Research Journal of Applied Sciences 3 (5): 359-368, 2008
ISSN: 1815-932X

Three Dimensional Geologic Framework Modeling from Drill Hole Data of Yangwu Proluvial-Alluvial Fan Deposits in Yuanping Depression of Xinding Basin, Shanxi Province, North China: A Case Study Using GMS 6.0

Y. Nowel Njamnsi, Bei Ji, Sun Ronglin and Liang Xing
Department of Hydrogeology, School of Environmental Studies,
China University of Geosciences, Wuhan 430074, China

Abstract: The Yangwu proluvial-alluvial fan is a broad fan-shaped deposit consisting of infilled with up to 200 m of Quaternary sediment and belongs to the arid and semiarid region. The sedimentary architecture, the distribution of lithofacies and of architectural elements in such heterogeneous deposits is of fundamental importance for the analysis of groundwater flow. Modeling focused on a spatial representation of the distribution of sediments of complex proluvial-alluvial deposits which form the porous water-bearing aquifer systems. This geologic framework model is the first of its kind for the area and was assembled using digital geologic map data, lithologic contour line maps and borehole information from 62 bore holes from a 317.76 km^2 area combined using Geographic Information System (GIS) and the TINs code and SOLID code in Groundwater modeling system (GMS 6.0) to form a volumetric, lithologic three-dimensional geologic model. Lithologic data were reduced to a limited suite of descriptors based on geologic knowledge of the basin and distributed in 3D space using interpolation methods. Lithologic variations are related to different depositional environments within the basin, related to periods of sediment input and river level changes which include proluvial piedmont fan, alluvial fan, channel, basin axis and lacustrine deposits. The resulting three-dimensional geologic model contains three lithostratigraphic units; Pliocene bedrock (N) and Quaternary proluvial-alluvial deposits (Q_1+N, Q_2 and Q_3) which consist of seven lithofacies: coarse sand, medium to coarse sand, medium to fine sand, sabulous sand, silty sand, clayey soil, clay units. The sequence is complex with abrupt changes in lithology occurring over short distances with unconsolidated alternating and interfingering sand, silt and clay reflecting a variety of sedimentary depositional environments. Comparisons of the computed model to geologic cross-sections indicate that this methodology produced a model that supports the conceptual model of the subsurface. The three-dimensional geologic framework model is useful for visualizing subsurface sediment distributions and geometries and will be used not only to better constrain the Quaternary depositional history of the region, but also to identify and delineate major aquifers and aquitards, which is an important step for understanding ground water flow system.

Key words: Three dimensional geologic framework model, GMS 6.0, Yangwu Proluvial-alluvial

INTRODUCTION

The subsurface geology of both the Yangwu proluvial-alluvial fan area within the Yuanping depression is not well understood. There is a complex combination of Cenozoic sedimentary and Neogene proluvial and alluvial deposits. Understanding and quantifying regional groundwater flow first requires a better understanding of the geology of this region. The inadequacy of subsurface geologic knowledge in the region equates to a lack of understanding of the hydrogeologic processes and properties of the region. These factors must be understood for effective use, management and conservation of groundwater in the region. The main water-bearing medium of Quaternary porous-water system in aquifer systems are the sole sources of portable water. Ground water is the primary source of water and is essential to support a growing population, agriculture, industry and the riparian habitat of the Yangwu River basin. Characterization of thesecomplex geologic features is important for understanding ground water flow paths, but generalization of geologic features is usually necessary for groundwater modeling. The basic geologic features, including stratigraphic relationships

Corresponding Author: Y. Nowel Njamnsi, Department of Hydrogeology, School of Environmental Studies, China University of Geosciences, Wuhan 430074, China

(i.e., sequence, thickness and continuity), bedding attitudes and structural features (i.e., faulting and folding), must be spatially characterized before defining the distribution of more complex features controlling preferential flow. We use the term geologic framework modeling to refer to modeling of these basic geologic features in three-dimensions.

The main objective of this study was to develop a conceptual model which describes the rough 3D geological set-up to a more cohesive picture of the aquifer structure and to make it more available in an easily understandable format. A general geomorphological analysis and thorough description of the depositional environment is included in the interpretation of the different geological units in the area. The geological characterization includes a geologic map, cross sections throughout the study area fracture orientations of the Archaean basement, fault orientation, tectonic classification of the basin. These features provide insight on the geologic history of the area, as well as the causes for the formation of the basin.

In recent years, many researchers have done much work on 3D modeling and visualization, moving from 2D and 2.5D to real 3D. However, real 3D visualization in geology has not been perfected. Geoscience researchers must do much more study and exploration (Xu and Niu, 2006). Three-D models have been presented for a range of study area scales and a variety of geological basins and depositional environments. Most of these studies have been regional in nature. Only a few studies have focused on modeling bedrock units (Arthur *et al*., 2002; Sweetkind *et al*., 2002) or constructing a model depicting both sediment and undeformed sedimentary rock strata (Ross *et al*., 2001; Thorleifson *et al*., 2001). A few studies have focused on specific depositional settings or landforms, for example eskers (Artimo *et al*., 2002). This study illustrates a geological framework for understanding the complex proluvial-alluvial sequence of the Yangwu proluvial-alluvial fan using the Groundwater Modeling System (GMS 6.0) software developed at the Engineering Computer Graphics Laboratory at Brigham Young University.

Physiographic and geologic setting: The Research area straddles 2 physiographic setting. These are the Yunzhong Mountain piedmont proluvial plain setting and the Hutuo River alluvial Plain, which are linked by the Yangwu River. The Yangwu proluvial-alluvial fan encompasses approximately 317.76 km^2 within the Yuanping depression, Central portion of the Xinding basin a representative Cenozoic rift basin, located in the northernmost of Fen River rift valley in Shanxi Province and belongs to the arid-semiarid region. Geographically, it is bounded by latitudes 38°43' N-38°53' N and longitudes 112°33' E ~ 112°48' E. It is bounded to the East by Wutai Mountain, West by Yunzhong Mountain, South by Xinzhou sub-basin and Jingsiang Mountain, North by Daixian and Shuozhou Fig. 1.

Yangwu River valley comprises rocks that discontinuously range in age from Archean to Quaternary and is characterized by a complex tectonic evolution. The Cenozoic rocks in Yangwu incline plain consist of a thick proluvil-allu-vial section underlain by Pliocene sedimentary rocks, which are inturn underlain by Archean metamorphic rocks of the Wutai group. The intermontane trough between the Yunzhong and Wutai Mountain is filled by a succession of Pliocene and Quaternary sediments. The sediments in the immediate subsurface are of three main types:

- Outwash/proluvial fan sedimentation generated by erosion of the Yunzhong mountain chains, comprising thick layers of rather poorly sorted sands, gravels and cobbles, with finer-grained silty/clayey interlayers. This type of sedimentation becomes more dominant in the proximity of the mountains. These sediments are often called proluvial.
- Lacustrine sedimentation.
- Hutuo river alluvial deposits.

The proluvium and alluvium ranges in thickness between less than a meter in the upper parts of the valley to 20 m downstream, but may reach up to 30 m in some localized depressions of the main valley. Sediments of valley fill typically possess good hydraulic parameters in and consist mainly of medium to coarse grained boulders to pebble gravel and sand with local deposits of fine sand and silt. Digital geologic map compiled by Geologic survey bureau of Shanxi province at 1:50,000 have defined the map distribution and provided detailed descriptions for the surficial geologic units (Fig. 1). This map was used to depict the character and distribution of the uppermost geological materials, from the point of view of texture, process and history. Based on this map deposits and can be grouped into zones based on the environment of deposition. The 2D map was then merged with drillhole data, with the aid of current knowledge on geological processes and history, to produce a 3D depiction of the subsurface geology down to the bottom of bedrock (sand and gravels of the early Pleistocene and red clay of the Pliocene). Based on this map coarse-grained surficial unit consist of Holocene to Pliocene roluvium, alluvium and diluvium sediments. In general, proluvial deposits are predominantly sandy

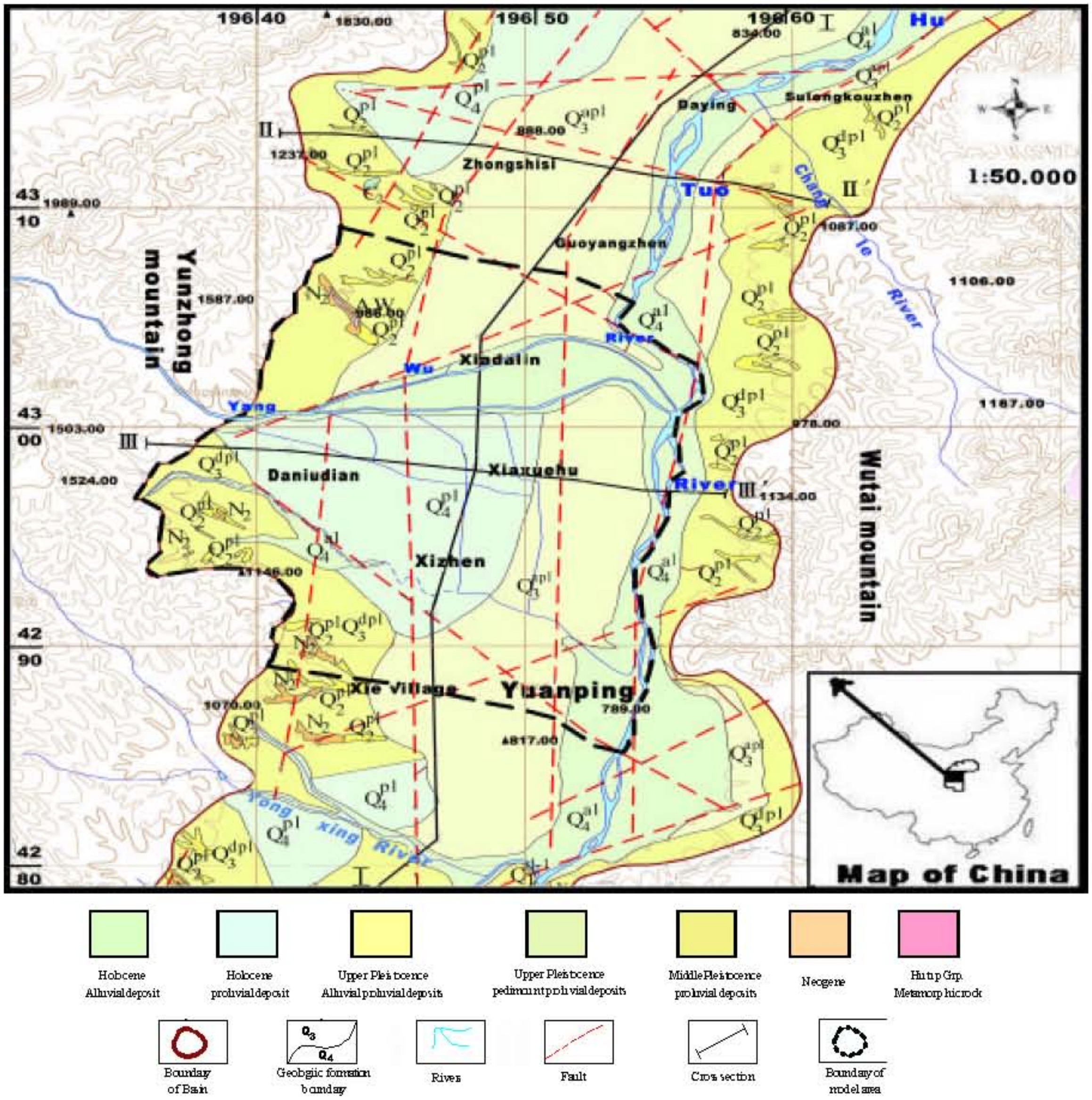

Fig. 1: Simplified geologic of the study area, modified from Geologic Survey Bureau Shanxi Province (1976)

gravel, whereas alluvial fans typically show a gradational decrease in grain size from proximal to distal fan with distance from the mountain front (Workman *et al*., 2002). Sediments generally are not cemented but tend to be more indurated with increasing depth. These deposits can be classified into 2 subgroups based on the mode of formation.

River deposits: These deposits are widespread in valleys of the Yangwu River and all its numerous tributaries and compose of clay, sand and well sorted pebble to cobble beds that consist of angular to sub angular debris. Swamps, composed of clay with sand and gravel are frequently found in the river valleys with thickness 3~15 m. They can further be classified as alluvial and lacustrine deposits by origin.

Slope deposits: Diluvial-proluvial deposits cover the slopes and foots of hills by river valleys and spread over relatively large areas and usually up to few dozen meters thick. In the middle of the slopes and at the foot the sediments form 15-30 m thick. Alluvial fans and diluvial-proluvial talus consisting mainly of sand and silt with debris. These deposits are characterized by poor sorting and lack of smoothing of clastic material. The proluvial deposits are represented by proluvial cones, which were deposited by streams and torrents draining from the Yunzhong Mountain. Such sediments are found in the Lower Yangwu river valley in particular. These sediments are represented mainly by (flood loams) sandy loam soil, the clay loam and gravel pebbles, thickness 3~15 m. The flood loam deposition is correlated with soil erosion (rain washing, gully erosion) that have been mainly affecting slopes, thus removing traces of possible occupation. Also, technogenic deposits created as a consequence of human activities can be identified.

Structurally, the Yuanping depression in which the proluvial-alluvial deposits is modeled is an active tectonic unit 50 km long, bounded to the West by piedmont fault zone of Yunzhong Mountain and to the East by the Piedmont fault zone of Wutai mountain. The basin is controlled by faults. The large marginal faults are developed on both sides of the graben. Figure 2 A and B. Faults and hidden faults are also developed with the basins and most of the faults are active and extend mainly in NNE-NE direction and less in SN-NNW direction. The repeatedly intense movement along the faults and the basins in the latest geological time caused repeated seismic activities in the basins and persistent subsidence of the basins and hence the Pliocene and Quaternary sediments were deposited up to 2000-3000 m in the basins (DENG *et al*., 1973; Research Group on Active Fault System around Ordos Block, State Seismological Bureau, 1988). All these indicate that the basin zone represents an area with intense natural variations, such as tectonic and climatic variations.

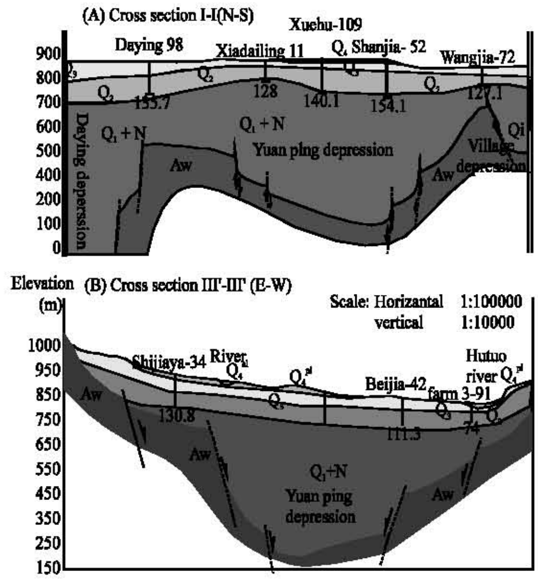

Fig. 2: A and B shows geologic cross-sections of the of yuanping depression from North to South and East to West. Modified from geologic survey bureau, Shanxi Province (1976)

MATERIALS AND METHODS

The major source of geological information for this research was obtained from geological survey records. The data types and formats are also different and can be classified into three kinds:

- Existing geology data. Ten cross sections and 1:50000 geology map from Hydrogeologic unit of Shanxi province Geologic bureau, 1976. These maps are in 2D and are on paper. The traditional geology models mainly depend on this kind of data.
- Borehole logs. The Model was constructed with information from 44 actual bore holes and 22 bore holes created by interpolation from existing cross sections. Drill data are accurate because underlying data are reliable.
- Manual geological input based upon geological observations or outcrop descriptions.

The development of a three-dimensional computer model of the Yangwu proluvial-alluvial fan was accomplished with the help of three integrated programs for data preparation, analysis and modeling; GIS and Surfer 8 for georeferenced data (spatial data) and Groundwater Modeling System (2000) (GMS 6.0) software developed at the Engineering Computer Graphics Laboratory at Brigham Young University for modeling process. This software (GMS 6.0) is commercially available from Environmental Modeling Systems, Inc. and a number of other engineering software clearinghouses. While GMS was specifically developed for modeling environmentally contaminated sites, it has an extensive suite of tools available for generating three-dimensional models of geologic sites that are equally well suited for traditional geotechnical modeling applications. The software was selected for this research because it is modular in that individual modules can be purchased to suit the needs of a particular organization thereby limiting expenditures to meet only required needs. GMS is a graphically based software tool providing facility through all aspects of the groundwater flow and transport modeling process. Facilities include geometric modeling of hydrostrati-graphy, 2 and 3 dimensional mesh generation, graphically based model input for specific flow and transport codes, interpolation and geostatistics as well as complete three-dimensional scientific visualization. Thus the property of GMS to transfer from geological to hydrogeological models makes it the most suitable since the resultant model will serve as bases for the groundwater flow modeling of the Yangwu proluvial-alluvial fan.

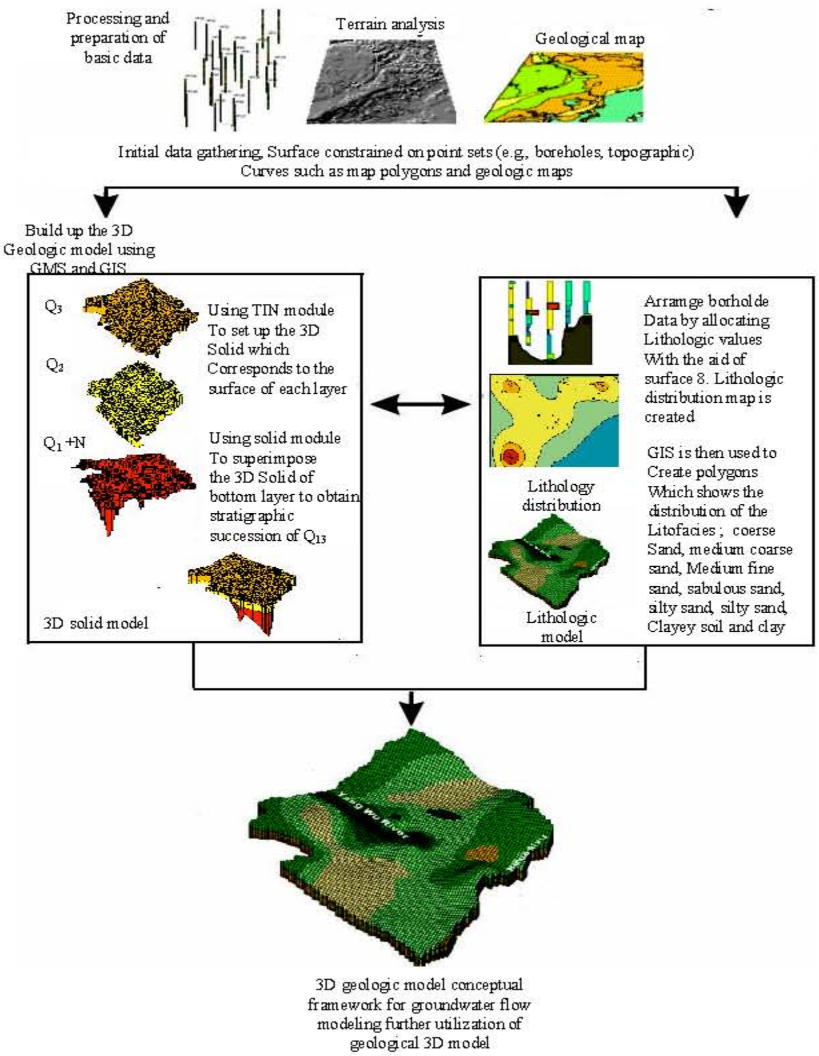

Fig. 3: Organization of methodology developed. GIS/GMS based on realization of 3D geologic model

Developed methodology: The GIS software was used in preparing images and shape files for location of study area, lithologic boundaries, out crops of geological formations, aquifer classification etc. These maps are exported to GMS and processed by the GMS Map module (Fig. 3). It also includes a set of Pre/Post processing tools for helping user in characterization of the model domain, model conceptualization, mesh and grid generation, geostatistics and output post-processing. Moreover, it incorporates a Map Module, which allows for GIS integration using image of an aerial photo or scanned-in map, or an AutoCAD drawing of the site. Drawing tools are also provided within the Map Module. The interaction between these programs was simple since they share similar input/output data format. All three programs operate in Windows environment and can be activated from the same machine. The modeling procedure is divided into pre-processing, processing (or model running) and post processing. Pre-processing is concerned with input data preparation, whereas post processing is used to present and analyze output results. Details of various steps are shown in the coming sections. The basic modeling technique used for geologic modeling with solid models is to define profile surfaces that separate dissimilar geologic materials. These contacts are developed from contacts between different materials in boring logs and represent the boundaries between geologic strata. Once the key profile surfaces are defined, solids are generated using boolean operations to represent the volumes occupied by each material to form a solid model representing all geologic strata in the modeled region of deposits. The process is thus rather simple in moving from known geologic data, the borehole data obtained in boring logs, to the three-dimensional representation of the subsurface conditions at a site. The modules used for development of three-dimensional

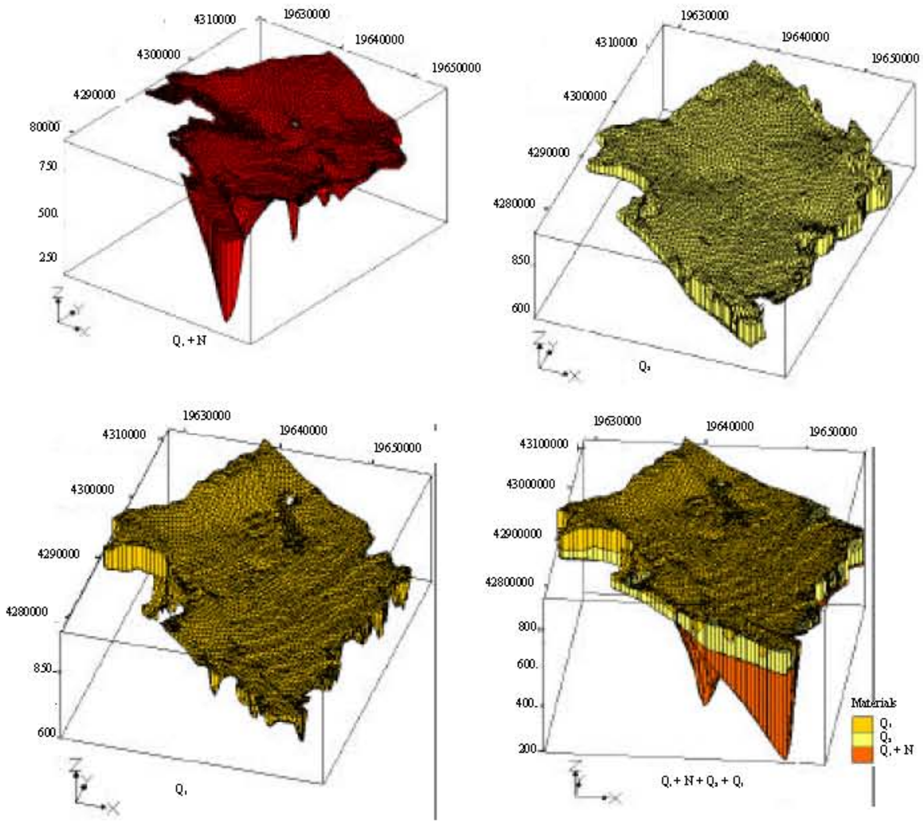

Fig. 4: Solids model developed from 3D borehole data of the quaternary aquifer of the Yangwu Proluvial-Alluvial Fan

computer models include the following. Borehole, TIN, Solids and Map Modules of GMS 6.0.

Data extraction from contour line map: Points are created form the contour line map because the boreholes are not enough to setup an accurate model. Digitization of contour line map which shows the bottom elevation of Q_{1-3}, amend (using GIS) and project into Gauss coordinate. Each contour line is assigned a value which corresponds to the elevation. The points on the contour lines created by GIS are extracted as save as. Txt file.

Creating solids: Three-dimensional profile surfaces describing the interface between geologic strata are represented in GMS using Triangulated Irregular Networks (TINs). The elevation of each stratigraphic unit's interface and the points created from the contour line maps are used to build the TIN model for the study area. Each TIN represents the surface of each layer (Q_{1-3},) which is continuous in the modeled area. The solid model is constructed from the TIN. Figure 4 shows the solid model which represents the stratigraphic structure of Q_{1-3}.

A graphical display of three-dimensional data and interpretations in 2-dimensional perspective view

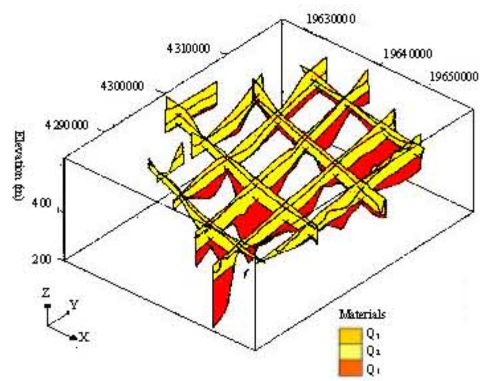

Fig. 5: Cross Sections across the Solids to Show the Complexity of the Stratigraphy in the Modeled Area

Stratigraphic changes can be displayed clearly in fence diagrams as shown in Fig. 5.

Creating lithologic model: The basin-fill is divided into three hydrostratigraphic units, Pliocene bedrock (N) and Quaternary proluvial-alluvial deposits (Q_1+N, Q_2 and Q_3) which consist of 7 lithofacies: coarse sand, medium to

Fig. 6: Borehole log (YP 42) showing the startigraph coulmn

Table 1: Lithologic classification based on drill hole descriptions. Example from drill hole YP 42

Interface elevation (m)	Interface depth(m)	Thickness (m)	Lithology code	Lithology
860	2.3	2.3	5	Sabulous sand
857.7	39.8	37.5	1	Coarse sand
820.2	70.68	30.88	1	Coarse sand
789.32	82.79	12.11	3	Medium-fine sand
777.21	86.59	3.8	7	Clay
773.41	88.44	1.85	7	Clay
771.56	99.5	11.06	1	Coarse sand
760.5	101.5	2	3	Medium-fine sand
758.5	104.58	3.08	7	Clay
755.42	111.28	6.7	3	Medium-fine sand
748.72	115.67	4.39	3	Medium-fine sand
744.33	116.3	0.63	7	Clay
743.7	116.75	0.45	2	Medium-coarse sand
743.25	126.65	9.9	7	Clay
733.35	127.06	0.41	1	Coarse sand
732.94	152.62	25.56	7	Clay

coarse sand, medium to fine sand, sabulous sand, silty sand, clayey soil, clay units. All sediments having similar hydraulic conductivity are grouped as one class. Data from 44 actual bore holes and 22 fictitious bore holes created by interpolation from existing cross sections where used with only few bore holes penetrating Q_1 at depths of ~170 m. As a result of the shallow nature of the most of the boreholes, the depth of the bottom of Q_1 is presumed from bore holes which penetrate Q_1 and the regional geologic conditions. The elevations of each stratigraphic interface and the Gauss coordinate are obtained from the borehole log. This information is tabulated into 3D geostatistics format readable by GMS. The stratigraphic units represented in each borehole log are divide into 10 layers to cover the total thickness of the quaternary deposit because the bottom of Q_1 is ~170m and most of the boreholes don't go beyond this depth. The first layer is 10 m and the others 20 m. Figure 6 and Table1 shows and example from borehole YP 42.

$$K_c = \frac{k_1m_1 + k_2m_2 + k_3m_3 + ...k_nm_n}{m_1 + m_2 + m_3 + ... + m_n}$$

where:

K_c : Comprehensive Hydraulic Conductivity.
K_i : Hydraulic Conductivity of each Stratigraphic. Unit within the Bole Hole Log.
i : 1, 2, 3 ... n.
m : Thickness of each Stratigraphic Unit.

From the above formula, we can calculate the compound parameter i.e. is the permeability coefficient of each layer.

Base on the hydraulic properties of the materials and the environment of deposition, the study area is mapped. On these bases it was divided into three zones: Piedmont, proluvial and alluvial facies. A contour map delineating the boundaries of the different zones is created. Due to the complex nature of the geologic materials, it was classified in to 7 categories as follows: coarse sand, medium to coarse sand, medium to fine sand, sabulous sand, silty sand, clayey soil, clay. On the basis of grain sizes, numerical values were assigned to each geologic material. The quaternary strata was divided into 10 layers to cover the total thickness of the quaternary deposit. The first layer is 10 m and the others 20 m. Surfer 8.0 was then use to interpolate the lithology contours to get the lithologic distribution map of each layer. This is then exported to GIS to create polygons showing the distribution of the different materials. Figure 7 shows the distribution of the different materials in layer 1. GMS6.0 is now used set up the lithologic model. Firstly, the Map and GIS modules of GMS are used to build the hydrogeologic conceptual model by dividing each lithology distribution map into grids according to precision of 500 × 500. Then the MODFLOW module of GMS is now used to build the lithologic model (Fig. 8).

The resulting model can correctly display the basins stratum lithology, distribution and can observe and analysis each layer. On the basis of these, we can assign the hydraulic parameters to each layer carry through the hydrogeologic numerical simulation. 2D cross sections can be created in horizontal and vertical directions everywhere in there search area and also can conveniently observe and analyze the hydraulic parameters.

Fig. 7: Spatial distribution of lithologic material in layer 1

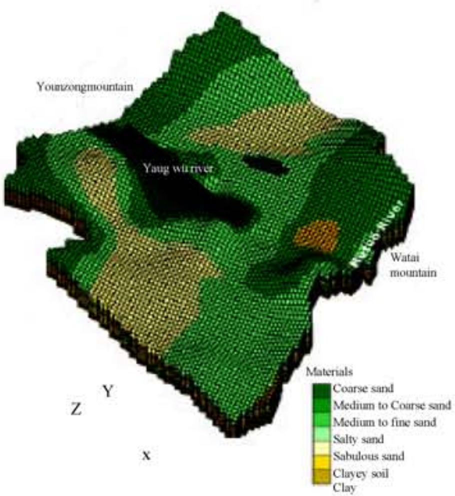

Fig 8: Lithologic model of the yangwu proluvial-alluvial fan

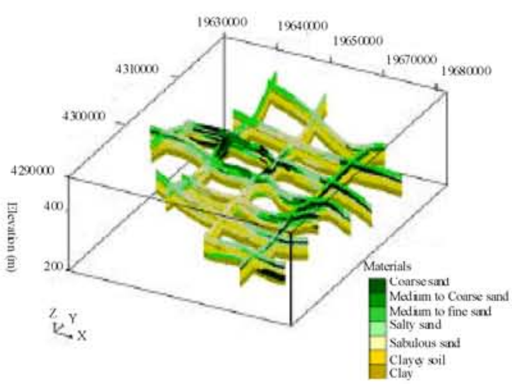

Fig. 9: Perspective view of vertical sections cut through 3D lithology model of yangwu proluvial-alluvial fan

Ten vertical cross sections (Fig. 9) cut through the 3D model display the results of the numerical interpolation as a fence diagram that highlights lithologic variations within the basin fill. In the fence diagram, the cross sections are colored according to the interpreted geologic units. Land surface is transparent so that the sections appear to hang in space. These sections clearly depict the sandy gravels associated with proluvial-alluvial fan complexes along the west and eastern margins of the basin.

DISCUSSION

In this study, a methodology to integrate different types of accessible geological information (boreholes, outcrops, cross-sections, geological maps) in a 3D geological model is presented. This methodology is based on structuring and storing in digital formats the various data of different type, nature and quality and then allowing reinterpretations. Solids were created from interpolating borehole data. Figure 6 shows the resulting solids and cross sections cut through the developed solids reflecting the complex stratigraphy of the Yangwu proluvial alluvial fan. This methodology is based on structuring and storing in digital formats the various data of different type, nature and quality and then allowing reinterpretations. For the purpose of this research, Q_4 was neglected because it is very thin and yields very little amount of water. Also, Q_1 and N were jointly considered one unit (as the bedrock) because it has and advance stage of consolidation and consists essentially of clayey material with a low hydraulic conductivity. This is because most of the bore holes do not penetrate to the bottom of N.

The reliable and usable data are then validated and selected for the 3D geological model reconstruction. With the given sources of information, the accuracy of the model depends strongly on the amount of data available, its nature and quality and its dispersion over the area of interest. In places where data are sparse or imprecise, interpretation is clearly needed. Hypotheses have thus to be made by expressing constraints to apply to model the geological surfaces. In this way, human knowledge and reflection can supplement the available data through explicit constraints. This methodology is also a very good opportunity to test and compare different geological hypotheses and select the most plausible. This interpretation was included in the separation of the different deposits into units related to periods of sediment input and river level changes.

CONCLUSION

The purpose of constructing such a three-dimensional geologic framework model is to obtain a consistent representation of the stratigraphic architecture, as it is understood from an integration bore hole data, cross sections, geologic map and geological information based on field observation and to use it for qualitative and quantitative geologic/hydrogeologic analyses. It is the view of the authors that a three-dimensional modeling approach is the most adequate way to capture the subsurface complexity of most geologic settings, which can lead, in the context of an integrated approach, to improved hydrogeologic appraisals. Finally, 3D solid and 3D lithogic models were developed. Deterministic modeling of the limited number of drill holes used produces broad lithologic trends, but it does not capture the lithologic details of highly discontinuous alluvial fan and channel complexes. Additional detail could possibly be arrived at through the use of additional drill holes and a finer model grid. However, this model is judged being reliable because there is clear visualization of the spatial distribution of the proluvial-alluvial deposits in three-dimension model is consistent to the reality. Nature as compared with the 2D Geologic map and the 3 D cross-sections developed model is similar to that drawn manually.

The final result of this Yangwu proluvial alluvial fan case study is the reconstruction of the original a broad fan-shaped deposit consisting of a variety of lithotypes. The proluvial facie extremely coarse and very poorly sorted near apex of upper fan, grading to relatively fine grained, better-sorted sediments in the distal fan majority of the material at the sites closer to areas of high relief (piedmont areas) whereas the alluvial deposits grade from coarse alluvial-fan deposits near the basin margins to finer grained alluvial deposits in the basin centre. The aim of this work was to provide a base for the groundwater flow modeling. In this application, geological formations were modeled as volumes composed of cells of a stratigraphic grid. This geometric framework can be used to evaluate the groundwater flow path.

LIMITATIONS

The results of the basin modeling must be regarded as an initial work because of the limited data. Despite the advantages of GMS 6.0 (graphical user interfaces for groundwater simulation) seen above, the method has limitation due to the fact that the fault are not visible on the model. This is because geological and geophysical data from different sources cannot be adequately imported and compared, 3D structures such as faults and faulted stratigraphic horizons are very difficult to model accurately the consistency of a geological model of faulted horizons cannot be thoroughly reviewed. Also, many manual corrections are still required to get fully satisfying results in complex settings and the model reliability is limited by data quantity and quality and, since it is a knowledge-based model, by the experience of experts and the efficiency of their interaction.

ACKNOWLEDGMENTS

This study is part of an M.S.c dissertation at the school of Environmental Studies, China University of Geosciences (Wuhan). Aspects of this research were undertaken as part of groundwater survey project titled Thematic research on groundwater resources and environmental problems of six big basins in Shanxi province of China (No. 200310400009) and were financially supported by China Geologic Survey and National Science Foundation of China (40472123).

REFERENCES

Arthur, J.D., J. Cichon, A. Baker, J. Marquez, A. Rudin and A. Wood, 2002. Hydrogeological Mapping and Aquifer Vulnerability Modeling in Florida: 2D and 3D Data Analysis and Visulaization. In: Thorleifson, L.H. and R.C. Berg (Eds.). Three-Dimensional Geological Mapping for Groundwater Applications: Workshop Extended Abstracts: Ottawa, Ontario, Geological Survey of Canada. Open File, 1449: 1-4.

Artimo, A., R.C. Berg, Abert, C.C., J and V.P. Salonen, 2002. Three-dimensional Geological Modeling of the Virttaankangas Aquifer, Southwestern Finland. In: Thorleifson, L.H. and R.C. Berg (Eds.). Three-Dimensional Geological Mapping for Groundwater Applications: Workshop Extended Abstracts: Ottawa, Ontario, Geological Survey of Canada. Open File, 1449: 5-7.

Deng, Q.D., K. Wang, Y. Wang, H. Tang, Y. Wu and M. Ding, 1973. On the tendency of seismicity and the geological set-up of the seismic belt of Shanxi graben. Sci. Geol. Sin., 1: 37-47.

Geologic Survey Bureau, 1976. Shanxi Province.

GMS (Ground Water Modeling System), 2000. Groundwater Modeling System Software, Brigham Young University, USA.

Research Group of State Seismological Bureau, 1988. Research Group of State Seismological Bureau, Active Fault System Around Ordos Massif, Seismic Press, Beijing (In Chinese).

Ross, M., M. Parent, M. Michaud, E. Boisvert and F. Girard, 2001. On the Construction of 3D Geological Models for Applications in Regional Hydrogeology in Complex Quaternary Terrains of Eastern Canada. In: Berg, R.C. and L.H. Thorleifson (Eds.). Geological Models for Groundwater Flow Modeling, 35th Annual Meeting, North-central Section GSA: Bloomington-Normal, Illinois, Illinois State Geological Survey. Open File Series, 2000-1, pp: 34-37.

Sweetkind, D.S., W.R. Belcher and C.C. Faunt, 2002. Hydrogeological Framework Construction, Using an Example from the Death Valley Ground-water Flow System, Nevada and California, USA. In: Thorleifson, L.H. and R.C. Berg (Eds.). Three-Dimensional Geological Mapping for Groundwater Applications: Workshop Extended Abstracts: Ottawa, Ontario, Geological Survey of Canada. Open File, 1449: 71-74.

Thorleifson, L.H., G.L.D. Matile, D.M. Pyne and G.R. Keller, 2001. Construction of a Geological Model of the Winnipeg Region for Groundwater Modeling. In: Berg, R.C. and L.H. Thorleifson (Eds.). Geological Models for Groundwater Flow Modeling, 35th Annual Meeting, North-central Section GSA: Bloomington-Normal, Illinois, Illinois State Geological Survey, Open File Series, 2000-1, pp: 52-54.

Workman, J.B., C.M. Menges, W.R. Page, E.M. Taylor, E.B. Ekren, P.D. Rowley, G.L. Dixon, R.A. Thompson and L.A. Wright, 2002. Geologic map of the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2381-A, scale 1:250, 000. http://pubs.usgs.gov/mf/2002/mf-2381/.

Xu, L. and X. Niu, 2006. Current status and prospects of the 3-dimensional visual simulation of geological bodies. J. Southwest University for Nationalities (Nat. Sci. Edn.), 1 (32): 151-154.