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title: **The extent of the unconfined aquifer based on the Dempster-Shafer theory on the example of postglacial sandur area**

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INTRODUCTION

The extent of hydrogeological elements are represented in the cartographic studies based on the point or exploration performed in the field. With respect to distances, those limits are of probable course, more or less similar to the real boundary. Error assessment of graphic presentation of the hydrogeological elements, such as extent of aquifer has not been expressed in values yet. Hydrogeology cartography offers diversified studies, due to the reliability of data used. It is connected with the accuracy and likelihood of estimation of the extent of groundwater bodies and their amounts. Information about reliability of hydrogeologic studies is especially useful to readers from other speciality. Maps with nonparametric scale gives the reader easy readable data about quality of source information from area of research.

In the environmental studies, the proper use of the information (or the lack of the information) leads to searching for way to represent this kind of data. It is argued that the application of Boolean logic (the all-or-nothing system) in the GIS design causes some problems (Leung, Leung, 1993).

THE MAIN OBJECTIVE

The main study objective was to evaluate the probability that the shallow unconfined aquifer could be found in each pixel location in a surface represented in the studied area. The shallow aquifer is here defined as the aquifer of minimum 2 [m] thick, and at the depth less than 15 [m] from surface.

THE AREA OF RESEARCH

The research area in the east part of the Pomeranian Lakeland in Poland was chosen for testing this procedure (Figure 1). This area lies within border of sheet of Geological map. The relief of the studied area is characterized by forms of fluvioglacial from the last (Veichselian) glaciation. The main form is outwash sediments (the Wda sandur) and in little part a moraine plateau (Figure 1). Only Cenozoic water bearing strata have been recognized within the log wells. The Pleistocene water bearing layers form the major aquifer for the studied area. It consists of one unconfined aquifer and two or three confined aquifer.

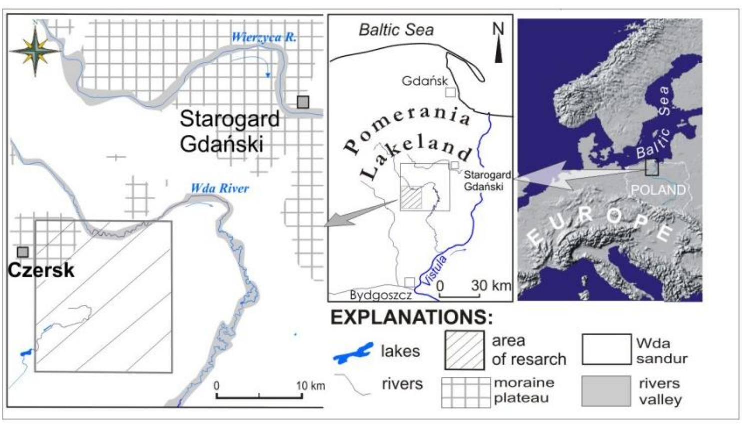

Figure 1. The location of the study site.

The hydrogeologic recognition of research area is weak. In study area there are 25 "hydrogeological recognition pixels" where drilled wells exist with logged geology profile and hydrogeologic parameters (Figure 2).

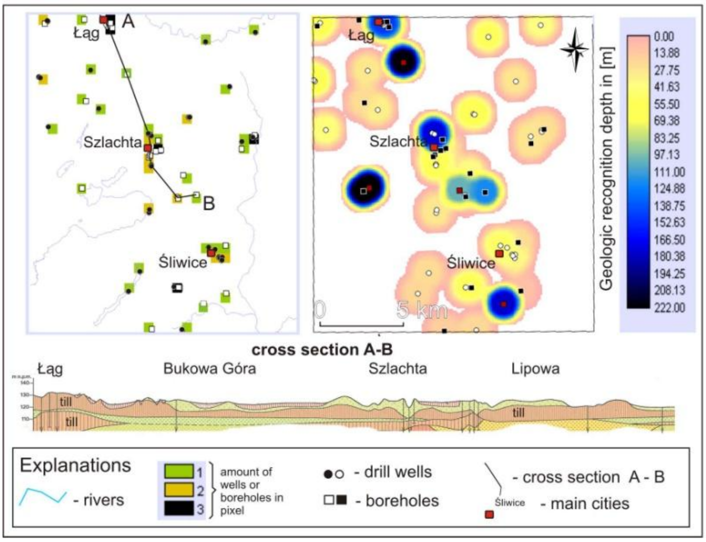

Figure 2. Location of "hydrogeological recognition pixels" on the research area (on the left), geologic recognition depth (on the right) and cross section (Trzepla, Drozd, 2005) (below).

METHODOLOGY

The Dempster-Shafer theory is an extension of Bayesian probability theory (Shafer, 1976). This theory makes a distinction between probability and ignorance and it allows for the expression of ignorance in uncertainty management (Lee et al. 1987; Klir, Yuan, 1995). By using the "belief functions" to represent the uncertainty of hypothesis, the theory releases some of the axioms of probability theory. The resulting system becomes a superclass of probability theory. Unlike Bayesian probability analysis, D-S theory explicitly recognizes the possibility of ignorance in the evaluation, i.e. the incompleteness of knowledge or evidence in the hypothesis (Eastman, 1999).

The research objective was performed on IDRISI raster based software program. In IDRISI, the BELIEF module can be used to implement the Dempster-Shafer theory. BELIEF constructs and stores the current state of knowledge for the full hierarchy of hypotheses formed from a frame of discernment. BELIEF first requires that the basic elements in the frame of discernment be defined. As the basic elements are entered, all hypotheses in the hierarchical structure will be created in the hypothesis list. For each line of evidence entered, basic probability assignment images (in the form of real number images with a 0–1 range) are required with an indication of their supported hypothesis.

The development of knowledge base

The research question guides us to define the frame of discernment — it includes two elements [present] and [absent]. The hierarchical combination of all possible hypotheses, therefore, includes [present], [absent] and [present, absent]. We are most interested in the result generated for the hypothesis [present] which mean existing of unconfined aquifer. The final results produced for the hypothesis [present] are dependent on how all evidence relate together in the process of aggregation.

Given knowledge about existing boring wells, dug wells and given expert knowledge about the occurrences of aquifers, each evidence is transformed into a raster layer representing likelihood that an unconfined aquifer exists. The aggregated evidence produces results that are used to predict the presence of an aquifer and evaluate the impact of each line of evidence to the total body of knowledge.

Several pixel maps of elements which confirm or deny the occurrence of the only unconfined aquifer were prepared for this study. At the beginning, each map included separately: point or area data in a scale 0 and 1. In the next stage, the information on each map was changed in order to work out membership functions. As a result, the pixel map with values from 0 to 1 was obtained. Finally, all the maps (information layers) were put to the BELIEF module and probability map was compiled regarding Dempster-Shafer theory.

Data input for the unconfined aquifer

To analyze the extent of the unconfined aquifer there is a need to collect the information about boring wells (as the best indicator of aquifers, or it's lack), dug wells and more indirect evidence of occurrences for the unconfined aquifer (springs, rivers, lakes, the area of extent of alluvial or outwash deposits). There is high probability that the unconfined aquifer will be inside or close to these forms.

For estimating the extent of the unconfined aquifer in a probabilistic scale the following data was selected:

- location of boring wells and boreholes from database of Hydrogeological Map of Poland (Herbich, 2005; Fert et al., 2005, Prussak, 2000). The geologic profile of wells or boreholes was taken from Central Hydrogeological Data Bank (Cabalska et al., 2005);
- location of dug wells from supplement of Hydrogeological Map of Poland – first groundwater horizons (Jankowski, Walczak, 2005);
- area of the extent of the moraine plateau and outwash (from Detailed Geological Map of Poland 1:50 000);
- course of main rivers and boundary of lakes.

CREATING PROBABILITY MAPS (FUZZYFICATION)

The stage of fuzzyfication is a procedure, which allows for converting a discrete/dichotomic image (binary map or bitmap) into pixel images (pixel map) with a probabilistic scale (from zero to one). The reliability of the obtained maps depends on the applied parameters of fuzzyfication controlled by a membership function. For this study the following assumptions were taken:

Membership function for boring wells

Wells are the best point markers of the aquifer. The point map with locations of the wells (with unconfined aquifer) were converted to raster (pixel) image and all the pixels in which well (or wells) were located, obtained the value: one. Also for these features, the area in the close vicinity of the wells should obtained high likehood of occurrence of an aquifer.

Radius of 300 [m] was used around pixel representing drill wells, so the pixel values representing probability of unconfined conditions are high in the close area and decreased down to the level of the background (Figure 3). The above distance was established subjectively as the optimal one after analyzing the hydrogeological conditions from the research area.

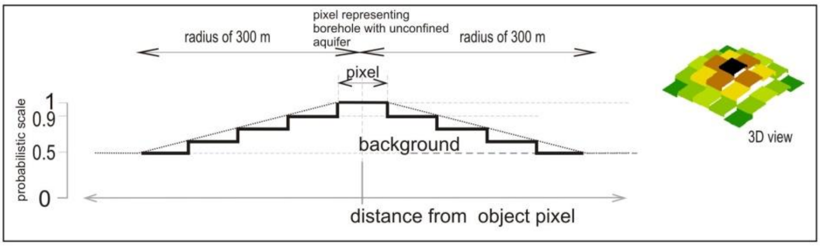

Figure 3. Graph of the membership function for drilled wells with unconfined aquifer.

Membership function for wells and boreholes with lack of unconfined aquifer

The value “0” was assigned for the pixels where boreholes exist and unconfined aquifer is not noticed. In the vicinity of those pixels, probability increases from “0” to the value of background for the range 300 [m] (Figure 4). The above distance was established subjectively as the optimal one after analyzing the geological and hydrogeological conditions from the research area.

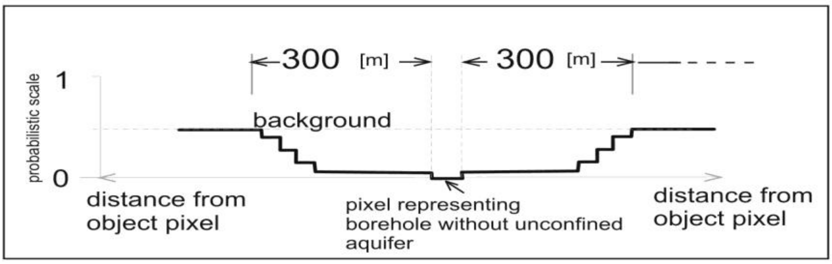

Figure 4. Scheme graph of the membership function for boreholes and drill wells without an unconfined aquifer.

Membership function for the area of outwash sediments and moraine plateau

In the research area of the extend the unconfined aquifer is associated with fluvioglacial outwash. The area of the outwash extent was digitized from the Detailed Geological Map of Poland in a scale 1:50 000 (Trzepla, Drozd, 2005; Ber, 2005). The rest of the area was classified as a logic negation, which means the area without sand sediments on the terrain surface (i.e. moraine plateau). Arbitrarily the value “0.8” was assigned to all the pixels which represent the area of outwash sediments and the river valley. For the remaining area a constant value “0.3” was established *a priori*.

Membership function for area in the vicinity rivers and lakes

Rivers and lakes are hydrologic objects with frequent connection to the aquifer, especially the unconfined aquifer. Close to a river or a lake there are often sand sediments with the aquifer, therefore, this vicinity to water indicates the plausibility for the aquifer. Only rivers that are longer than 5 km and lakes with the area bigger than 1 ha were analyzed.

After data analysis, the author found that there should be higher likelihood (the value of about 0.8) in the zone 100 [m] from the river bank or lake shores.

Stage of calculating

After processing data in the BELIEF module a set of maps was generated. These were maps of the degree to which evidence provided concrete support for the hypothesis (belief) and the degree to which that evidence did not disprove the hypothesis (plausibility). The probabilistic map of the extent of the unconfined aquifer in a research area was shown on the Figure 5.

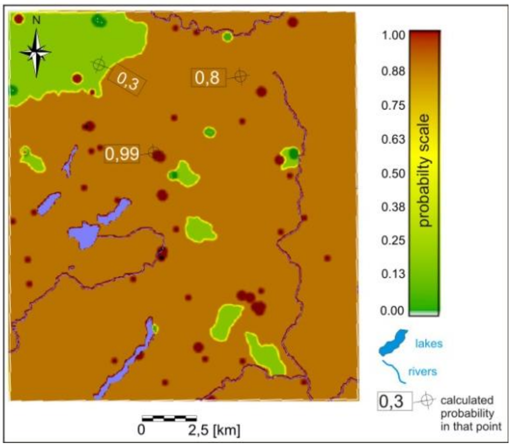

Figure 5. The probabilistic map of the extent of the shallow unconfined aquifer in a research area.

SUMMARY AND CONCLUSIONS

The limits of geological and hydrogeological structure presented on the cartographic studies contain often significant errors due to poor geologic and hydrogeologic recognition. The purpose of the methodology presented here is to produce a probabilistic information layer of the extent of the unconfined aquifer in the study area (Figure 5). It is an attempt to use Dempster-Shafer theory in hydrogeology. Taking into account the fuzzy set theory, the author calculates probability occurrence of shallow unconfined groundwater based upon hydrogeological elements (especially drilled wells and dug wells). Additional information for the probabilistic map are derived from hydrological and geomorphological investigations. The accuracy of such map is largely determined by the established membership functions.

The generated maps may be regarded as a supplement to a classic set of information concerning hydrogeology and which provides a new form of a map layer. The statistical description of the pixel value on the result map may be used for the assessment of reliability of hydrogeological model and as decision support for sustainable groundwater management.

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