of groundwater in many areas in Sweden, the risk for groundwater salinization is increasing. As a tool for municipal planners to assess the risk the Risk Variable Method (the RV-method) has been developed. The method is an expert system where a number of statistically processed parameters are assigned weights and added together to a final risk value. When estimating the spatially distributed uncertainty for each specific parameter and adding the values together, after weights have been assigned, the final uncertainty value is a help to validate the risk value. An implementation of the RV-method into a GIS environment makes it possible to perform a study over extended areas. The major problem when working with the GIS implementation is the database creation, both the collection of data and the assurance of a proper database quality. If these problems are solved the RV-method implemented in a GIS is a powerful tool in assessing the risk for salt groundwater in municipal areas. However, the method has so far been developed for the natural conditions prevailing in eastern Sweden and adapting to other areas needs a careful selection of variables and their ratings.

Introduction

Salt groundwater is a widespread and serious problem in large areas of southern and central Sweden, especially along the coastal zone. The problem is described by Lindewald (1985) and Olofsson (1992 and 1994). Various sources of the salts have been proposed such as intrusion of seawater, fossil salt groundwater from ancient seas and anthropogenic sources such as de-icing salt along roads and leachates from waste deposits. The salinization problem has increased within the last decades mainly due to an increased discharge of groundwater particularly during the summer season along the coastal areas. The groundwater supply in these areas is today mainly based on limited water resources in crystalline rock and the water is usually extracted from private drilled wells, with depths sometimes exceeding 100 m. The rocks usually show a strongly heterogeneous and anisotropic character. The flow occurs along fractures and is strongly depending of their genesis, mineral filling and probably of the prevailing rock stress pattern. The heterogeneous hydraulic conditions can be illustrated by the situation in the archipelago of Stockholm, where drilled wells located close to the shore may be totally fresh, whereas wells far from the coastline may exhibit clear effects of salt water intrusion.

Risk assessments for salt groundwater

Up to today, no judicial tools for control of construction of wells and extraction of groundwater for ordinary households, have been available outside detailed planned areas in Sweden. However, the increased salinization problem in many municipalities of Sweden has raised the necessity for some types of permission for extraction of groundwater in areas with limited freshwater resources (Grundvattenutredningen, 1994). Hence, it has been necessary to develop methods for quantitative as well as qualitative risk assessments for salinization of groundwater. Since the assessment should be used within municipal planning among decision makers, it must be clear, easy understandable and reliable. Several approaches have been tested. Numerical methods using finite elements or finite differences, which is commonly applied to coastal zones, can hardly be reliable within the strongly heterogeneous and anisotropic hydraulic conditions prevailing in crystalline rock areas of Sweden.

One method, which frequently have been used in Sweden, is the *Water Balance Method*, in which the discharge of groundwater from wells is compared to an estimation of the groundwater recharge, calculated as a fraction of the annual precipitation (Sund & Bergman, 1980, Tilly-Leander, 1990). When the discharge equals or exceeds the recharge, salinization will occur in the long run. However, the method is incorrect since it does not take into consideration the storage capacity of the aquifer. The crystalline rock itself is a very small reservoir with a kinematic porosity usually less than 0.05% (Carson & Oslo, 1981, Olofsson, 1991), which can only store a minor part of the potential recharge. The main part of the annual precipitation is also usually restricted to the summer period (July-August) when the groundwater recharge probably is very small or negligible.

Several qualitative vulnerability assessments using information of the geological and hydrogeological conditions have been developed, such as the well known DRASTIC method (Aller et al 1987) and the LeGrand-method (LeGrand, 1983). However, these methods are static, developed for pollution sources placed on the land surface within geohydrological conditions which significantly differ from the conditions prevailing in Sweden. Moreover, they do not take into account the uncertainty within the assessments, as would be desirable within decision making situations. Therefore, a new method, the *Risk Variable Method* (the RV-method) was developed with inspiration from the DRASTIC method. It has been manually tested within the Värmdö municipality, in the archipelago east of Stockholm (Bucht & Larsson, 1995). This paper describes the first attempt to adopt the RV-method over extended areas within the Norrtälje municipality, north of Stockholm, using the GIS technique.

The Risk Variable Method - a short description

The RV-method is an expert system which takes into account and evaluates topographical, hydrological, geological and technical variables (Figure 1). The expert parts of the method (the preparation stage) comprise selection of variables and their ratings. This is done once within a region (such as for eastern Sweden). The selection of variables in Sweden was carried out by statistical analyses of water chemistry in drilled wells from the Well Record Section at the Geological Survey of Sweden (SGU) and from local municipal archives. The variables include topography, hydrology (precipitation etc.), geology (type of soil and rock, soil depth) and technical variables (degree of land utilisation, well depths etc.). Finally, zonation factors are added, such as distance to the shoreline and distance to roads on which de-icing salts are used. The variables are subdivided into classes with variable risk values between +2 and -2 (where positive values mean that the variable decreases the risk for salinization). The variables have ratings varying between 1 and 3.

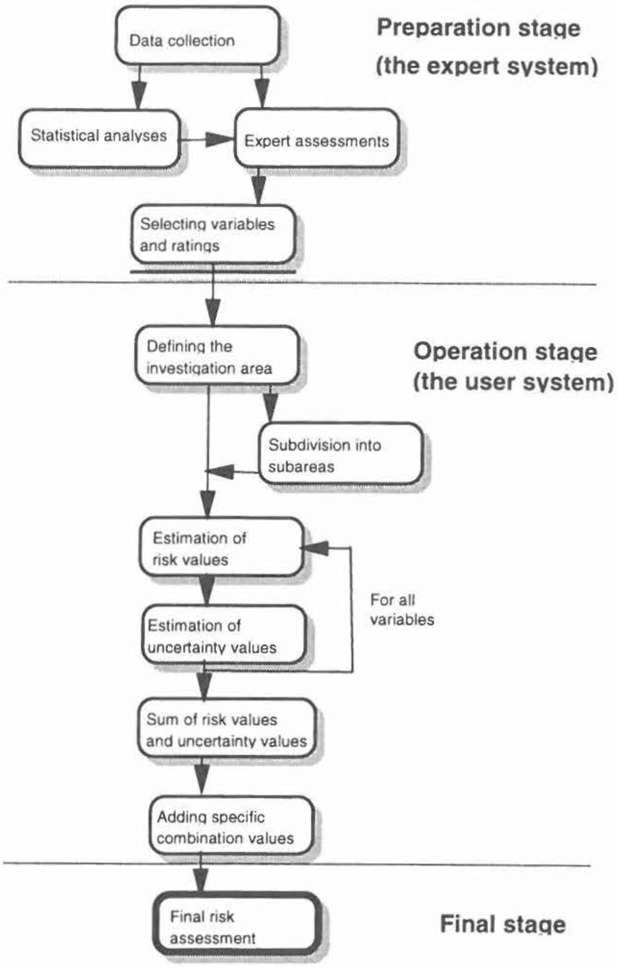
$$V_1 \times R_1 + V_2 \times R_2 + V_3 \times R_3 + \ldots + V_n \times R_n = \sum_{i=1}^{n} V_i \times R_i = FRV\ (\mathit{Final\ Risk\ Value})$$

where V_i = a risk value for a specific variable (-2 to +2) and R_i = the rating of the variable (1 to 3).

For each variable the operator also gives a value of the uncertainty within the classification of the variable. The uncertainty values vary between -1 and +1, where negative values represent a high degree of uncertainty. The uncertainty values are handed in a similar way as the variable values.

$$U_1 \times R_1 + U_2 \times R_2 + U_3 \times R_3 + \ldots + U_n \times R_n = \sum_{i=1}^{n} U_i \times R_i = FUV\ (\mathit{Final\ Uncertainty\ Value})$$

where U_i = an uncertainty value for a specific variable (-1 to +1) and R_i = the rating of the variable (1 to 3).



Name of variable	*Rating*
Natural variables	
Precipitation	1
Slope	3
Soils	2
Thickness of soil cover	2
Regional fracture zones	1
Local fracture frequency	1
Technical variables	
Well depth below sea level[a]	2
Degree of land utilisation	2
Localisation of discharge wells	2
Sanitary standard	3
Zone factors	
Distance to shore[a]	3
Distance to lakes	2
Distance to wetlands	1
Distance to main road	2
Distance to other salt sources	2

[a] not used in this study

Figure 1. Principal sketch of the Risk Variable Method and a tabulation of the different variables used in eastern Sweden.

Summation of the risk values and the uncertainty values gives the final risk value (FRV) and the final uncertainty value (FUV). However, some combination effects occur, which significantly increase or decrease the salinization risk. Hence the final risk value is adjusted for such effects, by using Specific Combination Values. The FRV and the FUV values can be plotted within the scattered bi-plot in Figure 2, where the axis represent the salinization risk and the uncertainty.

It must be clearly pointed out that the variables and ratings selected within this project and presented in Figure 1, only represent the most important factors for eastern Sweden. Adapting the RV-method to other areas with significantly different natural as well as technical conditions, needs careful selection of variables and ratings.

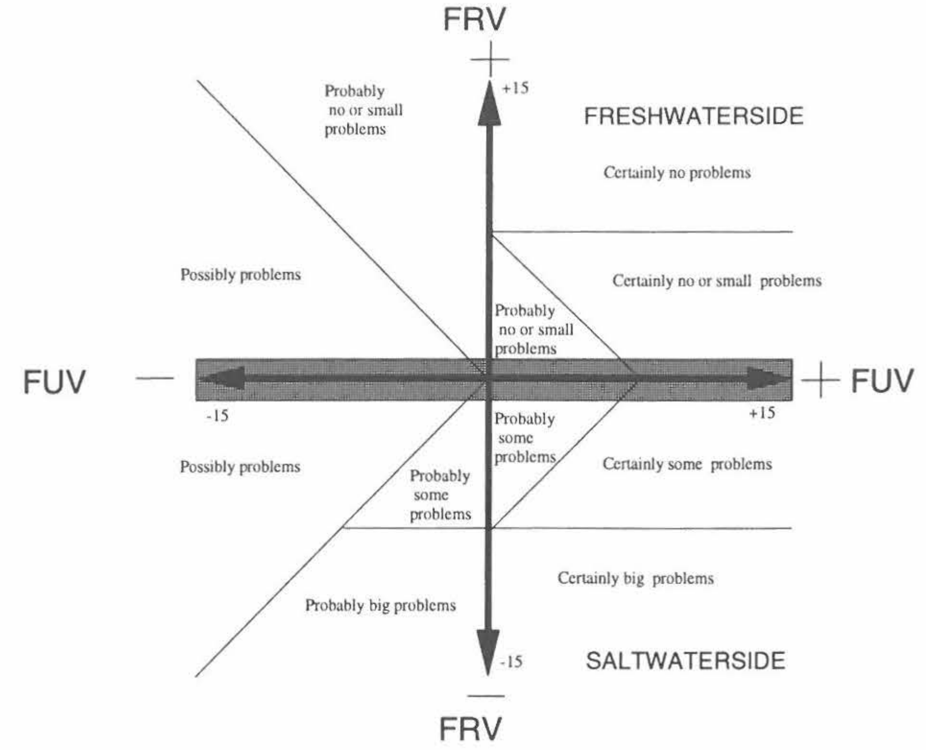


Figure 2. Principal graph for salt water risk analysis

The investigated area

The study was carried out within the south-eastern part of the Norrtälje municipality, in the County of Stockholm, Sweden (Figure 3). The study area has a size of 341 k^{m2}. The geology in the study area is representative for the region with hard crystalline rock which forms a hilly topography and soil layers of varying thickness. In the bottom of the narrow valleys a layer of post-glacial clay is overlaying the till that is found along the slopes. On the tops there are outcrop or just very thin layers of till. The area was covered by ice during the latest glacial period and has since then been surged by waves while the land has progressed from the sea. The area is sparsely populated with single houses and farms spread all over the area. There are also a few places or gatherings of houses within the area. The water supply is mainly based on private dug or drilled wells.

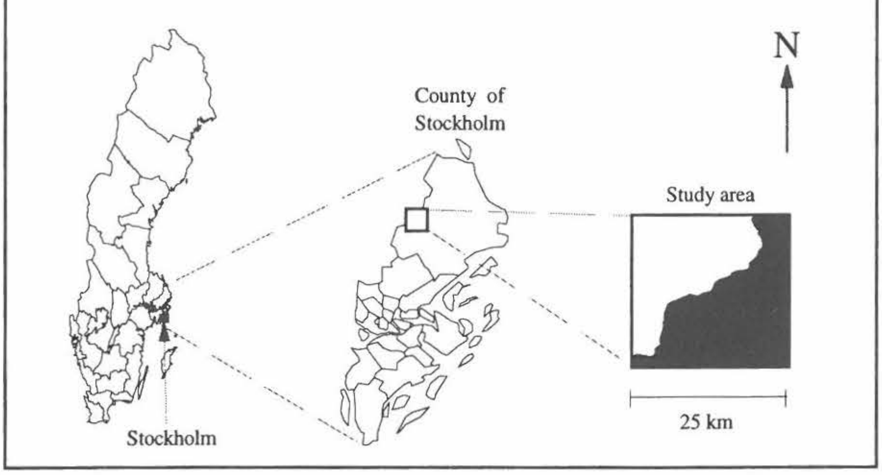


Figure 3. The study area.

The GIS-technique

Geographic Information Systems (GIS) is a tool for input, storage, resampling, analysing and presentation of spatial distributed digital data. During the last ten years the technique has developed very quick, mainly as a result of the progress in the development of computers. Another reason, and pre-requisite, for the rapid development of GIS is the availability of databases. This has so far been the major bottle neck for most people working with GIS, as it is expensive and tedious to transform data into digital form, but also because of problems due to transformation between different data storage formats. GIS software can be divided into two major categories that principally differ from each other in the way of storing and handling data. In a *raster based* system each map layer is built up of picture elements (pixels) that are small squares with a specific spatial resolution (the length of the square side), oriented in a regular grid. Each pixel is assigned a value that describes the property (e.g. soil class) or magnitude (e.g. altitude in a topographic map) of the area that is represented by that specific pixel in the map layer. A *vector based* system is based on vectors (points, lines or polygons) to which data bases with attribute data are coupled.

In this study a raster based GIS (IDRISI) has been used for implementation of the RV-method. The major part of the input data has been supplied as MapInfo files (vector based GIS). All data has been transformed to IDRISI-format with a spatial resolution of 50 m.

Database creation

For this project data has been supplied by SGU (soil map and data from the Well Record Section, e.g. well localisation, well depth and thickness of soil layers in the drilled wells), the National Land Survey of Sweden (Digital Terrain Model (DTM) and landuse map) and the Norrtälje municipality (data about sanitary standard, degree of land utilisation and delineation of areas with municipal responsibility for fresh water and waste water). The way to create the database for the project is described in the following. Figure 4 shows three different maps used in, or produced by, the process; a) DTM, b) soil map, c) map showing soil depth.

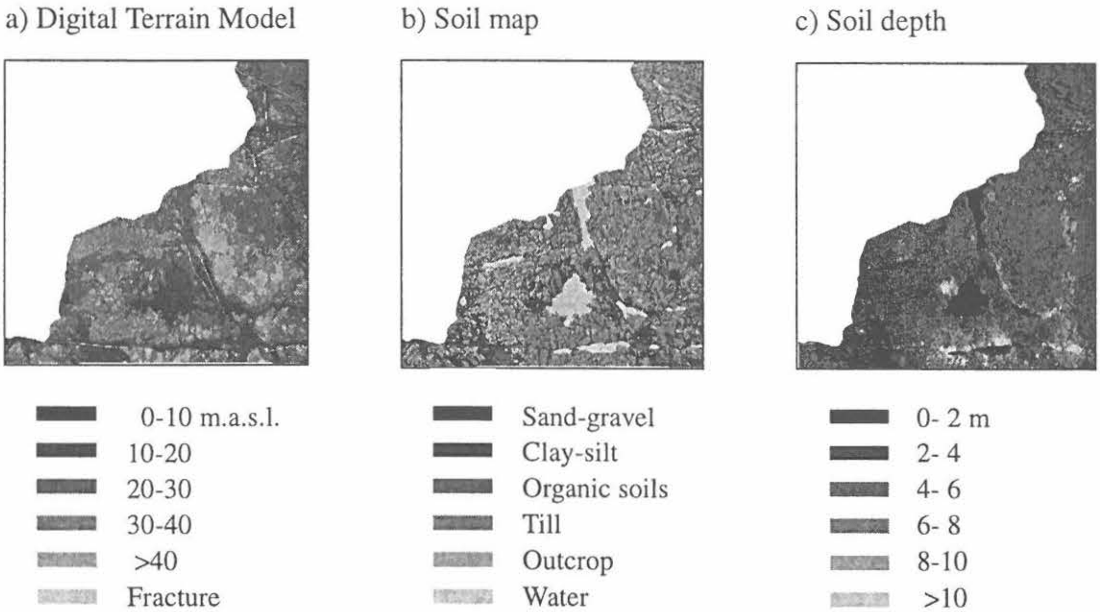


Figure 4. Maps showing a) Digital Terrain Model, b) soil cover and c) soil depth in the study area.

To calculate the *slope*, IDRISI has been used to process the DTM. The *soil* map has been reclassified to match the classes defined for the RV-method. To model the *soil depth* the soil map has first been classified into five classes (sand-gravel, clay-silt, organic soils, till and outcrop). Secondly, statistics about well depth has been extracted for wells situated in the different soil classes. This statistics has acted as a rule to assign a value of soil depth to each soil class. Parallel to this, an aerial interpolation has been performed using IDRISI with well depth as input data. These two maps has finally been combined by calculating the arithmetic mean value for each pixel to be used as a value for soil depth. The *regional fracture zones* have been digitised into IDRISI from the hydrogeological map (Engqvist & Fogdestam, 1984). To get a map layer describing the *local fracture frequency* a rock map has been digitised in the same way as for regional fracture zones and reclassified with respect to local fracture frequency according to information in the description to the hydrogeological map.

To produce a map for the *degree of land utilisation*, areas classified as built-up areas (high and low exploited) and industrial areas have been extracted from the landuse map and reclassified according to the RV-method. The input data for the *spatial distribution of discharge wells* has been the Well Record Section at SGU. On-screen digitising has been performed to sort out areas with a homogeneity in the spatial distribution of wells. A map for *sanitary standard* has been created by using and reclassifying the landuse map in combination with information about areas where the municipality is responsible for delivery of fresh water and treatment of waste water. *Distance to lakes* and *distance to wetlands* have been estimated by buffer analyses. Separate maps have been created for the *distance to roads* (that are treated with de-icing salt during the winter) and the *distance to other salt sources* (a landfill).

Two important parameters (in general) when assessing the risk for salt groundwater that do not affect the result in this study is the *precipitation* and the *distance to shore*. As there is no difference in precipitation within the area this parameter does not affect the result and as the study area is not a coastal area that variable has been excluded in this study.

Results

The resulting risk map from the RV-method implemented in a GIS is presented in Figure 5.

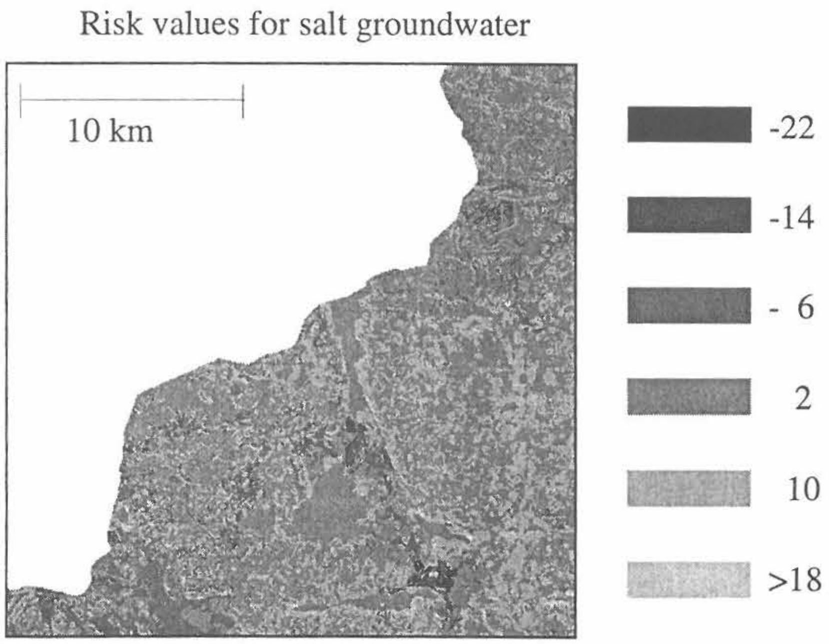


Figure 5. Risk map for salt groundwater.

This resulting map is simply produced by assigning the specific weight to each parameter before adding them together. The RV-method is a dynamic method in the sense that it allows the user to add or take away parameters that is not relevant for the actual study. In this study a parameter describing the well depth has been excluded as it is a site specific parameter without spatial distribution. In some cases it may though be interesting to take this parameter into consideration, for instance if the risk for salt groundwater will depend on the well depth when planning for drilling or dugging of new wells. Such an example is presented in Figure 6, where the risk value is presented for three different well depths; b) 40-70m, c) 0-10m and d) >90m.

From Figure 6b-6d it can be seen, using (b) as a reference that the risk in general decreases with smaller depth and increases with larger depth. In the shallow well (c) the increased risk along the diagonal linear structure in the centre of the image, that in practice is a road treated with de-icing salt during the winter and located on a sandy soil, is a result of a specific combination of parameters. Due to the conservative salt and the high hydraulic conductivity of the sand, the risk for finding salt groundwater in a shallow well in areas close to the road increases. In the other parts of the image the risk is lower due to the decreased withdrawal of groundwater from the rock aquifer. In a deep well (d), the risk is higher (in general) to find fossil salt groundwater and also to get an intrusion of seawater, and so the RV-method come up with a higher risk value.

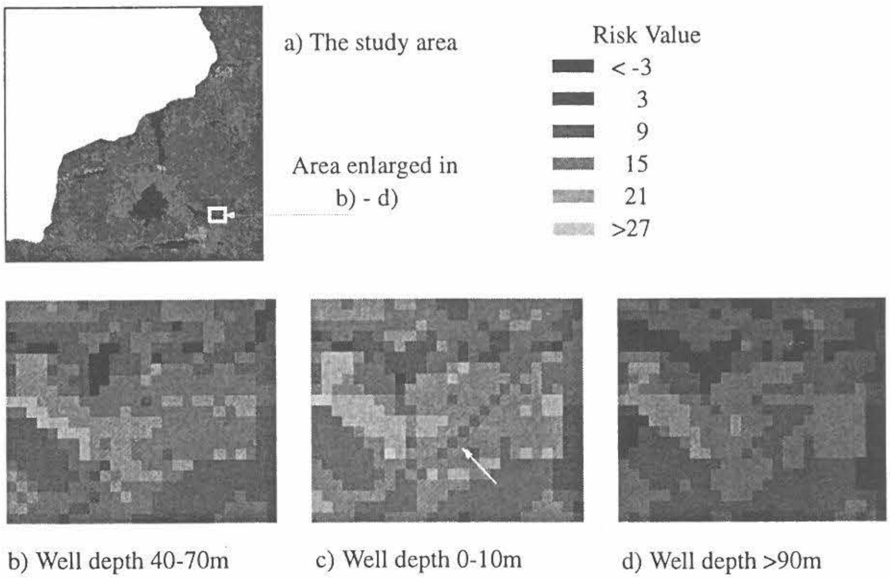


Figure 6. The risk value as a function of well depth. Figure 6b-6d are enlargements of the marked area in Figure 6a (pixelsize = 50 m).

Discussion

As expected, the creation of databases has been the major bottle neck in implementing the RV-method into a GIS. The problems have been of two major characteristics; problems due to transformation between different data storage formats and problems due to collection of data. In the first case it has mainly been technical problems including struggling with software and searching for existing modules able to transform a data set from one format to another. In the last case the problems have been related to questions of database quality. How much effort should be put in the construction and preparation of databases? The database quality is essential when working with GIS as the output will never be of higher quality than the input. This may sound basic but is important to keep in mind, especially when the risk map is to be used by politicians and decision makers that are not familiar with the new technology and its possibilities and limitations. When determining the quality of the input data, there are mainly two factors affecting the result; the reliability of the input data source and the spatial resolution, as it decides the proper scale for the decision support tool.

Another problem that is still to be solved is how to model the soil depth for an area. This parameter is important for the analysis as it is limiting for the storage of groundwater. If the input point data (as point vectors) is dense enough and evenly spread all over the area it would be possible to use the GIS for a simple area interpolation or kriging, but as this is not the case in the data used for this project, as well as for most other projects, the problem must be solved in an other way. One attractive way is to develop some kind of knowledge based/ruled system that combine knowledge about the regional topographical structures with detailed elevation data and data about thickness of soil. If it is possible to construct a filter for image processing that could recognise major structures in the topography, information about soil depth in different parts of the terrain (valleys, slopes and hills) could be coupled to it, and a final map of soil depth could be produced.

A coupling of the risk value to an uncertainty value is a way to improve and secure the quality and the reliability of the result. It is also a way to make users not familiar with the information technology aware of the uncertainties that is included in the result. Another advantage with the uncertainty value is that it can be used as a support for planning further investigations, for instance collecting of new data or improving the quality of existing data.

When working with collection of input data, it is of course important to make use of all different kinds of information available (maps, technical reports, municipal plans etc.). Another important source of information is people with local knowledge as officials at the local authorities and people living in the study area. Their knowledge about site specific parameters like sanitary standard (water consumption) and degree of land utilisation can normally not be substituted by other information sources.

The raster based technique has proved to be powerful in the analysis as in many other applications coupled to management of natural resources. Anyhow, in a further development of the technique and as a final product, it must be possible to use a vector based GIS as ArcInfo or MapInfo instead of IDRISI, as they are totally dominating the market, especially among local and regional authorities.

Conclusion

To combine the RV-method and GIS-technique is a good way for analysing the risk for salt groundwater over a spatially extended area, for instance as a tool for municipal comprehensive planning. In combination with the uncertainty value, the risk value can be a good support in making decisions about how to go on with further studies and investigations or where to put restrictions about groundwater discharge. As the RV-method is an expert system, it should be possible for officials at local authorities to perform the analyses by their own without needing support of experts in hydrogeology, geology and hydrochemistry, as long as they are supported with relevant and high-quality databases.

Further studies

The first thing to go on with in the project is to finish the implementation of the RV-method into the GIS environment, including both the risk value and the uncertainty value. A transformation of the resulting risk map to ArcInfo and/or MapInfo is also included in the task. The final step is to couple the qualitative RV-method to a quantitative water balance model. This integrated system could be a powerful tool for the authorities in their planning process answering questions not only where the risk is high or low for finding salt water in drilled or dug wells, but also how much groundwater that could be extracted before problems arise.

Acknowledgement

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