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A reassessment of the Lower Namoi Catchment aquifer architecture and hydraulic connectivity with reference to climate drivers

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We demonstrate the need for better representations of aquifer architecture to understand hydraulic connectivity and manage groundwater allocations for the ~140 m-thick alluvial sequences in the Lower Namoi Catchment, Australia. In the 1980s, an analysis of palynological and groundwater hydrograph data resulted in a simple three-layer stratigraphic/hydrostratigraphic representation for the aquifer system, consisting of an unconfined aquifer overlying two semi-confined aquifers. We present an analysis of 278 borehole lithological logs within the catchment and show that the stratigraphy is far more complex. The architectural features and the net-to-gross line-plot of the valley-filling sequence are best represented by a distributive fluvial system, where the avulsion frequency increases at a slower rate than the aggradation rate.

We also show that an improved understanding of past climates contextualises the architectural features observable in the valley-filling sequence, and that the lithofacies distribution captures information about the impact of climate change during the Neogene and Quaternary. We demonstrate the correlation between climate and the vertical lithological succession by correlating the sediment net-to-gross ratio line-plot with the marine benthic oxygen isotope line-plot – a climate change proxy. Pollens indicate that there was a transition from a relatively wet climate in the mid–late Miocene to a drier climate in the Pleistocene, with a continuing drying trend until present. Groundwater is currently extracted from the sand and gravel belts associated with the high-energy wetter climate. However, some of these channel belts are disconnected from the modern river and flood zone. We show that the cutoff between the hydraulically well- and poorly connected portions of the valley-filling sequence matches the connectivity threshold expected from a fluvial system.

KEY WORDS: groundwater, hydrostratigraphy, global climate change, Neogene, distributive fluvial system, Namoi Catchment.

INTRODUCTION

It is common to simplify the geometry of aquifers to enable the construction of groundwater flow models (Bear 2007; Giambastiani *et al.* 2012; Fitts 2013). A common concern where models have performed poorly is that the conceptual geological model is erroneous (Karlsen *et al.* 2012). In recent decades, there have been significant advances in the study of fluvial sedimentology (Weissmann *et al.* 2010; Blum *et al.* 2013) and hydraulic connectivity modelling (Hovadik & Larue 2010). We examine the lithofacies data in the Lower Namoi Catchment in the context of a distributive fluvial system (Nichols & Fisher 2007; Weissmann *et al.* 2010; Davidson *et al.* 2013).

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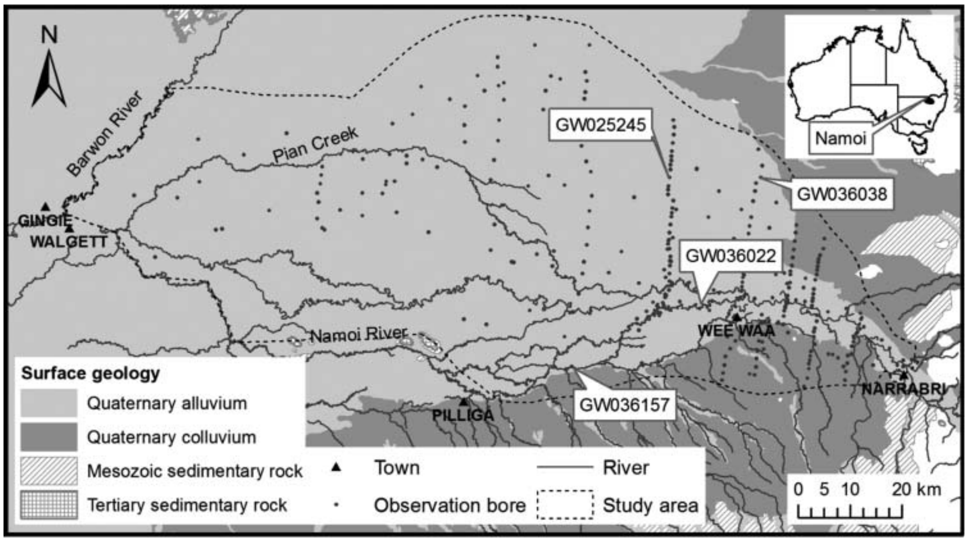

Figure 1 Case study site, Lower Namoi Catchment, New South Wales, Australia. Since 1966 groundwater has been extracted from the alluvial sediments to irrigate crops (mostly cotton). The Namoi River flows from east to west. Shown on the map is the extensive groundwater-monitoring network (data for the map were supplied by the Namoi Catchment Management Authority).

In the Lower Namoi Catchment (Figures 1, 2), groundwater has been extracted from the unconsolidated sedimentary aquifers to irrigate crops since 1966 (Courier 1967). Ongoing access to groundwater requires knowledge of how various portions of the aquifer system are connected. Historically, in groundwater models, the catchment has been represented as three aquifers (Williams *et al.* 1989; Merrick 2000; CSIRO 2007; Kelly *et al.* 2007). The valley-filling sequence, which is up to 140 m thick, is divided into the Cubbaroo Formation (lowest semi-confined aquifer, up to 60 m thick), Gunnedah Formation (intermediate semi-confined aquifer, up to 80 m thick) and Narrabri Formation (overlying unconfined aquifer, 10–40 m thick) (Williams *et al.* 1989). This conceptual geological framework has enabled good matching of the groundwater heads between the groundwater flow model and the groundwater level monitoring data in the central portion of the catchment but, in isolated monitoring bores, has poorly represented the aquifer behaviour in the northern, western and southern regions of the catchment (Merrick 2000). To improve the modelling of water movement throughout the Lower Namoi Catchment, a better representation of the aquifer architecture is required.

Based on a new analysis of 278 lithological logs throughout the catchment, we discuss concerns with the present conceptualisation of the valley-filling unconsolidated sedimentary sequence in the Lower Namoi Catchment. We analyse the historical borehole lithological logs as a first step towards constructing a more realistic representation of the complex fluvial aquifer. The lithological logs are interpreted in the framework of a distributive fluvial system, where the main trunk channel in the proximal portion of the catchment breaks down into a succession of smaller channels that meander across the landscape (Nichols & Fisher 2007; Weissmann *et al.* 2010; Davidson *et al.* 2013). Hydraulic connectivity through the vertical sedimentary succession is analysed by examining changes in the net (sand and gravel) to gross (total volume) ratio. Horizontal connectivity is examined by interpolating the lithological logs in 3D. This enables us to observe the migration(s) of the major paleochannel belts that occurred as the sediments filled the paleovalley.

To further understand the development of the valley-filling sequence, we examine the relationship between global climate change, as indicated by the stacked deep-sea benthic foraminiferal oxygen-isotope line-plot (Zachos *et al.* 2008) and the sedimentary succession.

GEOLOGICAL SETTING

Between the late Cretaceous and the mid Miocene, a paleovalley was carved through the early Cretaceous sedimentary rocks of the region (Williams *et al.* 1989). The axis of the main channel followed the northern boundary of the Lower Namoi Catchment (Figure 3). From the mid Miocene until present, the paleovalley was filled with reworked eolian and alluvial sediments, and these sediments store the groundwater used for irrigation.

Little has changed in the nature of the primary source material for the sedimentary sequence. Sediments that fill the valley are derived from the weathering and transportation of the Devonian through to Cretaceous sedimentary and volcanic rocks that border the catchment. Volcanic activity occurred in the adjoining Nandewar and Warrumbungle Provinces from 20.5 (Nandewar) through 13.3 Ma (Warrumbungle) (Wellman & McDougall 1974). Tomkins & Hesse (2004) deduced from the deformation of the mid Miocene basalt-filled valley that uplift occurred in the Macquarie Catchment associated with widespread volcanism at that time. The Macquarie and Namoi catchments have a common boundary on the western side of the Namoi Catchment. Kemp (2010) concluded from a combination of bedrock stream long-profiles and review of past studies that there was no uplift in the Lachlan Catchment since the mid Miocene. This catchment is located to the southwest of the Namoi Catchment.

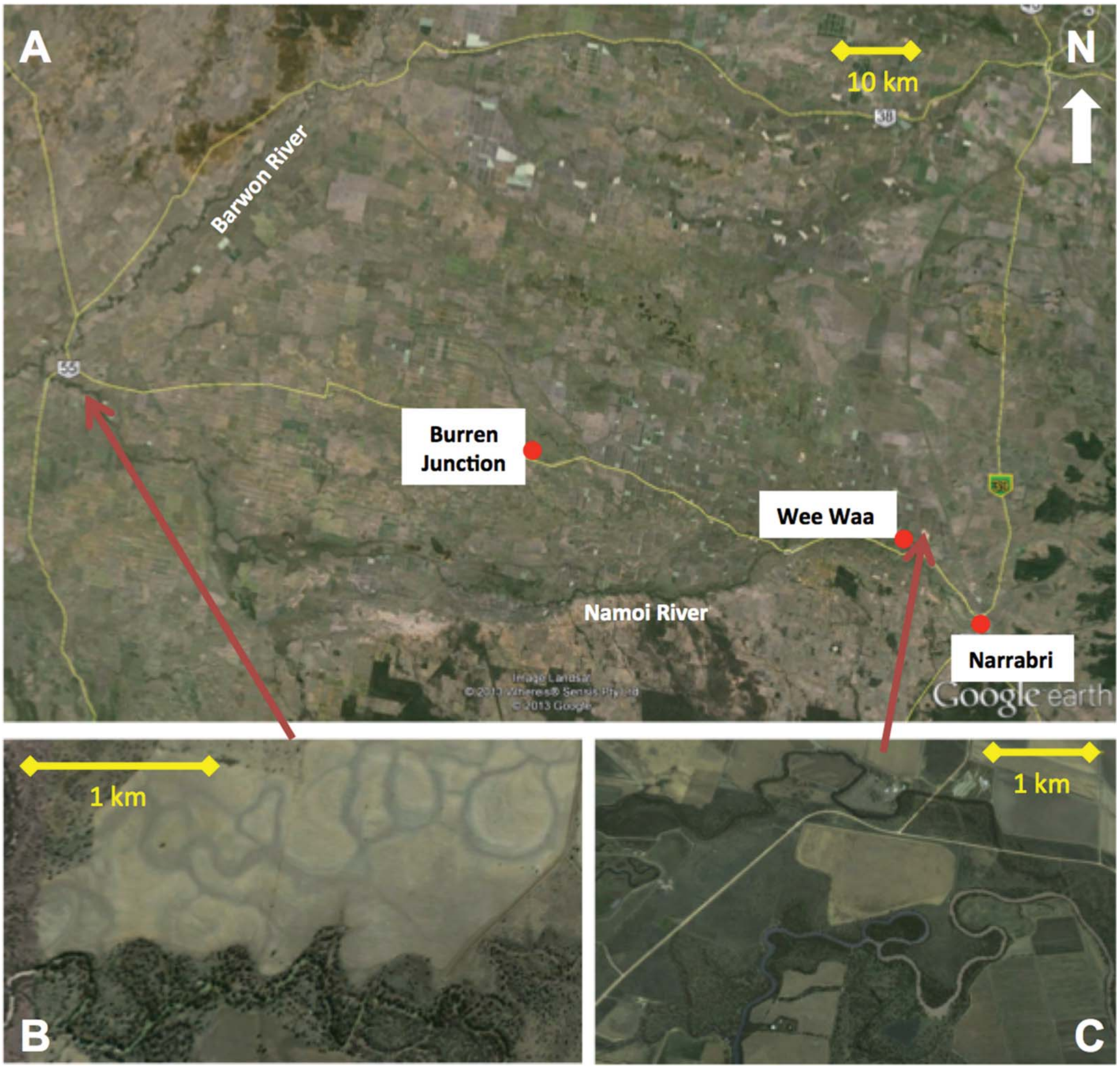

Figure 2 (a) Google Earth image of the Lower Namoi Catchment. The Namoi River flows east to west. The distributive form of the major meandering channels can be observed moving from the proximal portion of the catchment in the east near Wee Waa to the distal junction with the Barwon River. (b) Abandoned reaches, oxbows and truncated loops. (c) Bifurcation of the Namoi River near Wee Waa.

The present-day clayey silty soils (vertosols) that cover the landscape are a combination of reworked eolian deposits and alluvial flood deposits (Ward 1999). Eolian deposition peaked at 13 Ka. Near-surface channel sediments have been dated from 56 to 5.7 Ka (Ward 1999; Young *et al.* 2002; Wray 2009).

GROUNDWATER MONITORING AND HISTORICAL TRENDS

In the 1980s, volumetric metering was introduced to enable improved management and modelling of the groundwater resource. The cumulative groundwater extractions for each water year are graphed in Figure 4. To monitor the impact of groundwater withdrawals, an extensive groundwater-monitoring network was installed (Figures 1, 5, 6). Since the late 1960s, groundwater levels have been recorded at each location four or more times per year (Williams *et al.* 1989). In places, extensive groundwater extractions have caused the groundwater levels to fall (for example hydrographs GW030238 and GW025245, shown in Figure 5). At other locations, the groundwater levels are stable owing to flood recharge (GW036022) or are rising (GW036157).

LITHOFACIES DATA AND PROCESSING

Driller logs recorded during the installation of production and monitoring boreholes form the primary data set. A total of 278 borehole logs are used in the analysis.

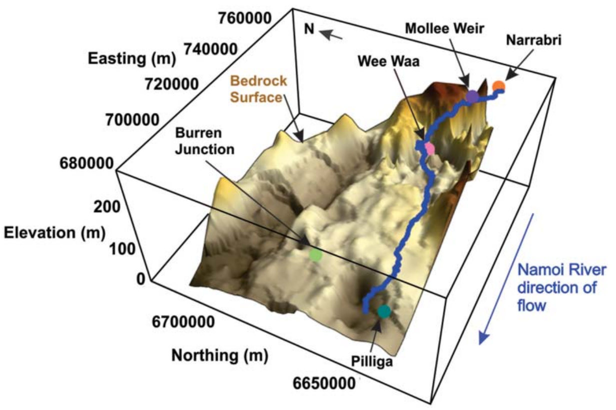

Figure 3 Lower Namoi Catchment lower Miocene erosional surface. The primary Miocene paleovalley ran along the northern boundary of the catchment. The present-day Namoi River shown flows east to west along the southern boundary, abutting Mesozoic sedimentary rocks. The colour-coded town and weir location spheres are used in Figures 5–8.

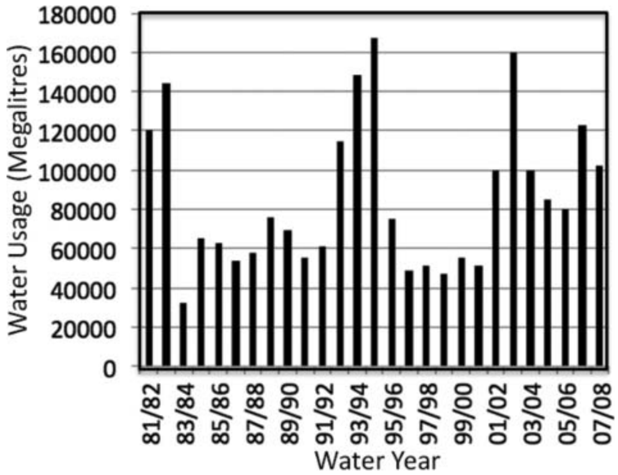

Figure 4 Lower Namoi Catchment annual groundwater usage between 1981/82 and 2007/08. Groundwater extraction occurs from spring through to late summer (modified from Ludowici 2010).

These are archived on the NSW Office of Water Pinneena GW CDs (http://waterinfo.nsw.gov.au/pinneena). For each borehole, the Pinneena GW CD contains information on the borehole coordinates, elevation, construction methods, casing types, slotted intervals, driller lithological logs and groundwater levels. Custom Mathematica scripts (www.wolfram.com) were written to extract and plot the data in 3D, and interpolate the lithological logs (Figure 6).

The dominant texture in the lithological descriptions was used to sort the data into low-permeability (clay and silt dominated) and high-permeability (sand and gravel dominated) classes. These indexed data were then interpolated in 3D space using nearest-neighbour gridding (Figure 7). It was possible to use this simple interpolator only because of the high density of boreholes. The facies distribution is dominated by layered strata that are laterally extensive, and the boreholes are perpendicular to

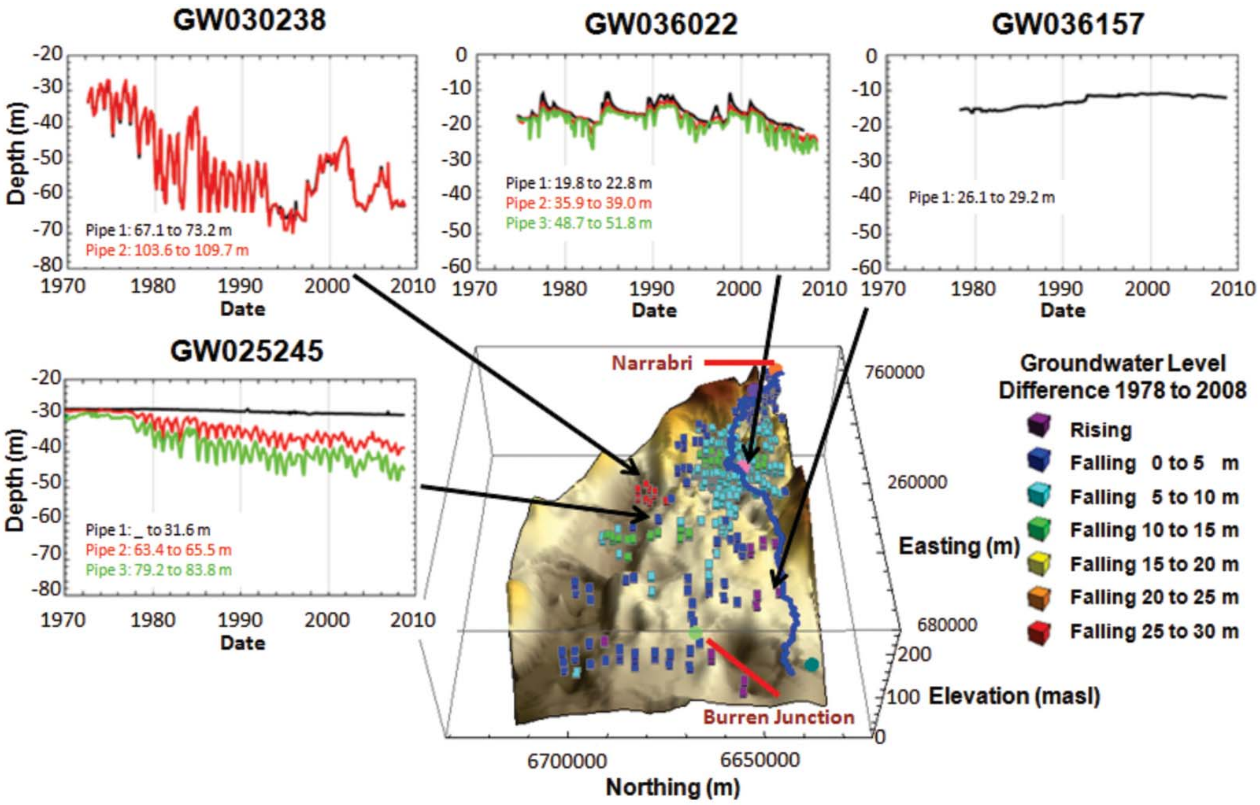

Figure 5 Lower Namoi Catchment groundwater level trends between 1978 and 2008. Selected hydrographs from representative paleochannel belts highlight the variable responses of the aquifer system to irrigation farming throughout the catchment.

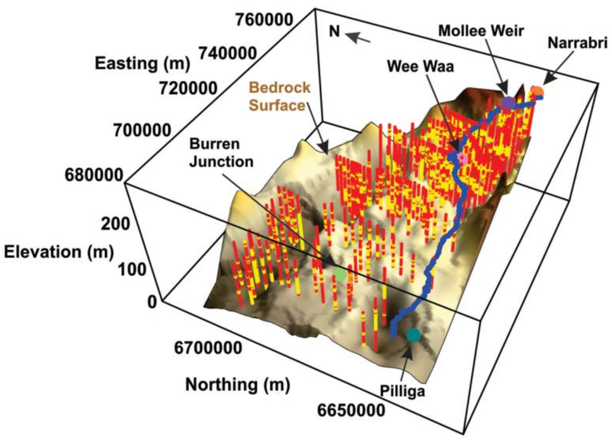

Figure 6 Lower Namoi Catchment indexed lithological logs from 278 borehole locations (clay and silt = red, sand and gravel = yellow).

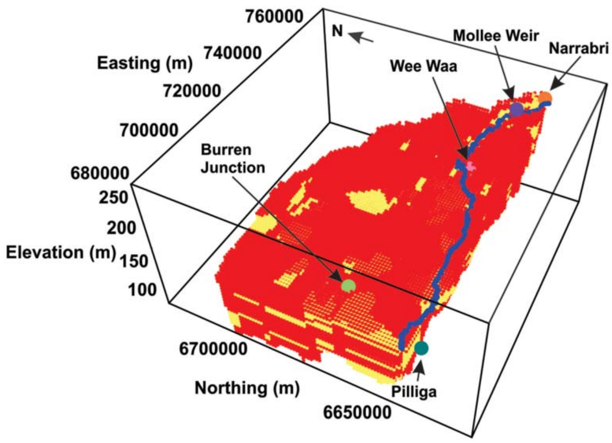

Figure 7 A three-dimensional facies model of the borehole lithological logs shown in Figure 6. The categorical data were interpolated using nearest-neighbour gridding (clay and silt = red, sand and gravel = yellow).

the layering. Under these conditions, nearest-neighbour gridding is a suitable interpolator of lithological logs (Tartakovsky *et al.* 2007). A series of horizontal slices was extracted from the facies model to highlight the location of the river-channel belt (indicated by a concentration of sand and gravel patches). For visual clarity, the low-permeability clay and silt data were removed to highlight the migration of the major paleochannel belt (Figure 8).

In the oil and gas sector, when evaluating the resource volume and fluid flow properties of the strata, it is common to quantify the net-to-gross ratio for the strata of interest, where the net is the permeable sand and gravel, and the gross is the total representative elementary volume. The proportion of high- or low-permeability aggradated sediment is predominantly a function of the climate, vegetation, distance from source, gradient, source material, accommodation space and tectonics.

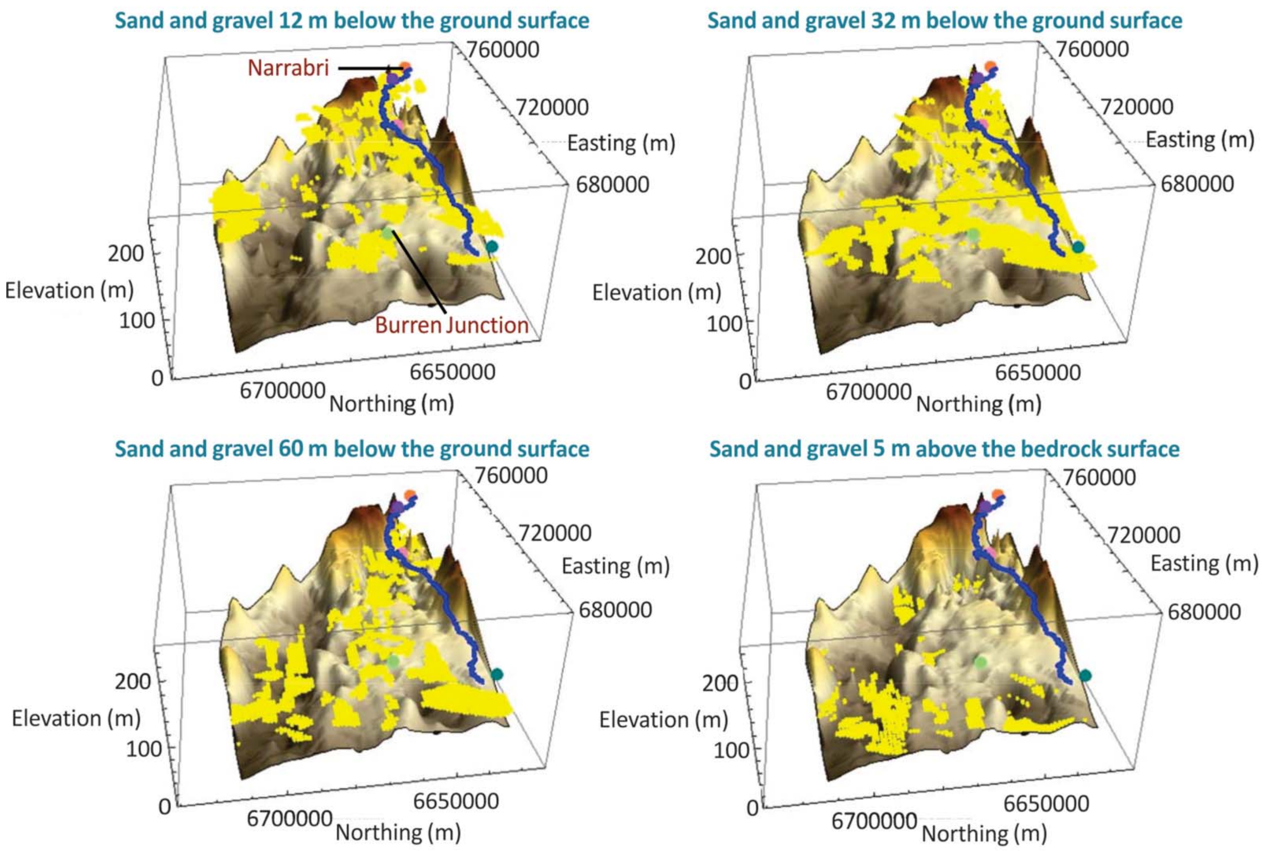

Figure 8 Horizontal slices through the facies model presented in Figure 7 highlighting the location of the sand and gravel units.

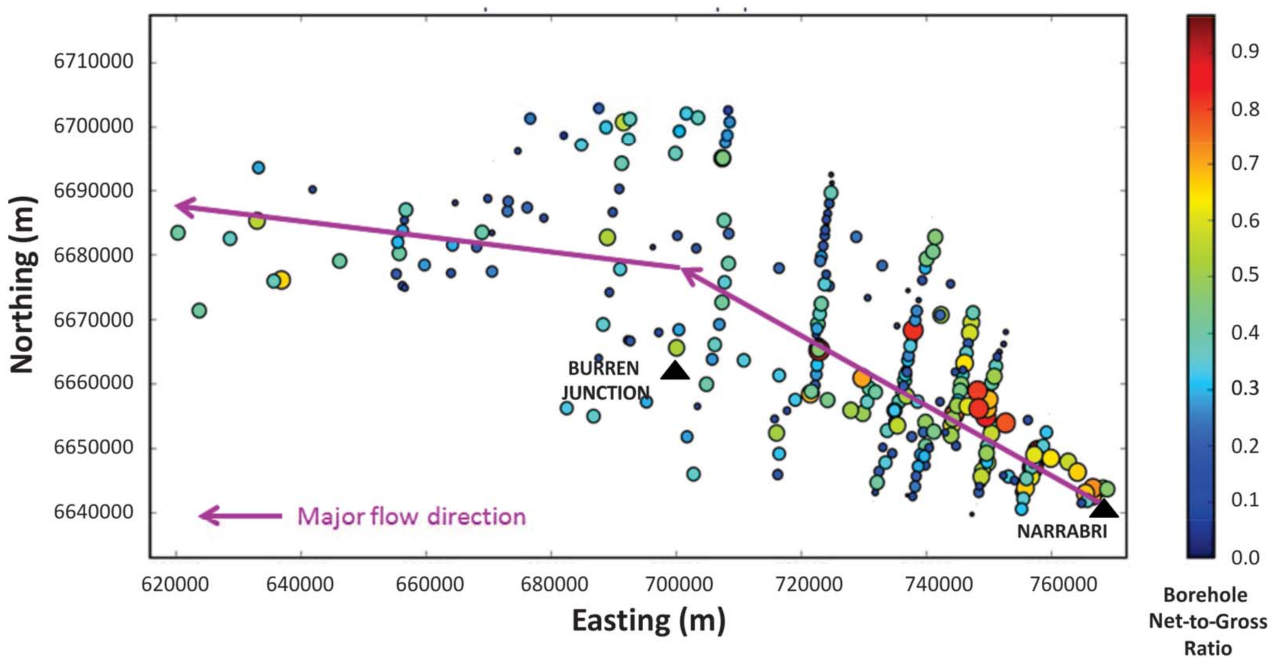

Figure 9 Net-to-gross ratio for the complete borehole lithological log shown in Figure 6.

There is no simple relationship between all the forcings and the resulting architecture of the valley-filling sequence (Gibling 2006), but there are some general rules (Gouw 2007; Nichols & Fisher 2007). The proximal portion of the catchment will have more connected sand bodies, while the distal portion will have fewer connected sand bodies. With respect to changes in the architectural features moving upwards through a valley-filling sequence, Gouw (2007) summarises three possibilities:

(a) When avulsion frequency increases at the same rate as the aggradation rate, the architecture does not change.
(b) When avulsion frequency increases at a slower rate than the aggradation rate, the channel-belt deposit proportion and channel interconnectedness decrease.
(c) When avulsion frequency increases at a higher rate than the aggradation rate, the channel-belt deposit proportion and channel interconnectedness increase.

For hydraulic connectivity to exist between all depths of the valley-filling sequence, there needs to be an overlap between the stacked point bar sheet and ribbon deposits. Extensive floodplain deposits and channel plugs reduce hydraulic connectivity. Recently, Larue & Hovadik (2006) and Hovadik & Larue (2010) assessed hydraulic connectivity in meandering fluvial systems by generating a number of synthetic models in which they varied the frequency of channels, their meander wavelength and dimensions, the occurrence of avulsion and the extent of overbank deposits. They established that when hydraulic connectivity in meandering river systems is measured in 3D, there is a cascading threshold between poor and good connectivity centred on a net-to-gross ratio of 0.3, where, above 0.3 there is good hydraulic connectivity between the sand and gravel bodies. The threshold zone is usually narrow, ranging from 0.2 to 0.4 (commonly defined by an S-curve). The results of these connectivity studies are used to provide insights into aspects of hydraulic connectivity in the Lower Namoi Catchment.

The portion of permeable sediment (net) is determined for the complete length of each borehole (Figure 6). A 2D map of the borehole net-to-gross ratio throughout the Lower Namoi Catchment is presented in Figure 9. Changes in vertical hydraulic connectivity through the valley-filling sequence are examined by plotting the catchment-wide variation in the net-to-gross ratio *vs* depth. This is shown in Figure 10b.

CLIMATE PROXY DATA

Martin's (1980) palynological ages provide the only dating of the sub-surface sediments in the Lower Namoi Catchment, and the pollen assemblages provide insights into past climates. The palynological dated intervals are shown in Figure 10b. Pollen assemblages indicate that closed forest covered the landscape, and that rainfall was greater than 1500 mm per year during the mid Miocene (Martin 1980, 2006). Only two bores (GW030118 and GW03545, just north of Narrabri), yielded pollens that could restrict the dates of the sediments from the Pliocene–Pleistocene. Sediments of this age were located from 30.2 to 42.7 m below ground level (mbgl). The Pliocene–Pleistocene pollen assemblages indicate that closed forest still dominated the landscape, but there were patches of open forest and herbaceous ground cover. The mean rainfall since 1890 is 658 mm per year (Australian Government Bureau of Meteorology, www.bom.gov.au). Prior to clearing for farming, the modern landscape

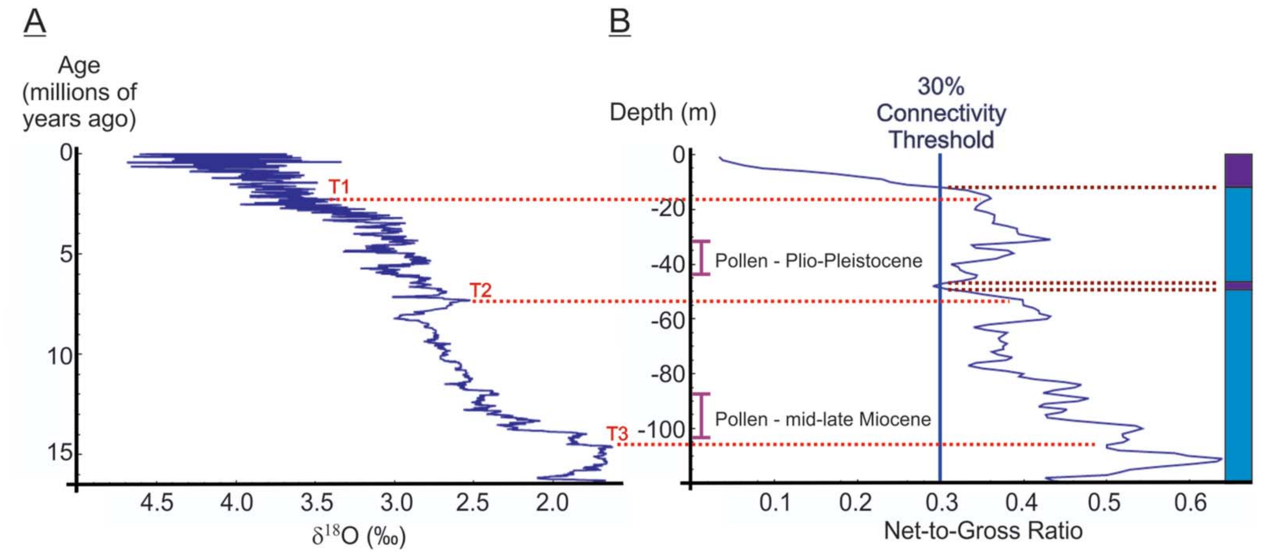

Figure 10 (a) Stacked deep-sea benthic foraminiferal oxygen-isotope line-plot (Zachos *et al.* 2008) (note: the x axis is plotted high to low moving left to right). (b) Net-to-gross ratio *vs* depth, using all the lithological logs referenced from the ground surface. The pink bands indicate the geological ages determined from palynological studies (Martin 1980). The 30% connectivity threshold from Larue & Hovadik (2006) is shown as a vertical blue line. Above 0.3, there is good hydraulic connectivity between the stacked sand and gravel bodies. Hydrostratigraphic zones based on the connectivity threshold are indicated on the right-hand side of the graph (blue and purple colours indicate intervals above and below the 30% connectivity threshold, respectively). T1, T2 and T3 are tielines highlighting similarities in the trends between line-plots A and B.

consisted of grassy and shrubby woodlands (Weston *et al.* 1980).

The insights into past climatic conditions provided by the limited data presented by Martin (1980) are consistent with climatic trends observable on a global scale and elsewhere in Australia throughout the Neogene and Quaternary. During the late Oligocene, a warming trend reduced the extent of Antarctic ice, and this trend continued until the late middle Miocene climatic optimum (17 to 15 Ma) (Zachos *et al.* 2001). It was approximately then that the base sediments of the Lower Namoi valley-filling sequence were deposited. From the mid-Miocene climatic optimum onwards, a cooling trend dominated globally, and the major ice-sheets on Antarctica were re-established. This resulted in aridification of the mid-latitude continental regions (Flower & Kennett 1994). The closing of the Indonesian seaway has also been attributed to causing additional aridification during the Pliocene (Krebs *et al.* 2011). McLaren & Wallace (2010) reviewed the known observations in the Australian geological record that indicate a relatively wet Miocene compared with more recent periods. These include the presence of Miocene–Pliocene lateritic weathering surfaces, tropical taxa in the Miocene coastal sediments and palynological observations indicating extensive temperate rainforest in southeastern Australia. By contrast, in the Pleistocene, dune fields developed in central Australia (Fujioka et al. 2009), and open woodlands and grasslands covered much of inland southeastern Australia (Martin 2006).

The amount of water moving through the landscape is a dominant control on hill slope erosion, riverine fluxes and sediment deposition (Gibling 2006; Nichols 2009; Leeder 2011). The gradual change from the wetter climate in the mid Miocene to the drier present-day climate should be reflected in the sediment texture. The wetter mid-Miocene rivers would have transported more clay- and silt-sized sediments out of the catchment, leaving behind a higher proportion of sand and gravel.

Tomkins & Hesse (2004) highlighted the correlation between the stacked deep-sea benthic foraminiferal oxygen-isotope data (a low δ^{18}O value indicates warmer average global temperatures) and sediment texture for the valley-filling sequences from two other catchments in the Murray-Darling Basin: the Lachlan and Macquarie catchments. The correlation between δ^{18}O values and sediment texture in the Lower Namoi Catchment is examined in finer detail in this paper. Figure 10a shows the stacked deep-sea benthic foraminiferal oxygen-isotope data set presented in Zachos *et al.* (2008) [We used the updated data set available from http://www.es.ucsc.edu/~jzachos/Publications.html (accessed July 2013)]. These data were smoothed using a median window filter of 30 neighbouring points.

DISCUSSION

Lithofacies and hydraulic connectivity

Bedrock geometry (Figure 3) influences connectivity at depth. The deeper lithological logs are all from boreholes slotted in the deep northern channel (Figures 3, 5). The net-to-gross ratio (Figure 10) is relatively high (greater than 0.5) for these deeper portions of the valley-filling sequence. This explains the appeal of initially placing irrigation boreholes into these paleochannels. However, groundwater-monitoring boreholes slotted in the deeper northern paleovalley all show a large decline in the measured groundwater level (for example, location GW030238 in Figure 5). This is due in part to the distance to the Namoi River and present-day flood recharge zones, but as will be discussed below, there is no clear pathway of connectivity via the permeable sediments at all depths.

The basement geometry near to and west of Walgett has not been mapped, so the distal controls on the valley-filling sequence are poorly understood. Immediately west of Walgett the Namoi River flows into the Barwon River. The centreline distance from the head of the catchment at Narrabri to the far west of the catchment at Walgett is approximately 170 km (Figure 1). Over such a distance a significant decline in stream velocity is expected (Leeder 2011). In Figure 9, the high net boreholes are all located in the proximal portion of the Lower Namoi Catchment. For the majority of the boreholes in the medial and distal portions of the catchment, the borehole net-to-gross ratio is less than 0.5. This is consistent with a distributive fluvial system (Nichols & Fisher 2007; Weissmann *et al.* 2010).

Throughout the upper Miocene, the major channel belt ran through the centre of the region between Wee Waa and Burren Junction (Figure 8, 60 m depth slice). Much of the groundwater is extracted from this channel belt. Just to the east of Burren Junction, there are multiple channel belts extending across the catchment from south to north. There are no sands or gravels in the northeast overlying the axis of the paleovalley present in the 60 m depth slice. In the northeast region, the presence of floodplain deposits at this level resulted in the defining of the Cubbaroo Formation (Williams *et al.* 1989). However, as discussed in more detail below, this is just one of many semi-confined zones formed as paleorivers meandered across the landscape, and these are not reflected in the existing three-layer aquifer representation of the catchment.

The continued southwards migration of the major paleochannel belt is observable in the 32 m and 12 m depth slices (Figure 8). Again, at these depths there are no continuous sand channels on the far northeast side of the catchment.

As the climate became drier, the clay content across the landscape increased (Figures 6, 7, 10), and the streamflow became confined to narrow anastomosing channels observable in the present-day landscape (Figure 2). Even in the near-surface sediments, there is evidence of a drying trend. Meander wavelengths suggest that bank full flows were two to three times greater in some near-surface paleochannels than those experienced by the present Namoi River (Young *et al.* 2002).

Connectivity between overlying channel-belts and ribbons is critical for sustaining access to groundwater. Replacement of any groundwater withdrawn from the aquifer requires a continuous, most likely tortuous, path through connected permeable sediments to flood and river recharge zones. The declining trend in net-to-gross ratio over time indicates that there is a decrease in connectivity between the stacked channel-belts in the sedimentary sequence (Figure 10). This suggests that avulsion frequency increased more slowly than the aggradation rate (Gouw 2007). The 30% connectivity threshold line is drawn on the net-to-gross line-plot. At the catchment scale, two intervals are above the threshold (indicated by the blue in the bar on the right of the graph) and two intervals are below the threshold (purple). The net-to-gross line-plot indicates that there is good connectivity at all levels deeper than 49 mbgl. From 49 to 46 mbgl, the net-to-gross ratio falls below the connectivity threshold. This low-connectivity layer gives support to the historical representation of an unconfined Narrabri Formation overlying the semi-confined Gunnedah Formation (Williams *et al.* 1989; Merrick 2000; CSIRO 2007). However, the previous three-layer representation places the semi-confining layer between the Narrabri and Gunnedah formations at 40 m, and this is too shallow based on the net-to-gross line-plot. The groundwater hydrograph set for location GW025245 (Figure 5) highlights the presence of a semi-confining layer. This is indicated by the clear divergence over time in the groundwater levels between pipe 1, slotted to 31.6 mbgl, and pipes 2 and 3, which are slotted from 63.4 to 65.5 and 79.2 to 83.8 mbgl, respectively.

Between 45 and 10 mbgl, the connectivity is high. This explains why many stock and domestic boreholes have successfully extracted water from these depths for over 50 years (DWE 2009). In this interval, the median net-to-gross ratio is lower than the interval from basement to 49 m. This is why the bores slotted in this shallower interval are lower-yielding (Williams *et al.* 1989) and only used for stock and domestic purposes. From the ground surface to 10 mbgl, the net-to-gross ratio indicates that the connectivity is below the critical threshold. This low connectivity interval has not been incorporated into any groundwater models of the region, because it is above the present water-table. However, this layer would have to be incorporated into any fully coupled surface-groundwater flow model.

The above 1D analysis is not completely supported by the slices through the 3D lithofacies model (Figures 7, 8), or by the groundwater hydrographs displayed in Figure 5. Historically, the focus has been on representing the valley-filling sequence as three aquifer layers, but Figures 7 and 8 clearly show that the 3D distribution of the paleochannel belts should be incorporated into the framework used in any spatial modelling of groundwater movement. Lavitt (1999, Chapter 6) also indicated the need to represent the valley-filling sequence of the Mooki Catchment (a sub-catchment in the headwaters of the Namoi Catchment) considering irregular facies distributions. Irregular facies architecture can now be incorporated into groundwater flow models using unstructured grids (Panday *et al.* 2013) or analytic element sub-domains (Fitts 2010).

The groundwater hydrograph set GW036022 (Figure 5) highlights that locally there can be good hydraulic connectivity from the ground surface to at least 48.7 mbgl. All hydrographs at this location respond to floods (observable as sudden rises in the groundwater level). The flood response is followed by a slow decline in the groundwater level between floods. This fall is in part due to the natural recession, but it is also due to pumping in the lower portion of the valley-filling sequence. Many boreholes in the proximal portion of the catchment have a net-to-gross ratio greater than 0.7 (Figure 9). Such high values indicate that hydraulic connectivity is likely at all depths.

Climatic impacts on the paleovalley filling alluvial sequence

It has been well established that the benthic foraminifera shell δ^{18}O values are correlated with the temperature and salinity of the water in which the foraminifera lived and that the δ^{18}O values can be used as a proxy for past global climate change throughout the geological record (Waelbroeck *et al.* 2002, Zachos *et al.* 2008). The lower the δ^{18}O values, the smaller the extent of ice coverage over the Earth. A low δ^{18}O value has been previously correlated with higher rainfall in eastern Australia. In a study of the valley-filling sediments in the Macquarie and Lachlan catchments, Tomkins & Hesse (2004) graphed the correlation between increasing δ^{18}O values and the transition from wet sclerophyll to open forests. They also highlighted the corresponding change from predominantly sand to clay deposition approximately 2–3 Ma ago. A graph of the median global benthic δ^{18}O values (Zachos *et al.* 2008) is aligned with the net-to-gross graph in Figure 10. The dominance of climatic forcing is clearly evident, but the alignment requires further dating of the Lower Namoi Catchment sediments before the δ^{18}O line-plot can be accurately scaled against the net-to-gross line-plot. Even in this unscaled form, the correlation is evident. Three tie points are highlighted on the graphs in Figure 10. The lowest δ^{18}O value corresponds to the highest net-to-gross ratio (T3 tieline, Figure 10). Tieline T2 highlights the corresponding fluctuation in δ^{18}O values and net-to-gross approximately 7 Ma ago. The major transition to aridity is highlighted by tieline T1.

Based on the net-to-gross analysis of the lithological logs and taking into consideration the strong influence of climate change on sediment deposition, the valley-filling sequence can be interpreted as one gradational distributive fluvial system, with decreasing hydraulic energy in the landscape moving up through the sequence, and dispersed energy moving from the proximal to the distal portion of the catchment. Dividing the valley-filling sequence into the Narrabri, Gunnedah and Cubbaroo formations cannot be substantiated: 'A lithostratigraphic unit is controlled entirely by the continuity and extent of its diagnostic lithologic features' (International Commission on Stratigraphy, www.stratigraphy.org). Only the clays in the upper 10 m could be mapped almost continuously across the landscape. This clay layer can be observed in the top of nearly all boreholes in Figure 6. All other depths throughout the valley-filling sequence reflect a continuous change from a mid-Miocene wet sub-tropical climate (>1500 mm rainfall) through to the drier present-day climate (658 mm rainfall). As the paleorivers meandered across the landscape, they left behind a heterogeneous mixture of sedimentary architectural features. At any one depth, the proportion of sand and gravel bodies *vs* overbank deposits is primarily a reflection of the prevailing climate.

Compared with present-day climatic conditions, the wetter Pliocene–Pleistocene climate and even wetter Miocene climate correlate with an increased occurrence of sand and gravel bodies occurring throughout the landscape shown in Figure 8 and a higher net-to-gross ratio in Figure 10. The relatively drier upper Quaternary (Fitzimmons *et al.* 2013) corresponds to the dominant presence of clay and silt in the upper 10 m of most lithological logs in Figure 6, the near-continuous upper surface clay and silt layer observable in the 3D facies model shown in Figure 7, and the rapid decline in the net-to-gross ratio in the upper 10 m of Figure 10.

The correlation between benthic δ^{18}O values, an indicator of global climate change, and the net-to-gross line-plot supports the findings of Kemp (2010) that there has been no significant tectonic movement since the mid Miocene. Despite differences in naming the sedimentary sequences in the Lachlan, Macquarie and Namoi Catchments, all follow a similar trend with a high proportion of gravel and sand at the base, and a sharp transition to increased clay and silt content at the Pliocene/Pleistocene boundary.

From the above climatic and dating observations, the groundwater hydrographs can be placed in hydrogeological context. At site GW030238, groundwater is extracted from the northern mid-Miocene paleochannel belt (refer to Figures 5, 8–10). There is no direct connection to flood recharge apparent in the hydrographs. At site GW036022, groundwater is extracted from the upper Miocene to Pliocene paleochannel belt. At this location, recharge from floods is clearly observable. At site GW025245, groundwater is extracted from the mid-Miocene paleochannel belt. This nested set of monitoring boreholes highlights the presence of a semi-confining aquitard, between the Miocene and paleochannel and the Pliocene–Pleistocene sediments. At site GW036157, recharge from irrigation deep drainage, floods and diffuse rainfall via upper Quaternary paleochannels is in excess of the rate of local groundwater extraction.

CONCLUSIONS

In a complex fluvial system, attempting to subdivide the valley-filling sequence into simple layers hinders the correct representation of the valley-filling sequence. The 1D analysis of the net-to-gross line-plot gives some support for representing the valley-filling sequence in the Lower Namoi Catchment by an unconfined aquifer overlying a semi-confining layer. It does not give support for the presence of a catchment-wide second semi-confining layer. Based on the net-to-gross line-plot, good hydraulic connectivity is predicted at all depths below 49 mbgl. There is poor hydraulic connectivity between 49 and 46 mbgl, and then good connectivity between 45 and 10 mbgl. The interpretation is different when the lithological logs are comprehensively examined in 3D.

In 3D, it can be shown that the major paleochannel belt migrated from the northern boundary in the mid Miocene to the southern boundary at present. Therefore, locally vertical hydraulic connectivity will reflect the migration of the permeable channel and impermeable floodplain deposits. It is this process that formed the semi-confined Cubbaroo Formation, but this is just one of many such isolated paleochannel deposits. At any depth, there is a concentrated belt of permeable channel deposits, indications of many truncated meandering channels defined by isolated sand and gravel bodies, and extensive floodplain deposits. The valley-filling sequence is a patchwork of semi-confined aquifers, not just the Gunnedah and Cubbaroo formations. This patchwork of well- and poorly hydraulically connected aquifers indicates that there will be a need to manage groundwater on a local scale.

From the mid Miocene until the present, the major trend in the net-to-gross line-plot shows that there has been a slow transition from a relatively high-energy depositional environment through to a low-energy environment. The correlation between the benthic $\delta^{18}O$ values and net-to-gross line-plots indicates that climate is a dominant control on the architectural features and sediment texture observed in the valley-filling sequence of the Lower Namoi Catchment. The valley-filling sequence of the Lower Namoi Catchment is best represented by a distributive fluvial system, where the channel-belt deposit proportion and channel interconnectedness decrease, progressing from the mid Miocene to the present.

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