Hydrol. Earth Syst. Sci. Discuss., 11, C3486–C3496, 2014
www.hydrol-earth-syst-sci-discuss.net/11/C3486/2014/

Hydrology and Earth System Sciences
Open Access
Discussions

Interactive comment on "Identifying flood recharge and inter-aquifer connectivity using multiple isotopes in subtropical Australia" *by* A. C. King et al.

A. C. King et al.

akingac@gmail.com

Received and published: 30 August 2014

The authors would like to thank Ian for his comments and observations. The paper has improved as a result of your input.

1 IAN CARTWRIGHT; REFEREE #1

Overall this is an interesting paper that is on a subject that would be of interest to the readers of HESS. As discussed in detail below, my main concerns relate to the rather general / vague descriptions of the data and the degree of justification of the interpretations. The 14C data are not interpreted well and that section needs more

work. Additionally, the study's conclusions are very specific and the authors should think about the broader implications in section 6, which would give the paper a better overall impact.

I hope that the authors find the comments useful in revising the paper.

Abstract. The abstract covers most of the material covered in the paper and does both cover the aims of the study and the major conclusions. It would be helped by putting a few key values in the text; for example the stable isotope values are important to the interpretation, but it is difficult to fully understand this without a few key values in the text. Similarly there are a fair number of qualitative terms such as "thick", "rapidly", "smaller" etc. Without quoting all your data having a few more details will give the reader a better idea of what the key evidence and details are.

Response: We have added some key values to the text, as per the reviewer's suggestion.

Change abstract to:

An understanding of hydrological processes is vital for the sustainable management of groundwater resources, especially in areas where an aquifer interacts with surface water systems or where aquifer-interconnectivity occurs. This is particularly important in areas that are subjected to frequent drought/flood cycles, such as the Cressbrook Creek catchment in southeast Queensland, Australia. In order to understand the hydrological response to flooding and to identify inter-aquifer connectivity, multiple isotopes (δ2H, δ18O,87Sr/86Sr, 3H and 14C) were used in this study in conjunction with a comprehensive hydrochemical assessment, based on data collected six months after severe flooding in 2011. The relatively depleted stable isotope signatures of the flood-generating rainfall (δ2H: -30.2 to -27.8‰ δ18O: -5.34 to -5.13 ‰ VSMOW) were evident in surface water samples (δ2H: -25.2 to -23.2‰ δ18O: -3.9 to -3.6‰ VSMOW), indicating that these extreme events were a major source of recharge to the dam in the catchment headwaters. Furthermore, stable isotopes confirmed that the flood generated significant recharge to the alluvium in the lower part of the catchment, particularly in areas where interactions between surface waters and groundwater were identified and where diffuse aquifer recharge is normally limited by a thick (approximately 10 m) and relatively impermeable unsaturated zone. However, in the upper parts of the catchment where recharge generally occurs more rapidly due to the dominance of coarse-grained sediments in the unsaturated zone, the stable isotope signature of groundwater resembles the longer-term average rainfall values (δ2H: -12.6, δ18O: -3.4‰ VSMOW), highlighting that recharge was sourced from smaller rainfall events that occurred subsequent to the flooding. Interactions between the bedrock aquifers and the alluvium were identified at several sites in the lower part of the catchment based on 87Sr/86Sr ratios; this was also supported by the hydrochemical assessment, which included the modelling of evaporation trends and saturation indices. The integrated approach used in this study facilitated the identification of hydrological processes over different spatial and temporal scales, and the method can be applied to other complex geological settings with variable climatic conditions.

Introduction. Reviewer 1: In general the introduction is a coherent to the topic and covers an appropriate amount of previous literature. The aims are well set out and also try to place the study in a global context. The description of the hydrogeology is not very detailed. There is some description of river flows and groundwater levels; however, there really needs to be some information on hydraulic properties, groundwater flow patterns and variation in the river stage. Given that this paper describes floods in a given year, a river hydrograph for that year (rather than an annualised discharge summary) would be useful.

Response: This is a good suggestion and a river hydrograph has been added to Figure 4. A groundwater hydrograph from an adjacent well has also been added to the figure (Figure 4a).

Reviewer 1: Pg. 3713, line 10. I'm not sure that this is the case. While annual recharge rates are often reported, most researchers would recognise that recharge (like pre-

cipitation, which is also often reported as an annual amount) is episodic on inter or multiannual time scales.

Response: The authors do not dispute the suggestion that most researchers understand that recharge can be episodic, only that this aspect of recharge is often overlooked (i.e. average recharge rates are often reported and applied in models). However, the third reviewer raised the same concern, so this sentence has been altered.

Change sentence to: While it is generally recognised that recharge is variable over time, the influence of episodic climatic events such as flooding are not very well understood.

Reviewer 1: Pg. 3713, line 16. Not clear what you mean by "enlarged pathway between surface-and groundwater, due to the increased width of the creek and the saturated zone beneath it". Also are you talking about disconnected ephemeral streams (which you mention at the end of the paragraph) or are you thinking about all streams.

Response: As the width of the creek increases, so does the width of the interface between the creek and the groundwater across which interaction can occur. For a disconnected stream, the interface between the groundwater and the surface water is not fully saturated. The text has been altered to account for this condition.

Change sentence to: enlarged pathway between surface-and groundwater, due to the increased width of the creek and the interface between groundwater and the creek across which interaction can occur.

Reviewer 1: Pg. 3716, line 7. Are there any estimates of transpiration rates, which I would imagine are significant at least in the forested areas?

Response: There are no estimates of transpiration rates for the forested area of the catchment. However, forested regions only compose a small proportion of the total area of the alluvium (<5% by area).

Reviewer 1: Pg, 3716, lines 20-25. Do you have any information about the peak flows from the dam during the high-rainfall period? The last part of section 2.1 is a little vague. What are the gradients, how much did the water levels recover? A few more specifics would help the reader get a picture of what exactly happened.

Response: The authors have added the peak flow rate to the text. Also, the reader will now be able to refer to Figure 4a, which shows a hydrograph of the groundwater and surface water levels in the period that encompasses the flood.

Change text to: Cressbrook Dam reached the overflow and discharged to Cressbrook Creek until 24 June 2011, with peak flows of approximately 330 m3/s. During the surface water sampling campaign (7–8 June 2011), approximately 0.5 m3/s was discharging from Cressbrook Dam (Toowoomba Regional Council, 2012) and Cressbrook Creek was flowing at approximately 0.7 m3 s-1 at CC3 (Fig. 3; DNRM, 2013), indicating that the majority of flow in Cressbrook Creek was probably derived from the dam during this period.

Reviewer 1: Section 2.2. Are there any more hydrogeological details available? For example, hydraulic conductivities would help with the assessment of recharge and the likelihood that there is significant flow from the basement into the alluvium.

Response: Unfortunately, there are no estimates of hydraulic conductivity for the bedrock.

Methods Reviewer 1: Pg. 3718, line 24. How wide are the bore screens (this is useful information as it defines how “mixed” the samples are).

Response: Bore screen information has been added to the paper.

Change text to: Alluvial boreholes are less than 20 m deep and they usually have a 3 m long screened section at the base of the alluvium,

Sections 3.1 & 3.2.

Reviewer 1: Quote your analytical precisions (major ions / CRDS missing). Section 3.2

is oddly ordered; it would make more sense to group this by analytical type rather than lab or water source.

Response: The authors think that the current order is appropriate. The analytical precision has been added where possible.

Reviewer 1: Section 3.3. This is out of place as it is not really methodology; suggest that you put it into the discussion section where you first use the modelling. Also, are your assumptions about mineral precipitation valid (dolomite commonly does not precipitate even when oversaturated – is there any indication that dolomite has precipitated in your catchment).

Response: The authors think that the methodology for the geochemical calculations is best placed in the methods section. The evaporation trends have been adjusted to exclude mineral precipitation of dolomite, as some samples were supersaturated with respect to dolomite. Fortunately, the adjustments to the figure do not affect the overall interpretation of the data.

Section 4 Reviewer 1: Section 4.1. This is difficult to follow without referring to the figures or table. Put the ranges of the values in the text and try and avoid qualitative descriptors (brackish, fresh, higher etc – be specific or define the terms if you are going to use them later).

Response: The authors have added more descriptive terminology to the text, including the range of specific conductance values for the alluvial waters and the proportion of SO4 compared to the total anions.

Change paragraph to: Surface waters are generally fresh (SC <850 μS cm-1; Table 2) with similar proportions of major cations (Na, Ca and Mg; Fig. 5). The major anions are Cl and HCO3 and the Cl/HCO3 molar ratio of water from Cressbrook Creek ranges from 0.92 to 1.35, with ratios generally increasing with with distance downstream. Alluvial groundwaters are fresh to brackish (SC 369 to 5930 μS cm-1) with no clear dominant major cations and low SO4 concentrations, with SO4/Cl molar ratio ranges from 0.001 to 0.21. The Cl/HCO3 molar ratio ranges from 2.9 to 33.9, with ratios increasing with salinity. The hydrochemistry of the bedrock groundwaters is highly variable, although the Na/Cl ratio is generally higher than in alluvial waters (Fig. 6).

Reviewer 1: Section 4.2. Again this section seems out of place as it is deals with interpretation not data description. Put this in the discussion section but more importantly you need to explain how the diagrams were plotted (either reference the source of the figures or the program that you used to plot them). There are no Al concentrations in your data, so you also need to explain how you estimated Al activities.

Response: The data is described in relation to whether the chemical composition is in equilibrium with minerals phases in the figure, but the ramifications of these observations are not discussed. Therefore, the authors are satisfied with the location of this section. With regards to the methodology used to plot the data, this is outlined in the Methods section.

The Al concentrations were collected with the other metals; this information has been added to the Methods section.

Reviewer 1: Section 4.3. Again this section would be more readable with a few key values and less qualitative descriptions.

Response: The weighted average of the rainfall at the Brisbane airport has been added to the text, so that they can be compared to the depleted flood-generating rainfalls (values are in text).

Change last paragraph to: During the 12 months prior to the June 2011 sampling campaign, rainfall stable isotope signatures were depleted compared to previous rainfall events, particularly during, and immediately prior to, the flooding in January 2011. Rainfall from December 2010 and January 2011 (316 and 424 mm respectively; BOM, 2012) was particularly depleted in δ 2H (-30.2 and -27.8, respectively) and δ18O (-5.34

and -5.13, respectively; Table 4), compared to the weighted average for rainfall, which was -3.4 and -12.7 for δ 2H and δ 18O respectively (Crosbie et al. 2012). Heavy rainfall events are often more depleted than average rainfalls (e.g. Taupin et al., 2002) . Reviewer 1: Section 4.4. I think that there are also Sr isotopes of rainfall in Ullman, W.J., Collerson, K.D., 1994. The Sr-isotope record of late Quaternary hydrologic change around Lake Frome, South Australia. Australia Journal of Earth Sciences 41, 37–45.

Response: Thank you for this information. The rainfall was collected from Woodlawoodlana, a site that is located approximately 500-600 km inland in South Australia. In contrast, the data from Raiber et al. (2009) was collected from approximately 60 to 100 km from the coast. The Cressbrook Creek catchment is located at a similar distance from the coast. The Sr isotope ratio increases with distance from the coast and this can be seen in the Sr ratio at Woodlawoodlana, which has a high strontium ratio of 0.71314. Therefore, the values from Raiber are more representative of the Cressbrook Creek catchment. Nevertheless, this reference has been added to the paper.

Add to text: In comparison, the rainfall 87Sr/86Sr ratio measured at Woodlawoolana located approximately 500-600 km inland in South Australia is 0.71314 (Ullman and Collerson, 1994).

Reviewer 1: Section 4.5. The section on 14C ages is not well written. I don't think that you can easily get δ13C values of -4 during closed-system calcite dissolution with calcite of ∼0‰ and an initial δ13C of say -19‰ (basically the water becomes oversaturated wrt calcite before you get that high); this is covered in Clark & Fritz (and elsewhere). More importantly, if you were to do it by calcite dissolution, all of your ages would be modern and some of the implied initial a14C's would be far higher than have ever been recorded.

There are examples of high δ13C calcite elsewhere in Australia (Cartwright et al., 2013. Applied Geochemistry, 32, 118-128; Cartwright I, 2010. Journal of Hydrology, 382, 174-187) which might be useful in interpreting the data. Whatever, this section needs much better discussion.

Response: The authors agree that more discussion is warranted to explain this and more detail has been added to the paper. With regards to the δ13C values, most of the crops grown in this region use the C4 carbon fixation pathway (e.g. corn and sorghum), as these plants use water more efficiently and irrigation water is often scarce. However, some drought resistant plants that use the C3 carbon fixation pathway (e.g. Lucerne) are also cultivated. This has important ramifications for this study, as explained in the changes to the text below.

Change last paragraph of the Results Section (Section 4.4) to:

The uncorrected 14C ages of the samples collected from B57, B36, B18 and B51 are 55, 345, 1025 and 1680 years BP, respectively. However, it should be noted that the 14C ages have not been corrected for interactions with carbonate minerals. Tritium analyses of the same samples (B57, B36, B18 and B51) indicate that they contain a modern component (i.e. less approximately 70 years old), with values of 1.02, 0.70, 0.50 and 0.13 TU, respectively. Add new section to the discussion – Radiocarbon groundwater residence times: The uncorrected 14C ages of the samples collected from B18 and B51 are 1025 and 1680 years BP, respectively; however, tritium analyses indicate that this groundwater has a modern component. This discrepancy between the apparent tritium ages and the 14C ages indicates that the 14C activity may have been altered by carbonate dissolution, or alternatively, that there has been mixing between an older water and a young water that contains tritium.

The Ca:Na ratio of the alluvial groundwaters ranges from 0.19 to 1.00, with an average of 0.54 and the Ca/Na ratio of the samples from B18 and B51 are 0.19 and 0.24. This indicates that significant calcite dissolution is unlikely, as groundwaters that have experienced significant calicite dissolution generally have Ca/Na ratios >1 (Mast et al., 1990; Leybourne et al., 2006).

Calcite dissolution can also be assessed using the δ13CDIC composition, which is af-

fected by interactions with organic materials and the aquifer substrate. The δ13CDIC composition of recharging groundwater is largely controlled by the composition of the decomposing plant matter. For plants that use the C3 photosynthesis, the δ13CDIC composition of the soil is usually around -23‰ whereas it is likely to be approximately -9‰ in areas with C4 plants (Clark & Fritz, 1997). The study catchment is located in a water-poor area and plant productivity is often limited by the lack of water. Therefore, landholders commonly cultivate plants that use water efficiently, such as those that use the C4 carbon fixation pathway (e.g. corn and sorghum). However, some drought resistant plants that use the C3 carbon fixation pathway (e.g. Lucerne) are also cultivated. Similarly, approximately 74% of grass species in the Cressbrook Creek region use the C4 carbon fixation pathway (Hattersley, 1983).

Assuming that approximately 60% to 90% of the 13C is derived from plants that use the C4 carbon fixation pathway, soil CO2(g) δ13CDIC values would be approximately -15‰ to -10‰.The δ13CDIC value will typically increase by around 7.9‰ as soil CO2(g) dissociates to HCO3- (at 25O C; Clark & Fritz, 1997), which will result in groundwater with δ13CDIC values between around -7‰ and -2‰.The δ13CDIC values at B18 and B51 are -4.4 and -4.9, indicating that there has probably been no significant dissolution of old calcite, and that the uncorrected 14C ages are valid. This is not unexpected, as the alluvium is composed primarily of components derived from erosion of silicate rocks, and it is unlikely to contain significant amounts of carbonate.

Change the second paragraph of the Hydraulic connectivity between bedrock and alluvium section (Section 5.3)

The sample from B90 has a stable isotope signature that indicates a substantial degree of evaporation (Fig. 8), whereas other alluvial samples assigned to Hydrochemical Facies 5 (B51 and B18) are isotopically more depleted. As previously mentioned, alluvial groundwaters assigned to Hydrochemical Facies 5 were probably subjected to significant amounts of evaporation. However, groundwater samples from sites B18 and B51 (Fig. 3) have a relatively depleted stable isotope signature considering their high Cl concentrations (Fig. 8), which suggests that these sites may have received seepage from depleted bedrock groundwater. Furthermore, the groundwater sample from B18 has a radiogenic 87Sr/86Sr signature similar to groundwater sampled from the granodiorite, which forms the bedrock at this site, and sample B51 has a low 87Sr/86Sr ratio similar to the Esk Formation samples (Fig. 9a). Also, the 14C groundwater ages of samples from B18 and B51 are greater than 1,000 years BP, but there is detectable tritium in these samples, indicating that the water is less than approximately 100 years old. This descrepancy is consistant with mixing of old bedrock groundwater with younger alluvial groundwater.

Section 5 Section 5.1 Reviewer 1: General comment. While I agree with most of the interpretation, the justification is not very good. Try to be more specific as to why the data lead to the conclusions that you make and try to integrate the major ions and isotopic data better.

Response: The authors believe that this concern has been ameliorated as a result of the discussion above. Thank you for the useful comments

---

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 3711, 2014.