

Development of a 3D Geological Mapping and Database Interface to Support Interconnected Groundwater and Surface Water Management

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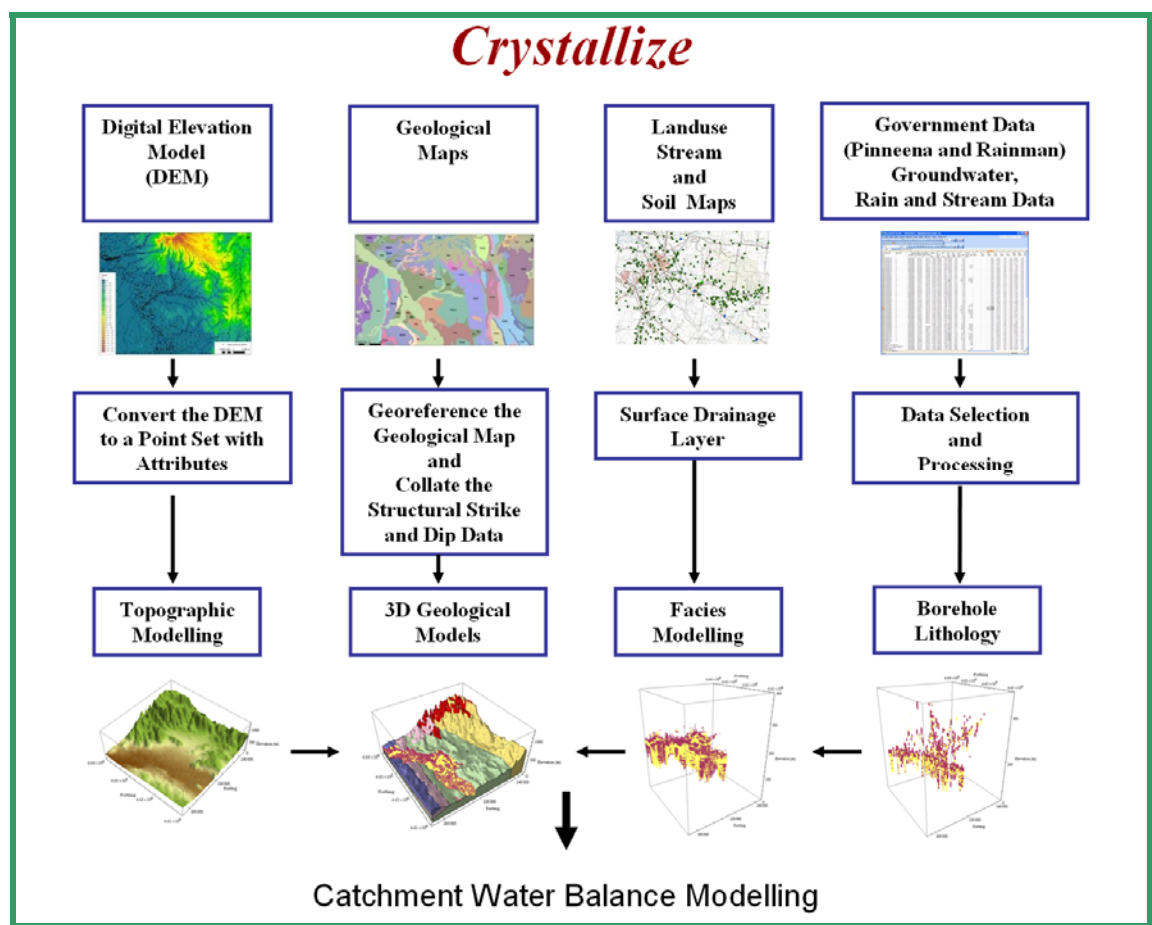
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1 Introduction

This project demonstrates one approach to coordinating and analysing hydrogeological data to help with the evaluation of catchment water management issues. The methodologies presented in this report are not intended to replace existing approaches to coordinating hydrogeological data being used by NSW state government water management departments. Rather the applications presented complement.

Four software programs are used for this project: MS Access, ArcGIS, *Mathematica* and FEFLOW.

MS Access (<http://office.microsoft.com/en-au/default.aspx>) is used to coordinate the data from the NSW Water Information Pinneena Groundwater Works CD, which is the primary data set for the bore construction details and the standing water level measurements. This information is combined with other continuously recorded climatic data from the Bureau of Meteorology and the Pinneena Continuous Flow CD into a single MS Access database.

ArcGIS (<http://www.esri.com/software/arcgis/index.html>) is used to coordinate all the 2D spatial information. Important information in this database includes the digital elevation model (DEM), geological maps, soil maps, landuse maps and the stream network.

Mathematica (Wolfram Research, Inc., 2008, <http://www.wolfram.com/>) is used for the plotting and analysis of the hydrograph data, for constructing the 3D conceptual site model of the catchment hydrogeology, populating the FEFLOW (www.dhigroup.com) mesh, and the post processing of the modelled groundwater hydrographs. The *Mathematica* notebooks developed for this project have been coordinated under the name *Crystallize*. These notebooks are to be placed in the public domain. To use the *Mathematica* notebooks requires the purchasing of a *Mathematica* license. The hydrograph analysis applications described in this report could all be used on the web by running the applications using Wolfram web*Mathematica*3 (<http://www.wolfram.com/>). This would make the information on the Pinneena CDs accessible to anyone in a visual format.

Only a few representative data analysis applications are presented, because there are numerous aspects to coordinating the data for a catchment, and approaches to analysing the data are open ended. The components that are presented demonstrate working with the databases, the workflow for key aspects of constructing a conceptual 3D geological model of a catchment, and pre and post processing information when using FEFLOW for the catchment water balance modelling.

A copy of the MS Access database, ArcGIS database, all the *Crystallize* notebooks (*Mathematica* .nb files), supporting Excel files and a MS Word document version of the notebooks are located on the accompanying USB memory stick. Below, the contents of the USB memory stick are described in more detail.

1.1 Comments on the Choice of MS Access

Three database systems dominate the commercial world: MS Access/SQL server, MySQL and Oracle (<http://www.mysql.com/why-mysql/marketshare/>). This project used MS Access because MS Access is used in most government water management organisations, making adoption easier.

Another advantage in using MS Access for a demonstration project is that the database can easily be transferred between offices and computers. Each of the other major database programs is tied to a server.

The database is designed with the expectation that it will need to be migrated to another platform at some stage. This is because MS Access is only meant to be a small scale database application. The MS Access database developed for this project can be migrated to any of the market leading database systems.

For details on the migration of MS access refer to:

- MS Access to MS SQL server (<http://support.microsoft.com/kb/237980>)
- MS Access to MySQL (<http://www.mysql.com/why-mysql/migration/>)
- MS Access to Oracle (<http://www.oracle.com/technology/tech/migration/focusareas/access.html>)

Further details about the information in the MS database are provided in Appendix 1 and the database is located in the folder Appendix1_Databases.

1.2 Comments on the Choice of ArcGIS

The decision to use ArcGIS for the 2D database was driven by a number of factors:

- Both the NSW Office of Water and the Namoi CMA already have people skilled in the use of ArcGIS;
- Many of the 2D data sets obtained from the various government agencies were already in an ArcGIS compatible format;
- *Mathematica* has functions that link directly to ArcGIS; and
- There is considerable interest in the use of ArcHydro for managing catchment data by various government departments.

Further details about the information in the ArcGIS database are provided in Appendix 1 and the database is located in the folder Appendix1_Databases.

1.3 Comments on the Choice of Mathematica

Mathematica was originally developed as a system for doing mathematical computations. It has evolved into a powerful environment for interacting with databases, spreadsheets and text files. It has a comprehensive library for visualising data in traditional graphs and as 3D objects. The flexible programming and visualisation environment has enabled the development of a new 3D geological modelling environment which costs a fraction of the market leading products (a copy of *Mathematica* is required, but the *Crystallize* notebooks are free). This was not the original goal of the project, but is a major outcome.

The *Mathematica* programs are run from inside notebooks. These notebooks are live documents; they contain the text, the programs, and the graphical outputs of the calculations. All the images that are created in the notebooks are interactive. The *Mathematica* notebooks associated with this project are to be placed in the public domain and marketed under the name *Crystallize*. The *Crystallize* notebooks are at the core of the workflow (Figure 1).

Eight examples of the application of *Crystallize* are presented:

- Appendix 3 (and folder Appendix3_Crystallize3DGeology) demonstrates how to build 3D geological models, which are used to provide the framework for the groundwater flow model;
- Appendix 4 (and folder Appendix4_CrystallizeFEFLOWmesh) shows how to populate a FEFLOW mesh;
- Appendix 6 (and folder Appendix6_CrystallizeFEFLOWHydrographs) gives an example of the post processing of the FEFLOW outputs, comparing the field measured versus the modelled groundwater hydrographs. Two methods are presented. In the first example continuous approximate functions are fitted to the measured and modelled hydrograph data sets and then the statistics are determined using the functions. In the second example the statistical comparisons are done on the field measured data points, and the estimated data points from the model;
- Appendix 7 (and folder Appendix7_CrystallizeHydrographs) illustrates how *Mathematica* links to the MS Access database and can be used to plot a single hydrograph set for a selected groundwater works number, or plot every hydrograph set in the database, saving the plots as individual images that can be loaded into other applications; and
- Appendix 8 (and folder Appendix8_Crystallize3DGroundwater) demonstrates the value of analysing the hydrograph data in 3D. The first example examines the long term trend in the recovered standing groundwater level. And the second example shows how the seasonal impact of groundwater pumping can be used to characterise aquifer connectivity, in particular, showing where to position a boundary between the unconfined and semi-confined aquifers from which the irrigation groundwater is extracted.

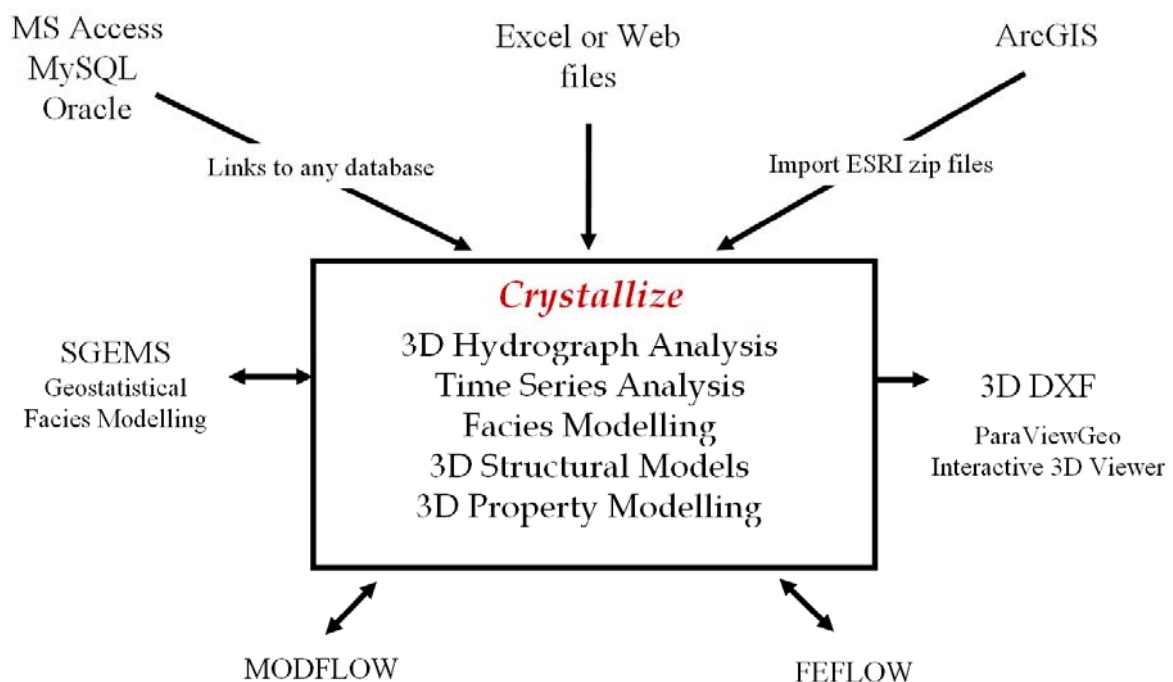


Figure 1. Schematic of the role of *Crystallize* in the analysis of catchment water data.

1.4 Comments on the Choice of FEFLOW

To date most catchment scale water balance models throughout the Murray-Darling Basin have used MODFLOW (<http://water.usgs.gov/nrp/gwsoftware/modflow.html>). The MODFLOW models consist of 1 to 3 layers which aim to capture the majority of the behaviour observed in the bore hydrographs (often an unconfined layer overlying one or two semi-confined layers). This is appropriate when the purpose of the catchment water balance model is to provide a feel for the sustainable use of groundwater. However, these MODFLOW models do not account correctly for the local point scale residence time of the water moving through the complex aquifer system, nor do they honour the sediment distribution in any detail and they cannot be used to investigate the migration of different water quality zones.

FEFLOW provides a framework that allows more geological complexity to be incorporated into the groundwater flow model. This project demonstrates how to incorporate a complex facies model into the groundwater modelling framework. Comprehensive details on FEFLOW modelling are presented in Appendices 4, 5 and 6 (and folders: Appendix4_CrystallizeFEFLOWmesh; Appendix5_FEFLOWmodel; Appendix6_FEFLOWhydrographs).

2 The Need for 3D Conceptual Geological Models of Catchments

There is growing awareness that managers need comprehensive 3D geological models of valley-fill aquifers if they are to manage these aquifers sustainably (Faunt et al., 2009). In particular, the accessible groundwater is in the sand and gravel rich palaeochannels. To understand the flow of groundwater through the aquifer system the palaeochannels need to be mapped and correctly incorporated into the groundwater flow models. This has clearly been demonstrated by the research and application of flow modelling in the petroleum industry, where most of the developments in facies modelling have been driven by the need for better production forecasts (Vargas-Guzman, 2009). Keogh et al. (2007) recently reviewed the development of fluvial stochastic modelling focusing on the petroleum sector. Many of the methods described by Keogh et al. (2007) have potential application in unconsolidated and consolidated sedimentary aquifers.

Constructing 3D geological models from multiple data sets (for example geological maps, well logs, geophysical surveys and digital elevation models), is a relatively mature process and there are now many advanced geological modelling packages available, including 3D GeoModeler (www.geomodeller.com), 3D and 4D Move (www.mve.com), EarthVision (www.dgi.com), EVS-MVS (www.ctech.com), Gocad (www.gocad.org), Jewel Suite (www.jewelsuite.com), Roxar (www.roxar.com), Petrel (www.slb.com) and Vulcan3D (www.maptek.com). These software packages have been used in many commercial and university research projects, however, they are costly and not widely used for teaching large classes, and have limited use in economically disadvantaged countries, and the groundwater sector. The procedure for constructing similar structural framework and parameter models using *Mathematica* was created for this project to address the concern about cost of the presently available 3D geological modelling environments.

To guide the visualisation of all aspects of the geometry and the distribution of parameters (porosity and hydraulic conductivity) of an aquifer, it has become common practice to build 3D geological models by collating the hydrogeological data from various sources (Jones et al. 2002, Artimo et al. 2003, Herzog et al. 2003, Lemon and Jones 2003, Pantea and Cole 2004, Robins et al. 2005, Ross et al. 2005, Bonomi 2009, Gallerini and De Donatis 2009, Wycisk et al. 2009). The visual coordination of data and the interpolation of sparse data sets throughout the domain of interest can

now be achieved using *Mathematica*. The procedure for constructing 3D geological models in *Mathematica* is demonstrated for the Maules Creek catchment in the *Crystallize* notebook `Crystallize_3D_Geological_Model.nb` located in the folder `Appendix3_Crystallize3DGeology`.

2.1 *Mathematica* as a Geological Modelling Environment

Mathematica is a comprehensive programming environment which has an extensive library of mathematical and graphics functions that can be integrated into small scripts to solve many numerical and spatial visualisation problems.

Previous applications of *Mathematica* in the field of geology include: the reconstruction of complex folded surfaces (Johnson and Moore 1993; Moore and Johnson 2001), simulation of hanging wall deformation (Perez 2000), displaying animated 3D structures of the Earth's interior (Sato et al. 2003), strain analysis of folds (Bobillo-Ares et al. 2004) and the mapping of tortuosity and porosity of porous media (Nakashima and Yamaguchi 2004). There are also numerous examples relating to the earth sciences in Haneberg (2004).

3D geological framework models are constructed by modelling geological features as surfaces, which intersect according to rules that allow the visual representation of the geological features of interest (Mayoraz et al. 1992, Mallet 1997, de Kemp 1998, de Kemp 1999, Jones et al. 2002, Mallet 2002, Lemon and Jones 2003 and Galera et al. 2003). These surfaces may represent continuous depositional surfaces, the tops of lenses, or intrusions. The surfaces may also be faulted and folded. The model thus consists of a sequence of volume elements, bounded on the top, bottom and sides by continuous functions across the modelling domain. Each volume element can then be populated with a geological parameter (for example hydraulic conductivity).

2.2 An Overview of Constructing a 3D Catchment Scale Geological Model

The major steps in the workflow for building a 3D geological structural and facies model are presented in Figure 2. There are three primary data sets used for building the 3D geological structural and facies model; the geological mapping details of the catchment, the DEM, and the driller bore lithology logs (Figures 2, 3 and 4).

For the unconsolidated sedimentary aquifer system the lower boundary is usually taken as the palaeovalley erosion surface. This is defined by the outcropping rock and the basement picks from the driller bore lithology logs (Figures 2 and 3). In areas of steep terrain the DEM can be sorted into sediment and rock data sets on the basis of the gradient. This process is described in detail in Haneberg (2004). A description of the DEM sorting calculations using the gradient method and a tutorial data set is located in the folder `Appendix2_DEMSorting`. An alternative approach to sorting the DEM based on elevation of the ground surface is presented in the *Crystallize* notebook `Crystallize_3D_Geological_Model.nb` located in the folder `Appendix3_Crystallize3DGeology`. The sorted DEM used for the Maules Creek catchment model is presented in Figure 4. The continuous blue patches are the inferred rock zones from the DEM and the points are the bedrock picks from the bores. The combined outcropping rock and the bore bedrock pick data are gridded to form a single surface, which forms the base of the model.

The next step is to fill the unconsolidated sediment volume with the facies model. The driller logs throughout the catchment are divided into two classes: low (clay) and high (sand and gravel) hydraulic conductivity. The space between the boreholes is then filled using k-nearest neighbour

(KNN). It has been demonstrated that KNN is a good classification interpolator of categorical data (Dubois et al. 2007, Tartakovsky et al. 2007). The facies model is then combined with the structural model to give the complete conceptual 3D geological model of the catchment (Figure 5). The workflow for constructing 3D geological structural and facies models is described in more detail in the *Crystallize* notebook *Crystallize_3D_Geological_Model.nb*, located in the folder *Appendix3_Crystallize3DGeology*.

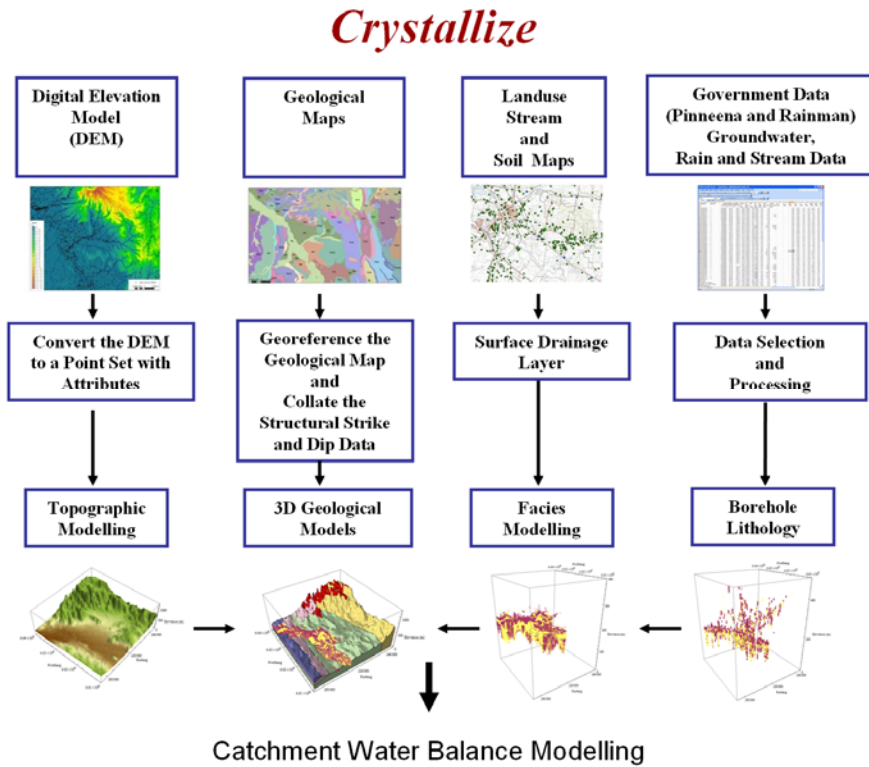


Figure 2. A schematic of the workflow for constructing a 3D geological structural and facies model, also called a conceptual site model.

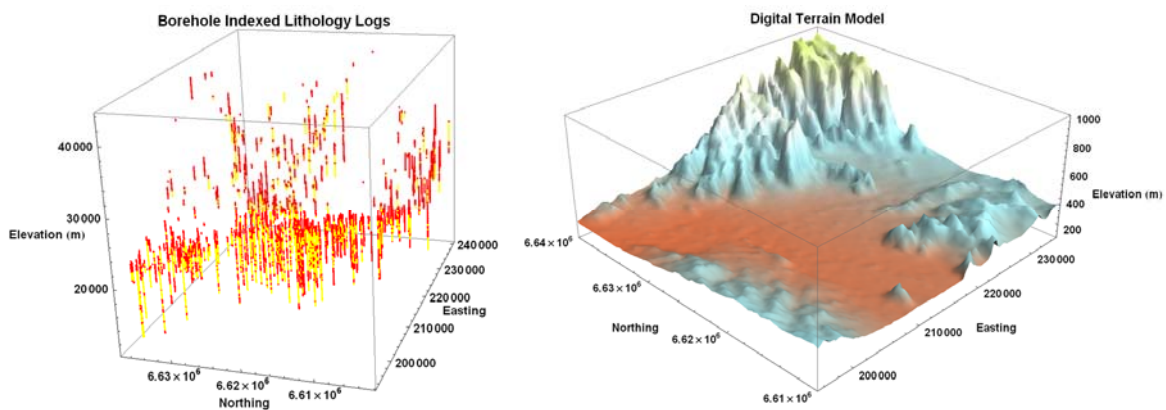


Figure 3. Data used to construct the 3D geological model; left the indexed borehole lithology logs (yellow - high hydraulic conductivity, red - low hydraulic conductivity sediments), and the DEM (Universal Transverse Mercator coordinate system zone 56, units metres).

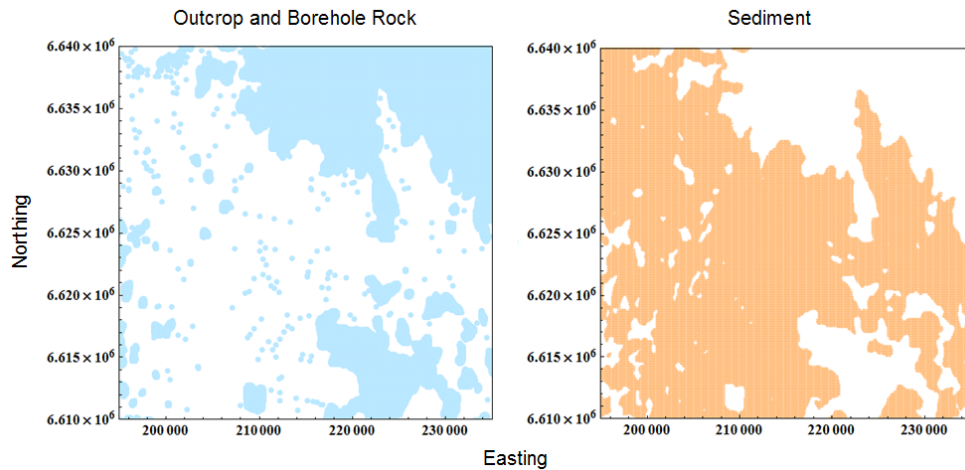


Figure 4. The aquifer bottom data is defined by the bedrock picks in the boreholes and the high gradient zones (rock outcrop) in the DEM (left), and the aquifer top is defined by the low gradient zones (sediments) in the DEM (right).

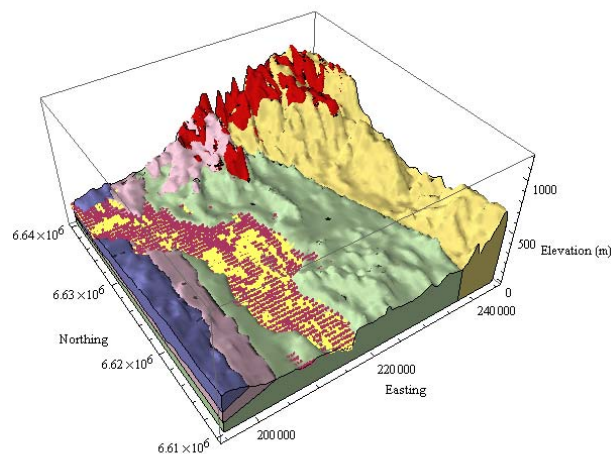


Figure 5: The Maules Creek 3D geological structural and facies model built using *Mathematica*. Each geological period is represented as a solid colour. The colour key used below is: Tertiary basalt (red), Jurassic (blue), Triassic (pink), Permian (green), and Carboniferous (yellow). In the unconsolidated sediment zone the purple is clay, and the yellow sand and gravel.

3 Groundwater Hydrographs

Throughout the Murray-Darling Basin in the unconsolidated sedimentary aquifers used for irrigation, numerous monitoring bores have been installed. The standing water level has been measured in these bores four or more times per year since installation (the majority were installed in the 1970s and 1980s). The hydrographs from these bores provide insights into how the aquifer system is responding to groundwater recharge events and irrigation extractions. Four representative *Crystallize* notebooks for hydrograph presentation and analysis are located in Appendices 7 and 8 (and folders: Appendix7_CrystallizeHydrographs and Append8_Crystallize3DGroundwater).

An example of the 3D bubble chart and 2D plot generated using the *Crystallize* notebook *Crystallize_3DGroundwaterHeadTrends.nb* is presented in Figure 6. The *Crystallize* notebooks in

Appendix 7 (folder Appendix7_CrystallizeHydrographs) are for the plotting of one or more hydrograph sets for a selected groundwater works number, while the notebooks in the Appendix 8 (folder Appendix8_Crystallize3DGroundwater) provide examples of the 3D analysis of the long term trend in the standing water level recorded in the bores, and the extent of the fluctuation in the groundwater level within a year. In regions where there are large groundwater extractions, mapping zones of high and low standing water level fluctuation provides a method for mapping aquifer connectivity in 3D. This can help with the construction of the catchment conceptual site model used for the catchment water balance modelling.

The results from the collation of the climatic, streamflow, groundwater usage, the conceptual 3D geological model and the 3D hydrograph analyses are presented in a time-lapse video (located in folder Appendix9_MaulesCreekTimeLapseVideo). This video gives a visual interpretation of the connection between rainfall, streamflow, groundwater usage and the recovered bore standing groundwater level (referred to as the head in the video).

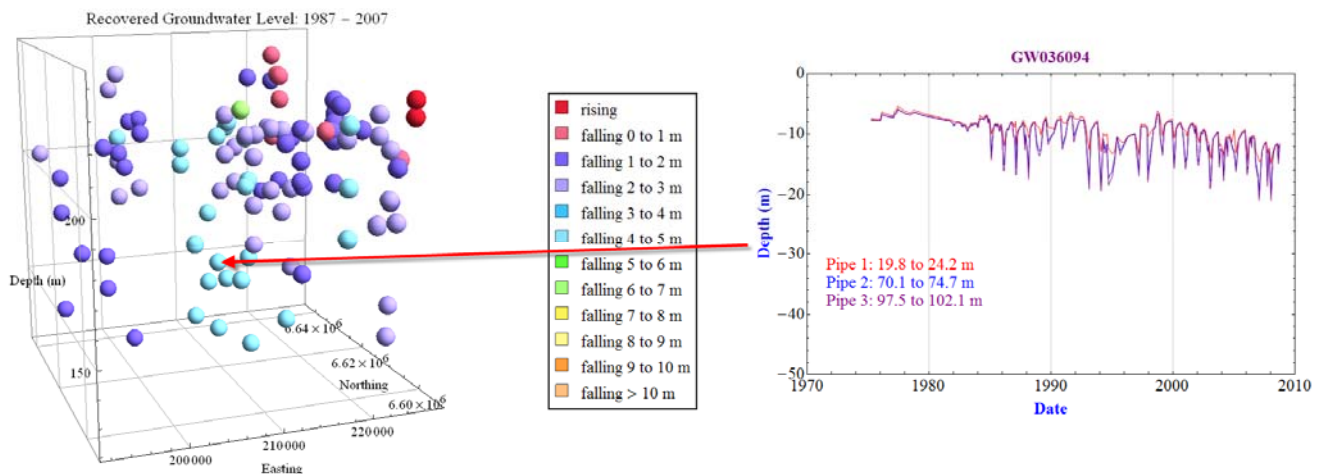


Figure 6. An example of the *Crystallize* 3D bore hydrograph analysis. Shown on the right hand side of the figure is an example of the groundwater works number hydrograph set that is automatically plotted when you click on a point in the 3D plot.

4 Groundwater Chemistry

In catchments throughout Australia there has been little consistency in the collection and analysis of groundwater chemistry data. In Appendix 10 there are four papers (Andersen and Acworth, 2007; Andersen et al., 2008; Patterson et al., 2008; Andersen and Acworth 2009) about the groundwater chemistry in the Maules Creek Catchment and adjacent reach of the Namoi River. These papers make use of the water chemistry data stored in the Maules Creek MS Access database. They demonstrate that analysing surface and sub-surface water chemistry is critical for understanding aquifer connectivity and the impact of irrigation extractions on groundwater movement, deep drainage and stream aquifer interactions.

The surface and sub-surface water chemistry clearly shows that there are distinct pathways of movement. In some intervals of the aquifer system there is recharge from young water (rainfall deep drainage, irrigation deep drainage, and stream recharge). In other portions of the aquifer old water, which is not mixing with the newer water, occurs. This work clearly demonstrates the need for incorporating water chemistry as part of assessing the sustainable use of groundwater.

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