

Investigation of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the Namoi River catchment – elucidating recharge sources and the extent of surface water/groundwater interaction

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Abstract Stable isotopes ^{18}O and ^2H were analysed in water samples from rainfall, surface water and groundwater within the semi-arid Namoi River catchment in NSW, Australia. The isotopic composition of rainfall events and groundwater samples plot along the Local Meteoric Water Line (LMWL). In contrast, the surface water samples of the Namoi River clearly show signs of evaporative enrichment and plot on a Local Evaporation Line (LEL) constructed for the area based on $\delta^{18}\text{O}$ and $\delta^2\text{H}$ time-series for surface waters of the Namoi River. The river samples have a distinctly lower slope than the LMWL which is due to evaporation. Shallow groundwater near the Namoi River shows considerable enrichment compared to average groundwater signatures and plots in between the LMWL and the LEL on a $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$ graph. These results clearly indicate that the Namoi River is recharging the shallow aquifer system. Conversely, the isotopic composition of surface water in the tributaries of Maules and Horsearm creeks are similar to groundwater indicating that these creeks are receiving groundwater discharge. This study reveals many complex hydrological processes occurring in the catchment. It would not have been possible to elucidate these processes without the use of stable isotope data.

Keywords: Stable isotopes, Hydrology, Groundwater, Surface water/groundwater interactions, Recharge

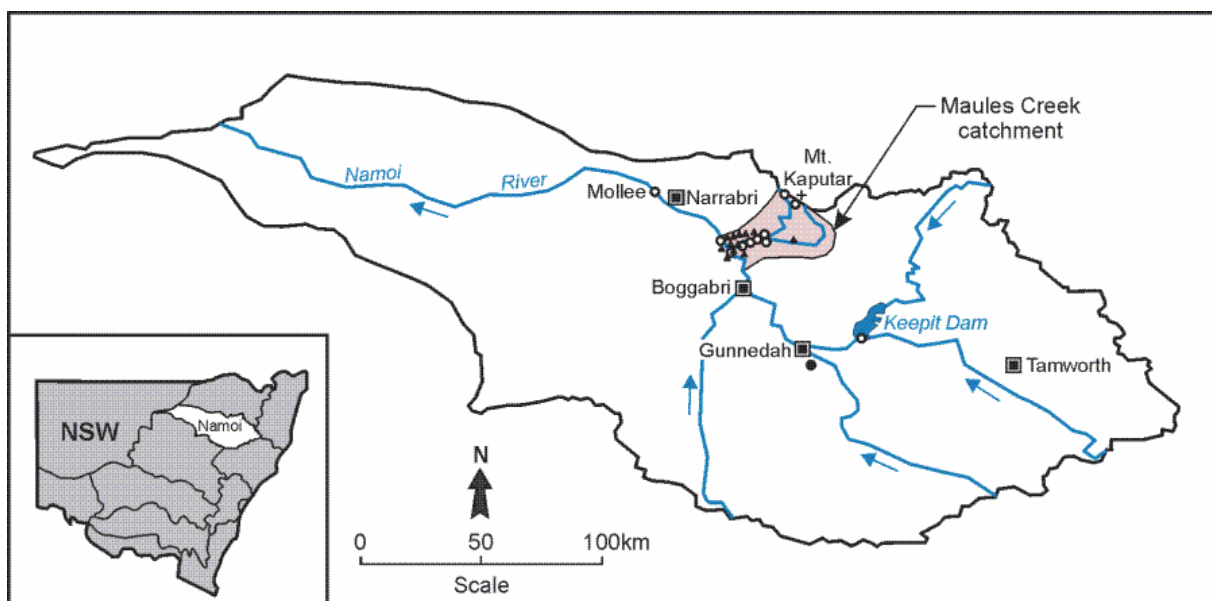


Fig. 1. The location of the Maules Creek catchment and sampling sites for rainfall (●), surface water (○) and groundwater (▲) in the Namoi catchment, NSW. The arrows refer to surface water flow direction.

1. Introduction

In arid and semi-arid regions where there is growing demand for irrigation, stock and domestic water uses, there is an increased need for science based decisions to implement sound water resource management planning. To date, this has largely been accomplished by numerical modelling of groundwater resources using a conceptual model based upon scarce available hydraulic head data (CSIRO 2007). However, it is increasingly realised that this approach may be insufficient to understand complex and dynamic hydrological processes such as recharge and surface

water/groundwater interaction. It is perhaps, particularly, insufficient for the assessment of resource sustainability.

This study demonstrates that the analysis of the stable isotopes of water (^{18}O and ^2H) can be extremely useful in providing further understanding of the hydrogeological processes occurring within a productive aquifer system and that these tools can then be used to further constrain the physical groundwater models developed for the area. Therefore, an interpretation of rainfall, surface water and groundwater samples, collected between 1998 and 2007, for the analysis of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ at various sites in the semi-arid catchment of the Namoi River, NSW, Australia (Fig. 1) is presented.

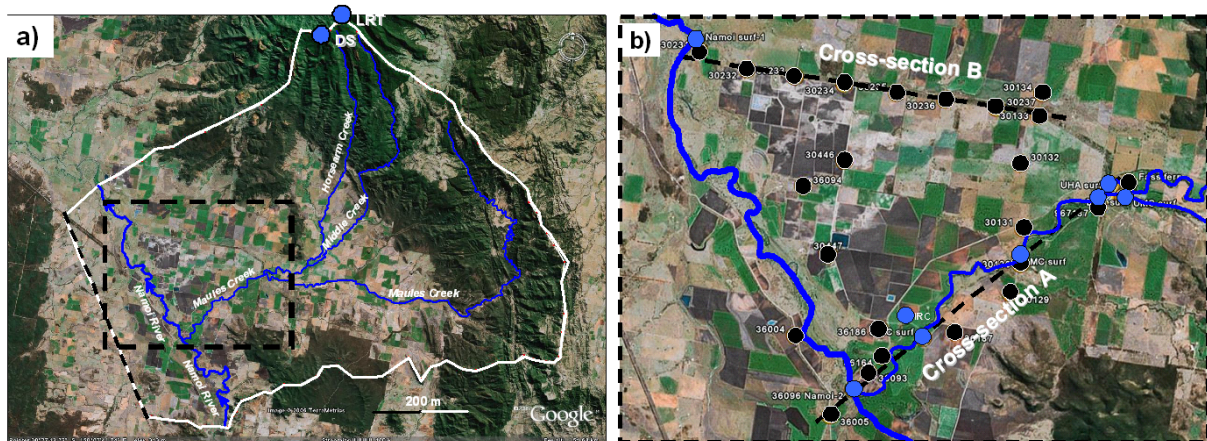


Fig. 2. a) The Maules Creek catchment showing major streams and the location of 2 surface water samples at Mt Kaputar (LRT and DS). Dashed line insert indicates the detailed field site area shown in b) with sampling sites and cross-sections. Black dots are groundwater sampling sites and blue dots are surface water sampling sites.

2. Methodology

Rainfall samples were collected near Gunnedah (Fig. 1) between March 1998 and January 2001 using a sampling system that prevented evaporative concentration of the captured rainfall sample (Timms and Acworth 2002). Surface water was sampled at several locations within the Namoi River catchment between 2002 and 2007. Surface water samples were collected from the Namoi River at: 1) Lake Keepit (a water supply dam), 2) Gunnedah, 3) between Boggabri and Narrabri and 4) Mollee Weir downstream of Narrabri (Fig. 1). In addition, surface water samples were collected between 2006 and 2007 from Maules and Horsearm creeks in the Maules Creek sub-catchment located between Boggabri and Narrabri (Fig. 1). Two surface water seeps were also collected from near the top of Mt Kaputar (1500 m) in the Nandewar Range (Fig. 2a). The two Mt Kaputar samples were collected in February 2007; one sample was taken from a surface seep on the basaltic plateau of Lindsay Rock Tops (LRT) and the other sample was taken from the collection pond at Dawson Springs (DS) downstream from a peat bog. Groundwater was sampled from 44 monitoring bores in the Maules Creek sub-catchment between August 2006 and September 2007 (Fig. 2b). The bores range in depth from 10 to 110 m bgs (below ground surface) and were purged for approximately 3 well volumes or until general parameters stabilised, prior to sample collection. All samples collected for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis were stored in 28 ml McCartney glass bottles. Samples were sent to CSIRO Land and Water in Adelaide, South Australia for analysis by Isotope Ratio Mass Spectrometry (IRMS). Reported precision was 0.15‰ for $\delta^{18}\text{O}$ and 1.0‰ for $\delta^2\text{H}$ and isotope ratios are expressed relative to Vienna Standard Mean Ocean Water (V-SMOW).

3. Results

3.1. Rainwater

The Local Meteoric Water Line (LMWL; $\delta^2\text{H} = 8.17 \cdot \delta^{18}\text{O} + 11.3$) for the area was based on 17 rain samples collected between March 1998 and January 2001 in the central part of the Namoi River catchment near Gunnedah (Fig. 1). The LMWL was calculated using individual rainfall events ranging from 3.6 to 57.6 mm. The rainfall data (Fig. 3) shows that there is a large degree of variability in results with $\delta^{18}\text{O}$ ranging from -11.4 to 1.5 ‰ and $\delta^2\text{H}$ ranging from -76.1 to 27.8 ‰. The LMWL is

parallel to, but slightly offset above the Global Meteoric Water Line (GMWL) shown in Fig. 3. The volume weighted isotopic average of the Gunnedah rain samples over the whole sampling period was calculated at $\delta^{18}\text{O} = -4.86\text{‰}$ and $\delta^2\text{H} = -24.67\text{‰}$ (see Fig. 3).

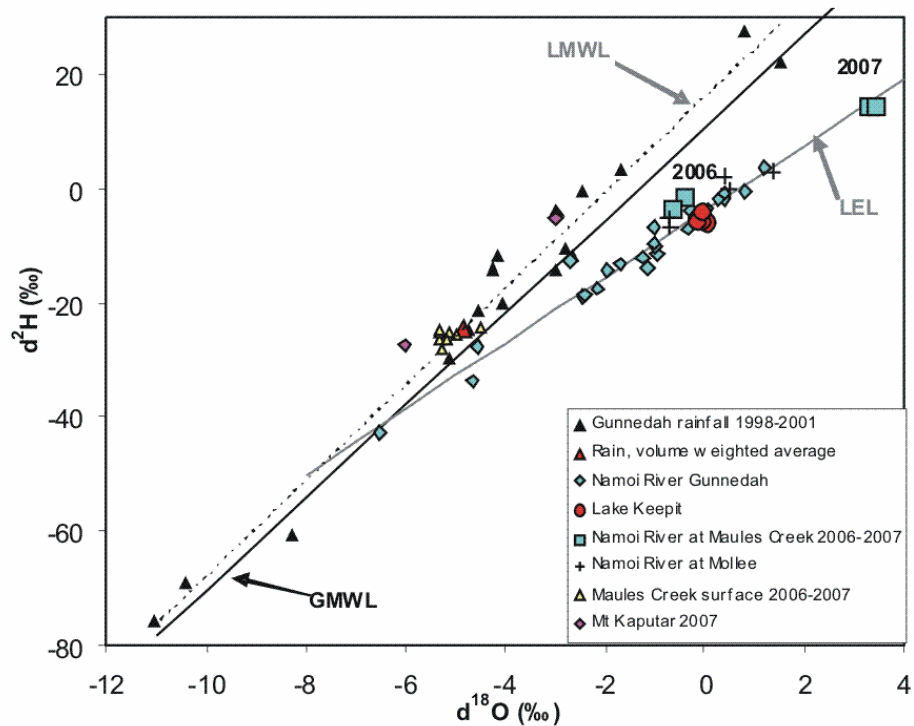


Fig. 3. Comparison of $\delta^2\text{H}$ (‰) and $\delta^{18}\text{O}$ (‰) (VSMOW) for rainfall and surface water. GMWL (Global Meteoric Water Line): $\delta^2\text{H} = 8.13 \cdot \delta^{18}\text{O} + 10.8$; LMWL (Local Meteoric Water Line): $\delta^2\text{H} = 8.17 \cdot \delta^{18}\text{O} + 11.3$ and LEL (Local Evaporation Line): $\delta^2\text{H} = 5.7 \cdot \delta^{18}\text{O} - 3.91$.

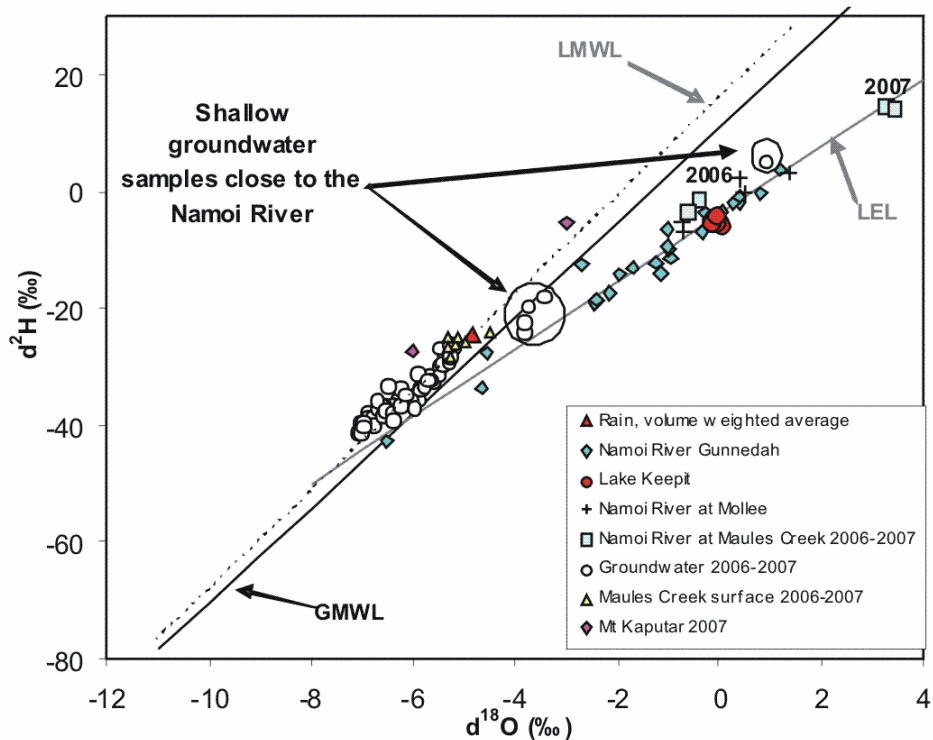


Fig. 4. Comparison of $\delta^2\text{H}$ (‰) and $\delta^{18}\text{O}$ (‰) (VSMOW) surface water and groundwater. GMWL (Global Meteoric Water Line): $\delta^2\text{H} = 8.13 \cdot \delta^{18}\text{O} + 10.8$; LMWL (Local Meteoric Water Line): $\delta^2\text{H} = 8.17 \cdot \delta^{18}\text{O} + 11.3$ and LEL (Local Evaporation Line): $\delta^2\text{H} = 5.7 \cdot \delta^{18}\text{O} - 3.91$.

3.2. Surface water

The majority of the surface water samples from various sections of the Namoi River plot below the LMWL, on a line which will be referred to as the Local Evaporation Line (LEL: $\delta^2\text{H} = 5.7 \cdot \delta^{18}\text{O} - 3.91$) for the area (Fig. 3). The LEL for this area was constructed by regression analysis of samples plotted in the $\delta^2\text{H}-\delta^{18}\text{O}$ space. Samples that plot on this line are indicative of waters that have undergone isotopic enrichment due to evaporation. A similar evaporative pattern is also seen for surface water samples in the Darling River, NSW, Australia (Meredith et al. 2007). In contrast to the Namoi River samples, the surface water samples from the tributaries of Maules and Horsearm creeks plot in a narrow cluster ($\delta^{18}\text{O}$: -5.3‰ to -4.5‰ and $\delta^2\text{H}$: -28.3‰ to -24.8‰) above the LEL, but close to the LMWL (Fig. 3). The two surface water samples from near the top of Mt Kaputar (in the Nandewar Range see Fig. 2a) plot considerably above the LMWL. The sample from the surface seep on the basaltic plateau of Lindsay Rock Tops (LRT: $\delta^{18}\text{O}$: -3.0‰ and $\delta^2\text{H}$: -5.3‰) was significantly enriched compared to the other sample which was taken from the collection pond at Dawson Springs (DS: $\delta^{18}\text{O}$: -6.0‰ and $\delta^2\text{H}$: -27.4‰) downstream from a peat bog. Both samples were collected after a prolonged dry period.

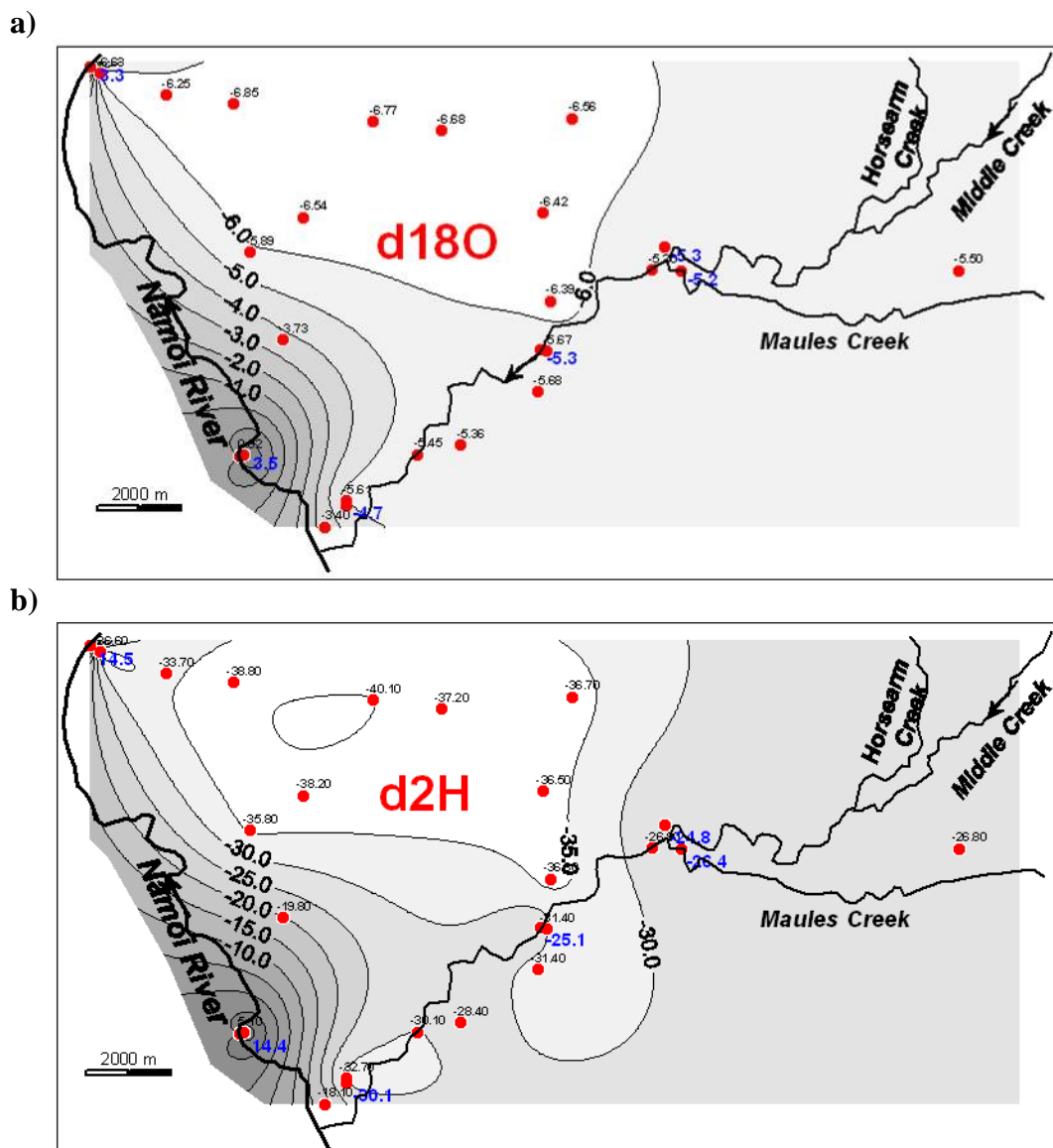


Fig. 5. Map plot of stable isotope signature in surface water and upper groundwater (< 30 m) for February 2007. a) $\delta^2\text{H}$ (‰) and b) $\delta^{18}\text{O}$ (‰). Blue numbers signify surface water samples.

3.3. Groundwater

Groundwater samples from the Maules Creek catchment (Fig. 2b) generally range from -7.1‰ to -5.2‰ for $\delta^{18}\text{O}$ and -41.5‰ to -26.6‰ for $\delta^2\text{H}$ with average values of $\delta^{18}\text{O} = -6.22\text{‰}$ and $\delta^2\text{H} = -35.31\text{‰}$ (Fig. 4). Most samples plot on or close to the LMWL (Fig. 4). However, a few groundwater samples show considerable enrichment compared to the bulk of the groundwater samples with $\delta^{18}\text{O}$ ranging between -3.8‰ and -0.9‰ and $\delta^2\text{H}$ ranging between -23.9‰ and 5.1‰ . They plot in between the LMWL and the LEL (encircled in Fig. 4). These enriched groundwater samples were sampled from shallow wells (11.5 to 22.8 mbgs.) close to the Namoi River ($< 1\text{ km}$) as illustrated by the spatial distribution of groundwater isotope ratios (Fig. 5). In addition, Figure 5 shows that the most depleted groundwater samples were collected from wells located near the Nandewar Range in the north. In the southern part and below Maules Creek, shallow groundwater samples have isotopic signatures that are higher and range from -5.7‰ to -5.2‰ for $\delta^{18}\text{O}$ and -31.4‰ to -26.9‰ for $\delta^2\text{H}$. These groundwater samples are comparable to the surface water samples from Maules Creek ($\delta^{18}\text{O}$: -5.3‰ to -4.5‰ and $\delta^2\text{H}$: -28.3‰ to -24.8‰). Figures 6 and 7 show how $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signatures vary along two cross-sections throughout the catchment (see Fig. 2b for location). The cross-sections are parallel to the overall hydraulic gradient in the aquifer as identified in Andersen and Acworth (2007a). In the cross-section along Maules Creek (Cross-section A) isotopic signatures of groundwater samples are slightly more depleted in the deeper parts of the aquifer with values ranging from -6.6‰ to -5.7‰ and -38.4‰ to -31.4‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively (Fig. 6a and b).

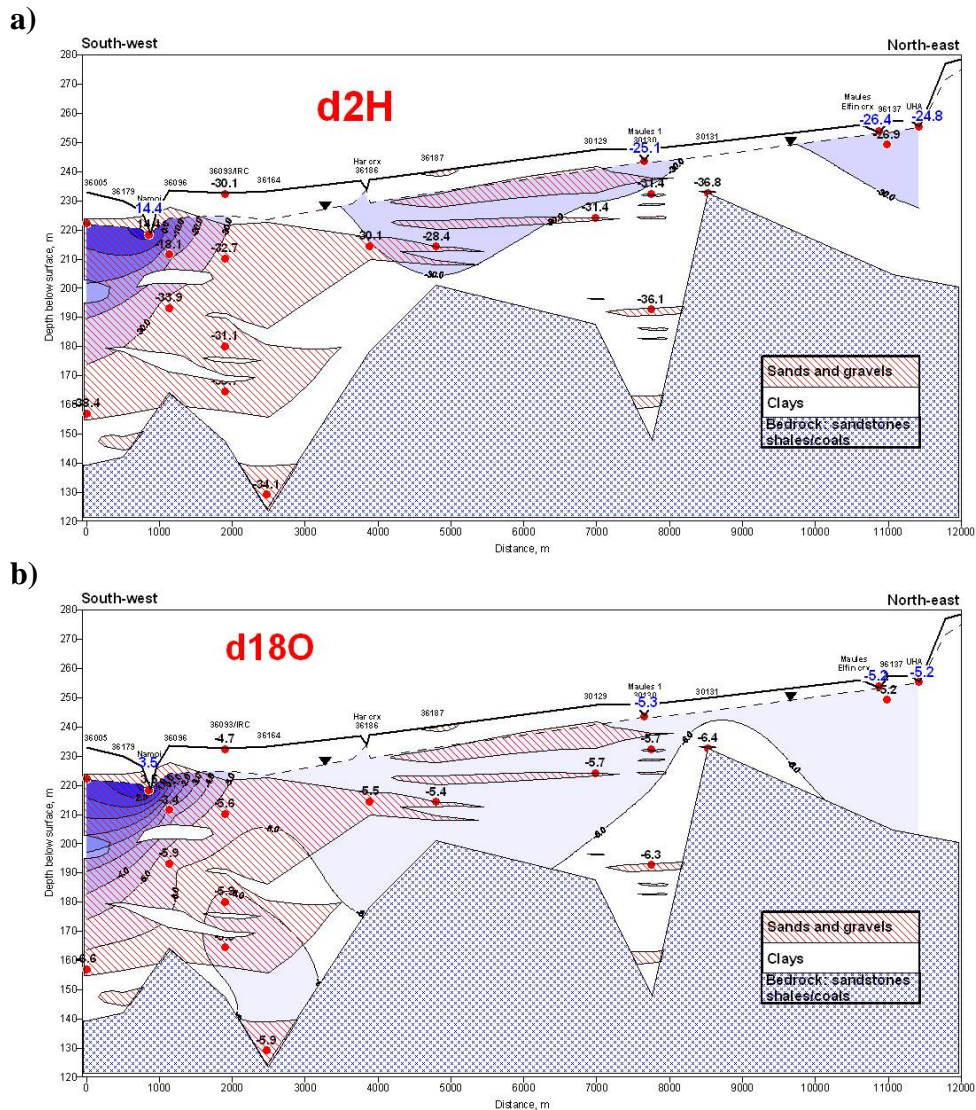


Fig. 6. Stable isotope data from February 2007 in a cross-section (A) along Maules Creek (for location see Fig. 2b) for a) $\delta^2\text{H}$ (‰) and b) $\delta^{18}\text{O}$ (‰). Blue numbers signify surface water samples.

To the north of Maules Creek in the northern cross-section (Cross-section B) groundwater isotopic signatures are more depleted than observed in the previous cross-section with $\delta^{18}\text{O}$: -6.0‰ to -7.1‰ and $\delta^2\text{H}$: -33.7‰ to -41.3‰ (Fig. 7a and b). In this part of the aquifer there also appears to be a decreasing isotopic signature with depth in the eastern and central part of Cross-section B. However, this is not the case for the deepest samples to the west near the Namoi River, where the more enriched samples are found at depth (Fig. 7).

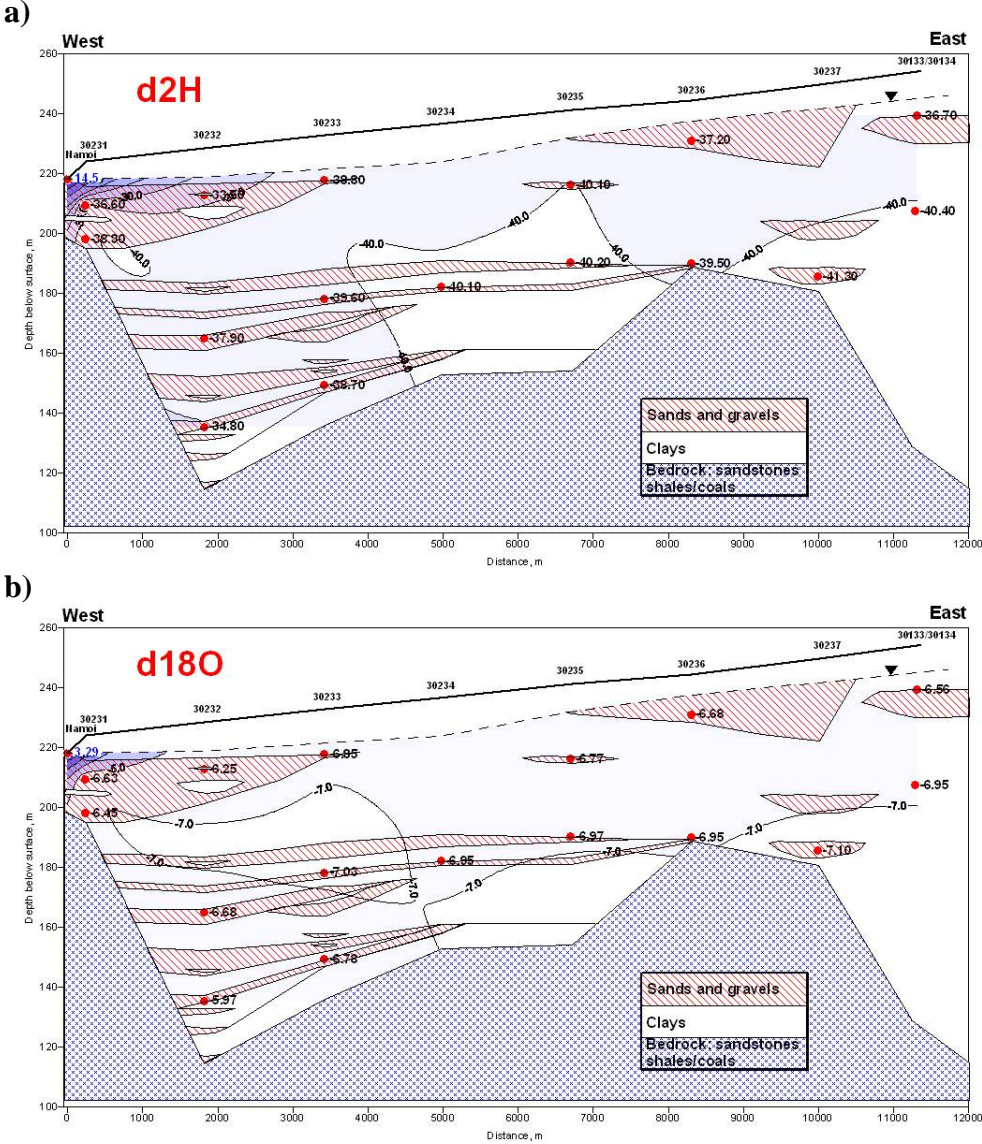


Fig. 7. Stable isotope data from February 2007 in the northern cross-section, B (for location see Fig. 2b) for a) $\delta^2\text{H}$ (‰) and b) $\delta^{18}\text{O}$ (‰). Blue numbers signify surface water samples (here of the Namoi River).

4. Discussion

Unravelling the sources of the observed isotopic signatures of the river water at this study site is complicated by the fact that there are numerous possible sources of inflow waters with different isotopic signatures (i.e. rainfall, dam release waters and groundwater base flow). In addition, surface water samples are susceptible to evaporative enrichment along the river system. The large degree of variability observed in the isotopic signatures of rain water for the area is due to the various types of rainfall events in the catchment i.e. large storm events would be likely to produce highly depleted rainfall signatures and small events would be expected to be more evaporative, particularly in this semi-arid environment. The variability in rainfall results is partly reflected in the Namoi River stable isotope signatures (Fig. 3). The surface water signatures also appear to be influenced by evaporative

enrichment as the water resides in the river channel or as storage in Lake Keepit. The large variability observed in the isotopic composition of rainwater and river water may appear to limit the use of these end-member waters for assessing aquifer recharge mechanisms. However, due to the high evaporation rates of this environment, most surface water samples from the Namoi River plot on the LEL imparting a distinct stable isotope signature. Furthermore, groundwater samples, at some distance from the river, plot in a relatively narrow cluster and have a fairly consistent signature close to the intersection of the LMWL and LEL (Fig. 4). Groundwaters that plot at the intersection of the LEL and the MWL often provide a useful empirical approximation of the weighted-mean isotopic composition of input waters to a catchment (Gibson et al. 2005). Therefore, groundwaters that plot near the intersection point of -6.5 for $\delta^{18}\text{O}$ and -43.0 for $\delta^2\text{H}$ are much more depleted than those of the amount weighted average rainfall values for the area ($\delta^{18}\text{O} = -4.86$ and $\delta^2\text{H} = -24.7$). These results indicate that the average recharge waters of this system are far more depleted than modern day rainfall recharge waters. In contrast, groundwaters sampled in close proximity to the river (<1 km distance) are much more enriched (Fig. 4). These results indicate that the proximal groundwaters have been recharged from the Namoi River, demonstrating that there is hydraulic connection between the groundwater and surface water system in this part of the study site. Thus, the isotopic enrichment of the Namoi River samples compared to the groundwater samples in the Maules Creek catchment indicate that there is a significant contrast in stable isotope signatures, enabling these stable isotope results to be used for studying surface water/groundwater interaction and in a qualitative manner to delineate river recharge to the groundwater system.

In stark contrast to the Namoi River samples, the surface water samples from Maules Creek have similar isotopic signatures to the underlying groundwater system (Fig. 4). This strongly indicates that the surface water in Maules Creek, at the time of sampling had a groundwater origin. Furthermore, the surface water in Maules Creek appears to have been subjected to very little subsequent evaporative enrichment in the creek. This is somewhat surprising considering that the surface waters sampled from Maules Creek in summer 2007 were taken more than 2 months after gauged surface water flow had ceased in the creek and they were obtained from what appeared to be stagnant pools of water. These results suggest that the pools are not stagnant and that water is flowing through the streambed sediments where evaporation is largely hindered. This was corroborated by surface water level measurements in the pools along the creek (Andersen and Acworth 2007a). Further to the west, there is a reversal in hydraulic gradient and this surface water appears to be recharging the aquifer as indicated by the slightly enriched signatures observed in the upper part of Cross-section A from 3000 to 7000 m in Fig. 6.

Closer inspection of the spatial distributions of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in the Maules Creek aquifer shows several different hydrological trends. It is interesting to note that the groundwater samples in general are significantly more depleted than the volume weighted average stable isotope composition of rainfall from the Gunnedah site (Fig. 4). Therefore, recharge processes other than rapid piston flow infiltration of rainfall is suggested. The much depleted signatures in the northern part of the aquifer (Fig. 5 and 7) could indicate either rapid infiltration of large and more depleted rainfall through the more coarse grained lithology of that region thus minimising evaporative enrichment, or perhaps the recharge waters are derived from the isotopically depleted precipitation that has fallen on the slopes of the Nandewar Range, which drains into the Maules Creek catchment from the north. According to Dangaard (1964) every 100 m rise in surface altitude causes an additional depletion in rainfall of -0.15 to -0.5‰ for $\delta^{18}\text{O}$ and -1 to -4‰ for $\delta^2\text{H}$. Taking the maximum altitude difference between the valley bottom (310 m at the Gunnedah Research station) and Mt Kaputar (1500 m) would yield additional depletion of -1.8 to -6.0‰ for $\delta^{18}\text{O}$ and -11.9 to -47.6‰ for $\delta^2\text{H}$. This altitude effect could well explain the observed depleted isotopic signatures in groundwaters, highlighting the significance of precipitation on the mountain range as a significant recharge source for the aquifer. Alternatively, it is possible that this groundwater could represent palaeo-waters recharged during cooler climates. However, the lack of consistent spatial trends (along the flow path from east to west or with depth) in Cross-section B (Fig. 7) renders this explanation unlikely, since a modern and more enriched signature should be expected in an upstream direction. Furthermore, the presence of NO_3^- , presumably derived from agriculture, at considerable depth (in some cases up to 80 m bgs.) in the aquifer indicates that at least a significant portion of the groundwater has recharged recently (Andersen & Acworth 2007b). The somewhat more enriched groundwater isotope signatures to the

south along Maules Creek either represent: a) a higher component of evaporative enrichment prior to recharge, b) recharge of isotopically less depleted rainfall at a lower altitude, or c) substantial recharge from Maules Creek. However, since the slope of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in all the groundwater data (Fig. 4) is parallel to the LMWL, it does not indicate any evaporative enrichment. The similarity in isotopic composition between groundwater and surface water in Maules Creek (Fig. 4 and 5) indicate a high degree of connectivity with discharge of groundwater into the creek in the upper reach and recharge back into the aquifer further downstream.

5. Conclusions

The results of this study show that $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of rainfall, surface waters and groundwaters provide an important tool for understanding hydrological processes such as recharge and surface water/groundwater interaction within semi-arid catchments. For the Maules Creek catchment in particular, it was found that the stable isotopes of water have two different relationships: one for Namoi River water and one for the regional groundwater of the catchment. The isotopic composition of the regional groundwater is relatively depleted and plots on the LMWL (Local Meteoric Water Line) of $\delta^2\text{H} = 8.17 \cdot \delta^{18}\text{O} + 11.3$. On the contrary, the surface water of the Namoi River generally plots to the right of the LMWL, clearly showing signs of evaporative enrichment. These surface waters plot on a LEL defined by: $\delta^2\text{H} = 5.7 \cdot \delta^{18}\text{O} - 3.91$. Shallow groundwater (< 22.8 m bgs) in the vicinity of the Namoi River (< 1 km) shows considerable isotopic enrichment compared to most groundwater samples in the region and plots in between the LMWL and the LEL. This clearly indicates the mixing of Namoi River water and regional groundwater and that, for the reach studied in this work, surface water from the Namoi River is recharging the aquifer. In contrast, the surface water collected from the tributary creeks of Maules and Horsearm do not show any noticeable effects of evaporation and plot on the LMWL with an isotopic composition similar to the groundwater situated upstream. This strongly suggests a groundwater origin for these surface waters. Groundwater discharge into the creek is further corroborated by temperature and geochemical data reported by Andersen and Acworth (2007a and b).

Spatial trends in isotopic composition were observed in the aquifer of the Maules Creek catchment with the most depleted groundwater isotopic values situated to the north, below the slopes of the Nandewar Range. The average isotopic composition of this groundwater was found to be considerably more depleted than the average composition of local modern rainfall collected in the valley. It is thus possible that the main source of recharge to the aquifer is from precipitation at higher altitude on the slopes of the Nandewar Range. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data presented in this study reveal many complex hydrological processes occurring in the catchment that have not previously been observed. The stable isotope data has proved invaluable in determining an appropriate conceptual model for the area studied. The results of this study can now be used to constrain previously constructed physical groundwater models that are commonly used for water resource management on a catchment scale.

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