

# A 3-DIMENSIONAL VISUALIZATION – DECISION SUPPORT TOOL FOR GROUNDWATER-SURFACE WATER CONNECTIVITY ASSESSMENT

Sultana Nasrin Nury<sup>1</sup>, Xuan Zhu<sup>1</sup>, Ian Cartwright<sup>2</sup>, Laurent Ailleres<sup>2</sup>

School of Geography and Environmental Science<sup>1</sup>, School of Geosciences<sup>2</sup>,  
Monash University, Wellington Road, Melbourne, Victoria  
Email : [snnur1@student.monash.edu.au](mailto:snnur1@student.monash.edu.au); [nurysn@yahoo.com](mailto:nurysn@yahoo.com)

## ABSTRACT

Groundwater is an integrated part of the water cycle. Most of the groundwater systems are connected with the surface-water system, and alteration of any system has impact on the other. This integrated surface and groundwater connectivity has significant water management and policy implications. For sustainable allocation of groundwater resource it is important to know how much water can be explored from the aquifer without disturbing the surface-water system. In addition, continuous pumping of groundwater lowers the water table and increases the water movement both in the horizontal and vertical directions. This process makes an aquifer vulnerable to contamination and it is necessary to identify the aquifer properties and geometry which may affect the vulnerability.

For groundwater exploration and sustainable management, scientists and water managers traditionally utilize conceptual and numerical on two dimensional (2-D) models using borehole data. Recently with the growing computing power, three dimensional (3-D) models are widely used for better decision making. In hydrogeology, 3-D subsurface modelling provides better understanding of the whole aquifer system regarding stratigraphy, geometry, volume etc. which are very necessary parameters for sustainable groundwater resource management. The interactive 3-D geological models provide a much better contextual environment to process, analyse and communicate the information than the 2-D model. 3-D visualisation and groundwater surface-water connectivity assessment of an aquifer is an integrated approach that could provide better information to the managers and to the policy makers for the sustainable management of water system.

Keywords: 3D geomodel, GIS aquifer, groundwater and surface water interaction, sustainable water future.

## INTRODUCTION

Every form of water in the water cycle is connected. With increasing climatic uncertainty groundwater becomes more of a concerned as an economic and alternative source of water. As an integral part of water cycle, extraction of underground water might have an influence on the surface water flow in the long run. On the other hand changes in surface water flow may change the groundwater recharge pattern. Aquatic ecosystems such as perennial streams and wetlands

can rely on groundwater, especially during the droughts that are common in Australia (Ladson, 2008). Also, landuse change can alter groundwater–surface water natural equilibrium, for example modification of land surface, from native vegetation to agricultural land, imposed increased water table in the water cycle equilibrium which can affect salt loads to rivers (Paul, 2006, Khan et al., 2007, Macumber and Fitzpatrick, 1987). On the other hand drying creeks and rivers may be resulted from pumping groundwater (Winter et al., 1998). In many Australian catchments, aquifers and surface water features are hydraulically connected (Macumber, 1991, NGC 2003). This integrated movement of water can have significant water management and policy implications (Ivković, 2006). Hence, effective management of water quantity and quality issues requires an understanding of the integrated surface water to groundwater connection. Integrated management of surface water and groundwater is critical for ensuring sustainability of the water resource (Winter et al., 1998).

Investigation of surface water flow is relatively less complex than groundwater flow because surface water flow can be differentiated and estimates based on the catchments. But groundwater basins are heterogeneous. The boundary is not necessarily congruent with the surface catchments boundary above and is not visible (Sophocleous and Perkins, 2000, Ransley et al., 2007). Visualization of the complex subsurface will enhance the understanding about the hydrogeological settings of the aquifer and estimation of the availability of water for development. Knowledge of the hydrogeological setting involves mapping the configuration and characteristics of the aquifer and groundwater flow systems, covering aspects such as aquifer geometry (thickness, gradient, edges, isolation, etc.), geological and stratigraphic configurations (fold, syncline, graben, intersections with the faults, facies changes, etc), and hydraulic properties such as transmissivity and storativity, and recharge and discharge mechanisms (Spottke et al., 2005). Recent advances in desk-top-based visualization software now provide an interactive environment where different related datasets can be displayed, integrated and analyzed in three dimensions (3D). 3D GIS (Geographic Information System) based Geomodel, offers a robust platform to depict the complex subsurface geology of an aquifer and opportunity to incorporate all the water related data to better understand the surface water and groundwater interaction in terms of recharge and discharge phenomena. This study aims to provide visualisation methods for better understanding and relationships between geology and water flow both in surface and subsurface in Barwon Downs Graben aquifer in Victoria. This aquifer contains good quality groundwater water which augments the Geelong water supply during the draught.

The focus is on an the integrated spatial data analysis approach which incorporate scientific data for various components: DEM, geology (lithology and structure), physiography and borehole data, water level, etc. This is an attempt to build a 3D visual model of Barwon Downs Graben aquifer architecture utilising generally available datasets in the public domain. This modelling tool is mainly developed for applications in the petroleum industry, although it is now increasingly used in the hydrogeological investigations.

## **BACKGROUND**

Barwon Downs Graben is situated approximately 70 km southwest of Geelong on the northern flanks of the Otway Ranges and extends from the Gellibrand in the southwest to the Birregurra in the east covering an area of approximately 500 km<sup>2</sup>(Petrides and Cartwright, 2006).

The region has a temperate climate with warm dry summers and cool wet winters. The average daily maximum temperature ranges between 25 to 27°C in summer and 12 to 14°C in winter. The average annual rainfall show distinct spatial variations: in the north-western part it ranges between 1200 to 1400 mm per year and gradually decreases towards north-easterly up to 600 to 700 mm per year. The average monthly rainfall from June to September is approximately 110

mm, but less than 50 mm between the months of January and March and potential evaporation exceeds rainfall from December to March. The period of potential recharge in this area is from May to September.

Groundwater investigations conducted in the Barwon Downs Graben since the early 1960s showed that it contained an extensive high-quality groundwater resource. This groundwater resource is an important source of water in “Barwon Waters” for the drought management plan of Geelong. The Barwon Water bore field consists of four production bores with a combined capacity to extract up to 50 ML/day. This bore field provided a significant contribution to Geelong’s water supply during the 1982/1983, 1988 to 1990, 1997, 2001, 2005 and present drought situation (SKM, , 2001). Barwon Water is licensed to extract 80,000 ML over a 10-year period with a maximum of 12,500ML in any year (Witebsky et al., 1995).

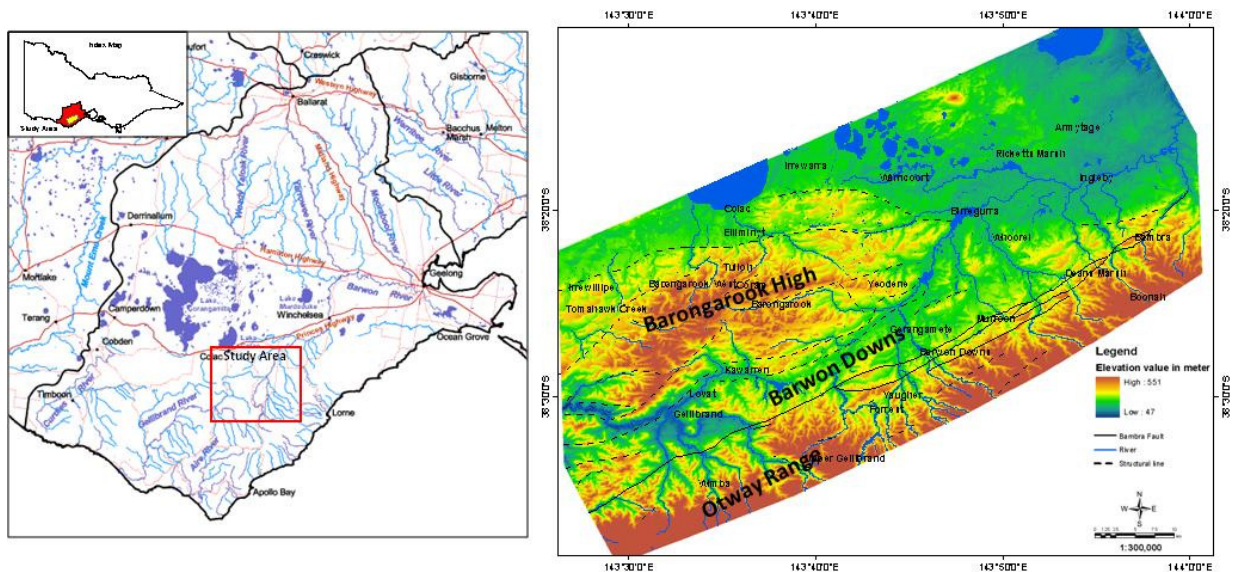


Fig. 1: Location Map of the study area.

This Graben aquifer is a small synclinal structure bounded by the Otway Ranges to the south and the Barongarook High to the west. The region is dominated by a series of NE/SW-trending folds and faults that make up the major structural elements of the graben (Petrides and Cartwright, 2006). This structural elements has significant influence on water flow both in surface and subsurface.

The subsurface consist of a complex multi layered suite of Mesozoic and Cenozoic sediments reflecting several depositional and tectonic events. Multiple subsurface layers are formed alternative aquifer and aquiterd with different water quality (Table 1). Among the layers the Eastern View Formation of lower Tertiary is the main aquifer system. Surface exposures of this formation in Barongarook and Otway Ranges considered as the recharge area (Tickell et al., 1991, Edwards et al., 1996). Surface exposure of aquifer makes the direct connections of surface water and groundwater. Where this layer is near to the surface and intruded by the river bed then water might flow from the aquifer towards the river or vice versa. The pattern of this water flow connectivity depends on the water level both in the aquifer and in the rivers and also on the lithological characteristics of the river bed.

From Surface this area seems as an isolated graben structure which might have limitations to sustainable water supply in long term (Petrides and Cartwright, 2006). On the other hand it has

been reported that bore field pumping in Barwon Down aquifer dried up the nearby Boundary creek flow (Witebsky et al., 1995) and water flow of the other river also reduced in this area. Different researcher estimated the volume, storage and elastic storage of water for this aquifer system in different time (Leonard, 1988, Leonard et al., 1983, Teng, 1996, Witebsky et al., 1995). But most of these are done based on the simplified assumptions of the layers and geological settings. In this context the specific objectives of this research are to characterize the geometry and heterogeneity and estimate the volume and water storage of the Barwon Downs aquifer based on 3-D visualization i.e., geomodelling using GIS techniques.

Table 1 Hydrostratigraphy of the study area (adopted from Tickell et al., 1991).

	Rock units	Lithological Description	Occurrence & distribution	Hydrogeologic characteristics	Salinity range (mg/L TDS)	Range of bore yields L/sec
Quaternary	Undifferentiated	Alluvial deposits sandy clay, clay, sand.	Surficial deposits only; occurs to the south and southeast of Lake Colac.	Unconfined aquifer to aquitard	poor quality?	Small
	Newer Volcanics	Basalt, scoria, tuff.	Occurrence mainly limited to area northwest of Lake Colac.	Unconfined to semi-confined fractured rock and previous media type aquifers.	500-7000	0.2 -45.0 typically 1.0 –to 10.0
	Upper Tertiary Sand	Sand, gravel, clay.	Colac area	Unconfined to semi confined porous media type aquifer	Unknow n poor quality	unknown
Tertiary	Gellibrand Marl	Marl, calcareous clay and silt, clayey limestone.	Outcrop in most areas except the Barongarook High.	Aquitard to minor aquifer, low hydraulic conductivity sediments	500-1500	0.1- 0.5
	Clifton Formation	Limestone, Limonitic sandy limestone.	Mainly subsurface in the Barwon Downs Graben; small outcrops in Kawarren area.	Confined Porous media type aquifer	500	Unknown 5.0?
	Demons Buff Formation	Marl, silty marl, marly limestone, mudstone.	Outcrops in eastern side of Barongarook High. Occurs subsurface in Barwon Downs Graben.	Aquitard leaky confining unit of low hydraulic conductivity		Negligible
	Upper Eastern View Formation	Quartz sand and gravel, calcareous sand, limonitic sandy limestone.	Occurs mainly subsurface in the Barwon Downs Graben. Limited outcrop on Barongarook High.	Confined to unconfined porous media type aquifer	200-500	10-50
	Middle Eastern View Formation	Quartz sand and clayey sand, silt.	Outcrops over much of Barongarook High. Excessive subsurface occurrence being particularly well developed in the Barwon Downs Graben.	Unconfined to confined porous media type aquifer	200-500	50-100
	Clay Horizons at the top of the lower Eastern View Formation	Clay, silt, ligneous, clay, minor brown coal.	Relatively thin unit. Occurs mainly only subsurface in the Barwon Downs Graben	Aquitard; low hydraulic conductivity sediments		
	Lower Eastern view Formation	Quartzose sand and gravel, lithic pebbles.	Mainly subsurface, small outcrops around Otway group contact on Brangarook High.	Confined to semi confined porous media type aquifer	200-500	50-30
	Cretaceous	Eumeralla Formation	Sandstone, siltstone, mud stone, conglomerate, thin coal seams.	Outcrops and sub crops on the Barongarook High. Elsewhere intersected at depths up to 600m	Unconfined fractured rock type aquifer. Regarded as groundwater basement	1000-3000

## **METHODOLOGY**

In this work subsurface 3-dimensional visualization has been done based on “Geomodelling” which was first defined by Mallet (1992) as, “Geomodeling consists of the set of all mathematical methods allowing modelling the topology, the geometry and the physical properties of geological objects in a unified way while taking into account any type of data related to these objects”.

The modelling procedure is subdivided into different steps which include at first the collection, sorting and importing the usable data into the modelling software. This initial work is very time consuming but is the base work for the whole modelling process. The borehole information, surface topography, surface geology, geological cross-sections, seismic profiles, structural elements, are the main input of this geomodelling for the Barwon Down Graben Aquifer. One of the main difficulties of using such varied data in 3D geological modelling was the heterogeneity of descriptions and interpretations. All the input data are free and collected from the relevant government organizations. Considering the data variability in nature and quality, a data-validation step was also employed. The collected data need to be processed in order to build a consistent dataset and project all the data in similar coordinate systems.

The ArcGIS 9.2 software was used for 2-dimensional GIS analysis and for 3-dimensional visualization and modelling GOCAD (Geological Objects Computer Aided Design) was selected which is one of the leading software packages employed in geomodeling. This software, which is developed by the GOCAD Research Group at the Nancy School of Geology (France) and its partners, is specifically designed to construct and analyse geologic objects and their properties (Ross et al., 2005). The developed methodology of ArcGIS and GOCAD has been implemented to model the subsurface. The data transfer between these software components was made through file exchanges. In ArcGIS Geological objects are represented by points, lines or polygons and these can be directly imported into GOCAD as cultural data like “point and curve objects”.

The second step involved with the construction of surfaces and the faults from collected data. The surfaces are built from DEM, surface geological map, geological cross-sections and borehole data. Once the geometry of the surface and contacts are correctly defined, then the interpolation algorithm is applied to the make interlocked surfaces.

The third step is the making the volume model from the interlocked surfaces. The interlocked surfaces formed the closed volumes that represent the geologic bodies. The surfaces thus act as “dividing walls” isolating 3-D regions (Mallet, 2002). Surfaces must form a closed volume and the line defined by the intersection of two surfaces should be unique and free of gaps. The topology should be consistent, as it allows calculation of volumes, visualization of separated objects and application of grid generation tools that maintain the geometric integrity of the geological model. Further discretization may also be achieved by using advanced gridding tools. The 3-D regions and grids were used to create sub-models for visualization of geologic setting, to generate continuous units and to calculate unit thickness and volumes. The volumetric geological model can further sliced in different cross section to check the geometry of the different layers (Ross et al., 2004, Connected water, 2008).

### **3D Geomodel of the study area**

The surface relief of the study area are modelled from a Digital Elevation Model (DEM) of Vicmap which consist of 20m X 20m grid cells. To manage the large data set, DEM of 20m grid has been resampled to 60m grid. Then it transformed as a point set with elevation attributes in

GIS and imported in GOCAD where Z property was calculated from the elevation values. Then the points are interpolated to generate the surface topography.

Digital surface geology map (1:250,000) of the study area has been collected from the Geological Survey of Victoria and subsetted it for the study area. It is an important data source of the geological boundaries and major structures. ArcGIS Shape file of geological boundaries, structural elements, river and water bodies are directly imported in GOCAD as curve object. Discrete closed curve of individual geological unit has been selected and used to generate the surface of that unit using “surface from closed curve” command. Once this surface is created, all borders are constrained to move only on a straight line in the Z direction. The outcrop boundaries are projected vertically onto the 3D topographic surface and range thickness constrain has been set to project the surface on DEM. 3D surface geological map is made with major geological units and shown in the figure 2. Other open curved objects like fault line, river and water bodies are vertically projected on the topographic surface.

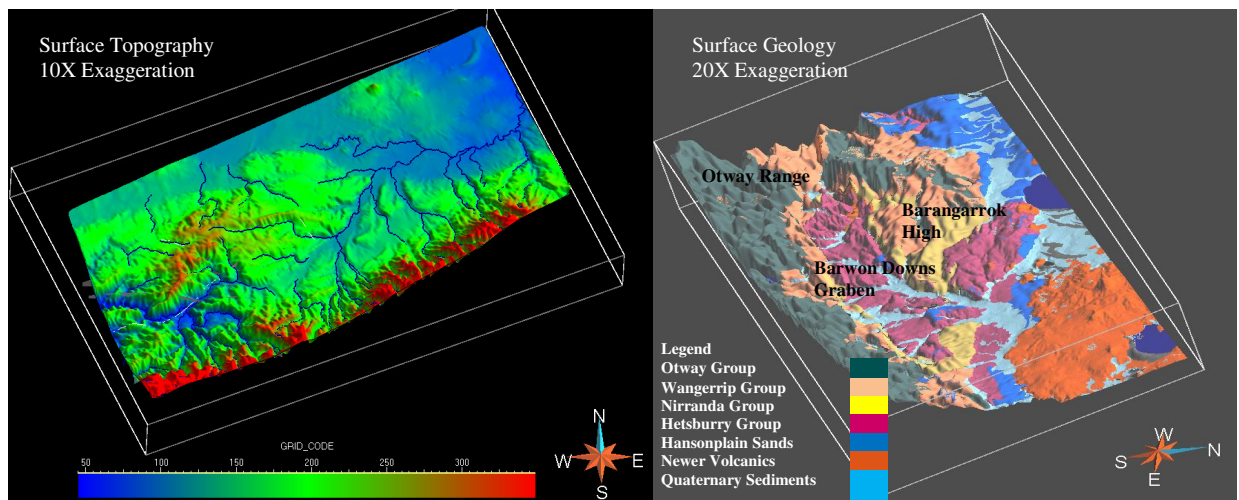


Fig. 2: 3D surface topography and surface geological Map.

Fault lines are imported in GOCAD as curve object. To individualize the faults, new curve parts are created by selecting individual fault line and then fault surface are made using “built in forms as tube (curves and expansion vector)” commands. Spherical coordinate of the faults converted into Cartesian coordinates. Azimuth, dip and depth of the fault plane are approximated from the different published reports.

Prior to the construction of the model surfaces of Barwon Downs Graben Aquifer area, one of the most challenging aspects of the modelling task was to adequately correlate borehole attributes to a given stratigraphic unit. In 2D GIS environment using ArcGIS, point shape of borehole locations are subsetting for the study area from the borehole database of Victorian Geological Survey. These point data then reprojected in GDA 1994 AMG zone 54 co-ordinate system. Elevation of these points then extracted from the DEM (20m). From the subsetting data, location of bore log and interpreted stratigraphic information has been sorted out using built-in database query function of the database. Stratigraphic information for each bore has been extracted from the database and stored them in a simple database file. After getting the entire data it has been carefully checked for the consistency in interpretation for each selected bore log. After making the entire interpreted data consistence these information then properly encoded with numeric value which is required for the 3D geomodelling software. In the Barwon

Downs area 11 stratigraphic layers are sampled from the bore log data (Table 2). On the other hand description of hydrogeological characteristics of these layers is collected from different published reports. All of these data with depth range are then stored as attribute of bore log location point map (Figure 3).

The processed information is then converted in ASCII format to load the data in GOCAD for geomodelling. New point set are created for individual geological unit base from imported bore log data. To individualize this point set, regions are made from numeric code of geological units by using property range command. During individualization of the point set some generalization are done because of limitations of data availability and distribution. These points are used as control points to constrains the created surface of geological unit base.

Table 2 Example of numeric code used in ArcGIS and GOCAD.

Age	Group	Formation name in data base	Reinterpreted Formation Name	Numeric Code in ArcGIS	Numeric Code in GOCAD	
Quaternary	Quaternary and Pliocene	Quaternary Sediments	Quaternary And Pliocene	1	1	
		Newer Volcanics		2		
		Hanson Plain Sand		3		
Tertiary	Heytsbury Group	Gellibrand Marl	Gellibrand Marl	4	2	
		Clifton Formation	Clifton Formation	5	3	
		Older Volcanics	Older Volcanics	6	4	
	Nirrandra Group	Demons Bluff Formation		Demons Bluff Formation	7	5
		Mepunga Formation		Mepunga Formation	8	
	Wangerrip Group	Eastern View Formation	Dilwyn Formation	Eastern View Formation	9	6
			Pember Mudstone Formation			
Pebble Point Formation						
Cretaceous	Sherbrook Group	Paratte Formation	Paratte Formation	10	7	
	Otway Group	Eumeralla Formation	Eumeralla Formation	11	8	

FID	Shape	BH_id	from_m	to_m	N_Code	formation	f_age	DEPTH	EASTING	NORTHING	RASTERVALU	Top
0	Point	47769	0	113	4	Gellibrand Marl	Miocene	197.51	751891	5746072	159	159
1	Point	47769	113	125	5	Clifton Formation	Oligocene	197.51	751891	5746072	159	46
2	Point	47769	125	179	7	Demons Bluff Formation	Eocene	197.51	751891	5746072	159	34
3	Point	47769	179	197.51	9	Eastern View Formation	Palaeocene	197.51	751891	5746072	159	-20
4	Point	47771	0	119	4	Gellibrand Marl	Miocene	345	751001	5745077	159	159
5	Point	47771	119	137	5	Clifton Formation	Oligocene	345	751001	5745077	159	40
6	Point	47771	137	214	7	Demons Bluff Formation	Eocene	345	751001	5745077	159	22
7	Point	47771	214	327	9	Eastern View Formation	Palaeocene	345	751001	5745077	159	-55
8	Point	47771	327	345	11	Eumeralla Formation	Kimmeridgian	345	751001	5745077	159	-168

Fig. 3: Example of stratigraphic information stored as attribute data of location point map.

Geological and geophysical cross sections of the study area are collected from the different published report. 35 new cross-sections are also created from the bore log and imported in GOCAD as 2D voxet image. Before importing these images they are clipped for only the data area and project using “voxet- resize with points” command in GOCAD providing the x, y, z- surface elevation and z-depth of each individual sections. From these cross sections, base boundaries of each geological unit are delineated considering the fault off-sets from the created fault surface. All the boundary lines are stored as curve object with proper name. Then a new

point set for each geological unit base is made by using the unit base boundary line and unit base point that are created from the bore log data.

A homogeneous triangulated surface is then created and used to generate all geological units. The refinement of this triangulated surface controls the scale of structures that can be represented. Where the density of data is high, small-scale structures will be smoothed. On the contrary, in the area where the data coverage is poor, additional constraints (such as constraints on layer thickness) will more strongly determine the bearing of surfaces. Once this surface is created, all borders are constrained to move only on a straight line in the Z direction. The outcrop boundaries are projected vertically onto the 3D topographic surface. Likewise, the borders equivalent to extent limits are projected vertically on the geological unit above or below according to the geometry of the formation. When the borders are projected, the points of the borders corresponding to geological boundaries are set like control nodes, meaning that they are not allowed to move during interpolations. The same process is applied for each geological unit. The individual point set which are derived from the bore log and unit boundary from cross sections are set as control points for each geological units. These control points constrain the subsurface topography of the units. All these operations are performed through the built in commands and scripts in GOCAD. Once all surfaces are built, cross-over between surfaces are removed by pushing a surface below or above a reference surface specifying a minimum thickness constraint. On the surfaces where little information is available, range thickness constraints are applied to constrain the target surface to remain within a range of distance from another surface. All the created surface then subset for area of interest which is mainly based on the available data density.

After building all the surfaces of geological units, the 3D geological volume model can be constructed as a stratigraphic grid or as a voxel. For the area of interest voxel model has made using triangulated surface layers to partition the volume in different region. The gridding of the voxel is created and specified according to the X- and Y-axis and the cell size in the horizontal plan (along X and Y) around 100m and 5m in Z direction are defined. It requires creating a stratigraphic order defining manually the unit's boundary.

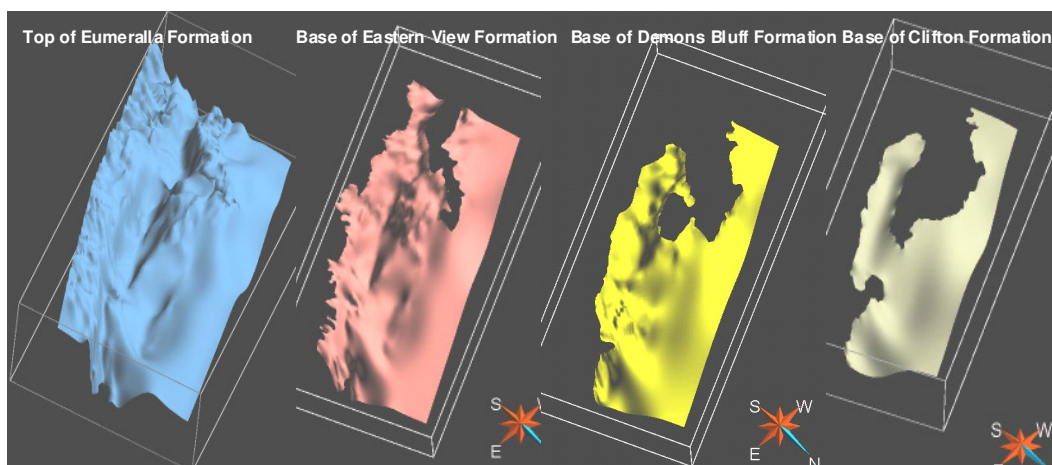


Fig. 4: The base of different geological unit.

Surfaces have to be selected to delimit top and base of the grid while outer borders of both surfaces are given by the area of interest. In order to model the main stratigraphic units, the DEM is used as top surface while the base is a surface with a constant depth at 800m below mean sea level.. The units are then built from base to top. This work consists in a systematic sequence of steps to specify grid characteristics through incorporating the layers in the model, then building the region. The next step builds the stratigraphic units and units are defined to

represent with 8 layers according to the property range. The operations are automatic or interactive with a possibility to select options to improve the modelling. Then, The 3D reservoir grid construction ends with creating 3D geological model of the Barwon Downs Graben aquifer in which each formation is represented by a region (Figure no. 5). This model then allows displaying each formation as a separate geometric volume and is also very useful to visualize as cross-sections.

## RESULTS AND DISCUSSIONS

3D volume model, enhance the visual interaction and understanding of the complex subsurface settings of different geological units as well as the hydraulic strata. This type of representation also helps the non-professionals to get idea about the subsurface complexity. From the volume model, each of the layers is individualized using their region properties and therefore volumes are calculated to estimate the water availability in each layer. One of the important requirements in groundwater management is to know how much water is available in subsurface of an area. Generally, to calculate these properties, volume of water bearing strata is generalized from thickness and area. But geomodel provide the layer volume considering the geological settings and also visual relation with the other units. This volume of layer information could use with specific yield to estimate the extractable water from an aquifer. In the following table 3 calculated volume of each layer from geomodel of the study area has given.

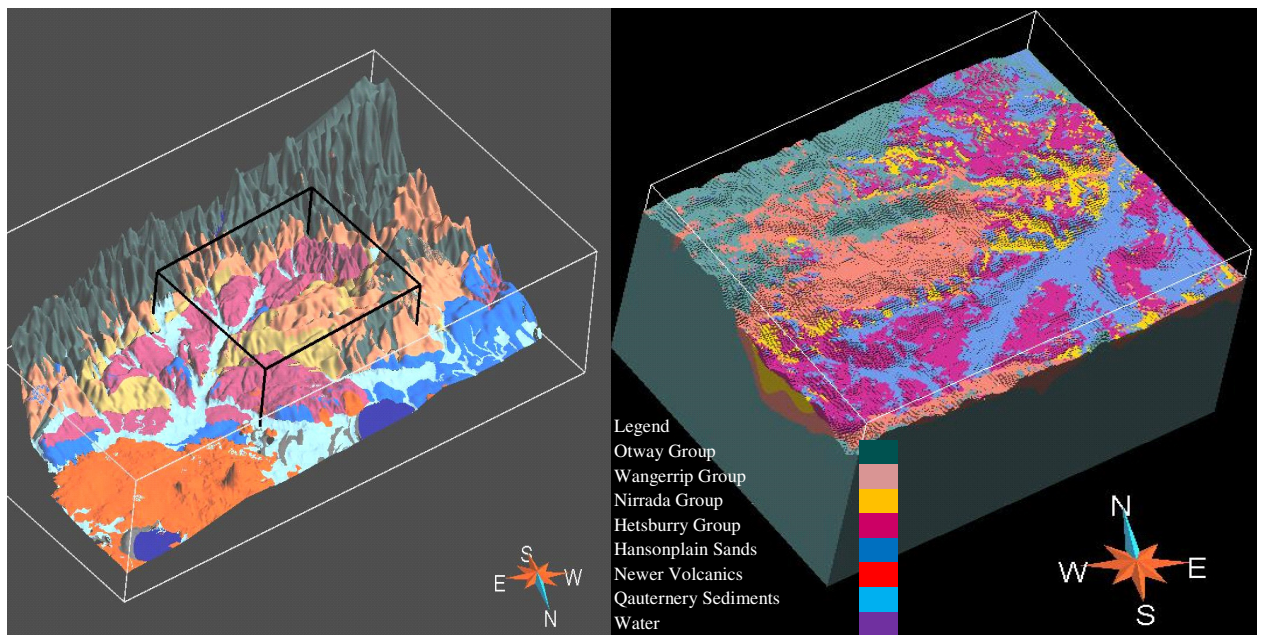


Fig. 5: Volume Model of the study area

Table 3 Calculated volume of the individual layer of the study area.

Numeric Code	Unit	Volume in m <sup>3</sup>	Hydraulic Properties
1	Quaternary & Pliocene Sediments	1.3 x 10 <sup>9</sup>	Minor Aquifer
2	Gellibrand Marl	1.85 x 10 <sup>10</sup>	Aquiterd
3	Clifton Formation	1.77 x 10 <sup>9</sup>	Minor Aquifer
4	Older Volcanics	1.49 x 10 <sup>8</sup>	Aquiterd
5	Demons Bluff Formation	1.62 x 10 <sup>10</sup>	Aquiterd
6	Eastern View Formation	2.81 x 10 <sup>10</sup>	Main Aquifer
7	Paratte Formation	2.92 x 10 <sup>8</sup>	Minor Aquifer
8	Eumeralla Formation	1.33 x 10 <sup>11</sup>	Regarded as groundwater basement

This geomoel can be further used for groundwater flow modelling through producing appropriate grids(Ross et al., 2002). One of the important use is to map the distribution and thickness of the confining layer and also hydrostratigraphy in the recharge area. In the study area, Lower Tertiary Eastern View aquifer is exposed at Barangarrok High and considered as the main recharge area. Thickness of this formation in this area is few meters and directly lying on the Cretaceous Eumeralla Formation. The Eumeralla Formation considered as the basement of the aquifer system which is a low permeable fractured rock. In this area the Eastern View aquifer is unconfined in nature and in the central part it becomes confined due to thick and continuous Gellibrand Marl as the confining layer.

From the model, it seems, the thickness and depth of the main aquifer increases towards the centre of the graben and follows the axis of elongation and decrease towards west and near to the boundary of the graben where gradient of this unit is very high (Figure 6). This unit is inclined towards the north east. Towards the center of the graben overburden thickness is higher

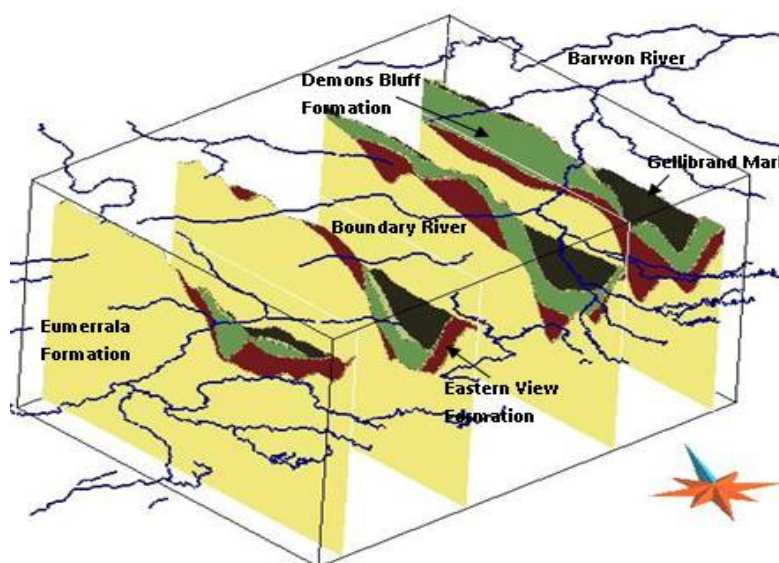


Fig. 6: Vertical cross-sections of the volume model with overlying river.

and makes the aquifer as confined in nature. The river parts, where it is connected with the aquifer can be identified from several cross-sections from the mode (Figure 6). Identifying these river parts is important to manage the environmental flow of the river and for the allocation of this resource. Changes in level of both surface and groundwater will change the water flow direction between river and aquifer. Changes in groundwater level data, cross-sections from

volume model, surface exposures, rivers and water extraction points can be used to identify the area where flow may be affected due to changes in groundwater level.

## CONCLUSIONS

In this paper, a 3D aquifer visualization (geomodel) is presented to integrate different types of accessible geological information for geomodelling. 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. This methodology provides a good opportunity to test and compare different geological data and select the gap area. This type of modelling can provide information to complement the development and management policy as a decision support tool for sustainable water extraction from an aquifer and surface water management. This volume model can be further used for the water flow modelling, vulnerability assessment, environmental analysis, etc.

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## **BRIEF BIOGRAPHY OF THE PRESENTER**

Sultana Nasrin Nury is a postgraduate Research Student in the School of Geography and Environmental Science, Monash University. She graduated in Geosciences from Bangladesh and has completed the Professional Masters degree in Spatial Science from the Institute of Earth Resource and Geoinformatics (ITC), the Netherland. She is working as an environmental geologist in Geological Survey of Bangladesh since 1999.