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3D time and space analysis of groundwater head change for mapping river and aquifer interactions

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Abstract: This study demonstrates how multidimensional spatial analysis of hydrograph data enables the 3D mapping of hydraulic pathways through complex sedimentary aquifer systems in the Namoi Catchment (New South Wales, Australia).

Historical groundwater head records over the past 40 years capture the influence of irrigation extractions. Analysing the head change throughout the aquifer in 3D and with respect to time clearly shows both the yearly and long term impacts of groundwater extractions on river-aquifer interactions. The 3D analysis also maps the recharge pathways, delineating the primary zones of recharge.

The hydraulic data were analysed and cross validated with lithological logs, groundwater temperature and pH values. Data analysis was undertaken using spatial analysis techniques available in ArcGIS and EarthVision facilitated by extensive use of Python scripting.

Some hydrographs show that aquifer heads respond to variations in extraction differently at different depths, indicating that there are impervious or leaky semi-impervious layers. Other hydrographs show heads from different depths all responding in the same way to extraction and subsequent recovery, indicating that locally the system is vertically hydraulically connected.

The head data were analysed over one year periods with no flood events. During low rainfall years, groundwater usage is at its highest level, resulting in maximum pumping related head change throughout the aquifer. Positioning the head values in 3D space at the slotted depth of the boreholes highlights hydraulic connectivity between boreholes and through the alluvial sequence.

Correlating lithological logs in sedimentary environments containing numerous sand and clay units is difficult. Mapping the horizontal continuity in head change aided the borehole log correlation, showing which sedimentary units are hydraulically connected. The 3D mapping of head change due to pumping stress enabled the 3D mapping of palaeochannels, clearly delineating the meandering path of pre-existing water courses and the link to the present day stream channels.

Spatial data analysis techniques adopted for this research have successfully enhanced the understanding of river and aquifer interactions and our knowledge of the 3D geometry of the aquifers, showing that shallow and deep aquifers are more complex than previously conceptualised for the region. The resulting 3D conceptual models have provided an improved framework for the construction of 3D groundwater flow models.

Presenting the data in 3D has also proved to be a powerful communication tool that can be used in public meetings, improving the conceptual understanding of water dynamics for all stakeholders. People who are not specialists in hydrology, but who are either users or managers of the water can obtain a better visual understanding of the impact of groundwater extractions.

Keywords: *head change, hydraulic connectivity, 3D spatial analysis, aquifer*

1. INTRODUCTION

Understanding exchanges between surface and ground water systems is critical for good management of water resources. In catchments where groundwater extractions for irrigation have significant implications for both the economy and the environment, knowledge of hydraulic pathways through the alluvial sequence is essential for sustainable water allocation and to guide water management policies.

Numerous methods have been discussed in the literature to quantify the interactions between surface and ground waters (Kalbus et al., 2006; Winter, 1999). Many studies have been done for NSW and in particular for the Namoi catchment investigating several approaches such as frequency analysis (Brodie et al., 2007), top-down approach (Ivkovic, 2009) and other more general approaches (Braaten and Gates, 2003). These methods define interactions between the river and aquifer for any given reach, but they do not yield a three dimensional conceptual understanding of the connectivity between the stream and underlying aquifer. Traditionally head data have been gridded in 2D. For this to be done correctly boreholes have to be allocated to individual aquifers, which requires extensive prior knowledge of the hydrogeology of a catchment. This paper demonstrates how 3D spatial analysis of borehole hydrographs, groundwater chemistry and lithological logs can be used to elucidate details about the 3D nature of complex aquifer systems and how this may influence surface and groundwater interactions.

To trial the visual analytical techniques the Namoi Catchment (Figure 1) was selected as this catchment has one of the highest levels of groundwater extraction in Australia. Groundwater extraction within the Namoi region accounts for 15.2 % (254.82 GL in 2004/05) of the total annual groundwater use from the Murray Darling Basin. This volume is extracted by around 14820 users (CSIRO, 2007). Most of the diverted surface water and extracted groundwater is used for irrigating crops, with minor extractions for mining, stock and domestic purposes. Recently, the proposed expansion of coal mining in the area has increased the need for a better understanding of the hydrology of the catchment**.**

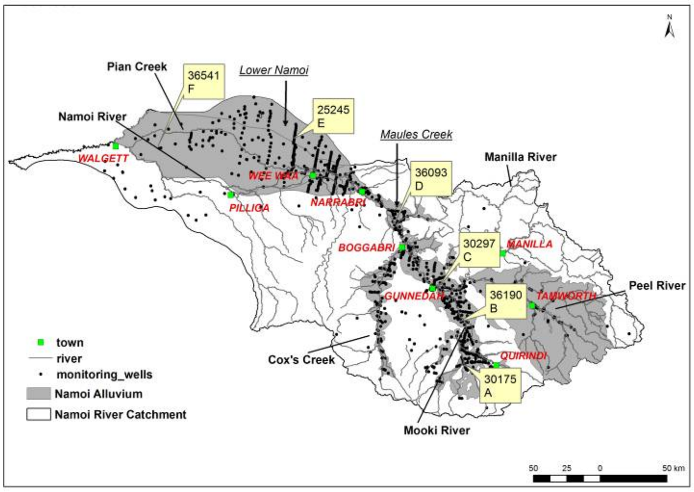


Figure 1. The Namoi River catchment (NSW)

2. THE NAMOI CATCHMENT HYDROGEOLOGY

The Namoi Catchment is situated in north-eastern New South Wales (NSW), Australia, and is bounded on the eastern side by Devonian and Carboniferous sedimentary and Cenozoic volcanic rocks that form the Great Dividing Range, in the south by the Permian sedimentary and Tertiary volcanics of the Liverpool Range, and on the west by the southern extension of the Cenozoic volcanics of the Warrumbungle Range and the westerly dipping Cretaceous and Jurassic sedimentary units of the Great Artesian Basin (GAB). To the north the Namoi Catchment is divided from the Gwydir Catchment by Tertiary volcanics and uplifted Permian sedimentary formations (NSWDMR, 2002). The water flows from the Great Diving Range in the east to the alluvial flats in the west. Flow is regulated by large water storages (Chaffey, Keepit and Splits Rock dams) built primarily to manage water for irrigation. Tributaries of the Namoi River include Cox's, Maules and Pian Creeks and the Peel, Mooki and Manilla Rivers.

Detailed discussions of the hydrogeology of the Namoi catchment exist in Gates (1980), Williams (1997), Lavitt (1999), Young et al., (2002) and McLean (2003). The central and eastern portions of the Namoi catchment are underlain by sedimentary and volcanic basement rocks dating from Permian through to the Tertiary. These formations form part of the Gunnedah Basin, which runs the length of the catchment. The westerly basement rocks are Jurassic and Cretaceous interbedded sandstones and siltstone sediments of the Great Artesian Basin (GAB). The alluvial aquifer systems consist of unconsolidated sediments deposited unconformably on a pre-Tertiary erosional surface, which generally represents the basement of the hydrogeological system. The alluvial sediments are subdivided into 3 formations based on palynology studies conducted by Martin (1980, 1981). The uppermost Narrabri Formation (approximately 30 m in thickness) consists of clays with minor sand and gravel beds of Pleistocene to Recent age. Underlying is the Gunnedah Formation (a semi-confined aquifer) of Pliocene to early Pleistocene age. It consists of fluvio-lacustrine sediments up to 70 m in thickness; predominantly gravel and sand and with minor clay beds. This is the productive aquifer used for irrigation. At the base of the sequence is the Cubbaroo Formation (a semi-confined aquifer) consisting of sand and gravel with interbedded clay deposited from Middle to Late Miocene (Williams, 1997). This aquifer is located in the Namoi River palaeochannel in the north of the catchment (Young et al., 2002). In some areas there is no hydraulic separation between the formations and they act as a single aquifer (CSIRO, 2007).

Throughout the Namoi Catchment since the 1960s various NSW state government water departments have installed groundwater monitoring boreholes (NSWG, 2007). The network consists of 305 groundwater borehole sites in the Upper Namoi and 258 boreholes sites in the Lower Namoi. Water levels in these boreholes have been manually recorded four or more times per year. This is the major data set used for this research. At each borehole location, from one to seven pipes have been installed and set at different depths depending on the occurrence of high yielding water bearing sediments. Generally the first pipe (pipe1 in hydrographs in figure 2) monitors the shallow aquifer while the other pipes (pipes 2 and 3 in figure 2), when present, are used to monitor intermediate and deep aquifers. Representative hydrographs along the axis of the Namoi Catchment are presented in Figure 2. Hydrograph A is at the head of the catchment in an area with no significant irrigation impact. Hydrograph B located adjacent to the Mooki River, demonstrates how the unconfined aquifer has been disconnected from the river by irrigation extractions. The flood plains of the Mooki and Namoi River have very low gradients typically falling 10 m in 1000 m. The river is incised into the flood plains approximately 5 m with the depth of water ranging from 1 to 3 m. Therefore, hydrographs near the river which have head reading below 10 m place the water table beneath the base of the river. In the 1970s, at the start of the development of irrigation in the region, hydrographs B had a water level 5 m beneath the ground surface. Now the water level is 20 m below the ground surface. Hydrographs C and D show how, between major floods, the rate of groundwater extraction exceeds the recharge from river, diffuse rain and irrigation deep drainage and causes the unconfined aquifer to oscillate from connected to disconnected. Hydrograph E located in the Lower Namoi shows a zone where the upper unconfined aquifer is hydraulically isolated from semi-confined aquifers which have declining heads with time due to groundwater extractions. Hydrograph F is in the far west of the catchment where there is no groundwater taken for irrigation. Here the Namoi River is disconnected from the unconfined aquifer. This is indicated by the depth to the water level in the boreholes (Ivkovic, 2009; Braaten and Gates, 2003).

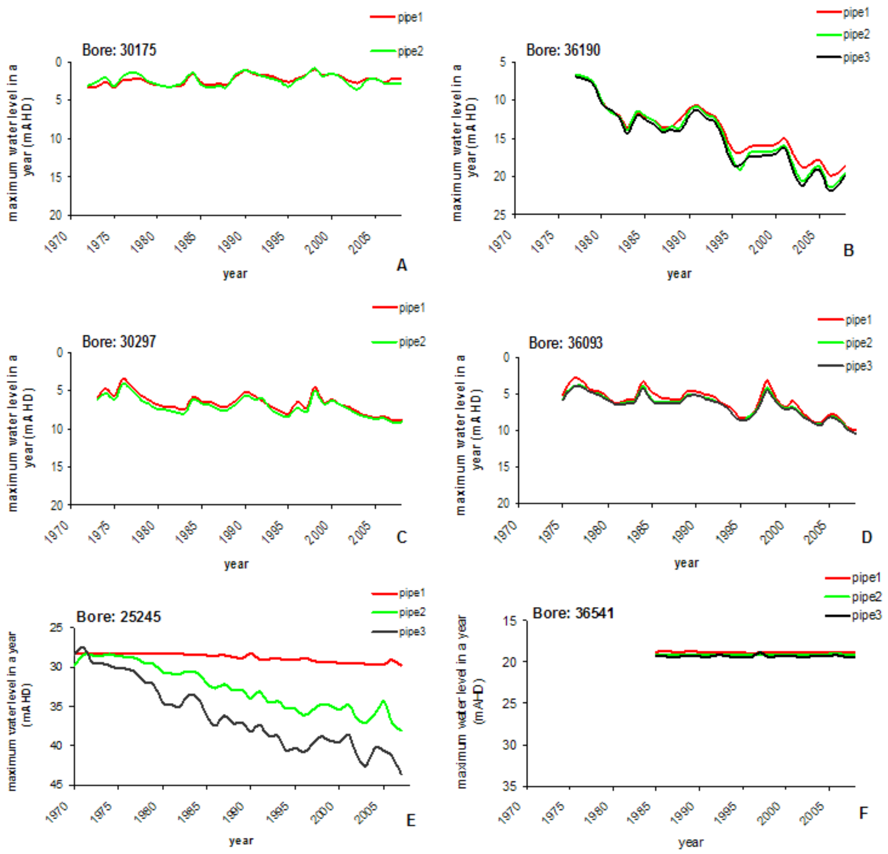


Figure 2. Representative borehole hydrographs. See Figure 1 for the borehole location.

3. METHOD

3.1. Hydrograph data analysis

In order to analyse the long term impacts of groundwater extractions on river-aquifer interactions, the highest relative change in borehole heads from 1980 and 2007 were plotted in 3D at the mid-point of the slotted interval (Figure 3). The highest heads usually occur in June or July just before the beginning of the pumping season, which runs from late August until February. During the pumping season the heads drop significantly throughout the semi-confined aquifers.

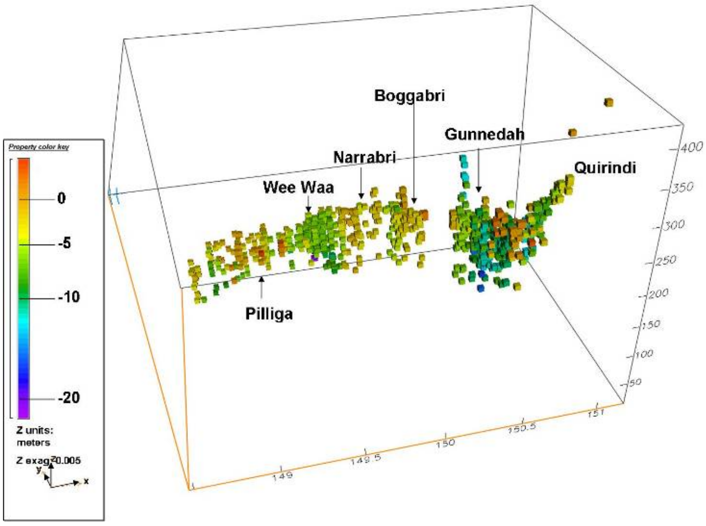


Figure 3. Relative change in head between 1980 and 2007. The purple and blue data points represent a decline in groundwater head > 10 m, green data a decline between 10 and 5 m, yellow dots a decline from 5 to 0 m and the orange to red points represent no decline or minor rise (0 - 3.5 m).

Borehole head change was also analysed over a time span of one year henceforth referred to as the OYHF (One Year Head Fluctuation) 3D distribution. This provides additional insights into the hydraulic connectivity and thus the geological layering throughout the aquifer system. The year 1993 was selected as this was a year with no floods and low rainfall causing high groundwater usage and thus high pumping related head change throughout the aquifer. Again the maximum variation in heads within one year for each borehole was plotted at the midpoint of the slotted interval.

3.2. 3D model generation

STRM 90 m DEM (Shuttle Radar Topography Mission 90 m Digital Elevation Model, downloaded from CGIAR_CSI web site http://srtm.csi.cgiar.org/) was imported via ArcGIS into EarthVision and used to represent the surface topography of the region. In order to define the aquifer limit the DEM was sorted in EarthVision into 2 domains, alluvium and rock outcrop, based on the topographic gradient. The indexing gradient was set in EarthVision by using Slope Analysis Tool which calculates the partial derivatives in X and Y directions. The rock outcrop data were combined with bedrock top elevations from lithological logs and gridded as a single surface to define the lower limit of the aquifer in the 3D geological models. To show the spatial continuity, the 1993 OYHF data were gridded in EarthVision using 3D ordinary kriging with an anisotropic spherical variogram model. The major axis was horizontal, azimuth 135°. Ranges for the major, minor horizontal and minor vertical axes were 40000, 35000 and 90 m respectively. Cross validation yielded a correlation coefficient of 0.91, indicating good interpolation.

The iso-surfaces of the kriged OYHF data indicate the geometry of the aquifer system and plotted in 3D they show the pathways of pressure transfer via the Namoi River palaeochannels. This is shown for the Lower Namoi portion of the catchment in Figure 4. Continuous zones of high head change (> 5 m) were used to map the palaeochannels (Figure 5). Lithological logs (from NSWG 2007) were imported into the OYHF model in order to visually cross validate the mapped palaeochannels (Figure 5). Temperature and pH changes throughout the aquifer in the Lower Namoi aquifer system were analysed in 3D. The water chemistry data used included government boreholes surveyed by McLean (2003), who sampled the water quality throughout the Lower Namoi during 1999 and 2000 and irrigation borehole data collected in 2006 (The, 2008). For each variable (temperature and pH) a property distribution model was generated in EarthVision using minimum tension interpolation/extrapolation algorithm (Briggs, 1974). The temperature and pH distribution models are presented in Figures 6 and 7 respectively.

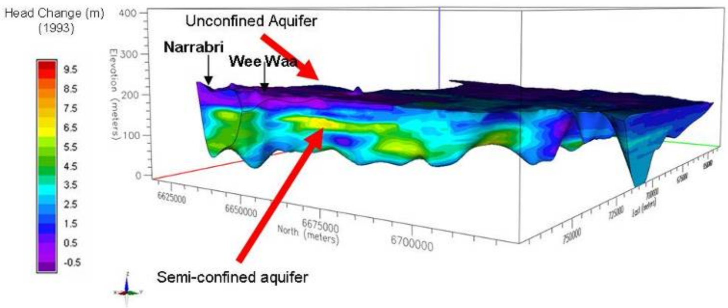


Figure 4. 1993 OYHF model of Lower Namoi catchment (looking south west) showing a shallow unconfined aquifer and a deep semi-confined aquifer. The first is characterised by small head change (purple to blue zones) and the deep aquifer is characterised by areas of large head change of >5 m (green to yellow zones) due to groundwater extraction.

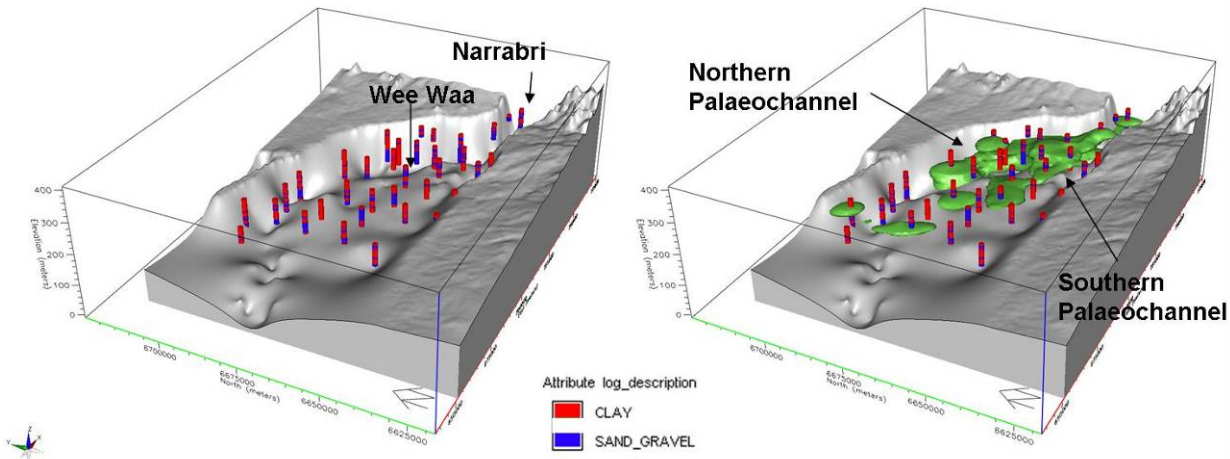


Figure 5. OYHF model of the Lower Namoi catchment showing the aquifer limit and lithological logs on the left side and the iso-surface of head change > 5 m on the right side (looking north east). The iso-surface follows the route of the Tertiary palaeochannels. The palaeochannels correspond to area of sand and gravel (blue colour) identified by the geology.

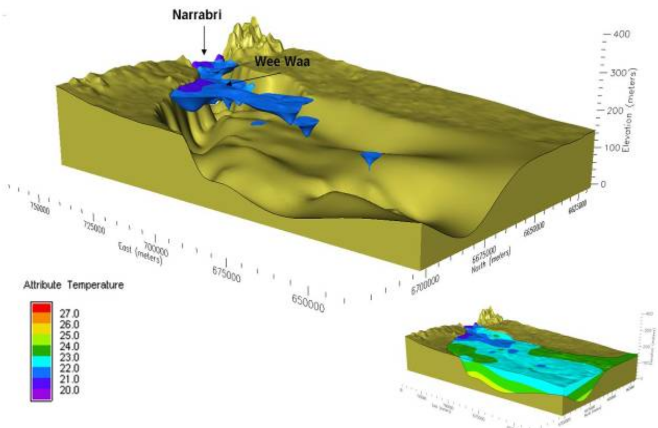
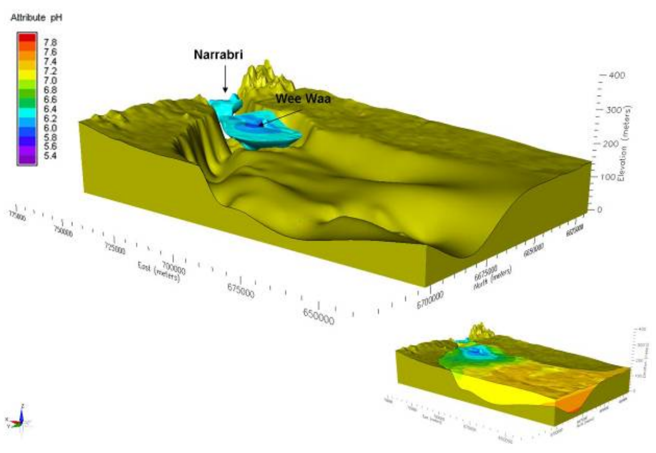


Figure 6. 3D groundwater temperature distribution model (°C) of the Lower Namoi bounded by the aquifer limit (looking south east towards Narrabri). The model in the lower right corner represents the complete distribution of the temperature while in the bigger picture the iso-surface represents a temperature < 20°C. Cooler river water that recharges the upper aquifer is impeded from reaching the deeper portions of the aquifer system.

Figure 7. 3D pH distribution model of the Lower Namoi bounded by the aquifer limit (looking south east towards Narrabri). The model in the lower right corner represents the complete distribution of the pH while in the bigger picture the iso-surfaces represent pH of 5.8 – 6.4 in the recharge zone. Low pH river water that recharges the upper aquifer is impeded from reaching the deeper portions of the aquifer system.



4. RESULTS AND DISCUSSION

Two areas of substantial head decline over the 28 year period are observable in Figure 3. The first area is in the central to northern portion of the Mooki River, between Gunnedah and Quirindi, where declines in groundwater head are greater than 10 m in many observation bores (hydrographs B in Figure 2, and the green, blue and purple dots in Figure 3). A second region of substantial decline in head occurs north of Wee Waa in the Lower Namoi (hydrograph E in Figure 2, and the green dots near Wee Waa, Figure 3).

The one year head fluctuation (OYHF) 3D distribution highlights the impact of an individual pumping season. Gridding the OYHF data using ordinary kriging in the Lower Namoi shows a large change in head where the groundwater has been extracted to meet the large irrigation requirements. The OYHF indicates the presence of a shallow unconfined aquifer and a deep semi-confined aquifer in the Lower Namoi, north of Wee Waa, while it is not well defined in some other portions of the Namoi catchment (Figure 4). There is no clear extensive lateral separation between the Cubbaroo and Gunnedah Formations as it has been conceptualised in previous studies (Merrick, 2000; CSIRO, 2007).

In Figure 5 the zones of high and low head change have been delineated by the > 5 m iso-surface. This iso-surface has the meandering characteristics of palaeochannels. The presence of the palaeochannels was confirmed by plotting the lithological logs in the same 3D space. There is good visual correlation between intervals of sand and gravels (blue lithological log intervals) and the > 5 m iso-surface. Two major palaeochannels are highlighted which bifurcate north of Wee Waa. The palaeochannels start low in the northern pre-Tertiary erosional surface and occur higher in the alluvial sequence moving southwards towards the current position of the Namoi River. This matches the progressive southward movement of the Namoi River described by Young et al. (2000). In the area between the northern and southern channels there is no connectivity due to the presence of a basalt ridge (Williams, 1997 and The, 2008). Sand and gravel sediments act as clear pathways of pressure transfer as a result of aquifer depressurisation due to groundwater extraction. In the northern palaeochannel the > 5 m iso-surface splits vertically and then rejoins. This locates the hydraulic divide between the Gunnedah and Cubaroo Formations.

Low pH (< 6.5) values and cool groundwater (< 20°C) occur only in the shallow aquifer and they support the interpretation of a recharge zone near Wee Waa (Figures 6 and 7). Cooler water zones potentially indicate recharge from the river. Water that has a long residence time reaches an equilibrium temperature in balance with the average yearly temperature and this temperature is higher than the river water temperature. There is a cooler water zone near Wee Waa in the upper aquifer. Cooler river water that recharges the upper aquifer is impeded from reaching the deeper portions of the aquifer system in the south east of the catchment. Low groundwater pH values indicating zones of recent recharge are confined to the shallow aquifer below Wee Waa, matching the same area indicated by cooler temperatures.

5. CONCLUSION

Traditionally, borehole head data have been gridded as 2D surfaces. In this research heads are placed at the midpoint of the slotted interval and then gridded in 3D. This approach has several advantages: no assumptions are made about assigning the screened section of a borehole to a specific aquifer; 3D pressure transfer throughout the aquifer system can be mapped and details on the aquifer geometry can be extracted from the data without prior assumptions. Analysing the long term change in head demarcates where the upper and lower aquifers are hydraulically connected by permeable sediments and where recharge from the river offsets groundwater extractions. Other data such as geophysical data could potentially be integrated in 3D to validate and improve the understanding of the aquifer geometry.

Correlating sedimentary units between boreholes is difficult in a multilayered sedimentary environment where there are no marker beds and where the main riverbed and secondary channels have meandered across the prehistoric plains. As the Lower Namoi model shows, in a region where there are numerous boreholes from which groundwater is being extracted simultaneously the 3D analysis of head variability within a year (OYHF models) clearly delineates the pathways of pressure transfer as water is drawn from the higher yielding sediments. The large change in head in the semi-confined aquifer compared to the small change in head in the upper unconfined aquifer clearly delineates the position of aquitards and palaeochannels.

Current MODFLOW models for the sub-catchments (Merrick, 2000, CSIRO 2007) represent the alluvial aquifer system as two or three layers; an unconfined aquifer overlying one or two semi-confined aquifers. This hydrograph analysis supports the layer models but indicates that tubular palaeochannels need to be incorporated into semi-confined aquifer layers that represent the Gunnedah and Cubbaroo layers.

Finally, the resulting 3D conceptual models improve conceptualisation of the regional hydrogeology for all stakeholders involved in water allocation and use. 3D models can be saved as a World Wide Web-viewable file in VRML 1.0 format and then converted into X3D which is the supported format for representing 3D computer graphic on the web.

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