Authors’ responses to reviews for hess-2014-444

Groundwater surface mapping informs sources of catchment baseflow

J. F. Costelloe[1], T. J. Peterson[1], K. Halbert[2], A. W. Western[1] and J. J. McDonnell[3, 4]

[1]{Department of Infrastructure Engineering, University of Melbourne, Australia}

[2]{Ecole Centrale de Nantes, Nantes, France}

[3]{Global Institute For Water Security, University of Saskatchewan, Saskatoon, Canada}

[4] {School of Geosciences, University of Aberdeen, Aberdeen Scotland}

Correspondence to: J. F. Costelloe (jcost@unimelb.edu.au)

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.

Anonymous Referee #1

General comment 1

The bore density in the catchment (98 bores per 311 km^2) seems remarkably high and is primarily due to the catchment having been investigated for water supply and damming purposes. This is not typical for most catchments. I wonder how the findings would fair if a lower density of groundwater measures were available. Say 50% of the current density? There is, of course, a break point when the geostatistics cannot really be applied anymore. Still, I wonder how much value there is in the groundwater observations when fewer observations in space are available. This could easily be checked by some random removal of data from the entire set and then kriging the remainder. What error is introduced? Cycling through realizations of the random removal in a Monte Carlo sense and systematically considering 10%, 20%, etc. removal would really give insights to stability and robustness of the approach. It would also shine light on true added value of considering groundwater maps. This would also help the study find resonance with those working in not-so-heavily instrumented sites (which would likely be prevalent in most parts of the world).

Authors' response

We agree that the study catchment has a unusually high density of groundwater monitoring bores due to previous hydrological resource studies (note that there were actually 88 bores with sufficient data for the mapping, not 98). It is for this reason that the Gellibrand catchment was chosen as a case study for investigating the value of groundwater surface mapping in estimating stream baseflow. It is common practice in hydrological research to investigate novel techniques in highly instrumented research catchments (often of very small size) for a proof of concept approach. We have taken a similar approach, albeit in a relatively large catchment. As the purpose of this paper is to investigate a proof of concept, there is insufficient space to conduct a rigorous Monte Carlo type analysis of the uncertainty generated by the number of bores used in the groundwater mapping and such an analysis may be difficult to generalise due to the uneven distribution of bores in the catchment (discussed further in the text). However, as an intial analysis we have reduced the number of bores by 62% (significantly greater than the 50% suggested by Referee #1). This analysis generated groundwater surfaces using only 33 bores within the catchment that have been screened at shallow levels (<40 m). This anslysis addresses both the concern of Referee #1 and also that of Professor Cartwright in regards to separating deeper bores screened within the Eastern View Formation. The additional analysis has been added to Section 3.4 and Figs. 5-7. Fig. 5 shows an example of groundwater surfaces from the two datasets. Figs. 6 and 7 show the use of the two sets of data in the analysis of changes in saturated ground surface (Fig. 6) and changes in saturated volume (Fig. 7) between months. The use of the two datasets in terms of uncertainty analysis is discussed in Section 4.2.

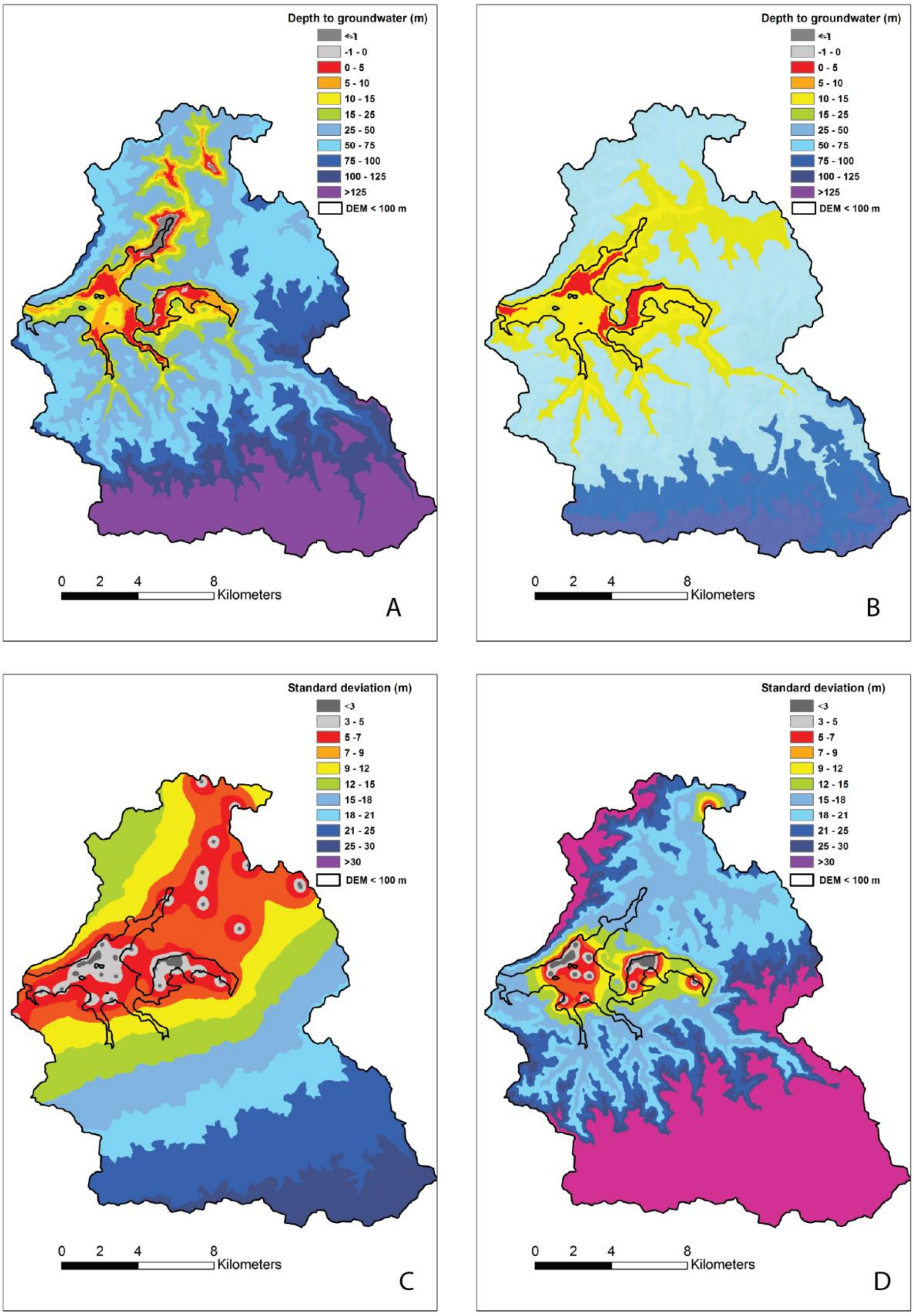

Figure 5. Depth to groundwater maps (A – ‘potentiometric surface’ (all bores), B – ‘water table’ (shallow bores)) and kriging standard deviation (C – potentiometric surface, D – water table) for 1st September 2009. Areas of shallow or intersecting (artesian) groundwater are restricted to the Gellibrand River (centre) and Love Creek (north) valley floors.

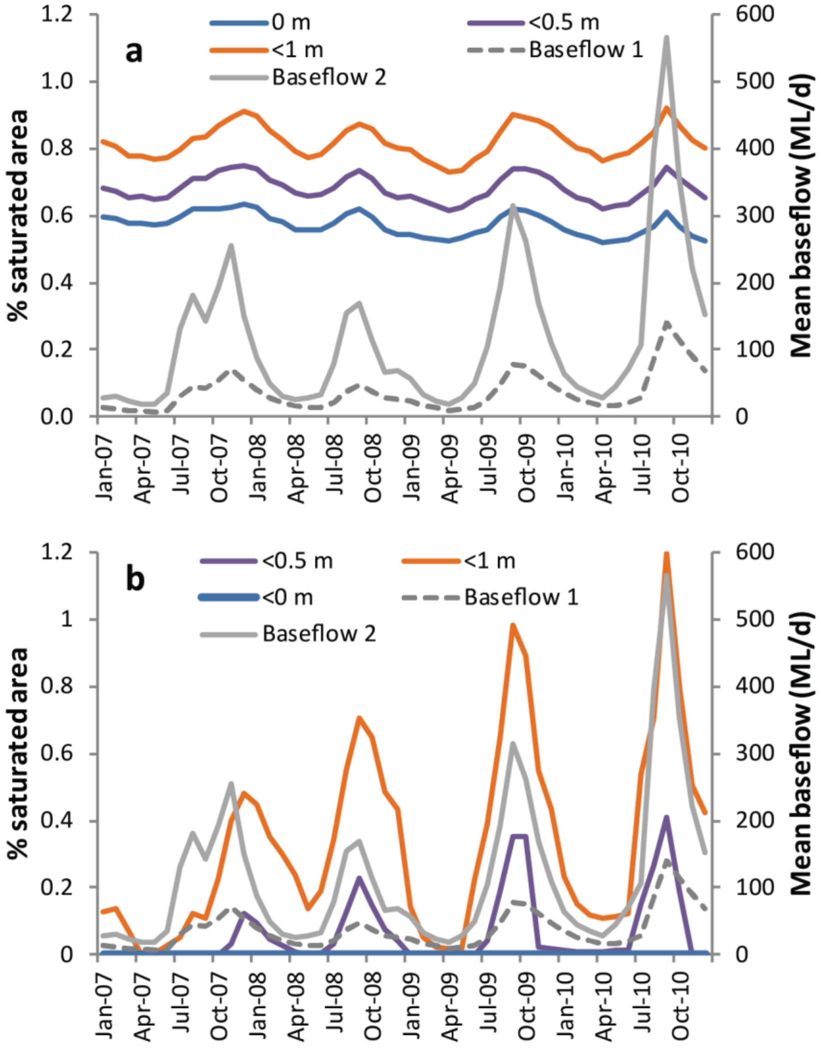

Figure 6. Percentage saturated area (intersection of groundwater surface with land surface) variations over time for the potentiometric (all bores) dataset (a) and the water table (33 bores) dataset (b) for the catchment area with elevation <100 m. The position of the water table is shown for three depths (0, 0.5, 1.0 m) to allow for uncertainties in the mapping of the depth to water table. The mean daily baseflow for each month is shown for two sets of Eckhardt filter parameter values calculated from the the Bunker Hill gauging record. Baseflow 1 uses the low BFI_{max} value (a=0.988, BFI_{max}=0.20) while Baseflow 2 uses a higher BFI_{max} value (a=0.988, BFI_{max}=0.60).

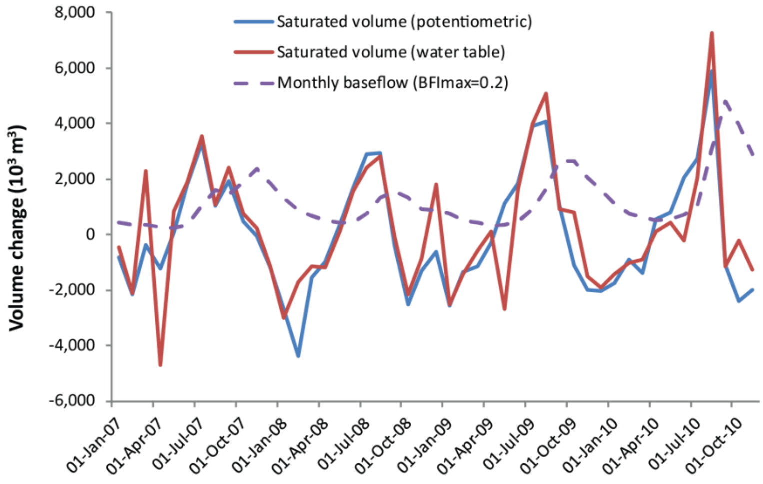

Figure 7. Monthly variations in saturated volumes for the catchment area with elevation <100 m for both the potentiometric and water table datasets and for monthly baseflow derived from Eckhardt analysis (using BFI_{max} value of 0.2).

Section 4.2 (Discussion), P19, L26-32, P20, L1-15.

“ The generation of the potentiometric surface (using 88 bores) and the water table (using 33 bores) gives an indication of the sensitivity of the use of groundwater surface mapping to the amount of data available. The maps generated from the two datasets showed some differences, particularly in the minimum depths to groundwater and the increase in the standard deviation of the water table dataset (e.g. see Fig. 5). The increase in the standard deviation of each monthly groundwater surface from the use of fewer bores demonstrates the expected result that confidence in the groundwater mapping analysis will decrease with fewer data points. However, in the case of the Gellibrand catchment, the similar estimates of monthly saturated volume changes from both datasets (Fig. 8) indicated that the relative differences between monthly groundwater surfaces generated by the two datasets were small. This is probably because most monitoring bores in both datasets were located in the valley floors and so confidence in the interpolated water table surfaces was highest in these areas. These areas are also of most interest in investigating groundwater – river interactions. The effectiveness of groundwater mapping as a water resource assessment tool will depend on the number of monitoring bores within a catchment but the question of how many monitoring bores are required will be highly dependent on the catchment size and spatial distribution of bores. In this study area, monitoring bores were commonly located in clusters and transects of limited length and these locations were likely determined by ease of access for drilling and the specific aims of past investigations rather than to optimise the spatial distribution of groundwater observations for catchment wide water table mapping. As a result, the uncertainty of groundwater surface maps would be very catchment specific and difficult to generalise to other locations.”

General comment 2

The mass balance separations (Table 1) are very useful. I think these would be more useful if some level of uncertainty was included in the analysis. There must be some way to show uncertainty bounds in these estimates? Either by considering spatial variations across the various end members and/or temporal variations in the stream samples themselves. This will help demonstrate how robust the estimations are that separate between the two “unknown” flows in the system. Can you make statements about differences between these two flows given the uncertainty in the separation estimates?

Authors’ response

We acknowledge that the inclusion of uncertainty analysis for the mass balance estimates is required. The two end-members with the greatest range in their chemical compositions are the groundwater and ungauged tributary streamflow (see Supplement A). As suggested by Referee #1 and Professor Cartwright, we have investigated how this uncertainty affects the mass balance estimates. This has been done by varying the groundwater ionic compositons by one standard deviation, as this end-member generally has the largest variance in composition. The range of valid groundwater and ungauged tributary discharges resulting from this uncertainty analysis is included in Table 1. These additional analyses are explained in the Methods and Results.

Section 2.4 (Methods), P10, L8-11.

“To explore the uncertainty in the mass balance estimates, the composition of the groundwater end-member was varied by ± one standard deviation, as this end-member had the largest standard deviation for two of the ions (Cl, Na, see Supplement A) used in the calculations.”

Table 1. Estimates of groundwater discharge (Q_{gw}) and ungauged tributary discharge (Q_{ut}) using mass balance analysis and mean measured compositions of groundwater and ungauged tributary flow. The values within the brackets are the range of valid discharges generated by varying the groundwater composition by one standard deviation for each ion used in the analysis. Q_{res} is the residual discharge after accounting for the gauged discharges within the study catchment and the following value in brackets is the ratio of Q_{res} to the total streamflow measured at Bunker Hill gauging station.

Date	**Q_{gw} (MLd^{-1})**	**Q_{ut} (MLd^{-1})**	**Q_{res} (MLd^{-1})**	**Tracer**	**Method**
21/1/13	14.0 (4.0-14.0)	2.8 (2.8-12.8)	16.8 (0.45)	Cl-Ca	Two end-member
21/1/13	12.0 (7.0-12.0)	4.8 (4.8-9.8)	16.8 (0.45)	Cl-Mg	Two end-member
21/1/13	14.8 (1.3-14.8)	2.0 (2.0-15.5)	16.8 (0.45)	Ca-Mg	Two end-member
21/1/13	- (4.4-7.6)	- (9.2-12.4)	16.8 (0.45)	Na-Mg	Two end-member
21/1/13	- (10.3)	- (6.5)	16.8 (0.45)	Na-Ca	Two end-member
21/1/13 – 28/1/13	13.7 (5.3-13.7)	1.8 (1.8-10.2)	15.5 (0.45)	Cl	One end-member series
21/1/13 – 28/1/13	7.1 (3.8-12.6)	8.4 (2.9-11.7)	15.5 (0.45)	Na	One end-member series
21/1/13 – 28/1/13	13.7 (8.9-13.7)	1.8 (1.8-6.6)	15.5 (0.45)	Ca	One end-member series
21/1/13 – 28/1/13	13.7 (7.7-13.7)	1.8 (1.8-7.9)	15.5 (0.45)	Mg	One end-member series
21/1/13 – 28/1/13	4.7 (3.3-8.2)	10.8 (7.3-12.2)	15.5 (0.45)	^{18}O	One end-member series
21/1/13 – 28/1/13	8.1 (4.6-8.1)	7.5 (7.5-10.9)	15.5 (0.45)	^{2}H	One end-member series
7/6/13	25.2 (20.5-25.4)	59.6 (59.4-64.3)	84.8 (0.43)	Cl-Na	Two end-member
7/6/13	48.8 (35.6-53.2)	36.0 (31.6-49.2)	84.8 (0.43)	Na-Mg	Two end-member
7/6/13	38.2 (7.5-38.2)	46.6 (46.6-77.3)	84.8 (0.43)	Cl-Ca	Two end-member
7/6/13	68.9 (36.6-68.9)	15.9 (15.9-48.2)	84.8 (0.43)	Cl-Mg	Two end-member
7/6/13	9.8 (9.8-16.6)	75.0 (68.2-75.0)	84.8 (0.43)	Na-Ca	Two end-member
7/6/13 - 11/6/13	- (18.8-29.9)	- (17.1-28.2)	47.0 (0.41)	Cl	One end-member series
7/6/13 - 11/6/13	2.2 (1.2-20.5)	44.8 (26.5-45.8)	47.0 (0.41)	Na	One end-member series
20/6/13	14.7 (10.0-14.9)	31.0 (30.8-35.7)	45.7 (0.38)	Cl-Na	Two end-member
20/6/13	42.4 (3.8-42.4)	3.3 (3.3-34.3)	45.7 (0.38)	Na-Mg	Two end-member
20/6/13	- (44.5)	- (1.2)	45.7 (0.38)	Cl-Mg	Two end-member
20/6/13	- (0.2-1.0)	- (34.8-35.6)	45.7 (0.38)	Cl-Ca	Two end-member
20/6/13	- (15.3-17.9)	- (17.9-20.5)	45.7 (0.38)	Na-Ca	Two end-member
18/6/13 - 20/6/13	51.9 (31.3-51.9)	0.3 (0.3-20.9)	52.2 (0.42)	Cl	One end-member series
18/6/13 - 20/6/13	- (27.3-36.4)	- (15.8-24.9)	52.2 (0.42)	Na	One end-member series
18/6/13 - 20/6/13	- (36.9)	- (15.3)	52.2 (0.42)	Cl-Na	Two end-member series
18/6/13 - 20/6/13	- (17.3-45.2)	- (7.0-34.9)	52.2 (0.42)	Ca-Mg	Two end-member series
16/12/13	5.3 (5.3-26.6)	30.6 (9.2-30.6)	35.8 (0.30)	Na-Ca	Two end-member
16/12/13	17.1 (0.2-17.1)	18.7 (18.7-35.8)	35.8 (0.30)	Cl-Ca	Two end-member
16/12/13	- (16.2-16.6)	- (19.2-19.6)	35.8 (0.30)	Na-Cl	Two end-member
16/12/13	- (3.8-12.6)	- (23.2-32.1)	35.8 (0.30)	Na-Mg	Two end-member
16/12/13	- (18.0)	- (17.8)	35.8 (0.30)	Ca-Mg	Two end-member
16/12/13	- (2.3-33.4)	- (2.4-33.6)	35.8 (0.30)	Cl -Mg	Two end-member

Section 3.3 (Results), P12, L20-23 and P13, L5-12.

“ The valid range of groundwater and ungauged tributary discharges generated by varying the groundwater end-member concentration by ± one standard deviation are shown in brackets after the values generated by the mean groundwater composition in Table 1.”

“ Allowing for variation within the groundwater end-member composition demonstrated the uncertainty in the range of valid flux estimates. The mass balance analyses indicated that the ungauged tributary flow term was often significant (consistent with field observations) but difficult to separate from the groundwater discharge term. This was likely due to the similarity in signature between these two end-members. The possibility of the ungauged tributary flow forming a distinctively different physical end-member to regional groundwater discharge (i.e. representing a different store and flow path) is further investigated in Section 3.5."

General comment 3

It is confusing when considering the saturated volume estimates from the groundwater maps (around P12421L5). Was the specific yield taken as 0.3 and held constant spatially over the entire region? That is a fairly strong assumption given the inherent heterogeneity in soils (and subsequently specific yield) one would expect both across the catchment and into the ground. I would have anticipated a much more thorough consideration of the specific yield variability especially since this estimate is a cornerstone of the study. Looking at the title of the study, I would have expected spatial explicit estimates of water volumes coming from the groundwater maps. Instead all the variability in the water table maps is filtered through a constant specific yield. A better job representing the 3D variability of specific yield and its subsequent impact variability in potential groundwater contribution is required. Further, the uncertainty in specific yield should be considered since they are typically difficult values to estimate. Regardless, this lack of accounting for soil variability in the estimations is worrisome since the differencing of the groundwater maps is the more novel aspect of the study. If some variability in specific yield is not considered, then it would be recommended to remove these estimates (at which point the study gets a bit thin).

Authors' response

A uniform specific yield value of 0.3 was used in the analysis of monthly changes in saturated volume. This value was used as an upper bound on the possible groundwater contribution to streamflow as this upper bound is the most comparable to baseflow filter estimation (Cartwright et al., 2014). We acknowledge that accounting for spatial heterogeniety in the specific yield would refine this analysis. There are no pump test data available in the catchment but Atkinson et al. (2014) used a specific yield value of 0.1 for the main aquifer, the Eastern View Formation (Wangerrip Group), consistent with the porosity of this unit (Love et al., 1993). Other groundwater modelling studies in this region have used a specific yield of 0.1 for all the main geological units in the catchment (Heytesbury Group, Eastern View Formation, Otways Group, SKM (2010)). We have investigated how varying the specific yield, using a realistic range, for different units affects the estimates of saturated volume change for areas within the <100m mask (Table 2). Given the paucity of specific yield data for the hydrogeological units within the catchment, we consider that this broad-scale uncertainty analysis is robust. We note again that we are particularly concerned with identifying an upper bound on the conversion of mapped saturated volume changes to possible discharge to streamflow. Therefore, we consider that the range of specific yield values used in the analysis (Table 2) captures that aim and this analysis is reported in the Results.

Section 3.4 (Results), P14, L24-33, P15, L1-21.

"For months in the water table dataset with declining saturated volumes (i.e. periods where changes in saturated volume are dominated by discharge), we used a range of specific yield values to convert the total volume change to a volume of discharged water for areas within the <100m mask (Table 2). There are no pump test data for the catchment but Atkinson et al. (2014) used a specific yield of 0.1 to estimate recharge for the Eastern View Formation (Wangerrip Group), consistent with the effective porosity of this unit (Love et al., 1993). A hydrogeological modelling study in similar units of the Otway Basin used specific yield values of 0.1 for both aquifers and aquitards in their calibrated model (SKM, 2010). We use a range of realistic but relatively high (Nwankwor et al., 1984) specific yield values from 0.05-0.3 for the different geological units within the <100 m elevation mask for the groundwater surfaces (see Fig. 1). The estimates of the ratio of monthly baseflow (from Eckhardt filter) to monthly mapped volume change, shown in Table 2, are generated using the same specific yield values across all geological units and also by varying the values consistent with expected hydrogeological properties (i.e. specific yield of alluvium > Wangerrip Group > Heytesbury Group). We consider that this range of estimates based on these specific yield values provides an upper bound to the groundwater discharge, particularly since any phreatic evapotranspiration flux, which would also account for some of the volume changes, is not considered. For the study period of 2007-2010, only three months showed a ratio of <1 between the monthly baseflow time-series (generated using BFI_{max} values of 0.2 and 0.6) and the corresponding monthly change in mapped water table volume (i.e. saturated volume change > baseflow), using the range of specific yield values. The median ratio for both baseflow time-series ranged between 2.0 and 32.2 (Table 2), with more realistic (i.e. smaller) specific yield values generating the larger median ratios (i.e. saturated volume change << baseflow) compared to specific yield values considered to represent an upper bound. The late summer to early winter period (January to June, n=17) had median ratios 10-15% less than the late winter to early summer period (July to December, n=20) but both periods had months with very large (>10) ratios. These results indicate that the monthly baseflow fluxes are significantly larger than can be explained by groundwater discharge from the valley regions during most months of the year and requires a significant additional flux of ‘slow flow’ into the river (see also Fig. 9).”

Table 2. Minimum, median and 90th percentile values for ratio of monthly Eckhardt filter baseflow to ‘water table’ volume changes using a range of specific yields (S_{y1} - Wangerrip Group, S_{y2} – alluvium, S_{y3} – Heytesbury Group aquitards). Filtered baseflow time-series were calculated using *a* value of 0.988 and BFI_{max} values of 0.2 or 0.6. Only months with declining volume changes were used in the analysis.

	Min ratio		**Median ratio**		**90th perc. ratio**	
S_{y1}, S_{y2}, S_{y3}	**BFI_{max} = 0.2**	**0.6**	**0.2**	**0.6**	**0.2**	**0.6**
0.1, 0.3, 0.05	0.41	0.89	3.23	10.81	27.3	57.3
0.1, 0.2, 0.05	0.41	0.89	3.88	12.89	28.4	61.7
0.1, 0.1, 0.05	0.41	0.89	6.77	18.06	38.0	80.2
0.15, 0.3, 0.05	0.27	0.59	2.52	8.59	15.9	33.9
0.05, 0.05, 0.05	0.82	1.78	11.9	32.21	49.8	12.5
0.1, 0.1, 0.1	0.41	0.89	5.96	16.11	24.9	60.2
0.2, 0.2, 0.2	0.21	0.45	2.98	8.05	12.4	30.1
0.3, 0.3, 0.3	0.14	0.30	1.99	5.37	8.3	20.1

General comment 4

Finally, there is a lack of quantification with regards to relating the groundwater volume estimates to the hydrograph separations. The manuscript presents results as time series comparison (Figure 10 for example). Would it be more informative to relate the various techniques to each other? How similar are the various flow estimate techniques and over what periods are they more alike and more different? Currently, there is too much qualitative analysis regarding the timing of peaks in one dataset compared to another. These qualitative statements should be firmed up with some quantification and statistics. This will really drive home the utility of the groundwater maps for constraining estimates.

Authors' response

We have changed Figure 10 (now Figure 9) from a time series plot to a series of scatter plots that better illustrate the relationships between the various estimates of baseflow and groundwater discharge from our analyses. The discussion in Section 4.1 has also been changed to better discuss the results presented in the revised Figure 9.

Section 4.1 (Discussion), P16, L17-32, P17, L1-30.

"Digital baseflow filters separate out the 'slow flow' component of streamflow. As such, they provide an effective upper bound on possible groundwater discharge to streamflow (Cartwright et al., 2014). This was tested by plotting scatter plots of baseflow estimates for the Gellibrand River from Eckhardt digital filter analysis, residual streamflow (i.e. Bunker Hill discharge less other gauged tributaries lagged by one day – Upper Gellibrand, Lardner Creek, Love Creek) and tracer mass balance analyses (Fig.9 a, b, c) for the 2011-2013 period. The tracer estimates include the range of estimates from Atkinson et al. (2015) for sampling from known dates conducted in 2011-2012 using ^{222}Rn and Cl mass balance, plus the results from this study for sampling in 2013 using major ions (shown as mid-points of the range for each date shown in Table 1). None of these estimates are directly comparable as they measure different components of baseflow but their comparison is informative. The digital filter time-series estimates baseflow from the entire catchment upstream of Bunker Hill gauging station. The Atkinson et al. (2015) estimates are for the groundwater discharge component of streamflow measured over the alluvial valley reach (approximately two thirds of the Bunker Hill to Upper Gellibrand reach, see Fig. 1) and use a two end-member mass balance approach (tributary inflow was not considered). The tracer mass balance results from our study are for the groundwater discharge component of baseflow over the Bunker Hill to Upper Gellibrand reach and account for ungauged tributary inflow. For additional comparison, the residual monthly discharge, monthly baseflow and the monthly saturated volume change for months with decreasing volumes were plotted (Fig. 9d). The saturated volume change was calculated with a realistic specific yield range (set 0.15, 0.3, 0.05 in Table 2) that produces a relatively high estimate of groundwater discharge compared to estimates using other specific yield values (see Table 2).

The tracer estimates of groundwater discharge and the residual discharge generally show a consistent relationship (Fig. 9a). The Atkinson et al. (2015) estimates coincided with the residual discharge, except for two outliers from one date sampled on a small rising limb, but neither method separates out in-reach tributary flow from groundwater discharge. The tracer estimates from this study used the residual discharge as an upper bound in their estimation and so show a high correlation and a negative bias with the residual discharge. When the tracer estimates are plotted against two baseflow filter estimates (Fig. 9b, using a=0.988, BFI_{max}=0.2 and a=0.988, BFI_{max}=0.6) the relationships are poorly correlated and with the tracer estimates both under- and over-estimating relative to the baseflow filter estimates. The use of the larger BFI_{max} value (0.6), more consistent with the recommendations of Eckhardt (2005), results in the tracer estimates having a more negative bias relative to the baseflow filter estimates. The daily residual discharge is also compared to the baseflow filter estimates over the period 2007-2013 (Fig. 9c). The use of the larger BFI_{max} value results in baseflow generally higher than the residual flow (but with considerable scatter) while the lower BFI_{max} value results in baseflow generally lower than the residual discharge, particularly at high discharges. Finally, the mapped monthly changes in saturated groundwater volume (see Fig. 7) were plotted against the monthly residual discharge and baseflow filter estimates (using a=0.988, BFI_{max}=0.2 and 0.6) over the 2007-2010 period (Fig. 9d). The saturated volume changes were typically lower than both the residual discharge and the two baseflow discharges, consistent with the the residual and baseflow measures providing an upper bound to groundwater discharge within the study reach. Even the groundwater volume change is more likely to represent an upper bound estimate than an unbiased estimate due to the use of a relatively high specific yield range and not accounting for phreatic evapotranspiration."

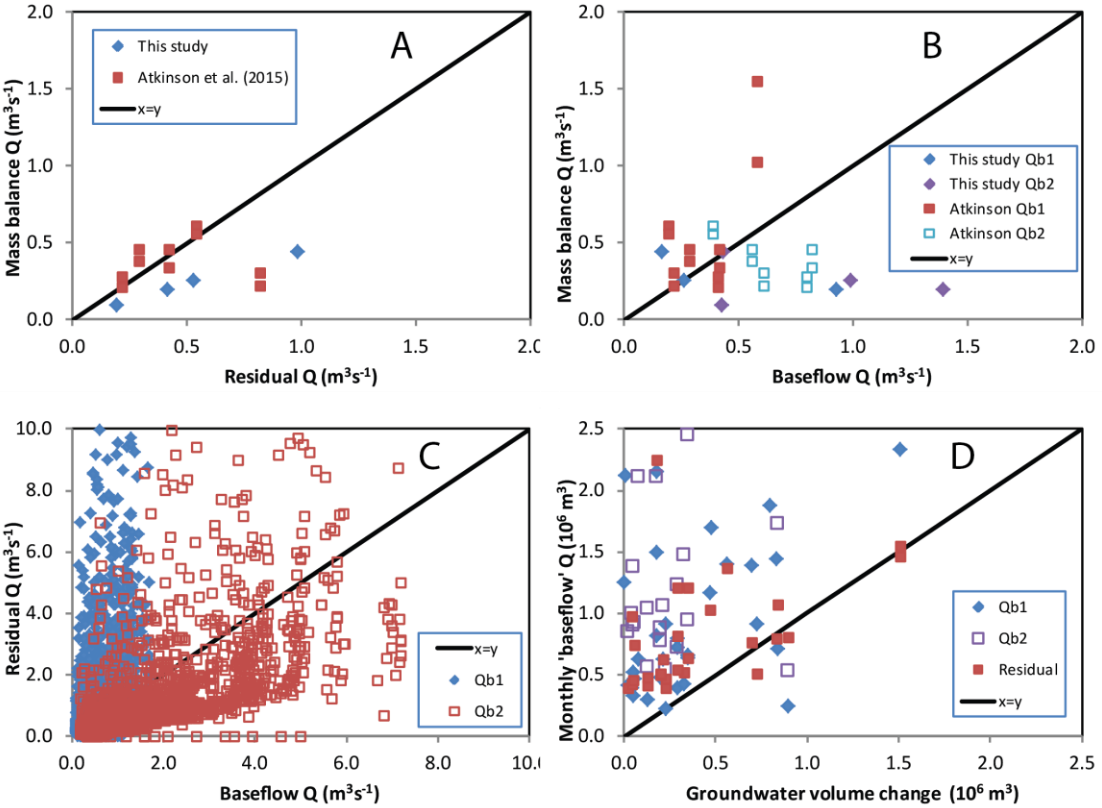

Figure 9. Scatter plots showing various estimates of baseflow and groundwater discharge. (a) Mass balance tracer estimates (from Atkinson et al. (2015) for 2011-2012 and mid-point of range shown in Table 1 for 2013) for groundwater discharge against the residual streamflow (Bunker Hill streamflow less upstream gauged streamflow). (b) Mass balance tracer estimates against the Eckhardt filter baseflow estimates (Qb1 uses a=0.988 and $\text{BFI}_{\max}$=0.2, Qb2 uses a=0.988 and $\text{BFI}_{\max}$=0.6). (c) Residual discharge against Eckhardt filter baseflow timeseries for 2007-2013. (d) Saturated volume changes (using specific yield set 0.15, 0.30, 0.05 from Table 2) against residual flow and Eckhardt filter baseflow timeseries.

Minor/Editorial Comments

P12406L2: All “ff” where formatted strangely in my version.

Authors – Manuscript pdf file on the HESS website does not show any problems.

P12408L20: How does this compare to recent work by Brutsaert (2008)? Brutsaert, W. (2008), Long-term groundwater storage trends estimated from streamflow records: Climatic perspective, Water Resour. Res., 44, W02409, doi:10.1029/2007WR006518

Authors – The common use of the slowest recession curves to define one of the parameters used in baseflow analysis has been explained in the Introduction and the Brutsaert (2008) reference has been included.

Section 1 (Introduction), P3, L21-28

"There is typically significant variability in recession curves from a given catchment suggesting a range of processes, stores and flow paths (e.g. deep and shallow groundwater flowpaths, interflow, bank storage) affecting baseflow (Tallaksen, 1995; Jencso and McGlynn, 2011; Chen and Wang, 2013). The regional unconfined groundwater may drive only some of this response (Cartwright et al., 2014) and the baseflow derived from unconfined groundwater is commonly defined by the slowest recession flows that form the lower bound (e.g. the 95th percentile) of all recession curves used in the analysis (Brutsaert, 2008; Eckhardt, 2008)."

P12410L21: Well, I am guessing you mean any given date within the period of observation?

Authors – Line changed in Section 1 (Introduction, P5, L18-19) to "any given date within the period of observation".

P12413L14: How is having a water table 1m below the surface "nominally saturated"? I appreciate the effort to consider variations in this arbitrary part of the work, but what realism is retained with these values? 25cm is already quite far away from the soil surface for saturation.

Authors – These depths were chosen to capture the uncertainty in the position of the groundwater surface relative to the ground surface. Part of this uncertainty arises from the interpolation (the error standard deviation often exceeds 1 m, Figure 5), part from the DEM and also part from the fact that the DEM doesn't capture any sub-grid scale features, such as stream channels. Given this interpolation uncertainty and the possiblity of groundwater discharging when the water table is below the nominal DEM elevation, we feel it is necessary to look at shallow water tables in addition to water tables at the surface. The text has been altered to draw attention to this uncertainty.

Section 2.2 (Methods), P8, L6-20.

" The depth to groundwater was calculated by difference from the SRTM representation of the ground surface and used to measure changes in the percentage of the catchment with very shallow groundwater surfaces (nominally "saturated" within the uncertainty range of the groundwater surface position) over the period of mapping. This was done for the parts of the catchment with an elevation of <100 m in order to analyse changes in the saturated area around the valley floor and lower slopes of the catchment where most monitoring bores were located and hence confidence in the water table mapping was highest. Three threshold depths to the water table (0, 0.50, 1.0 m) were used to determine changes between the seasonal maximum (spring) and minimum (autumn) saturated areas. The threshold depths were not calibrated but were arbitrarily chosen to capture some of the uncertainty in the groundwater position (i.e. see Figure 5 for an indication of the standard deviation in the groundwater surface positions) as mapped for each month. In addition, changes in total volume below the mapped groundwater surface (i.e. volume containing sediments and pore spaces) between months were calculated using the groundwater surface maps, again using the catchment area below 100 m elevation."

P12413L22: Would be good to see the equations used here to help make sense of all the parameters mentioned in this section.

Authors – The Eckhardt equation has been added to the text.

Section 2.3 (Methods), P8, L22-27.

"The Eckhardt (2005) two parameter, digital recursive filter (1) was used to produce baseflow time-series for the Gellibrand streamflow record at the Bunker Hill gauging station (Station number 235227).

$$b_k = \frac{(1-BFI_{max})ab_{k-1}+(1-a)BFI_{max}Q_k}{1-aBFI_{max}} \qquad (1)$$

Where b [L^3/T] is the baseflow discharge, Q [L^3/T] is the total streamflow discharge, k [T] is the time-step, and a [-] and BFI_{max} [-] are parameters requiring calibration."

P12415L7: Should the ions have charges?

Authors – HESS does not require that ions are assigned charges in the text but we will accept the direction of the editors on this point.

Figure 2: It might be the printout I am working from, but I cannot see multiple baseflow separations in this figure. It would be simple to have three panels and show each separation separately.

Authors – Figure 2 has been amended to show the baseflow using the mean BFI_{max} parameter calculated for this study (0.2) and also using a higher BFI_{max} value (0.6) based on the work of

Atkinson et al. (2015) and the suggested value for perennial rivers with porous aquifers (0.8) from Eckhardt (2005). The comparison with higher BFI_{max} values was suggested in the review of Professor Cartwright and Fig. 2 is shown in our response to Professor Cartwright. The different baseflows are shown as solid coloured lines to make the figure clearer.

Figure 4: Strange symbol in the word "Concentration".

Authors – We assume that Referee #1 was referring to Figure 5 but the pdf file on the HESS website does not show any problems with this figure.

Figure10: I cannot follow this figure. It has too many small dots and not sure what I am supposed to be comparing. Would it make more sense to plot the various parameters against each other rather than against time?

Authors – Figure 10 has been changed as suggested by Referee #1 and is now Figure 9 (see response to general comment 4).

References

Abedini, M. J., Nasseri, M., and Burn, D. H.: The use of a genetic algorithm-based search strategy in geostatistics: application to a set of anisotropic piezometric head data, Comput. Geosci., 41, 136-146, 2012.

Atkinson, A. P., Cartwright, I., Gilfedder, B. S., Cendón, D. I., Unland, N. P., and Hofmann, H.: Using 14C and 3H to understand groundwater flow and recharge in an aquifer window, Hydrol. Earth Syst. Sci., 18, 4951–4964, 2014.

Atkinson, A. P., Cartwright, I., Gilfedder, B. S., Hofmann, H., Unland, N. P., Cendón, D. I., and Chisari, R.: A multi-tracer approach to quantifying groundwater inflows to an upland river; assessing the influence of variable groundwater chemistry, Hydrol. Process., 29, 1-12, 10.1002/hyp.10122, 2015.

Bredehoeft, J. D., Papadopulus, S. S.,and Cooper, H. H. Jr.: Groundwater: the water budget myth in scientific basis of water resource management. National Research Council Geophysics Study Committee, National Academy Press, Washington, DC, pp 51–57, 1982.

Brutsaert, W.: Long-term groundwater storage trends estimated from streamflow records: Climatic perspective, Water Resour. Res., 44, W02409, doi:10.1029/2007WR006518, 2008.

Cartwright, I., Gilfedder, B., and Hofmann, H.: Contrasts between chemical and physical estimates of baseflow help discern multiple sources of water contributing to rivers, Hydrol. Earth Syst. Sci., 18, 15–30, 2014.

Eckhardt, K.: How to construct recursive digital filters for baseflow separation, Hydrol. Process., 19, 507-515, 2005.

Love, A. J., Herczeg, A. L., Armstrong, D., Stadter, F., and Mazor, E.: Groundwater flow regime within the Gambier Embayment of the Otway Basin, Australia: evidence from hydraulics and hydrochemistry, J. Hydrol., 143, 297–338, 1993.

Nwankwor, G. I., Cherry, J. A., and Gillham, R. W.: A comparative study of specific yield determinations for a shallow sand aquifer, Ground Water, 22, 764-772, 1984.

Ortiz, C. J. and Deutsch, C. V.: Calculation of uncertainty in the variogram, Math. Geol., 34, 169-18, 2002.Perrin, J., Mascré, C., Pauwels, H., Ahmed, S.: Solute recycling: An emerging threat to groundwater quality in southern India, J. Hydrol., 398, 144-154, 2011.

SKM, (2010), Glenelg Hopkins CMA groundwater model – final model development report, Report to the Victorian Department of Sustainability and Environment, available at: https://ensym.dse.vic.gov.au/docs/GlenelgHopkins_TransientModelReport_FINAL.pdf, last access: 5 February 2015, 2010.