

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

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Thank you Referee #3 for your constructive comments and suggestions. The paper has benefited from your input.

1 ANONYMOUS; REFEREE #3

The paper uses a multi tracer approach to assess the importance of flood recharge to the alluvial groundwater, the recharge processes, and the influence of recharge by bedrock groundwater. The paper is of clear interest for the readers of HESS, and the multi tracer approach and the generated data set is really interesting and valuable.

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Nevertheless, the manuscript needs some additional work before I can recommend it for publication in HESS. My biggest concern is the structure and content of the discussion section, and in parts of the result section. Both sections are, in my opinion difficult to read and the argumentation and the story line hard to follow. To me reading these section feels a little bit like the reader should figure out the story line and filter important things on her/his own. I do think the authors need to do a better job in leading the reader through this huge amount of data, filtering the important points and leading the story based on the outlined research questions. Right now I don't see how the research questions have guided the results and discussion sections, but this is crucial for readability. A second limitation of the discussion is the pure focus on the current case study and only very limited discussion in the frame of general research about stream-alluvial aquifer-recharge topics in ephemeral or intermittent stream systems.

How are processes similar, how is the work going beyond previous work, etc. Lot of work was done in different environments like Israel and Southern Africa (Lange, 2005, JoH; Dahan et al., 2008, Groundwater; Klaus et al., 2008, JoH; Morin et al., 2009, JoH; and more to find with a quick search) that focussed on the importance of transmission losses and also included the role of diffusive recharge by bedrock groundwater to the alluvial aquifer. Also I would recommend the recent paper of Baudron et al (2014 HP), that also employed a multi-tracer approach (^{14}C , ^{13}C , ^2H , ^{18}O , ^3H) to determine aquifer recharge in semiarid southern Spain. Further I was wondering how the different tracers add understanding to the recharge processes. Would we achieve the same results if not using ^{14}C or tritium? Further, some quantitative work would add clear value to the current manuscript, e.g. presenting GW levels, perform mixing calculates, etc. What could be interesting would be longitudinal chemistry/isotope profiles in the alluvium? This might allow a better way to visualize the results

Detailed comments: Reviewer 3: 3713 L6-9: Please reformulate

Response: This sentence has been rewritten.

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Change to: Sustainable management of these alluvial aquifers is critical, but to enable this, a good understanding of recharge processes is required, together with an appreciation of the different groundwater sources and the spatial variability of this recharge (Hrachowitz et al., 2011; Dogramaci et al., 2012).

Reviewer 3: 3713 L10: I don't think that in regions with strong seasonality the recharge as being constant in time.

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 reported). However, the first 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 events such as flooding is not very well understood.

Reviewer 3: 3714 L12: Reading the intro to this point I was not completely convinced that these are the pressing research questions that we need to tackle. Please try to be more convincing.

Response: The last two paragraphs of the introduction have been rewritten. An extra reference was added to the penultimate paragraph (Baudron et al., 2014), as per the referee's introductory comment, and the significance of the paper has been more clearly highlighted.

Change the last two paragraphs of the introduction to:

The objective of this study is to demonstrate how multiple environmental isotopes ($\delta^2\text{H}$, $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$, ^3H and ^{14}C) in combination with a comprehensive hydrochemical assessment can be applied to: (1) assess the significance of floods as a major recharge source; (2) identify recharge processes and connectivity between surface water and groundwater; and (3) identify areas where the alluvium is recharged by the underlying

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highly diverse bedrock (inter-aquifer connectivity). Multiple isotopes are increasingly being used to identify inter-aquifer connectivity (e.g. Dogramaci and Herczeg, 2002; Raiber et al., 2009; Cartwright et al., 2010a, 2012; Costelloe et al., 2012;; Baudron et al., 2014); nevertheless, studies of this kind are still challenging due to the complexity of the hydrochemical interactions that result from inter-aquifer groundwater flows.

Many studies have used surface- and groundwater compositions (i.e. isotopes, and major and minor ions) to report on the connection between streams and alluvial groundwater (e.g. Soulsby, 2007; Barrett et al., 1999; Kirchner et al., 2010; Mandal et al., 2011; Morgenstern et al., 2010; Siwek et al., 2011; Négrel and Petelet-Giraud, 2005). However, studies that use isotopes and hydrochemistry to assess the connectivity between alluvial aquifers and intermittent or ephemeral streams (e.g. Kumar et al., 2009; Vanderzalm et al., 2011), or report specifically on the effects of episodic groundwater recharge from flooding (e.g. Cartwright et al., 2010b; Cendón et al., 2010; Simpson et al., 2013) are less common. This study uses groundwater stable isotopes together with a detailed assessment of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in rainfall to assess episodic recharge. Rainfall isotope time-series data are commonly used to assess long-term trends in groundwater recharge (e.g. Zhu, et al. 2007, Praamsma et al. 2009); however, they are rarely applied to assess event recharge of shallow aquifers (e.g. Scholl et al. 2004; Gleeson et al. 2009). The value of considering time-series data of rainfall stable isotopes in hydrogeological investigations is clearly demonstrated by this study, and the outcomes will be important for the management of the alluvial groundwater resources of the study area and for understanding flood-related processes in similar alluvial settings.

Reviewer 3: 3714L 26ff. See citations above, and many more work that focussed a lot on transmission losses and related recharge of alluvial aquifers in ephemeral streams. Although in usually drier environments.

Response: The authors added one of the references that the referee suggested (Baudron et al. 2014). However, the other references focus on the use of hydrographs

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to assess transmission losses. The authors did not intend on drawing attention to all studies that focus on surface water-groundwater interactions in the last paragraph of the introduction. No doubt there is a very large body of work relating to this subject. We were focussing on those studies that use isotopes and hydrochemistry to assess these interactions. This has been made more apparent in the revised introduction (see above).

Reviewer 3: 3715L3-4: Is there a chance that this work can be relevant beyond the specific catchment? I think there is, but that needs to be outlined by the authors.

Response: This paragraph has been revised to highlight the broader relevance of our research (see above).

Reviewer 3: P3716L6: "infiltration" I am not sure about the way the authors use the term. Do they mean actually the infiltration of water into the soil, or more percolation and potential recharge to the underlying aquifer. Because infiltration itself is a very fast process, while recharge and percolation can then be influenced by ETP from the soil.

Response: The authors have replaced infiltration with recharge.

Reviewer 3: P3717L16: Terms as "generally low" can be found throughout the manuscript (e.g. fresh), and I think that this is very subjective. I think the authors should avoid such terms.

Response: Referee #1 raised this same concern. The paper has been adjusted to remove the subjectivity of these ambiguous terms.

Reviewer 3: P3721ff. Please lead the reader and present what you regard as important information and how they connect. What is important and what is not? Possible to add some groundwater well data?

Response: The authors have added a hydrograph encompassing the flood period. The hydrograph now includes measurements from the creek and an adjacent well.

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Reviewer 3: P3721L20-3722L13: What is the slope of the evaporation line?

Response: The authors calculated the slope of the evaporation lines and added this to the figure (the data points used in this calculation are highlighted) and the text.

Change text to:

The slope of the groundwater evaporation line is approximately 3.2.

Reviewer 3: P3721L20-3722L13: If you do a regression based on the sample points do they intersect with the MWL at the point of rainfall?

Response: We performed a slope analysis of the groundwater samples that plot in between the evaporative trend lines initiating from the depleted rainfall. This information has been included in the figure.

Additional information added to Fig 8a:

$y = 3.1X - 12.2$; $R^2 = 0.81$ (the data points used in this calculation are highlighted in the figure) . Reviewer 3: P3722L15ff. What is the uncertainty introduced in your interpretation by the missing of local input data?

Response: The range that is presented is indicative of the range that would be expected at a site that is approximately 70 km from the sea. Also, the concentration of sea water is also presented, and this represents the lower value that would be expected in rainfall near the ocean. Furthermore, if the actual strontium concentration of rainfall was greater than the range presented here, it would not affect the interpretation of the data.

Change to:

Strontium isotope ratios of surface and groundwaters in the Cressbrook Creek catchment range from 0.7042 to 0.7119 (Fig. 9), although most samples are within a narrower range of 0.7051 to 0.7078. No measurements of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of rainwater were conducted for the study area, and as a consequence, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

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of rainfall used in this study (Fig. 9a) are based on data from elsewhere in Australia. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of rainfall are typically similar to modern seawater (0.7092; Dia et al., 1992) near the coast, but they become progressively more radiogenic inland due to the addition of atmospheric dust. Strontium isotope measurements of rainfall from Hamilton, Casterton and Willaura in Victoria (south-eastern Australia), which are located approximately 60, 70 and 100 km from the coast respectively, were 0.7094, 0.7097 and 0.7107 (Raiber et al., 2009). In comparison, the rainfall $^{87}\text{Sr}/^{86}\text{Sr}$ ratio measured at Woodlawoolana located approximately 500-600 km inland in South Australia is 0.71314 (Ullman and Collerson, 1994). The Cressbrook Creek catchment is approximately 70 km from the eastern coast of Australia (Fig. 1). Assuming a similar increase of the strontium isotope ratios of rainfall with increasing distance from the coast, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Cressbrook Creek catchment may be in a similar range to those reported by Raiber et al. (2009), although it is acknowledged that local factors and temporal variability can have a substantial influence. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of rainfall at Cressbrook Creek should not be significantly different to the range presented in Fig 9a, and any local variations would not affect the hydrological interpretation.

P3723L4: I do think the authors could try to give the mean residence times tritium and C^{14} based.

Response: Modelling of the radiocarbon groundwater ages is generally subjected to large uncertainties and is beyond the scope of this paper and the authors consider the qualitative assessment is suitable given the context of this paper. Furthermore, a recent paper by Suckow (2014) questions the value of performing such calculations based on single measurements. Also, it is difficult to model the mean groundwater age based on the tritium analyses, as there are two different recharge processes: i.e., groundwater is recharged via both direct (diffuse) recharge and channel leakage. Therefore, a simple approach to modelling the groundwater age would not be representative of the actual conditions. A more detailed investigation would be required and this is beyond the

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scope of this paper.

P3724L9: How were the facies determined? By eye, cluster analysis?

Response: The clusters were determined according to the major ion proportions, based upon visual inspection of the Piper diagram. This information has been added to the paper.

Change to:

Surface and groundwaters in the upper part of the catchment are generally fresh, with SC values of $<700 \mu\text{S}/\text{cm}$ (Table 2; Fig. 3), whereas salinities are moderately higher in the lower catchment. Five hydrochemical facies have been identified based on a visual analysis of major ions proportions (Fig. 5). Hydrochemical Facies 1 to 3 contain fresh water samples ($\text{SC} < 1150 \mu\text{S}/\text{cm}$; Table 5) and samples assigned to these facies have similar concentrations of Ca, Mg and Na (no dominant cation), and low SO_4 concentrations (2.5 to 62.9 mg/L); therefore, these three groups are mainly distinguished by the relative proportions of Cl to HCO_3 . Hydrochemical Facies 1 is mostly composed of fresh bedrock groundwater samples, but interestingly, it also includes one surface water sample (OCK). This group is characterised by HCO_3 -dominated waters with molar $\text{HCO}_3:\text{Cl}$ ratios of ≤ 5 . Si concentrations are relatively high (median SiO_2 concentration of 43 mg/L) and low nitrate concentrations (median NO_3 concentration of 0.15 mg/L; Table 5). Hydrochemical Facies 2 and 3 are composed of fresh water samples with slightly higher Cl concentrations than samples assigned to Hydrochemical Facies 1 (49 to 297 mg/L). Hydrochemical Facies 4 and 5 both contain brackish groundwaters (SC ranges from 1145 to 13,750 $\mu\text{S}/\text{cm}$) with Cl as the dominant anion, but the samples in Hydrochemical Facies 5 have a median NO_3 concentration of 4.0 mg/L, compared to those in Facies 4 which have a median NO_3 concentration of just 0.19 mg/L (Figs. 5 and 6 and Table 5).

P3726L4-8. These lines are painful to read. Please try to avoid such long nested sentences; more concise.

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Response: The authors have followed the suggestions of the referee and have modified these sentences.

Change to:

Evaporation processes are evident from stable isotopes measurements, which show that most samples collected during this study are displaced significantly to the right of the Brisbane and Toowoomba MWL (Fig. 8a).

P3727L19ff. What is the amount of dam release water in the hydrograph event? Can the slope of the evaporation line be a relic from the enriched lake water?

Response: The dam was at 7.5% of total capacity prior to the flood, so the majority of the water flowing from the dam to the creek was from recent rainfalls. Also, the depleted $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values indicate that the surface water and groundwater is largely sourced from the heavy rainfalls that occurred at the time of the flood.

P3728L4ff. The language and style of these lines should be improved. Often confusing.

Response: The authors have replaced diffuse infiltration of rainfall with direct recharge.

P3731-3732: How does this study go beyond the status quo? What is new? Please present that in the conclusions. There is a lot of potential here.

Response: The study highlights processes that are analogous to other settings where the upper layers of the alluvium contain relatively low permeability sediments. The most important point in this regard is that direct recharge does not generate significant recharge in the lower parts of the catchment, and that recharge predominately occurs during and after large rainfall events and/or flooding. However, in areas where the alluvium is coarse grained, recharge is likely to occur during more moderate rainfall events. The conclusions have been reworded to further highlight this conclusion (see below).

P3731L22-24: No need the repeat research questions. But please give the answer to

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the research questions clearly and concise in the conclusions.

Response: The conclusion is often read in isolation, and, where this is the case, the reader will benefit from a concise summary of the objectives. However, the conclusions have been re-written to make this summary more concise.

Change Conclusions to:

This study outlines the benefits of the simultaneous application of multiple environmental isotopes (^2H , ^{18}O , $^{87}\text{Sr}/^{86}\text{Sr}$, ^3H and ^{14}C) in rainfall, groundwater and surface water in combination with a comprehensive hydrochemical assessment. The aim was to study the influence of a flood on groundwater recharge and to assess the hydrological connectivity of an alluvial aquifer system with associated streams and underlying highly diverse bedrock aquifers.

Groundwater evolution is largely controlled by silicate dissolution and evapotranspiration processes, as demonstrated by the silicate stability diagrams, theoretical evaporation curves and saturation indices. In the Upper Catchment, rainfall is quickly recharged through relatively coarse-grained alluvial sediments. Conversely, rainwater infiltrates more slowly in the Mid and Lower Catchment, particularly in the flood-plain distal to Cressbrook Creek, as indicated by the lower tritium and ^{14}C values and the elevated salinity. In contrast, surface water leakage to the alluvial aquifer is an important mechanism for maintaining groundwater quality and for the generation of recharge in the lower part of the catchment.

The flood-generating rainfall in 2011 was isotopically more depleted ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) than the long-term weighted average, and groundwater from the lower part of the catchment plots along an evaporative trend line that intersects the meteoric water line near this depleted, flood-generating rainfall of December 2010 and January 2011. This confirmed that the flood events of January 2011 generated significant recharge, whereas infiltrating water from smaller rainfall events is subject to evapotranspiration, especially in the lower part of the catchment where the unsaturated zone is relatively thick and

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the permeability is low. Recharge from episodic flooding is probably important in other similar settings where low permeability sediments are incised by stream channels. Groundwater in the Upper Catchment follows an evaporative trend initiated from rainfall that is intermediate to the long-term weighted average rainfall and the “flood rainfall”. The floods of 2011 also generated significant recharge in this part of the catchment. However, as the evaporative trend is initiated from a more enriched rainfall signature (i.e. closer to the long-term weighted average), it appears likely that smaller rainfall events also generate groundwater recharge here, probably due to the more permeable and thinner soil material in this part of the catchment. The study clearly demonstrated the value of time-series rainfall stable isotope data for the identification of hydrological processes such as aquifer recharge and the generation of baseflow resulting from flooding.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were used to identify bedrock seepage to the alluvium at several locations. This conclusion was supported by the ^3H and ^{14}C data, which show that the alluvium contains a mixture of older, bedrock derived groundwater and more recently recharged groundwater. The connectivity between the alluvium and the bedrock is likely to be spatially and temporally variable.

The complementary use of multiple isotopes and hydrochemistry of rainfall, groundwater and surface water enabled an effective assessment of hydrological processes throughout the catchment, including recharge of the alluvial deposits from surface water flows and variable bedrock aquifers, recharge specifically from flood events and an understanding of isotopic and hydrochemical parameters in the context of variable climatic conditions.

P3732L9: How is infiltration linked to travel time of groundwater? StorageCapacity/Recharge=Residence time? The infiltration should be again replaced by recharge. Bc only the amount of water that arrives in the alluvial groundwater body would play a role. Not every water that in the surface recharges to groundwater.

C3510

Response: Infiltration has been replaced by direct recharge.

L16: What about mixing? Was groundwater body mainly “dry” before the event, what is the approx. ratio between water stored in the GW and water recharged by the event? Response: A hydrograph has been added to the ‘Hydrogeological setting’ section to demonstrate this. Also, a paragraph has been added to Section 5.2.3 highlighting that heavy rainfalls are often depleted in $\delta^2\text{H}$ and $\delta^{18}\text{O}$, using the example of a flood that occurred in 1974, which also had very depleted rainfall ($\delta^2\text{H}$, -64.2‰ and $\delta^{18}\text{O}$, -9.5‰).

Change first paragraph of the Mid to Lower Catchment section (Section 5.2.3) to:

Most groundwaters from the lower part of the catchment also follow the evaporative trend that intersects the meteoric water line near the flood-generating rainfall of December 2010 and January 2011, indicating that groundwater was recharged rapidly by channel leakage and/or that the flood generated substantially more recharge than other smaller rainfall events. Heavy rainfall events often have depleted stable isotope signatures. This is demonstrated by the depleted signatures of rainfall during the 2011 flood, and during other flood events. For example, the most devastating flood to affect southeast Queensland occurred in 1974, and the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of rainfall during this event were -64.2‰ and -9.5‰ respectively (IAEA/WMO, 2014).

References Good overview of literature, but rather than outlining the work on stream-gw interactions in perennial streams, authors should look more into the papers that dealt with the interaction and recharge in dryland environments, since that seems to fit more from the processes to this work. I gave some examples, but lots of work done all over the world.

Response: There is a large body of work that relates to surface water and groundwater interactions; however, the authors have chosen to include studies that use hydrochemistry and isotopes to assess these interactions, as the value of the study is largely related to the novel use of isotopes to assess these interactions.

C3511

Tables If the authors introduce the separation of the catchments in sub catchments, this labelling should be included in tables. Figures Fig.3, it is difficult to find and read sampling points. Maybe leaving out geology (or its color) since it is already presented in fig2? Or any other way that makes this figure more user friendly. Figure 8b. This figure is rarely explained in the manuscript (i.e. how you infer your interpretation on it). I also wonder how the cluster were determined? Thanks for the read, it is a great data set you compiled there.

Response: The authors have included the sub-catchments in Table 2 and 3. The clusters were determined by assessing the major ion proportions, as displayed in the Piper diagram in Figure 5; this has been clarified in the text, as outlined above.

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