Authors’ responses to reviews for hess-2014-444

Groundwater surface mapping informs sources of catchment baseflow

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We thank Anonymous Referees #1 and #2 and Professor Ian Cartwright for their considered and insightful reviews of our paper. Their helpful comments and suggestions have been addressed below with responses to each individual comment. The page number and line number of changes made in the revised manuscript are provided for each comment.

Professor Ian Cartwright

The main comment that I have is regarding the bores used for the water-table mapping. Being familiar with the area, there are numerous groundwater bores constructed for the reasons outlined in the paper. However there are two to three sets in the Gellibrand Valley. Many of the bores are shallow and probably located in the near-surface alluvial aquifers that interact directly with the rivers. However, there are numerous bores in the underlying confined Eastern View Formation. The head levels in these two aquifers can be very different (generally there are large upwards gradients between the Eastern View and the alluvials and many of the deeper bores). Given the large number of bores in the area it is difficult to see exactly which ones have been used for data analysis but presumably they are all in aquifers that can be reasonably expected to be hydraulically connected such that a potentiometric surface can be constructed. There needs to be more detail of which bores were used for this analysis.

Authors' response

We have separated all bores from the original dataset of 88 bores in and around the catchment into those with screened depths <40 m. The subset of shallow screened bores is considered to represent the unconfined water table while the total dataset of bores represents more of a potentiometric surface of the regional groundwater (typically in the Eastern View Formation). The groundwater surfaces were mapped using both sets of bores and the results are presented for both sets. The use of the smaller subset also addresses the question raised by Referee #1 about how sensitive the groundwater surface mapping is to a smaller set of bores being used. We have also added additional supplementary material (Supplement B) detailing the bores used in the study. The derivation of the two sets of groundwater surfaces are described in the Methods (Section 2.2, see below) and incorporated into the analysis and results (e.g. Figs. 6, 7). The results and discussion have been described in our response to the first comment of Referee #1

Section 2.2 (Methods), P7, L2-13.

"Eighty-eight groundwater monitoring bores in and around the boundary of the Gellibrand catchment were identified and water level data were extracted from the Victorian Groundwater Management System (http://www.vvg.org.au/cb_pages/gms.php). The area contains a relatively large number of monitoring bores due to earlier investigations for a potential damming of the Gellibrand River and also extraction of groundwater for urban water supply (SKM, 2012). Groundwater surfaces were constructed from the total dataset and also from a subset of 33 bores with screened depths of <40 m that only occur within the catchment boundary (bore details in Supplement B). The total dataset contains bores that are screened at greater depths in the Wangerrip Group (main aquifer) and these typically show higher heads relative to nearby bores screened at shallower depths (typically in the Quaternary alluvium). Groundwater surfaces from the total dataset represent more of a potentiometric surface while the smaller dataset of shallow bores represents a water table surface."

Introduction

1. I’m not sure exactly what you mean by “unconfined” – I presume that you mean an aquifer that is intercepted by the stream rather than one which unconfined throughout the catchment.

Authors’ response

We have refined our definition of unconfined groundwater to that suggested by Professor Cartwright.

Section 1 (Introduction), P2, L21-25.

“The separation of baseflow contributions from regional groundwater (i.e. where aquifers are unconfined in the vicinity of streams) from other shallower sources, like interflow, bank storage return and perched aquifer discharge, is technically difficult to quantify. Nevertheless, this is fundamentally important for quantifying how regional groundwater extraction may affect baseflow in rivers (Wittenberg, 1999).”

2. Given that you use both tracers and physical parameters, it is worth mentioning that these techniques often yield disparate results as they classify water differently. Specifically, as transient stores of water (eg bank return flows) are likely to be chemically similar to the river, then a chemical mass balance will record them as event water while a digital filter will record them as part of the slow flow. The last paragraph on page 12407 views baseflow from the physical perspective, from a geochemical perspective baseflow is all water that looks chemically different from rainfall.

Authors’ response

In the definition of baseflow we have noted that this is from a physical perspective and also identified that tracer methods can deliver different results to physically based methods.

Section 1 (Introduction), P2, L29-30.

“From a physical perspective, the baseflow component of streamflow is the sum of the slow flow pathways into the river (Ward and Robinson, 2000).”

Section 1 (Introduction), P4, L3-10.

“ Tracer data are also commonly used to estimate groundwater discharge to streams (Cook et al., 2003; McGlynn and McDonnell, 2003; Cartwright et al., 2011; Atkinson et al., 2015). The tracer approach relies on the assumption that different contributors to streamflow have distinctive and invariant chemical, isotopic or radiogenic end-member signatures that can be apportioned in the streamflow mixture (McCallum et al., 2010). From a geochemical perspective, mass balance estimates of baseflow using tracer data can differ from estimates made by digital recursive filters as some slow flow components (e.g. bank storage) can be geochemically similar to quick flow components (Cartwright et al., 2014)."

Methodology

This is generally clearly explained; however seen the comment above regarding the choice of bores and the aquifers that they monitor. Also as discussed below, I think that your BFI value needs more justification.

Authors' response

These two points have been addressed separately. The choice of bores is addressed in the response to the general comment and the BFI value is addressed in the comments about Results.

Results

1. The BFI used in the Eckhardt filter seems anomalously low. As explained in section 3.1, values closer to 0.8 are expected for this type of catchment. Although you note this, do you have an explanation? Adopting a BFI which minimises overestimates of baseflow wrt total stream flow sounds logical, but are there other studies that you can point to which have done this to lend some support for this methodology. I guess the related question is what the results would be if a higher BFI were adopted?

Authors' response

The Eckhardt filter is generally applied using the constraint that estimated baseflow ≤ total streamflow for each time-step. This is an arbitrary constraint and was not applied in the formulation of the filter (Eckhardt, 2005). We have taken the approach of investigating use of the filter without this constraint (except in the comparison of baseflow to other estimates of groundwater discharge in Fig. 9) and using $\mathrm{BFI}_{\max}$ values derived from our own analysis and from the literature (Eckhardt, 2005; Atkinson et al., 2015). We have followed the recommendation of Professor Cartwright to investigate the effects of higher estimates of

BFI_{max} in our analysis. Therefore, we have included in the analysis two additional baseflow time-series using the Eckhardt (2005) recommendation of 0.8 for the BFI_{max} parameter and also using the maximum BFI estimate of 0.6 identified using tracer analysis by Atkinson et al. (2015) as the BFI_{max} value. The resulting differences in the estimated baseflow analysis using the Eckhardt filter are shown in Figure 2 and also explained in the text in Section 2.3, 3.1, 3.4 (Fig. 6 – see response to comment 3 of Referee #1) and 4.1 (Fig. 9 – see response to comment 4 of Referee #1).

Section 2.3 (Methods), P9, L4-9.

"The BFI_{max} parameter (representing the maximum value of the baseflow index, i.e. baseflow/total streamflow, that can be modelled by the filter algorithm) was chosen to minimize periods of baseflow greater than observed streamflow. The filter is typically applied with the condition that $b_k \leq Q_k$ (Eckhardt, 2005) but this is an arbitrary constraint and we explore the resulting baseflow time-series without this condition, except where stated."

Section 3.1 (Results), P10, L21-31, P11, L1-7.

" The Eckhardt baseflow estimates produce patterns that follow the highly seasonal pattern shown by the overall river discharge and indicated that baseflow significantly contributed to overall streamflow (Fig. 2). The a parameter values declined moderately as the threshold flow percentile value to define recession periods increased (30^{th} – 0.990, 40^{th} – 0.988, 50^{th} – 0.985). The BFI_{max} parameter values that minimized periods of baseflow greater than streamflow clustered around 0.2 but showed slight increases as a decreased (30^{th} – 0.20, 40^{th} – 0.20, 50^{th} – 0.22). The resulting baseflow time-series using these parameter values were similar and the time-series using a=0.988 and BFI_{max}=0.20 is shown in Fig. 2. This method used for determining the BFI_{max} parameter produced values below the recommended range (~0.8 for perennial rivers with porous aquifers, Eckhardt, 2005) and lie closest to the recommended BFI_{max} value (0.25) for perennial rivers with hard rock aquifers. In Fig. 2 we also show baseflow time-series using a=0.988 and the recommended BFI_{max} value for a river such as the Gellibrand (0.80), and also using the maximum baseflow index value (0.60) found for the Gellibrand River using tracer-based analysis by Atkinson et al. (2015). Using the condition of $b_k \leq Q_k$, the filtered baseflow time-series produced mean monthly BFI estimates of 0.48-0.55 (BFI_{max}=0.20-0.22) and 0.63-0.58 (BFI_{max}=0.60-0.80) during the summer-autumn period (December – May), and 0.21-0.24 (BFI_{max}=0.20-0.22) and 0.47-0.58 (BFI_{max}=0.60-0.80) during the winter-spring period (June – November)"

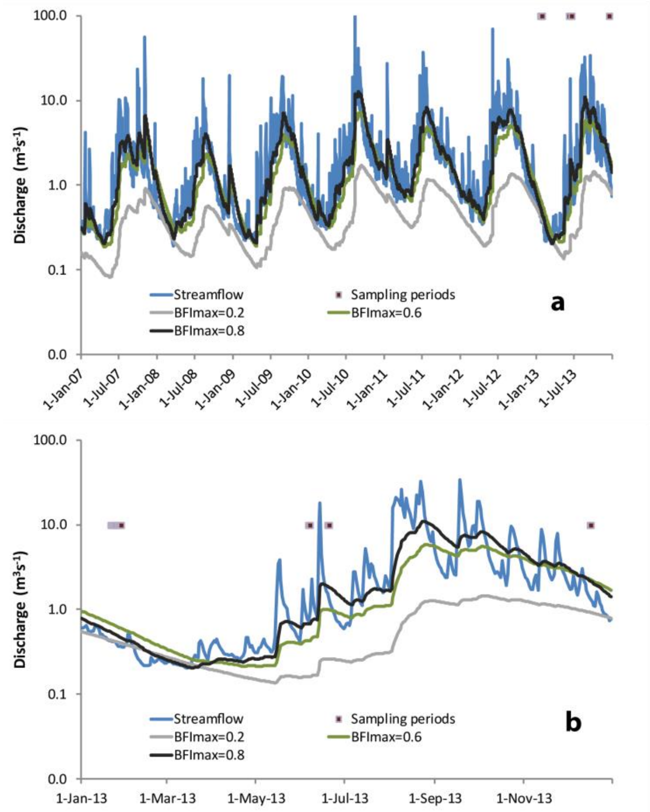

Figure 2. (a) Hydrograph at Bunker Hill gauging station (235227) illustrating the seasonality of flow. Three baseflow separation hydrographs generated using different BFI_{max} parameter values (0.20, 0.60, 0.80 and *a*=0.988) for the Eckhardt filter are displayed, along with the periods of hydrochemical sampling of streamflow during 2013. (b) Hydrograph for 2013 to illustrate the detail of variations in baseflow using different BFI_{max} values without the constraint of $b_k \leq Q_k$.

2. I am not certain that the stable isotopes (section 3.3) add very much to this study. The values (Fig. 4) overlap and the differences between the sampling rounds are subtle. The interpretation on Page 12417 that the lower 18O values in winter possibly reflect differences in source or imply a short residence time may be correct although some of the difference could be related to evaporation in the warmer months increasing 18O (and this probably should be mentioned if the data are retained). Without the estimate of evaporation, it is difficult to use the stable isotopes for mass balance (especially given the large relative variability in the groundwater).

Authors' response

The isotope data do not support a large influx of groundwater discharge into streamflow and this is consistent with the major ion analysis and groundwater surface volume changes. However, the minor differences in isotopic end-member signatures between regional groundwater and tributary streamflow and possibility of evaporitic enrichment mean that the isotope data do not strongly contribute to the findings of the paper. Therefore, we have accepted the suggestion of Professor Cartwright and removed Figure 4 and associated isotopic analysis from the paper.

3. Section 3.4. I am not certain that that Fig. 6 shows the difference between March and September (page 12420, line 10); looking at the caption to Fig. 6, it seems to be just the September data (depth to water and the SD of the kriging)? This needs clarification.

Authors' response

In the original Figure 6 (Fig. 5 in the revised version) the March 2009 areas of artesian groundwater were shown as polygons and this was shown in the legend of the figure. However, these polygons have been removed from the revised figure as the focus of the figure has changed to comparing groundwater surfaces generated from the potentiometric and water table datasets. In the text, to cover the point being made in the original Fig. 6, we have stated that the spatial locations of areas of shallow groundwater do not vary greatly between months.

Section 3.4 (Results), P14, L9-17, P13.

"For both groundwater datasets the results are generally not consistent with changes in the saturated area being the dominant driver of peak variations in baseflow, as measured by the Eckhardt filter. In particular, the potentiometric dataset shows a far more consistent range in seasonal peaks compared to the digital filter estimated baseflow. While the water table dataset does show a similar pattern in seasonal peaks, the water table rarely reaches the land surface, The saturated areas largely coincided (e.g. see Fig. 5) and were restricted to the valley floor of the catchment and with little variation in the location of these areas between dates. The restriction of the saturated areas to the valley floors indicates little regional groundwater discharge into minor tributaries and this is analysed further in Sect. 3.5."

Discussion

Section 4.1. The chemical mass balance would be improved by the discussion of uncertainties as noted by one of the other reviewers. Possibly propagating the variability in the groundwater composition through the calculations would achieve this. Additionally, the impact of the assigned BFI could be considered (especially as it appears to be lower than expected).

Authors' response

We have addressed the uncertainties in the chemical mass balance by varying the groundwater end-member compositions by one standard deviation for each ion and the results are shown in Table 1 and described in Section 3.3 (see response to comment 2 of Referee #1). The relationship between the mass balance tracer estimates and different baseflow filter estimates (particularly those generated with higher BFI_{max} values) are shown in Fig. 9 (see response to comment 4 of Referee #1).

Conclusions

Some perspective regarding the impact that bore numbers and bore density has on the results would be useful to researchers considering applying this to other catchments.

Authors' response

We have added the following text to Conclusions to provide the requested perspective.

Section 5 (Conclusions), P21, L2-20.

" Geostatistical mapping of unconfined groundwater surfaces provides a useful, independent dataset for investigating sources of fluxes contributing to baseflow estimated by traditional digital filter and tracer end-member approaches. In particular, the method can provide added confidence in the lower bound of baseflow estimates that best correspond to regional groundwater discharge in both low and high flow periods. Specifically, the groundwater surface dataset can be used to identify whether variations in discharge area (i.e. groundwater intersecting the land surface) or saturated volume can explain seasonal variations in baseflow, as estimated using digital filters. This dataset is particularly useful in humid, hilly catchments where interflow or perched aquifer discharge is likely to be a significant process and where the different 'slow flow' fluxes have similar low salinity chemistry that hinders end-member analysis. Sufficient monitoring bore data to construct water table maps are not available in all catchments and the method is likely to be restricted to catchments where groundwater investigations have resulted in the existence of an adequate bore network. The adequacy of the network will depend on catchment size, the spatial distribution of bores (i.e. uniform versus non-uniform distribution, location relative to the drainage network) and the spatial correlation of the monitored water level. However, where adequate monitoring data are available, this method adds significant value to water resource management by making better use of an independent, but often under-utilised, dataset that can inform groundwater contributions to streamflow."

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