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MINIMAL GEOLOGICAL DATA FOR MODELLING COMPLEX HYDROGEOLOGICAL SYSTEM USING GIS

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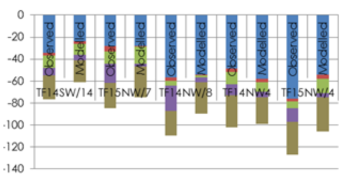
Graphical abstract



Abstract

Geological model is part of groundwater modelling processes. 3D geological models such as GSI3D and GOCAD are used extensively for modelling subsurface geology. These models require multiple input datasets from boreholes, geology maps, and geophysical data. However, due to insufficient definitive data, widely spaced data points that are interpolated were usually used for representation of a geological unit. Since the requirement of extensive data is always the main issue, a geological model is only applied for an area with sufficient data. In this study, minimal and accessible spatial datasets were used in the model for representation of the geological unit. These datasets were chosen to allow the model to be applied in areas of limited datasets. Via the GIS platform, the methodology was developed for the representation of geology in particular the aquifer unit. The raster surface of the geological layer was created in GIS using the information of dip, strike and faults displacement taken from the geological map. The developed GIS based geological model is capable of viewing a geological cross section, modelling the thickness and outcrop boundary of an aquifer unit. The model was tested by reconstruction of the geology map for the Slea catchment, in the United Kingdom and prediction of the thickness of the Lincolnshire Limestone aquifer.

Keywords: Geological model, groundwater model, GIS, aquifer

1.0 INTRODUCTION

The geological model is the root of groundwater modelling. The geological framework of the aquifer system, the aquifer properties (such as its thickness and hydraulic conductivity) were initially defined through the geological model. Subsurface geological information is usually presented in a 2D graphical map or cross section (Turner, 2006). For geological modelling, 3D modelling software such as GSI3D, Vulcan and GOCAD [1, 2, 3 & 4 is generally applied and GIS regularly used for registration of model input data before exported to 3D software. Developing a simpler groundwater model at least for screening groundwater status is crucial. Taking advantage of Geographical Information System (GIS) tools, this model explores the potential of GIS tools for modelling groundwater flow systems. As sufficient groundwater data is always the main limitation in using existing groundwater models, the main aim of this study is to develop a model using minimal and accessible input parameters. Subsurface geology is multilayered and includes a number of stratigraphy units, geology types and structures. Descriptions of subsurface geology (such as stratigraphy units, geological type) basically take into account the effect of geological structures (such as dips, strikes and faults). The geological beds range from being as thin as a flatbed to more complex geological beds. The plane orientation is described in terms of dip and strike of the plane. The features geological beds are usually recorded in the geological map by a set of dip and strike lines. Each unit of subsurface geology is a 3D volume. Because of GIS cannot handle true 3D, the structure is represented by having one GIS layer representing the elevation of the upper surface of each geological layer (see Figure 1). Surfaces in GIS are represented as raster arrays of elevations and these elevations can be calculated by assuming that the geological beds are planar and have a uniform strike, dip and thickness. However, various dip and strike angles can be used to estimate the elevation of a geological unit.

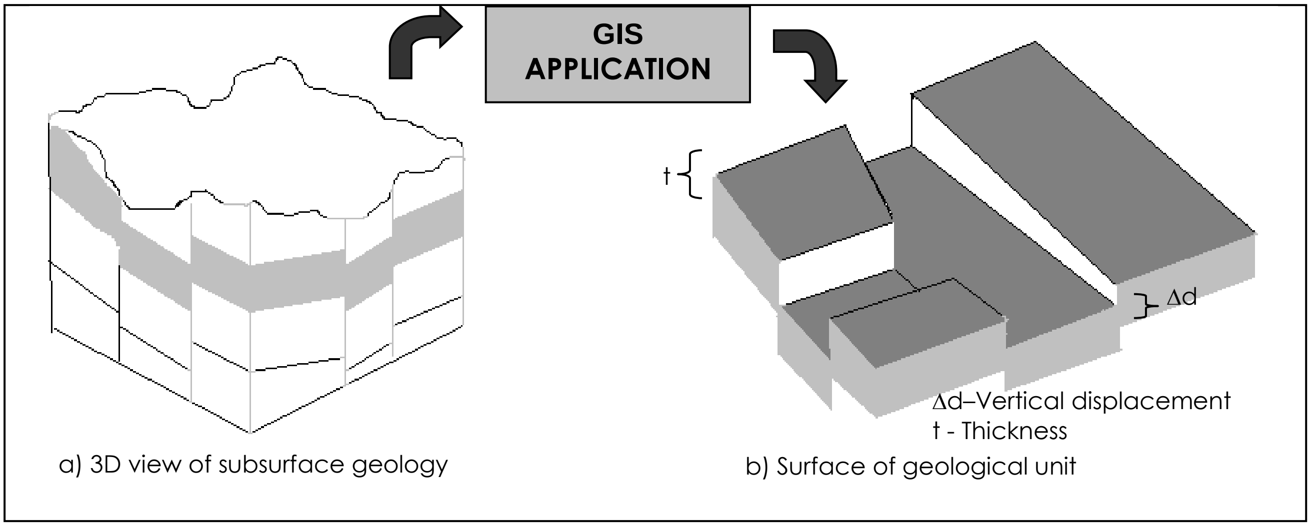


Figure 1 Conceptual diagram of GIS based geological representation

2.0 GIS BASED GEOLOGICAL REPRESENTATION

In this study, the surface of a geological unit was modelled by representing the top layer of the geological unit. The top layer of a geological unit was represented as raster arrays of elevations. Known and estimated strata elevations were used to represent the top surface of a geological unit. In the model, two approaches were used. The first approach was based on the assumption that the surface of the geological layer was a planar surface. Therefore, a single plane equation was used in the model for the creation of a geological layer. The planar equation is expressed as;

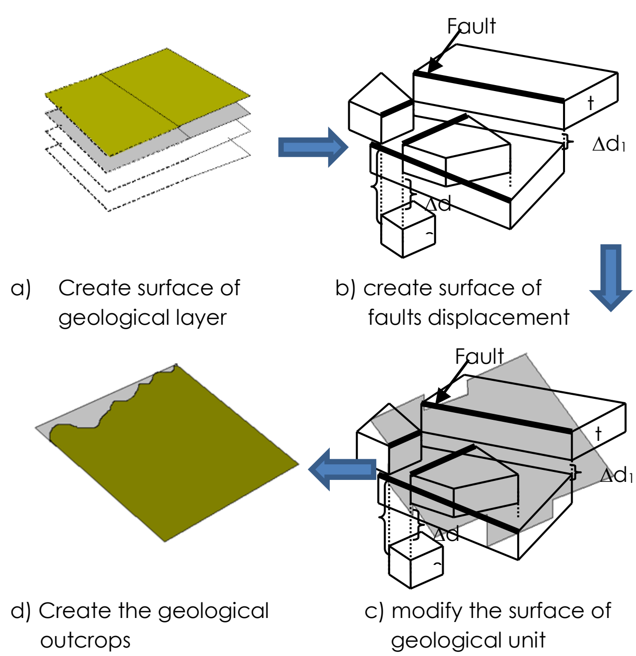
$$z = Ax + By + C \tag{1}$$

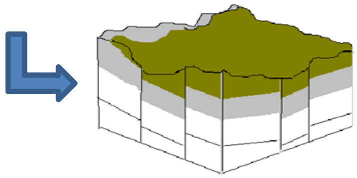
z is the elevation, x and y are the coordinates of a point on a plane and A, B and C are constant coefficients. A is the apparent dip in x direction and B is the apparent dip in y direction. Given the dip and strike angle, A and B can be calculated as shown in equation 2 and 3 and constant C is by rearranging equation 1.

$$A = \alpha \cos\theta \tag{2}$$
$$B = \alpha \sin\theta \tag{3}$$

This initial method only used several known points of elevation (on the ground surface) of one geological unit in order to develop the plane equation. The plane equation (equation 1) was used to estimate the elevation of any points of that geological unit. Finally, the surface of geological unit was created by converting the known and estimated points of elevation as a raster surface. This procedure can easily be done via the GIS tool.

The developed methodology was tested by reconstruction of a geology map. The geological map was reconstructed by merging the outcrop boundary from various geological units.





e) Reconstruct the geology map and represent the 3D of subsurface geology

Figure 2 Modelling procedures for development of GIS based geological model

The outcrop boundary was created by overlaying the modified surface of a geological unit onto the digital elevation model (DEM) of the ground surface. Then, the intersection between the surface of the geology and the ground surface was identified. These intersections showed the boundary of the geological outcrop. These processes were prepared separately for each geological unit. To create the geological map, these outcrops were then merged into one layer using the mosaic tool in GIS. Figure 2 show the graphical illustration of modelling procedures for development of GIS based geological model.

3.0 RESULTS AND DISCUSSIONS

3.1 Reconstruction of Geological Map of Lincolnshire Limestone Aquifer of the Slea Catchment, United Kingdom

The Lincolnshire Limestone aquifer is one of the major aquifers in the United Kingdom. Since the 1970s, a number of mathematical models have been developed for hydrogeological studies of the Lincolnshire Limestone aquifer [5, 6, 7, 8, 9, 10, 11& 12]. Slea catchment was selected for modelling groundwater particularly the geological aspect using a simpler model.

The geology around the Slea catchment is divided into four main series, the Quaternary, Middle to upper Jurassic (Ancholme Group), Middle Jurassic (Great Oolite and Inferior Oolite) and Lower Jurassic (Lias). The key feature of solid geology in the Slea catchment is the Lincolnshire Limestone formation. The model developed in the current study was tested by representation of twelve geological formations in the Slea catchment (Figure 3).

Figure 3 Geology map of the Slea catchment (Derived from 1:50000 scale BGS Digital Data under licence 2008/008 British Geological Survey ©NERC

The information on geological structures was gathered from the geological map and memoirs of Grantham (Sheet 127). For representation of geological layer, the model assumed that each geological unit has a uniform dip angle. Dominant dip angle of 0.5° and dip direction of 115° was used in the model. There is no major downthrow fault in the study area. However, there are various faults and these were assumed as normal faults.

For the reconstruction of the geological map, only a few faults that caused major displacement in geological outcrop were modelled. Modified surfaces of the geological unit and the DEM of the ground surface were used in the current model to create the outcrop boundary. A raster calculator operation was used to identify the intersection between the surface of the geological unit and the ground surface. This intersection divided the surface of the geological unit into areas below and above the ground surface. The intersection was the boundary of the geological outcrop. Then, the outcrop boundaries from various geological units were combined into a single map for reconstruction of the geological map.

3.2 Model validation

Four geological maps were reconstructed of the Slea catchment based on two types of raster analysis of the trend surface and tension-spline surface (based on with no faults or with faults effect). Figure 4 shows an example of geology map constructed by the model (trend surface analysis with fault effect).

Figure 4 Modelled geology map using trend surface analysis

The accuracy of the developed model was validated by comparing the modelled outcrops with the original geology map of the study area. Analyses were done based on matching analysis of the modelled and original geology map using the Kappa statistical analysis and comparing the outcrop boundary. Table 1 show the percentage of correct outcrops classification based on the matched pixels of outcrop classification between the original and modelled maps. 3. Model 3 using Tension-Spline surface geology with no faults effect have better percentage matched (> 85%). The estimated strata elevation and thickness of the geological unit were also validated with the boreholes records that were recorded by British geological Survey.

Table 1 Percentage of correct geological outcrops classification

No	Geological layer	Percentage of matched pixels (%)			
		Model 1	Model 2	Model 3	Model 4
1	Ampthill clay	99	99	99	99
2	West Walton	87	96	96	97
3	Oxford clay & Kellaways	75	78	90	91
4	Cornbash	52	54	64	65
5	Blisworth	53	53	74	73
6	Rutland	38	36	62	64
7	Lincolnshire Limestone	88	88	83	83
8	Grantham	50	50	88	88
9	Northampton Sand	35	35	63	63
10	Whitby mudstone	75	75	86	86
11	Marlstone	56	56	68	76
12	Charmouth Mudstone	92	93	91	98
Average matched pixels		78	80	86	87

Two validation data were used to validate the model outputs; 1) Geology map and 2) borehole records. The borehole records were collected from the British Geological Survey. From the borehole records, the strata elevation and the thickness of each geological unit were collected. However, there were only a few borehole records available in the study area and only five formations were validated with the recorded data (Figure 5). The best estimation of strata elevation is Oxford Clay and Kellaways Formation.

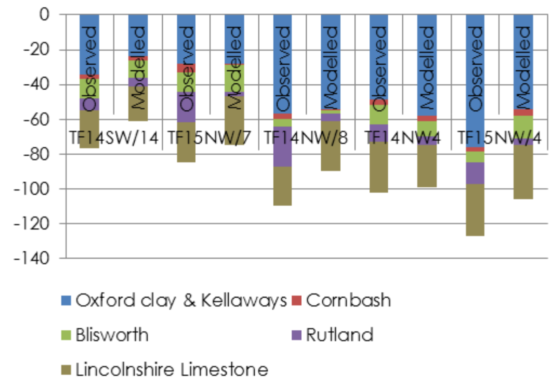


Figure 5 Cross section between modelled and observed data at the borehole points

In the previous studies that worked on the Lincolnshire Limestone aquifer used thickness was based on interpolated data from recorded boreholes or existing studies such as that from [8]. The thickness of Lincolnshire Limestone aquifer was estimated in the current model. To validate the result, the aquifer thickness was compared to the observed data from the boreholes. Table 2 shows the comparison of thicknesses between estimated and the recorded data.

Table 2 Comparison of thicknesses for Lincolnshire Limestone aquifer

Point	Borehole	*Recorded(m)	Estimated (m)	Difference
1	TF15NW/4	30	31	1
2	TF15NW/7	23	28	5
3	TF14NW4	29	24	-5
4	TF14NW/8	23	29	6
5	TF14SW/14	22	20	-2

Note *recorded data from British Geological Survey

In general, the difference between the recorded and estimated thickness was small (between +26% and -17%). In borehole TF15NW/4, the discrepancy is only 3%. Based on five borehole points, the estimated thickness ranged between 20 m and 31 m. The aquifer thickness was perfectly estimated within the range of thicknesses used by the previous researchers [11, 5, 13 & 14].

4.0 CONCLUSION

In general, the development of the geological model in the current study attempted to minimise the model input data. A GIS-based geological model was developed in the current study for representation of the geological unit. Using GIS operations, the geological unit was represented as a raster surface of elevation. The model used spatial datasets (geology map and DEM) and geological structures information (such as dip angle and faults) to estimate strata elevation.

As a conclusion, the results show that the application of developed geological model for representation of geological units in the study area was successful. The developed geological model was able to represent the geological units of the study area. The model successfully reconstructed the geology map. Although overall prediction of geology map was only a 78% matched with the original geology map, some of the geological outcrops were almost a 100% match.

This finding also proved the potential of GIS in modelling 3D volume of subsurface geology. The estimated aquifer thickness was found consistent with previous data used by other researchers. Therefore, this tool should be further explored for modelling groundwater.

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