“New baseflow separation and recession analysis approaches for streamflow” by M. K. Stewart, Hydrol. Earth Syst. Sci. Discuss., 11, 7089–7131, 2014

Response to Anonymous Review #2

Note In the paper I used the term “baseflow fraction”, but this will be called “baseflow index” or “BFI” here and in future paper revisions.

I appreciate the thoughtful comments of Anonymous Referee #2, and think that they will lead to a considerably improved paper.

Review “This discussion paper presents a new method to separate base flow from rapid flow in River hydrographs. The author claims that the technique is based on evidence from tracer studies, and the approach essentially assumes that the slow response following facilitation events actually comprises two components, an initial "bump" followed by a subsequent "rise", rather than the simple one component which is normally used. A second key assertion of the paper is that base flow separation should be done prior to recession analysis, rather than the other way around which has always been the convention.”

Reply An additional unique (as far as I am aware) feature of the BRM method is the fitting of the baseflow plus a fast recession to the streamflow following a flow event.

Review “Whilst this discussion paper is generally well written and contains some useful review of the literature and several interesting ideas as to how baseflow separation approaches may be improved, there are several fundamental problems that I feel preclude it from being accepted for publication in this journal. The level of discussion as to the detailed shortcomings of existing models is lacking, and a comparison between the declared new method and existing approaches is also absent. I think this material is certainly of some interest, but much more as a single case study with interesting results from a few hydrological events, rather than the basis of a widely-applicable method. I do not see how any amount of modification would change this, and therefore I recommend the paper be rejected, but invited for resubmission as a comment article or refocused very much as a case study.”

Reply I believe that the ideas and the application of the ideas in the paper deserve wide circulation. The reviewer acknowledges that the paper contains “several interesting ideas as to how baseflow separation approaches may be improved” (reviewer’s second paragraph) and writes “I do not necessarily disagree with the author’s assertion that recession of both rapid run-off and baseflow are of interest to the hydrologist” (reviewer’s issue 4).

The specific criticisms that “The level of discussion as to the detailed shortcomings of existing models is lacking” and “a comparison between the declared new method and existing approaches is also absent” are addressed below (in the replies to reviewer’s issues 2 and 4). These criticisms imply that different methods of baseflow separation give very different results, when in fact most methods give rather similar BFIs (e.g. Gonzales et al., 2009). Since Gonzales et al., (2009) recently carried out a comprehensive comparison of baseflow separation methods (nine non-tracer methods and one tracer method), I did not think it necessary to repeat it here. However, I do agree that the BRM method should be compared with the Eckhardt (2005) method (since this is probably the most developed of the filter methods) as well as to the Hewlett and Hibbert (1967) method. This is given below (reply to reviewer's issue 4).

Review "My recommendation is based on the following 4 major issues:

1) The title of the paper is inappropriate. The manuscript does not detail new approaches, it speculates as to how a particular approach may be applied, using a considerable amount of expert judgement, to particular events, in particular catchments. I do not see how this can be declared a new powerful method without considerable empirical evidence over a wide range of catchments and events, and without the need for highly subjective judgements (p7103: "the baseflow fractions during the periods tested were first estimated based on examination of the streamflow and previous experience with the catchment, and were kept constant during the optimisation process to give a constraint on f and k. A well-chosen estimate of baseflow fraction appears to be sufficient. . ."). It is also heavily reliant upon local knowledge and local tracer evidence which is not always available."

Reply I respect the reviewer's opinion, but think there is no doubt that the paper presents new approaches to baseflow separation and recession analysis, and therefore that the title <u>is</u> appropriate. The reviewer offers no evidence to the contrary (in terms of prior publication of the ideas, nor have I seen any). The specific criticism is that the paper "speculates as to how a particular approach may be applied". This is simply a perjorative way of saying that the paper presents a new approach.

The BRM baseflow separation method is a two-parameter recursive digital filter in the same sense as that of Eckhardt (2005), and analogous to the one-parameter filters of Lyne and Hollick (1979), Chapman (1991) and Chapman and Maxwell (1996), and also Hewlett and Hibbert (1967). Consequently, it is just as applicable to streamflow as they are. But the BRM method has three other features, 1. Like the Chapman (1991) and Chapman and Maxwell (1996) filters, it is based in a general sense on tracer evidence (references given in the paper P7095, L3-4 and L14-15) which shows rapid baseflow responses to rainfall (giving the 'bump' of the BRM method). 2. In addition, the BRM method contains a second longer-term type of response to rainfall (the subsequent 'rise', P7096, L23-25). The two responses are specified by the two parameters, 3. The BRM baseflow plus a fast recession is fitted to the streamflow recession. The good fits observed provide support for the shape of the BRM baseflow (i.e. the 'bump' and the 'rise') and therefore the form of the BRM filter (Eqs. 6 & 7).

Another criticism is that the paper applies the BRM method using "a considerable amount of expert judgement, to particular events, in particular catchments". Regarding the first phrase, the reviewer himself (or herself) says "All approaches to separate streamflow hydrographs require assumptions" (reviewer's issue 4). The BRM method uses no more expert judgement than any other baseflow separation method. The second phrase refers to the fact that the paper examines winter and summer events, however more importantly the paper also examines the master recession curve based on three years of data (Pearce, 1984), which renders the criticism invalid. The third phrase refers to the fact that the BRM method has not been widely applied yet. This does not seem a valid objection to a new method. The paper applies the method to the Glendhu GH1 catchment, a second paper is near submission applying it to the Toenepi Catchment in New Zealand, and brief applications to a couple of other catchments have yielded satisfactory results. Whether the method eventually proves to be "a new powerful" method will depend on testing by others. In the meantime, I believe that the ideas deserve wider circulation.

Again, the reviewer says that application of the BRM method in the paper is "heavily reliant upon local knowledge and local tracer evidence which is not always available". The BRM method is no more reliant on local knowledge than any of the other methods, and certainly is not in any way reliant on local tracer evidence. The local tracer evidence in the paper is only used for comparison with the baseflow separation after it was determined by the BRM filter.

Review "2) A major argument during the introduction literature review, largely drawn from other recent publications on baseless [sic] separation, is that more than one method should be used as different methods often give different answers. It is somewhat puzzling why the author chose not to demonstrate the difference between this new method and previous ones given the strength of argument for a multi-method approach set out in the introduction."

Reply This criticism is not correct. With regard to baseflow separation the paper states "However, arbitrary as they may be, most of the methods yield results that are quite similar (e.g. Gonzales et al., 2009 obtained baseflow fractions [BFIs] ranging from 0.76 to 0.91 for nine non-tracer baseflow separation methods, not too different from their tracer-based result of 0.90)" (P7091, L12-15). Given this similarity, I did not think that much space in an already long paper should be devoted to demonstrating the differences between the BRM method and other methods. However, there are differences in shape between the BRM and Eckhardt (2005) methods for example (demonstrated below) that I will describe in more detail in the modified paper.

In respect of recession analysis, on the other hand, the paper quoted Stoelzle et al. (2013) that "a multiple methods approach to investigate streamflow recession characteristics should be considered" (P7092, L2-4). This is a focus of the paper particularly in relation to the possibility of drawing misleading information regarding catchment reservoirs from streamflow recessions because streamflow is composed of two components and analysis yields mixed information not characteristic of either component. The main message of the paper is that quickflow and baseflow components should be examined as well as streamflow on recession plots. I plan to change the title to "New baseflow separation and recession analysis approaches for streamflow: Does recession analysis of streamflow yield misleading information?"

Review "3) The method is a modified version of that proposed by Hewlett and Hibbert (1967), which is a very simple form of baseflow separation. There are far more sophisticated methods, many alluded to in the text, but no justification as to why this particular method should be chosen and modified."

Reply This is not a valid criticism of the paper. It was convenient to start with and modify the Hewlett and Hibbert (1967) method <u>because</u> it is a very simple method, and the assumptions or implications of the method did not conflict with the BRM method (in particular the bump).

Review "4) A central argument of the manuscript is that baseflow separation should be performed before recession analysis. However the paper does not explain why recession analysis is conventionally performed prior to baseflow separation. Eckhard (2005) clearly explains why recession analysis is required by linear filters, and he further demonstrates that most linear filters for baseflow separation typically require two parameters - a recession constant, and the maximum allowable base flow index. More theoretical approaches required a selection of an appropriate period with no surface run-off, and subsequent fitting of an assumed set of equations to the obtained hydrograph. I do not necessarily disagree with the author's assertion that recession of both rapid run-off and baseflow are of interest to the hydrologist, but the author has merely stated this assertion without any evidence. All approaches to separate streamflow hydrographs require assumptions. In the case of digital filters, it is the choice of a low flow period to approximate the recession constant, a, and then the selection of a BFI_max. In the case of more theoretical approaches it becomes the form of recession relationship, as detailed in the manuscript. However, in order to declare the conventional approach unsuitable, it is essential to first explain (and then demonstrate) why the old methods are inappropriate, and then present a new method that requires fewer assumptions and produces more physically-meaningful results, in comparison to the existing methods. This manuscript does not present such an argument."

Reply This is a thoughtful argument that seems to be based mainly on the Eckhardt (2005) paper. Recession analysis has traditionally been applied to streamflow only. The justification for this would appear to be the argument advanced by Kirchner (2009) that his "approach makes no distinction between baseflow and quickflow. Instead it treats catchment drainage from baseflow to peak stormflow and back again, as a single continuum of hydrological behavior. This eliminates the need to separate the hydrograph into different components". It may also simply be that nobody has seen the need for applying recession analysis to separated components as well as to the streamflow before. My contention is that this separation is essential to avoid drawing misleading conclusions regarding catchment reservoirs if the recession analysis is applied to the early part of the streamflow recession. This is because quickflow and baseflow come from very different sources in catchments. Only baseflow is present during the late part of the streamflow recession so there is no confusion due to mixing during the late recession. This is explained in the paper (Section 8.2).

The Eckhardt filter uses a recession constant a (= B_t/B_{t-1}) extracted from the late streamflow recession by fitting an exponential curve to the recession. There is no problem with this provided it is the late (quickflow-free) part of the curve. There could be minor concerns that the late recession (e.g. at GH1) is not exponential but quadratic, and therefore a tends to increase slightly as the recession proceeds. The second Eckhardt parameter BFI_{max} (the maximum allowable base flow index) is less easy to quantify, but Eckhardt (2005) has given broad guidelines based on catchment type. Others have calibrated BFI_{max} by fitting the Eckhardt filter to tracer separations (Gonzales et al., 2009, Zhang et al., 2013) or by use of a backwards filter (Collischonn & Fan, 2013).

So in summary the Eckhardt approach is considered perfectly suitable provided that the baseflow recession constant a is determined from the late part of the streamflow recession. It was not my intention to cast doubt on it or other baseflow separation methods, except insofar as tracer measurements have shown that baseflow responds relatively quickly to rainfall (as well as probably on a longer time-scale). These tracer observations are the justification for the shape (i.e. bump and rise) of the BRM baseflow. Incidentally, the rapid baseflow responses shown by tracer studies indicate that low-pass filtering is not appropriate or only partially appropriate for determining baseflow from streamflow hydrographs (low-pass filtering is given as a raison d'être of the Eckhardt (2005) filter).

The ideas in the paper were applied to the Eckhardt (2005) method in addition to the Hewlett & Hibbert (1967) and BRM methods for the Glendhu GH1 Catchment, to widen the investigation to other filter baseflow separation methods. The Hewlett & Hibbert and BRM parameters used are as given in the table in the paper (repeated in Table 1 below). The parameters for the Eckhart filter were assigned according to the methods described by Eckhardt (2005). The recession constant a was determined from the master recession curve at GH1 given in the paper by fitting an exponential to the part of the curve more than 2.5 days after peak flow. The BFI_{max} was taken as 0.8 (appropriate for a perennial stream with porous aquifer, Eckhardt, 2005).

The resulting separations are given in Figs. 1a-f for the winter event. Each pair of figures for the three methods shows the sum of the baseflow and a fast recession fitted to the streamflow recession (Figs. 1a, 1c, 1e) and the calculated baseflow in the month of August 1996 (Figs. 1b. 1d, 1f). The fits for all of the methods to the streamflow are good (see standard deviations in Table 1). The different baseflows have different shapes but give similar BFIs (Table 1). The BRM method produces the best fit of the three methods.

Table 1 also has data for the twin summer peaks, which have been fitted here by one baseflow and two fast recessions for each of the three methods. The Hewlett & Hibbert and BRM baseflows produce good fits and BFIs of 0.95. The Eckhardt baseflow does not produce such a good fit and curiously the BFI produced by applying the filter to the February 1996 streamflow is 0.84 (greater than the BFI_{max} assumed for the event). If BFI_{max} is allowed to become an adjustable parameter then a BFI_{max} of 0.94 gives the best fit to the streamflow and a BFI of 0.93, which is close to those obtained by the Hewlett & Hibbert and BRM methods. Note that the latter optimisation procedure for fixing BFI_{max} (which uses streamflow data alone, like the Collischonn and Fan, 2013) is not the same as that used by Gonzales et al., 2009 and Zhang et al., 2013, because they adjusted BFI_{max} to fit tracer separations.

References

Chapman, T. G.: A comparison of algorithms for streamflow recession and baseflow separation, Hydrol. Processes, 13, 701-714, 1999.

Chapman, T. G. and Maxwell A. I.: Baseflow separation - Comparison of numerical methods with tracer experiments, In Proceedings of the 23rd Hydrology and Water Resources Symposium. Hobart, Australia, 539-545, 1996.

Collischon, W. and Fan, F. M.: Defining parameters for Eckhardt's digital baseflow filter. Hydrol. Process. 27, 2614-2622. DOI: 10.1002/hyp.9391, 2013.

Eckhardt, K.: How to construct recursive digital filters for baseflow separation, Hydrol. Process., 19, 507–515. DOI: 10.1002/ hyp.5675, 2005.

Gonzales, A. L., Nonner, J., Heijers, J. and Uhlenbrook, S.: Comparison of different baseflow separation methods in a lowland catchment, Hydrol. Earth Syst. Sci., 13, 2055-2068, 2009.

Hewlett, J.D. and Hibbert, A. R.: Factors affecting the response of small watersheds to precipitation in humid areas, in Forest Hydrology, edited by W. E. Sopper and H. W. Lull, pp. 275–290, Pergamon, Oxford, 1967.

Kirchner, J. W.: Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modelling, and doing hydrology backward, Water Resour. Res., 45:W02429, doi:10.1029/2008WR006912, 2009.

Lyne, V. D., Hollick, M. Stochastic time-variable rainfall runoff modelling. Hydrology and Water Resources Symposium , Institution of Engineers Australia, Perth. 89-92, 1979.

Stoelzle, M., Stahl, K. and Weiler, M.: Are streamflow recession characteristics really characteristic? Hydrol. Earth Syst. Sci., 17, 817–828, 2012.
Su, N. G.: The Unit-Hydrograph Model for Hydrograph Separation, Environ. Internat., 21, 509–515, 1995.
Zhang, R., Li, Q., Chow, T. L., Li, S. and Danielescu, S.: Baseflow separation in a small watershed in New Brunswick, Canada, using a recursive digital filter calibrated with the conductivity mass balance method, Hydrol. Processes, 27, 2659-2665, 2013.

Table 1. Parameter values for the Hewlett & Hibbert (1967) (k), BRM (f and k) and Eckhardt (2005) (BFI_{max} and a) baseflow separation methods applied to the Glendhu GH1 Catchment, New Zealand.

Baseflow separation method	BFI[a]	f[a] %	k[a] mm $d^{-1}h^{-1}$	BFI_{max}[a]	a[a]	sd[a] mm d^{-1}
Winter peak (16/8/96)						
Hewlett & Hibbert	0.715	--	0.00766	--	--	0.20
BRM	0.715	16	0.000864	--	--	0.11
Eckhardt	0.68	--	--	0.8	0.9982	0.26
Summer peaks (12&13/2/96)						
Hewlett & Hibbert	0.95	--	0.00376	--	--	0.021
BRM	0.95	18.5	0.00255	--	--	0.014
Eckhardt	0.84	--	--	0.8	0.9982	0.085
Eckhardt (optimised)	0.93	--	--	0.94	0.9982	0.020

[a]BFI is the baseflow index, f bump fraction, k slope parameter, BFI_{max} maximum BFI value, a recession constant, and sd standard deviation.

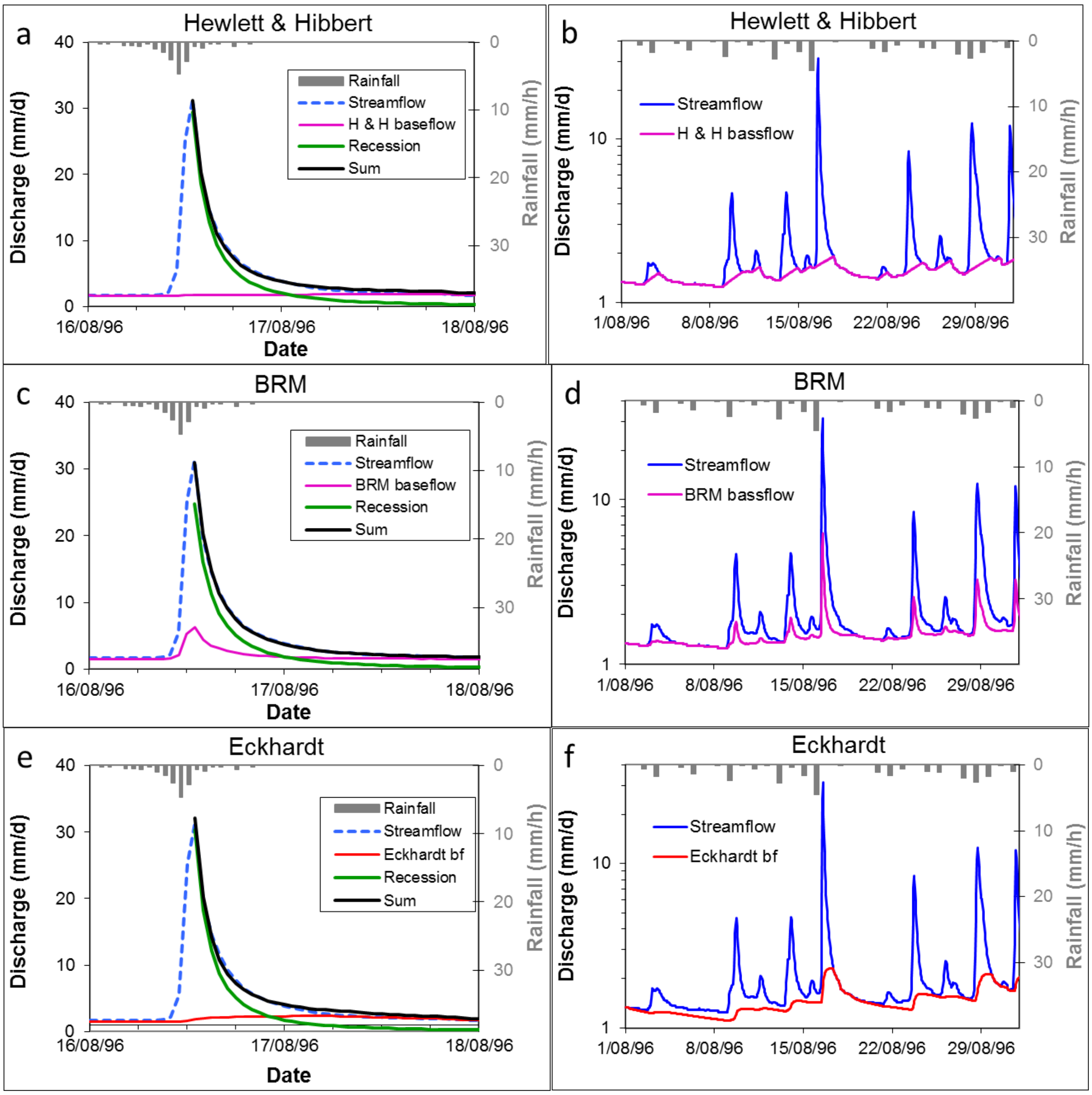

Figure 1. (a, c, e) Baseflow separations and fits to streamflow for the Hewlett and Hibbert (1967), BRM and Eckhardt (2005) methods. (b, d, f) Baseflows calculated using the three methods for August 1996. Note the logarithmic scale.