3D Dendrogram Analysis for Mapping Aquifer Connectivity and Flow Model Structure

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ABSTRACT

Mapping the connectivity within a valley-fill unconsolidated aquifer system is fundamental for water resource management. This paper demonstrates a data-driven approach for mapping 3D hydraulic connections using groundwater hydrographs from the Namoi Catchment in NSW, Australia, where the groundwater system is stressed due to extensive pumping that supports irrigation agriculture. Groundwater levels have been monitored for up to 40 years at about 900 locations, over an area of 42000 square kilometers. Pumping impacts and floods generate unique signatures throughout the bore hydrographs that allow 3D hydraulic connections to be estimated. Hierarchical clustering of the groundwater hydrographs is used to infer structure and connectivity within the complex aquifer system. The hydrographs are grouped according to their Manhattan distances and a catchment scale dendrogram is used to map 3D connectivity at various scales, yielding insights about the 3D aquifer structure. To date, the catchment has been modeled as an unconfined aquifer overlying two semi-confined aquifers. The clustered hydrographs broadly agree with this conceptual model. However, the dendrogram analysis provides new insights into the connectivity that need to be incorporated into future models. In particular, new vertical pathways of connectivity and discontinuity have been estimated that will have important management ramifications with respect to recharge, river impacts and sustainable use.

INTRODUCTION

Mapping the three dimensional hydraulic connections within a catchment is important for understanding the impact of surface water and groundwater extractions. In addition, if we are to successfully model connected surface and sub-surface water movement we must have an appropriate conceptual model of the hydraulic connections. In this paper clustering of standardized stream and groundwater hydrograph data is used to map the three dimensional hydraulic connections in a 120 m thick alluvial aquifer, located in the Lower Namoi catchment, Australia. The methodology presented can be applied to any catchment with a multiyear spatial and temporal hydrograph data set. The Lower Namoi catchment is one of the major irrigation districts in Australia, and both surface water and groundwater have been used to support irrigation farming since the 1960s. As irrigation agriculture expanded an extensive stream and groundwater hydrograph monitoring network was installed to observe the impact of the irrigation sector on water resources. Historically the catchment has been modeled using a 3-layer MODFLOW model consisting of an upper unconfined aquifer overlying two semi-confined aquifers (Merrick 2001, Williams *et al.* 1989). Based on the clustering analysis results it will be demonstrated that this conceptual model needs to be refined.

Lower Namoi Hydrogeology

The Lower Namoi Catchment is an alluvial valley occupying an area of 5100 km^2 in northern New South Wales (NSW), Australia. The valley-filling sediments are generally subdivided into three formations. At the base of the sequence is the Cubbaroo Formation, which is a deep, narrow palaeochannel, 3 to 10 km in width running along the northern boundary of the valley (Figure 1). The Gunnedah Formation overlies the Cubbaroo Formation and covers the pre-Tertiary bedrock surface in the valley south of the extent of the Cubbaroo Formation. From the top of the Gunnedah to the ground surface is the Narrabri Formation. Further details on the hydrogeology are presented in Williams (1986) and McLean (2003).

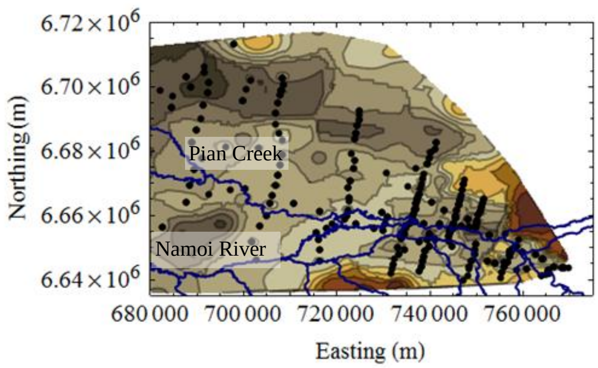


Figure 1. Pre-Tertiary bedrock surface in the Lower Namoi Valley, showing locations of monitoring bores and rivers.

Groundwater Monitoring Data

The NSW Government Department of Water & Energy maintains a database of groundwater monitoring data, which was used in the analysis implemented in this paper. A monitoring site consists of one or more bores, where each bore may contain one or more pipes with slotted openings at varying depths below the ground. Groundwater levels are recorded manually and the sampling frequency varies considerably, but it is usually between monthly and six monthly. There are around 350 groundwater-monitoring sites in the Lower Namoi Catchment, including more than 700 pipes. Impacts of pumping and flood events create unique signatures throughout the hydrographs allowing 3D hydraulic connections to be estimated.

HYDROGRAPH CLUSTERING

The methodology implemented in this paper was to cluster groundwater hydrographs based on their signal similarity (calculated using an appropriate distance measure) and then to visualize the spatial locations of the corresponding bore clusters. The algorithm, described below, was implemented using the *Mathematica* software package.

Clustering Methodology

The first step in the clustering methodology was to choose the time-period and set of groundwater hydrographs to be included in the analysis. Hydrographs with continuous records spanning the selected period were required to enable valid distance measures to be calculated. A simple algorithm was implemented to choose the period maximizing the number of available hydrographs, given minimum hydrograph duration.

A critical component of the algorithm was the choice of distance function used to measure the signal similarity between hydrographs. The purpose of the function was to estimate the hydraulic connectivity of aquifers penetrated by the monitoring bores. Two bores penetrating a connected aquifer are likely to experience similar hydraulic conditions and have hydrographs that are similar in shape. However, the absolute magnitude of variation in water levels may differ, since the response to a forcing, for example groundwater pumping or flood recharge, attenuates with distance.

Each hydrograph was linearly interpolated and then resampled on an even grid. To remove the effects of position (groundwater level depth) and scale (magnitude of water level variation), the resampled hydrographs were standardized. The dissimilarity between each pair of standardized timeseries was then calculated using the Manhattan distance, which has the advantage that it is less sensitive to outliers than other distance measures such as Euclidean distance. The standardized timeseries data were clustered using agglomerative hierarchical clustering (Ward 1963). Strengths of hierarchical clustering include that it does not require the number of clusters to be specified *a priori* and it allows analysis of system structure via dendrogram plots. The clustering algorithm was sensitive to the method used to determine inter-cluster linkage. A variety of options was tested and Ward's method of minimum variance dissimilarity consistently gave the best results.

The final step was to visualize the 3D spatial locations of the groundwater bores. Bore depth was calculated as the midpoint of the slotted opening in the monitoring pipe. To aid in the visualization of the spatial regions encompassed by the bore clusters, the polygons (convex hulls) enclosing them were plotted.

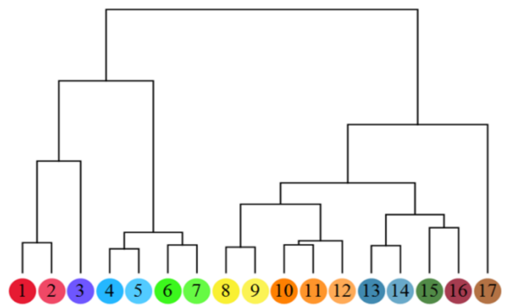
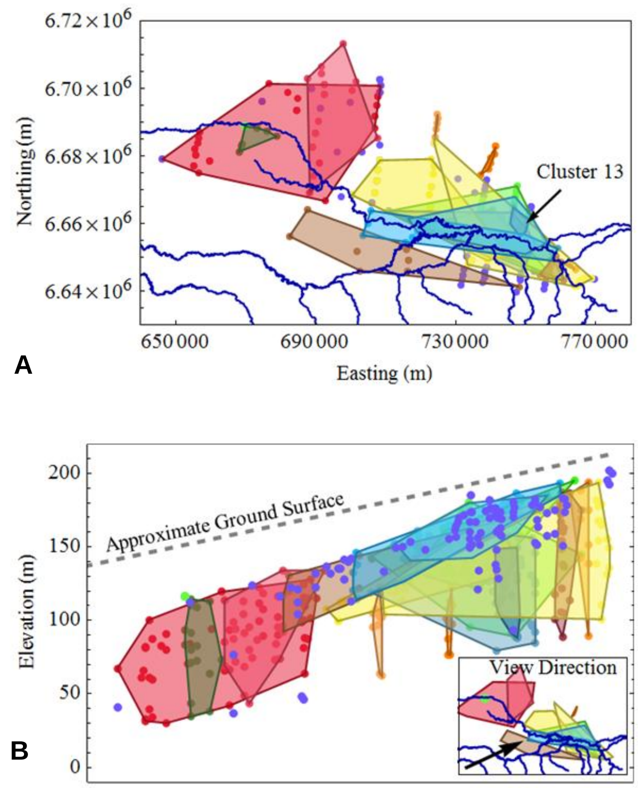


Figure 2. Dendrogram showing the top 17 levels of the hierarchical clusters.



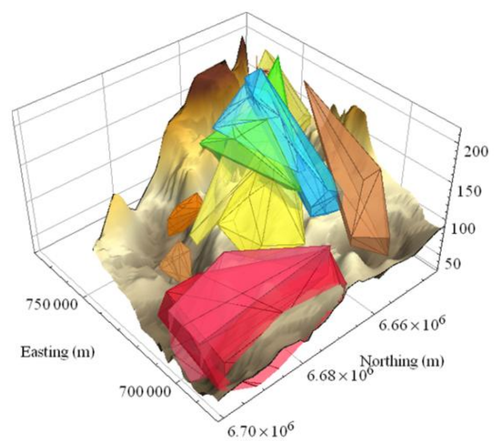


Figure 4. 3D bedrock surface and convex hulls enclosing each bore cluster.

Figure 3. Plan (A) and elevation (B) projections of the 17 bore clusters and the convex hulls enclosing them.

Clustering Results

The clustering methodology was applied to identify aquifer boundaries and flow pathways. Approximately 550 hydrographs spanning the 30-year period from February 1980 to March 2010 were selected, linearly interpolated, resampled at intervals of 30 days and clustered. Figure 2 shows only the first 17 levels of the Lower Namoi Catchment dendrogram, as the full dendrogram was too large to display. The dendrogram represents distances between hydrograph clusters by the length of the vertical lines connecting them. The 17 clusters at the base level of the dendrogram have been color coded so that closely linked clusters have similar colors.

Figure 4 provides a 3D plot of the spatial locations of the bore clusters and the convex hulls enclosing them, while Figure 3 shows 2D plan and elevation projections. Cluster number 3 is plotted as bore points only, as the convex hull of this cluster obscures the view of other clusters. Clusters that were closely linked in the dendrogram occupy overlapping spatial regions, which indicates that the clustering methodology is able to identify hydraulic connectivity. Representative hydrographs for clusters numbers 3, 5 and 13 are shown in Figure 5.

In the upper (eastern) portion of the catchment, the clusters broadly agree with the conceptual model of an unconfined aquifer (Narrabri Formation) overlaying a semi-confined aquifer (Gunnedah Formation). The shallow clusters, numbers 4, 5 and 17, follow the Namoi River and the upper reaches of Pian Creek, suggesting they represent an aquifer connected to the river. Cluster 3 is a large cluster that spans the breadth of the catchment. However, the majority of the bores in this cluster are in the shallow upper

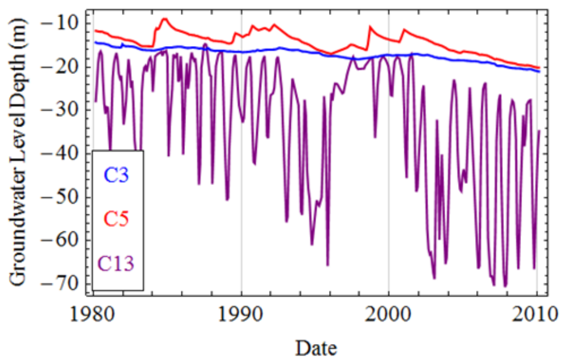


Figure 5. Representative hydrographs from clusters numbers 3, 5, and 13.

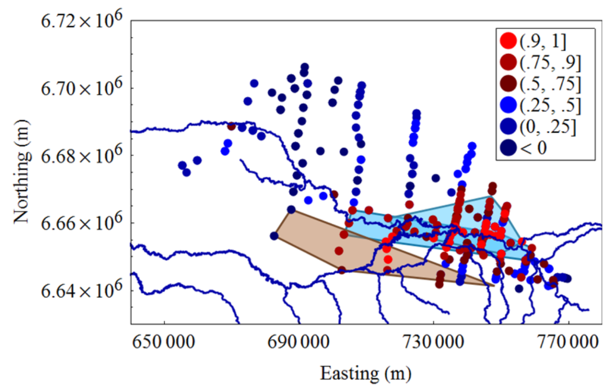


Figure 6. Correlation of monitoring bores with streamflow and locations of clusters 4, 5 and 17.

portion of the catchment, with some slightly deeper bores under the Namoi River. It appears that the clustering algorithm has misclassified the bores in the lower catchment and that they should have been assigned into clusters 1 and 2, or a new cluster. Studying clusters 1, 2 and 3 shows that the differences between the hydrographs composing them are subtle.

Clusters 13 and 14 drop into the deep palaeochannel (Cubbaroo Formation) that runs along the northeastern boundary of the catchment alluvium. Cluster 13, in particular, corresponds to a region of the aquifer known to have become disconnected from the river due to excessive groundwater extraction (Giambastiani *et al.*, 2009). Groundwater levels in this aquifer have fallen by more than 10 meters during the last 30 years. Cluster numbers 10 and 12 also lie in the palaeochannel.

Clusters 1 and 2 in the western end of the catchment indicate a single connected groundwater region, and do not support the layered aquifer model, unless this area is given a high ‘leakage’ value between aquifers. Further investigation of this region is required. The region also contains cluster 15, which corresponds to the point where the palaeochannel crosses Pian Creek.

CONNECTIVITY TO THE RIVER

Rivers are the most significant sources of groundwater recharge in the Lower Namoi (McLean, 2003). Connectivity of surface and groundwater was investigated via a correlation analysis of streamflow and groundwater levels. Streamflow data could have been included in the cluster analysis, but it was considered separately as it required different transformations of the groundwater data.

Correlation Methodology

Raw streamflow data gives poor correlation with groundwater levels, due to the very different behavior of the two systems. To enable correlation analysis to be performed, the monthly cumulative streamflow departure (CFD), which utilizes the same concept as cumulative rainfall departure (Weber and Stuart, 2004), was calculated. The CFD for month number *j* is given by

$$CFD_j = \sum_{i=1}^{j} (x_i - \bar{\boldsymbol{x}})$$

where x_i is the total streamflow for month *i* and $\bar{\boldsymbol{x}}$ is the mean monthly streamflow during the period. The CFD can be viewed as a very simple, yet effective, model of the recharge and gradual discharge behavior of groundwater aquifers in response to streamflow.

Groundwater hydrographs throughout the Lower Namoi display a downward trend due to the long-term effects of extractions. To isolate the recharge response, hydrographs were linearly rescaled so that maximum water levels at the start and end of the time period were equal. Finally, Pearson’s correlation coefficient was calculated for each pair of CFD and de-trended groundwater timeseries.

Correlation Results

Results of the correlation analysis are presented in Figure 6 and showed that recharge to groundwater occurs mainly in the upper portion of the catchment, which agrees with findings of other studies (e.g. Merrick, 2001). At the sampling timescale used in the analysis, a lag in recharge response was generally not observable. Bores displaying a strong correlation with streamflow were mainly contained in cluster numbers 8, 9 and 17, confirming that these bores penetrate a shallow unconfined aquifer. The remaining slightly deeper bores with small positive correlations (in the range 0.5 to 0.75) were almost all contained in cluster 3, supporting the interpretation that this cluster represents a shallow aquifer semi-connected to clusters 8 and 9.

DISCUSSION

For many catchments, large databases of groundwater, streamflow, rainfall and other data are readily available, and this resource is often underutilized. This paper has demonstrated that clustering of groundwater hydrographs can be used to infer physically meaningful information about aquifer structure and groundwater flow pathways in a complex alluvial system. A simple, yet effective, means of analyzing groundwater response to streamflow was used to identify regions of groundwater recharge. The results of the method broadly agreed with current conceptualizations of the catchment hydrogeology, but also highlighted areas that did not fit this model.

An advantage of the data driven approach is that it allows rapid assessment of connected surface – groundwater systems at a large scale. The methodology is generic and could easily be applied to other catchments. However, the clustering algorithm is sensitive to the choice of distance measure and cluster linkage, and further work should be done to examine the robustness of results. Future work will incorporate analysis of other hydrogeological data, such as rainfall records and lithological logs. Results of the research will inform development of a spatially aggregated, conceptual model of surface – groundwater interactions in the Lower Namoi Catchment.

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