Editor Initial Decision: Reconsider after major revisions (20 Oct 2014) by Dr. Jim Freer: Comments to the Author

Editor Comment
First I thank the reviewers and the author for their very useful correspondence on this paper. I believe the editors have made some clear points that need to be addressed in the final manuscript and if this would be acceptable for publication in HESS. From the reviewer comments and author responses I suggest the following that include some major changes:

Reply I greatly appreciate the work of the Editor on this manuscript.

Editor Comment
1) I agree the manuscript needs to be made more readable. I agree that reviewer 1 has covered most of the areas that need attention. The author says he will work on these and that will need significant improvement in the manuscript

Reply Major changes have been made to the manuscript particularly in response to the comments of Anonymous Referee #1. In particular, I have drastically changed the structure (it is now structured as: 1. Introduction, 2. Methods, 3. Results of Application of New Approaches, 4. Discussion and 5. Conclusions) and removed the sections concerned with isotope and transit time theory.

I realise now that a major problem with the paper is that it has two main messages (the new baseflow separation method and the need for a new approach to recession analysis). I have now tried to make these clearer without separating the paper into two papers as it probably needed.

Editor Comment
2) I agree the technical elements of the paper need better development. This goes hand in hand with other comments made by both reviewers about the general applicability of this method. I do have some sympathy that the title is miss-leading and I do feel the case has not been made about how the method has utility across a range of catchment types. I do feel if these are not addressed (with further studies) then a modification to the title will be appropriate. I would argue a minimum of 3 catchments of different scales and behaviour would be appropriate to state that the method has been properly explored as a general approach and any shortcomings identified (or that the approach can be successfully applied)

Reply The paper is still focussed on the one catchment (Glendhu) so I have changed the title as suggested in comment 6) below. The reasons for not including three catchments are 1) there was insufficient time to do justice to three catchments, and anyway 2) the catchments I planned to use were similar in scale and baseflow index, although very different in hydrogeological character.

The applicability of the method is addressed by devoting more attention to describing how the method was applied, and particularly bringing out the two ways of applying the method (i.e. simulating tracer separations or based on hydrometric information when there is no tracer data).

Editor Comment 3)
3) I agree the literature does not appear to be adequately followed by the author and this does need improvement. There are other papers I have already mentioned (Lamb et al. being one), others by Martyn Clarke and all are exploring recession methods. This generally needs to be improved throughout

Reply A wider selection of the literature (particularly more recent work on baseflow separation and recession analysis) has been cited in line with the comments of Anonymous Referee #1 and the Editor. The two papers above are included. Other papers related to transit time theory etc. have been removed.

Editor Comment 4)
4) There are a number of comments from Reviewer 1 that again criticism the utility about the method and again this is because the method has been applied to one particular catchment. The emphasis and title of the paper will need to be re-written if the author cannot apply this to additional catchments as there is little discussion of the dangers of suggesting a method without further exploration and if experience and data needs will mean general applications will not be possible or easy

Reply I have changed the title. I now consider the application of the baseflow separation method in much more detail in the new section 3 (Results of Application of New Approaches to Glendhu GH1 Catchment) and 4.2 (Calibration of the BRM Algorithm).

Editor Comment 5)
5) Most of the minor comments from reviewer 1 appear to be well covered by the author

Reply I have implemented essentially all of the comments of Reviewer #1, especially in regard to describing the technical assumptions to apply the method, improving the link to the literature (especially the recent literature), extensively revising the structure of the paper and giving an expanded description of the Glendhu Catchment. The minor comments have also been dealt with in accordance with what I said in my reply to Reviewer #1.

Editor Comment 6)
6) I think what reviewer 2 is driving at is that the methods application is one catchment and a nice detail of that analysis has been conducted by the author. I agree the title reads as if this is a method for general applicability, but this has not been demonstrated and in fact is not discussed in this way in the conclusions. To state that approaches are misleading cannot in essence be based on one catchment unless that is clearly clarified in the context of the paper. No such discussion is currently generated. I would argue more a title like. A promising new base flow method and recession approach for streamflow applied at one catchment in New Zealand - could be more appropriate for

example

Reply I have changed the title as suggested. I think that if I make clear what I think is important about the methods suggested then readers will be able to see their relevance. For the new baseflow separation method this is the more accurate simulation of tracer separation results (demonstrated at Glendhu) and for the new recession analysis approach this is the effect that the varying mixture of components in streamflow has on how it appears on recession plots and therefore how it can give misleading power-law slopes (also I believe demonstrated at Glendhu). These can be stated quite simply and are general ideas that are not intrinsically associated with one catchment so whether they were applied at one or three or fifty catchments doesn't seem to me to really change their nature. Of course they may not work on some catchments – this should now be taken care of by the new title.

The methods of Hewlett and Hibbert (1967) and Eckhardt (2005) are now included for comparison with the BRM.

The manuscript has been changed very extensively, and the way the BRM was applied has also been changed – not that I thought the earlier way was wrong, but the new way demonstrates that there are two alternative ways of applying the method. The two ways are reconciled in Section 4.2.

The comments of Reviewer #2 have led to extensive changes of the paper in line with my reply to Reviewer #2.

Editor Comment 7)
7) I do agree the justification of why base flow recession should be applied first and the linkage to other methods deserves more attention. The difficulty again is the evidence base of one catchment in confirming this and the author needs to get this right in the context of the one study they provide. I appreciate the long response from the author on this and good points are made, I will look out for ensuring the right balance in this discussion is made int eh final manuscript

Reply The three digital filter baseflow separation methods (H & H, Eckhardt and BRM) are now compared in terms of their fidelity in simulating tracer separations, and the new BRM method is clearly superior (because it was developed for that purpose).

A wider literature has been examined on the new recession analysis approach and I think the idea is now presented more in context with previous ideas on the subject. I have also modified how I see it since plotting the baseflow on recession plots is not necessarily helpful because of the calculation procedure. The important part is the effect that the varying mixture of components in streamflow has on how it appears on recession plots and therefore how it can give misleading power-law slopes. This is seen by plotting quickflow and streamflow e.g. Fig. 6c.

Editor Comment Can I note I will send this manuscript out for further review after the next major correction of this manuscript are obtained, best wishes

MANUSCRIPT FOR HYDROLOGY AND EARTH SYSTEM SCIENCES

A promising new baseflow method and recession approach for streamflow at Glendhu Catchment, New Zealand

~~New baseflow separation and recession analysis approaches for streamflow~~

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Abstract

Understanding and modelling the relationship between rainfall and runoff has been a driving force in hydrology for many years. Baseflow separation and recession analysis have been two of the main tools for understanding runoff generation in catchments, but there are many different methods for each and no consensus on how best to apply them. TheA new baseflow separation method presented, which here (the bump and rise method or BRM) is simulates the shape of tracer-determined baseflow or pre-event water more accurately than previous methods. Application of the method by calibrating its parameters, using (a) tracer data or (b) an optimizing method, is demonstrated for the Glendhu Catchment, New Zealand. The calibrated algorithm is then applied to the Glendhu streamflow record. is justified by being based generally on the more objective tracer separation methods and by being optimised by fitting to the recession hydrograph. The new recession approach advances the thesis that recession analysis of streamflow alone gives misleading information on catchment storage reservoirs because streamflow is a varying mixture of components of very different origins and characteristics (at the simplest level, quickflow and baseflow as identified by the BRM method). Recession analyses of quickflow, baseflow and streamflow show that the steep power-law slopes often observed for streamflow at intermediate flows are artifacts due to such mixing and are not representative of catchment reservoirs. Using this baseflow separation method, the thesis is advanced that recession analysis should be applied to the separated components (quickflow and baseflow), because of their very different origins and characteristics, rather than to the streamflow itself because analysing the latter alone gives misleading results. Applying baseflow separation before recession analysis could shed sheds new light on water storage reservoirs in catchments and may possibly resolve some current problems with recession analysis. It may also have implications for rainfall-runoff modelling. Among other things it shows that both quickflow and baseflow reservoirs in the studied catchment have (non-linear) (quadratic) characteristics. in the studied catchment (Glendhu, New Zealand).

1 Introduction

Interpretation of streamflow variations in terms of catchment characteristics has been a major theme in hydrology for many years in order to improve catchment and stream management. Two of the main tools for this task are baseflow separation and recession analysis (Hall, 1968; Brutsaert and Nieber, 1977; Tallaksen, 1995; Smakhtin, 2001). Baseflow separation aims to separate streamflow into two components (quickflow and baseflow), where quickflow is direct runoff following rainfall, and baseflow is delayed streamflow during periods without rain. Recession analysis aims to model the decrease of streamflow during rainless periods to extract parameters descriptive of water storage in the catchment. In a similar way, transit time analysis determines transit time distributions of water in the stream and catchment in order to quantify flowpaths and storages through the catchment. To fully understand and satisfactorily model the movement of water and chemicals through catchments, it is necessary to understand in detail the water stores and flowpaths (Fenicia et al., 2011; McMillan et al., 2011; Beven et al., 2012; Hrachowitz et al., 2013).

The technique of baseflow separation has a long history in practical and scientific hydrology because knowledge about baseflow is very useful in predicting low flow progressions and understanding water quality variations. However, the many baseflow separation methods have been regarded with suspicion for a long time ~~. B~~because they ~~many baseflow separation methods~~ were often associated with “the Hortonian view of catchments” (Beven, 1991)~~,~~ ~~and are~~or were considered “to a large extent, arbitrary” (Hewlett and Hibbert, 1967~~; Beven, 1991~~).~~, the technique has been regarded with suspicion for a long time although it is still used practically. Some recent modelling studies have avoided using baseflow separation altogether, although it may be embedded in later modelling calculations. However~~Nevertheless, arbitrary as they may be, most of the methods yield results that are quite similar (e.g. Gonzales et al., 2009 obtained long-term baseflow fractions (i.e. baseflow indexes, called BFIs below) 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), and all show that baseflow is often quantitatively important in annual flows and, of course, very important during low flows. This work contends that baseflow should also be considered during middle and high flows, because streamflow during ~~high flow~~such events is composed of comparable amounts of both quickflow and baseflow ~~components~~ (e.g. Sklash and Farvolden, 1979) and they are produced by very different mechanisms. It is believed that process descriptors such as hydrograph recession constants (or transit time distribution parameters) should be determined on separated components, not total streamflow, because the latter is a mixture and therefore gives misleading results. All such process descriptors should be qualified by the components they were derived from. Putting it simply, the contention is that to properly understand the streamflow hydrograph it is first necessary to separate it into its quickflow and baseflow components. While this may be considered obvious by some, recession analysis has not previously been applied to other than the total streamflow.

Recession analysis also has a long history for practical hydrology reasons, but Stoelzle et al. (2013~~2~~) recently highlighted large discrepancies between different methods of analysis, in particular contrasting recession parameters derived by the methods of Brutsaert and Nieber~~,~~ (1977), Vogel and Kroll~~,~~ (1992), and Kirchner~~,~~ (2009). Stoelzle et al. suggested that “a multiple methods approach to investigate streamflow recession characteristics should be considered”. This indicates that the general technique itself is in some disarray, and that there is little general consensus on how best to apply recession analysis to streamflow.

This paper presents a new method of baseflow separation (called the bump and rise method or BRM~~ method~~) which simulates the shape of tracer-determined baseflow or pre-event water more accurately than previous methods. The two BRM parameters are calibrated by (a) fitting to tracer data if it is available, or (b) using an optimizing process if it is not. The calibrated BRM filter is then applied to the streamflow record. Two other baseflow separation methods (those of Hewlett and Hibbert (1967) and Eckhardt (2005)) are compared with the BRM. ~~is optimised by fitting to the recession hydrograph and based generally on the results of tracer hydrograph separations~~. The paper ~~It~~ also takes a fresh look at the application of recession analysis for characterising runoff generation processes in the light of surprising effects of first separating the baseflow. Recession analysis of streamflow can give misleading slopes on a recession plot particularly at intermediate flows because streamflow is a varying mixture of components (at the simplest level, quickflow and baseflow). When quickflow, baseflow and streamflow are all analysed, the effect of the more rapidly receding quickflow on the streamflow can be seen. The same procedure ~~is applied to flow duration curves~~gives insight into the processes of streamflow generation at each exceedence percentage when applied to flow duration curves (Section 2.4). The methods are illustrated using streamflow data from the Glendhu Catchment in Otago, South Island, New Zealand. ~~The new approaches may be opening a new door to understanding of catchment functioning.~~

2 ~~A New Method of Baseflow Separation~~Methods

2.1 Baseflow Separation

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Justification for making baseflow separations rests on the dissimilarity of quickflow and baseflow generation processes in catchments. Evidence of this is given by the different recession slopes, and chemical and stable isotope compositions of early and late recessions in hydrographs (examples are given for Glendhu, see below). In addition, transit times of stream water show great differences between quickflow and baseflow. While quickflow is young (as shown by the variations of conservative tracers and radioactive decay of tritium), baseflow can be much older with substantial fractions of water having mean transit times beyond the reach of conservative tracer variations (4 years) and averaging 10 years as shown by tritium measurements (Stewart et al., 2010, 2012; Michel et al., 2014). For these reasons, it is believed that it is not justifiable to treat the streamflow as a single component, but that at least two components should be considered by applying baseflow separation to the hydrograph before analysis.

Streamflow at any time (Q_t) is composed of the sum of quickflow (A_t) and baseflow (B_t)

$$Q_t = A_t + B_t \qquad (1)$$

where time steps are indicated by the sequences …Q_{t-1}, Q_t, Q_{t+1} … etc. The time increment is ~~normally~~ one hour in the examples given below, but can be days in larger catchments or any regular interval. Quickflow or direct runoff results from rainfall events and often drops to zero between events, while baseflow is continuous as long as the stream flows. As shown by the names, the important distinction between them is the time of release of water particles to the stream (i.e. their transit times through the catchment). They are supplied by fast and slow drainages within the catchment, direct precipitation and fast storage reservoirs (soil stores) supply quickflow, and slow storage reservoirs (groundwater aquifers) supply baseflow. This simple separation has proven to be effective in many catchments, and is practical for the general case considered here. However, particular catchments may have a variety of different possible streamflow components that could be separated in principle. Fig. 1 gives a recession curve showing the two flow components and the early and late parts of the curve. The late part of the recession curve starts when baseflow dominates streamflow (i.e. quickflow becomes very small).

Many methods have been developed for baseflow separation (see reviews by Hall, 1968; Tallaksen, 1995; Gonzales et al., 2009). Baseflow separation methods can be grouped into three categories: analytical, empirical and chemical/isotopic or tracer methods. Analytical methods are based on fundamental theories of groundwater and surface water flows. Examples are the analytical solution of the Boussinesq equation, the unit hydrograph model and theories for reservoir yields from aquifers (Boussinesq, 1877; Su, 1995; Nejadhashemi et al., 2003).

Empirical methods based on the hydrograph are the most widely used (Zhang et al., 2013), because of the availability of such data. The methods include 1) recession analysis (Linsley et al., 1975), 2) graphical methods, filtering streamflow data by various methods (e.g. finding minima within predefined intervals and connecting them) (e.g. Sloto and Crouse, 1996), 3) low pass filtering of the hydrograph (Eckhardt, 2005; Zhang et al., 2013), and 4) using groundwater levels to calculate baseflow contributions based on previously determined relationships between groundwater levels and streamflows (Holko et al., 2002).

One widely-used empirical method for small catchments was proposed by Hewlett and Hibbert (1967) who argued that: "since an arbitrary separation must be made in any case, why not base the classification on a single arbitrary decision, such as a fixed, universal method for separating hydrographs on all small watersheds?" They separated the hydrograph into "quickflow" and "delayed flow" components by arbitrarily projecting a line of constant slope from the beginning of any stream rise until it intersected the falling side of the hydrograph. The steady rise is described by the equations

$$B_t = B_{t-1} + k \qquad \text{for} \qquad Q_t > B_{t-1} + k \tag{2}$$
$$B_t = Q_t \qquad \text{for} \qquad Q_t \leq B_{t-1} + k \tag{3}$$

where k is the slope of the dividing line. The slope they chose was 0.05 ft^3/sec/$mile^2$/hour (0.000546 m^3/s/km^2/h or 0.0472 mm/d/h). ~~Other authors have adapted the method by changing the value of the constant (k) to be more suitable for their catchments.~~ This universal slope gives a firm basis for comparison of BFIs between catchments.

Tracer methods use dissolved chemicals and/or stable isotopes to separate the hydrograph into component hydrographs based on mass balance of water and tracers. Waters from different sources are assumed to have unique and constant (or varying in a well-understood way) compositions (Pinder and Jones, 1969; Sklash and Farvolden, 1979; McDonnell et al., 1991). These tracer methods allow objective separation of the hydrograph, but it is important to consider just what water components are being separated. For example, deuterium varies much more in rainfall than it does in soil or groundwater, which has average deuterium concentrations from contributions from several past events. When the deuterium content of a particular rainfall is very high or very low, it becomes an effective indicator of the presence of “event” water in the stream, compared with the “pre-event” water already in the catchment before rainfall began (as shown in Fig. 2a adapted from Bonell et al., 1990). Baseflow separations (i.e. identification of a groundwater component) have been more specifically shown by three-component separations using chemicals and stable isotopes (Bazemore et al., 1994; Hangin et al., 2001; Joerin et al., 2002; Iwagami et al., 2010). An example of separation of direct precipitation, acid soil and groundwater components using silica and calcium is given in Fig. 2b redrawn from Iorgulescu et al. (2005).

A remarkable and by now well-accepted characteristicaspect of these separations is that the components including groundwater often respond to rainfall as rapidly as the stream itself. Chapman and Maxwell (1996) noted that “hydrograph separation using tracers typically shows a highly responsive old flow”. Likewise Wittenberg (1999) comments “tracers such as ^{18}O … and salt … [show] that even in flood periods outflow from the shallow groundwater is the major contributor to streamflow in many hydrological regimes”. And Klaus and McDonnell (2013) observe “most [tracer studies] showed a large preponderance of pre-event water in the storm hydrograph, even at peak flow”. This has been a general feature in tracer studies and includes all of the components tested whether quickflow or baseflow (e.g. Hooper and Shoemaker, 1986; Bonell et al., 1990; Buttle, 1994; Gonzales et al., 2009; Zhang et al., 20132). In the case of groundwater, the rapid response is believed to be partially due to rapid propagation of rainfall effects downwards (by pressure waves or celerity) causing rapid water table rise and displacement of stored water near the stream (e.g. Beven, 2012, page 349; McDonnell and Beven, 2014; Stewart et al., 2007, page 3354).

Chapman and Maxwell (1996) and Chapman (1999) compared baseflow separations based on digital filters (like the low pass filters referred to above) with tracer separations in the literature and identified a preferred two-parameter algorithm given by

$$B_t = \frac{m}{1+C} B_{t-1} + \frac{C}{1+C} Q_t \qquad (4)$$

which approximately matched the tracer separations. m and C are parameters identified by trial and errorfitting to the pre-event hydrograph identified by tracers. Wittenberg (1999) and Wittenberg and Sivapalan (1999) used their inverted nonlinear reservoir algorithm which describes baseflow as a sequence of recessions of groundwater recharges

$$B_{t-1} = \left(B_t^{b-1} + \frac{(b-1)}{ab} t\right)^{1/(b-1)} \qquad (5)$$

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combined with a procedure for connecting pre-storm lower baseflow with post-storm higher baseflow after each groundwater recharge event has occurred. Equation 5 is the inverted form of equation 11 applied to a time step, and a and b are constants. Equations 4 and 5 give baseflow separations that are similar in shape to that given by the BRM method below. Eckhardt (2005) demonstrated that some previously published digital filters (Lyne and Hollick, 1979; Chapman and Maxwell, 1996; Chapman, 1999) could be represented by a more general digital filter equation by assuming a linear relationship between baseflow and baseflow storage (see equation 9 below). Eckhardt’s filter is

$$B_t = \frac{(1-BFI_{max})aB_{t-1}+(1-a)BFI_{max}Q_t}{1-aBFI_{max}} \quad (5)$$

where parameter a is a recession constant relating adjacent baseflow steps during recessions, i.e.

$$B_t = aB_{t-1} \quad (6)$$

and is determined by recession analysis. On the other hand, there was no objective way to determine parameter BFI_{max} (the maximum value of the baseflow index that can be modeled by the algorithm corresponding to low-pass filtering of a wave of infinite length). Eckhardt (2005) suggested that typical BFI_{max} values can be found for classes of catchments based on their hydrological and hydrogeological characteristics. Others have pointed out that these BFI_{max} values should be regarded as first approximations, and more refined values can be determined using tracers (Eckhardt, 2008; Gonzales et al., 2009; Zhang et al., 2013), by a backwards filtering operation (Collischonn and Fan, 2013) or by the relationship of two characteristic values from flow duration curves (i.e. Q_{90}/Q_{50}, Smakhtin, 2001; Collischonn and Fan, 2013).

2.1.1 The new baseflow separation method

The new baseflow separation method put forward in this paper (hereafter called the bump and rise method or BRM) has an algorithm chosen to simulate tracer separations simply but as accurately as possible. is also based on the evidence from tracer separations. Tracer separations hese show rapid baseflow responses to storm events (the "bump"), which is followed in the method by a steady rise in the sense of Hewlett and Hibbert, (1967) (the "rise"). The steady rise is justified by increase in catchment wetness conditions and gradual replenishment of groundwater aquifers during rainy periods. The size of the bump (f) and the slope of the rise (k) are regarded asasparameters that can be optimised in particular catchments by fitting to the hydrograph recessionof the recursive digital filter that can be applied to the streamflow record. The separation procedure is described by the equations:

$$B_t = B_{t-1} + k + f(Q_t - Q_{t-1}) \quad \text{for} \quad Q_t > B_{t-1} + k \quad (67)$$
$$B_t = Q_t \quad \text{for} \quad Q_t \le B_{t-1} + k \quad (78)$$

where f is a constant fraction of the increase or decrease of streamflow during an event. The values of f and k can be determined from tracer measurements, like the parameters of other digital filters. If no tracer information is available, f and k can be determined by an optimization process as described in an earlier version of this paper (Stewart, 2014a). An advantage of the BRM method (like the Chapman (1999) and Wittenberg (1999) methods) is that while it is generally based on the tracer evidence, it can be applied using streamflow data alone. An unusual feature of the BRM method is that two types of baseflow response are included, a short-term response via the bump and a longer-term response via the rise.

2.23 Recession Analysis

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Recession analysis also has a long history. Stoelzle (~~2012~~2013) recently highlighted discrepancies between methods of extracting recession parameters from empirical data by contrasting results from three established methods (Brutsaert and Nieber, 1977, Vogel and Kroll, 1992, and Kirchner, 2009). They questioned whether such parameters are really able to characterise catchments to assist modelling and regionalisation, and suggested that researchers should use more than one method because specific catchment characteristics derived by the different recession analysis methods were so different.

The issue of whether storages can be represented by linear reservoirs or require to be treated as non-linear reservoirs has been widely discussed in the hydrological literature (in the case of recession analysis by Brutsaert and Nieber, 1977, Tallaksen, 1995, Lamb and Beven, 1997 and Fenicia et al., 2006, among others). Lamb and Beven (1997) identified three different storage behaviours in the three catchments they studied. Linear reservoirs only require one parameter each and are more tractable mathematically. They are widely used in rainfall-runoff models. Non-linearity can be approximately accommodated by using two or more linear reservoirs in parallel, but more parameters are required (three in the case of two reservoirs). Linear storage is expressed by the formulation

$$V = Q/\beta \qquad (~~8~~9)$$

where V is storage volume, and β is a constant (with dimensions of T^{-1}). The exponential relationship follows for baseflow recessions

$$Q_t = Q_o exp(-\beta t) \qquad (~~9~~10)$$

where Q_o is the streamflow at the beginning of the recession.

However, evidence for non-linearity is strong (Wittenberg, 1999) and the non-linear formulation is often used

$$V = \alpha e Q^b \qquad (11~~0~~)$$

where ~~a~~ e and b are constants. This gives the recession equation

$$Q_t = Q_o[1 + \frac{(1-b)Q_o^{(1-b)}}{\alpha e b} t]^{1/(b-1)} \qquad (12~~1~~)$$

The exponent b has been found to take various values between 0 and 1.1, with an average close to 0.5 (Wittenberg, 1999). b=1 gives the linear storage model (equations 8 and 9). For b=0.5, equation 11 reduces to the quadratic equation

$$Q_t = Q_o \left[1 + \frac{1}{ae}.Q_o^{0.5}.t\right]^{-2} \qquad (13~~2~~)$$

This quadratic equation is similar to the equation derived much earlier by Boussinesq (1903) as an analytical solution for drainage of a homogeneous groundwater aquifer limited by an impermeable horizontal layer at the level of the outlet to the stream

$$Q_t = Q_o(1 + \alpha t)^{-2} \qquad (14~~3~~)$$

where α is

$$\alpha = KB/PL^2 \qquad (15~~4~~)$$

Here K is the hydraulic conductivity, P the effective porosity, B the effective aquifer thickness, and L the length of the flow path. Dewandel et al. (2003) have commented that only this quadratic form is likely to give correct values for the aquifer properties because it is an exact analytical solution to the diffusion equation, albeit with simplifying assumptions, whereas other forms (e.g. exponential) are approximations.

In order to generalise recession analysis for a stream (i.e. to be able to analyse the stream's recessions collectively rather than individually) Brutsaert and Nieber (1977) presented a method based on the power-law storage-outflow model, which describes flow from an unconfined aquifer into a stream. The negative gradient of the discharge (i.e. the slope of the recession curve) is plotted against the discharge, thereby eliminating time as a reference. This is called a recession plot below (following Kirchner, 2009). To keep the timing right, the method pairs streamflow $Q = (Q_{t-1} + Q_t)/2$ with negative streamflow recession rate $–dQ/dt = Q_t – Q_{t-1}$.

Change of storage in the catchment is given by the water balance equation:

$$\frac{dV}{dt} = R - E - Q \qquad (16~~5~~)$$

where R is rainfall and E is evapotranspiration. Assuming no recharge or extraction, we have

$$\frac{dV}{dt} = -Q \qquad (17~~6~~)$$

from whence equation 10 leads to

$$-\frac{dQ}{dt} = \frac{1}{~~a~~eb} Q^{2-b} = cQ^d \qquad (18~~7~~)$$

The exponent d allows for both linear (d=1) and non-linear (d≠1) storage outflow relationships, with d=1.5 giving the frequently observed quadratic relationship (equation 12). Authors who have investigated the dependence of -dQ/dt on Q for late recessions (low flows) have ~~generally~~ often found d averaging close to 1.5 (e.g. Brutsaert and Nieber, 1977; Wittenberg, 1999; Dewandel, 2005; Stoelzle et al., 2013~~2~~). Higher values of d were often found especially at higher flows, e.g. Brutsaert and Nieber (1977) found values of d = 3 for the early parts of recessions.

Recent work has continued to explore the application and possible shortcomings of the recession plot method. Rupp and Selker (2006) proposed scaling of the time increment to the flow increment which can greatly reduce noise and artifacts in the low-flow part of the plot. Biswal and Marani (2010) identified a link between recession curve properties and river network morphology. They found slopes of individual recession events in recession plots (d values) averaging around 2 and ranging from 1.1 to 5.5. In a small (1 km^2) catchment, McMillan et al. (2011) showed that individual recessions plotted on the recession plot "shifted horizontally with season", which they attributed to changes in

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contributing subsurface reservoirs as streamflow levels changed with season. This explanation is analogous to the approach below in that two water components with different storage characteristics are implied. The slopes of individual recessions in their analysis were in excess of 2 with the low-flow tails being very much steeper. In medium to large catchments (100 - 6,414 km^2), Shaw and Riha (2012) found curves of individual recessions "shifted upwards in summer relative to early spring and late fall curves", producing a data cloud when recessions from all seasons were combined. They speculate that the movement with season (which was similar, but less extreme to that seen by McMillan et al., 2011 above) was due to seasonal changes of catchment evapotranspiration. They found that the slopes of individual recessions were often close to 2 and had an extreme range of 1.3 to 5.3.

Problems in determining recession parameter values from streamflow data on recession plots are due to 1) different recession extraction methods (e.g.i.e. different selection criteria for data points), and 2) different parameter- -fitting methods to the power-law storage-outflow model (equation 17). Depending on 1) tThere is generally a very broad scatter of points on the plots, which makes parameter- -fitting difficult. in 2). Clearly evapotranspiration is likely to play a role in producing some of the scatter because evapotranspiration was neglected from equation 16.

2.2.1 The New Recession Analysis Approach

However, it is believed that part of the scatter as well as the steep slopes of recession curves often observed at intermediate flows in recession plots are due to as shown below applying recession analysis being applied to streamflow (during early parts of recessions) rather than to its separated components. As shown below, the changing proportions of quickflow and baseflow in streamflow during early parts of recessions cause recession analyses of streamflow to give mixed messages, i.e. misleading results not characteristic of storages in the catchment because the storage for each component is very different. This has has probably led to some previous recession analysis studies giving misleading results in regard to catchment storage in cases where early recession streamflow has been analysed.

2.43 Flow Duration Curves

Flow duration curves (FDCs) represent in one figure the flow characteristics of a stream throughout its range of variation. They are cumulative frequency curves that show the percentages of time during which specified discharges were equalled or exceeded in given periods. They are very useful for practical hydrology (Searcy, 1959), and have been used as calibration targets for hydrologic models (Westerberg et al., 2011).

FDCs can also be determined for the separated stream components as shown below (Fig. 5d). Although FDCs for streamflow are not misleading and obviously useful in their own right, FDCs of separated components can give insight into the processes of streamflow generation at each exceedence percentage.

5 Transit Time Analysis

The different flowpaths of water through catchments means that streams aggregate water with different transit times. Consequently, streamwater does not have a single transit

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time, but has a transit time distribution (TTD) with a mean transit time (MTT). The distribution is described by a conceptual flow model.

Rainfall incident on a catchment is affected by immediate surface/near surface runoff and longer-term evapotranspiration loss. The remainder constitutes recharge to subsurface water stores. Tracer (chemical or isotopic) concentrations in the input are modified by passing through the hydrological system (as represented by the flow model) before appearing in the output. The convolution integral and an appropriate flow model are used to relate the tracer input and output (Maloszewski et al., 1983). The convolution integral is given by

$$C_{out}(t) = \int_{o}^{\infty} C_{in}(t-\tau)\, h(\tau)\, d\tau \qquad (18)$$

where C_{in} and C_{out} are the input and output tracer concentrations in the precipitation and streamflow respectively. t is calendar time and the integration is carried out over the transit times τ. h(τ) is the flow model or response function of the hydrological system. An additional term may be included for chemical or radioactive decay, but is not shown here. The TTD for the catchment is determined by matching the simulation to tracer measurements.

The selected flow model is normally assumed to apply to all of the samples from a particular stream (McGuire and McDonnell, 2006), because equation (18) applies to steady flow, although it is becoming clear that flow models change with catchment wetness (McGuire and McDonnell, 2010; McDonnell et al., 2010; Morgenstern et al., 2010; Birkel et al., 2012). Transit time analysis has mostly been applied to measurements on total streamflow based on the variations of environmental isotopes or chemicals (McGuire and McDonnell, 2006). However, there have been a number of studies where transit time distributions (TTDs) have been determined on different flow components (e.g. Maloszewski et al., 1983; Uhlenbrook et al., 2002; Stewart et al., 2007; Stewart and Thomas, 2008) using both chemical/stable isotope variations and tritium. These give better insight into the runoff generation processes.

3 Results of Application of New Approaches to Glendhu GH1 Catchment

The BRM baseflow separation method is applied to Glendhu GH1 catchment to investigate its applicability, demonstrate how it is applied and present what it reveals about the catchment. The results are compared with those from two other widely-used baseflow separation filters, the Hewlett and Hibbert (1965) method (called the H & H method below) and the Eckhardt (2005) method (called the Eckhardt method). We need to know the values of the parameters of these methods in order to apply them, the parameters are k (the universal slope of the rise through the event) for the H & H method, BFI_{max} (the maximum value of the baseflow index that can be modeled by the Eckhardt algorithm) and a (recession constant) for the Eckhardt method, and f (bump fraction) and k (slope of the rise) for the BRM method.

The parameter k for the H & H method has the universal (arbitrary) value of 0.0472 $mmd^{-1}h^{-1}$, as explained above. Estimation of the Eckhardt parameters is not so simple (see above) and has similarities to the estimation of the BRM parameters. There are two ways of determining the Eckhardt and BRM parameters: (1) By adjusting the baseflow parameters to give the best fits between the baseflows and the tracer-determined pre-

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event or baseflow water. This is regarded as the only objective way, and is able to be used in this paper because deuterium data is available for Glendhu (Bonell et al., 1990). But it requires tracer data during events which is not generally available for catchments. (2) Where there is no tracer data, the parameters can be estimated in several ways. In the prescribed Eckhardt method, a is calculated from the late part of the recession by an objective procedure. BFI_{max} is estimated to a first approximation based on the hydrological and hydrogeological characteristics of the catchment (Eckhardt (2005), and possibly more precisely by hydrograph methods suggested by Collischonn and Fan (2013) (see below). For the BRM, the BFI can be estimated approximately from catchment considerations (in analogy with the Eckhardt method) and possibly more precisely by a flow duration curve method suggested by Collischonn and Fan (2013). The BFI can then be used as a constraint while optimising the fit between the sum and the streamflow (where the sum equals the baseflow plus a fast recession). This optimising procedure was used in the earlier version of this paper (Stewart, 2014a). The optimising procedure was also applied to the H & H and Eckhardt methods in the Author's Reply (Stewart, 2014b).

Once baseflow separation has been achieved, recession analysis via the recession plot can be applied to the separated quickflow and baseflow components (the new approach suggested here), in addition to the streamflow (the traditional method). Whereas the streamflow can show high power law slopes (d values of 2 or more), the components generally have slopes around 1.5. However, note that the baseflow is a subdued reflection of the streamflow because of its calculation procedure (equations 6 and 7) ~~the baseflow~~ in the early part of the recession. In the late part of the recession, the baseflow and the streamflow are the same. Flow duration curve analysis can also be applied to the components as well as to the streamflow in order to show the makeup of the streamflow at each exceedence percentage.

In the following, the characteristics of the Glendhu Catchment are briefly described, then the three baseflow separation methods are applied and compared, and then the effects of applying recession analysis and FDC analysis to the separated components as well as to the streamflow itself are examined. The methods are then applied to the master recession curve

~~6 Glendhu Catchment~~

3.1 Hydrogeology of Glendhu Catchment

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GH1 catchment (2.18 km^2) is situated 50 km inland from Dunedin in the South Island of New Zealand. It displays rolling-to-steep topography and elevation ranges from 460 to 650 m.a.s.l. (Fig. 3). Bedrock is moderately-to-strongly weathered schist, with the weathered material filling in pre-existing gullies and depressions. Much of the bedrock-colluvial surface is overlain by a loess mantle of variable thickness (0.5 to 3 m). Well-to-poorly drained silt loams are found on the broad interfluves and steep side slopes, and poorly drained peaty soils in the valley bottoms.

Amphitheatre-like sub-catchments are common features in the headwaters and frequently exhibit central wetlands that extend downstream as riparian bogs. Snow tussock (Chionochloa rigida) is the dominant vegetation cover and headwater wetlands have a mixed cover of sphagnum moss, tussock, and wire grass (Empodisma minus). The mean annual temperature within GH1 at 625 m.a.s.l. elevation is 7.6C, and the mean annual rainfall is 1350 mm/a. Annual runoff is measured at all weirs to an accuracy of ±5% (Pearce et al., 1984).

Pearce et al. (1984) showed that GH1 and GH2 (before the latter was forested), had very similar runoff ratios. Long term precipitation and runoff at GH1 weir average 1350 mm/a and 743 mm/a respectively (Fahey and Jackson, 1997). Actual evapotranspiration of 622 mm/a was measured for tussock grassland in the period April 1985 to March 1986 at a nearby site in catchment GH1 (570 m a.s.l.) by Campbell and Murray (1990) using a weighing lysimeter. The Priestley-Taylor estimate of PET was 643 mm/a for the period, and 599 mm/a for 1996, so ET for GH1 is taken as 600 mm/a. The GH1 hydrological balance is: Precipitation (1350 mm/a) – ET (600 mm/a) = Runoff (743 mm/a), and loss around the weir is clearly negligible (Pearce et al. 1984). Comparison of runoff from GH1 and GH2 (after the latter had been forested for 7 years), showed that there was a decrease of 260 mm/a in GH2 runoff due to afforestation (Fahey and Jackson, 1997). Consequently, the GH2 balance is: Precipitation (1350 mm/a) – ET (860 mm/a) = Runoff (483 mm/a). The increase in ET for GH2 is attributed to increased interception (with evaporative loss) and transpiration.

Bonell et al. (1990) carried out separation of event and pre-event waters using deuterium and chloride concentrations to investigate the runoff mechanisms operating in GH1 and GH2 at Glendhu (see example in Fig. 2a). The results showed that for quickflow volumes greater than 10 mm (over the catchment area), the early part of the storm hydrograph could be separated into two components, pre-event water from a shallow unconfined groundwater aquifer, and event water attributed to "saturated overland flow" (Bonell et al., 1990). The pre-event water responded more rapidly to rainfall than event water. The late part of the storm hydrograph consisted of pre-event water only. Hydrographs for smaller storms had pre-event water only, but this may be partly because measurement accuracy of the deuterium may not have been sufficient to detect event water in these smaller events.

3.2 Application of Baseflow Separation Methods

~~7 Application of the BRM Baseflow Separation Method to Glendhu Streamflow~~

~~7.1 Winter and summer events~~

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Fig. 2a showed the pre-event component determined using deuterium during the large storm on 23 February 1988 (Bonell et al., 1990). The pre-event component has a BFI of 0.529 during the event (Table 1). Baseflows determined by the three baseflow separation methods are compared with the pre-event component in Figs. 4a-c. The goodness of fit of the baseflows to the pre-event water was determined using least squares,

$$sd = (\sum(B_i - PE_i)^2/N)^{0.5} \qquad (19)$$

where PE_i is the pre-event water at each time step, and N the number of values.The H & H baseflow is totally inflexible with a pre-determined parameter and does not match the BFI or shape of the pre-event hydrograph at all well (its BFI is 0.255 and sd is 6.41 mm/d, Table 1, Fig. 4a).

The Eckhardt baseflow with prescribed parameters (BFI_{max} = 0.8 for a porous perennial stream, a = 0.99817 calculated from the baseflow recession) does not match the pre-event hydrograph well either (BFI = 0.272, sd = 6.34 mm/d, Fig. 4c). However, a better match of the BFI and a slightly better fit is found with the optimized version when both BFI_{max} and a are treated as adjustable parameters using the method of Zhang et al., 2013 (i.e. BFI_{max} was adjusted first to match the Eckhardt BFI to the pre-event BFI, then a was adjusted to improve the fit between the shapes of the baseflow and the pre-event hydrographs, then the steps were repeated, etc.). An extra constraint was to prevent the Eckhardt baseflow falling too far below the streamflow at very low flows. These give a BFI of 0.524, which is the same as that of the pre-event hydrograph (0.529, Table 1), and the baseflow has a similar shape to the pre-event water (Fig. 4c), but the peak is delayed in time giving only a small improvement in the fit (sd = 5.40 mm/d).

The BRM baseflow gives a BFI of 0.526, the same as that of the pre-event hydrograph, and the fit between the two hydrographs is very close (sd = 1.98 mm/d, Fig. 4e). This reflects the choice of the algorithm to mimic tracer baseflow separations (equations 7 and 8), which it does very well.

The three methods have been applied to hourly streamflow data for 1996. A sample of each is shown for a two-week period in Figs. 4b, 4d and 4f. Only this short period is shown because otherwise it is difficult to see the baseflow clearly. The parameters used are listed in Table 2 along with the annual BFI values determined. The H & H baseflow rises gradually through the stormflow peak, then follows the falling limb of the streamflow after it intersects with it. The prescribed Eckhardt baseflow also rises gradually through the peak then stays close to the recessing streamflow. The optimised Eckhardt baseflow rises sharply then falls sharply when it intersects the falling limb of the streamflow, and then gradually falls below the recessing streamflow curve. The BRM baseflow mirrors the streamflow peak then follows the falling streamflow after it intersects with it. It is also instructive to compare the BFI values derived by the various methods.The H & H method gives a BFI of 0.679, the Eckhardt methods BFIs of 0.617 and 0.754 and the BRM method a BFI of 0.780 (almost the same as the Q_{90}/Q_{50}–derived BFI of 0.779, see below).

Table 2 also shows estimates based on the characteristic flows from the flow duration curve (Q_{90}/Q_{50}). Smakhtin (2001) observed that the ratio of the two characteristic flows could be used to estimate BFI, and Collischonn and Fan (2013) derived equations connecting Q_{90}/Q_{50} and BFI_{max} and BFI based on results from fifteen catchments of varying sizes in Brazil. Their equations were

$$BFI_{max} = 0.832\frac{Q_{90}}{Q_{50}} + 0.216 \qquad (20)$$

$$BFI = 0.850\frac{Q_{90}}{Q_{50}} + 0.163 \qquad (21)$$

These have been used to determine BFI_{max} and BFI in Table 2 (marked as FDC BFImax and FDC BFI for clarity) for comparison with those derived using the three baseflow separation methods. There is a close correspondence between the FDC BFI and the BRM BFI, as noted, but the others are not particularly close. The backwards filter method of Collischonn and Fan (2013) has also been applied to estimate the BFI_{max} values for the

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prescribed and optimized Eckhardt parameters (Table 2). The resulting BFIs do not agree particularly well with the BFIs obtained from the other methods.

The second way of determining the BRM parameters was described in the earlier version of this paper (Stewart, 2014a). Streamflow data was available for a summer month (February 1996) and a winter month (August 1996). These had different BFIs, but the bump fractions (f) obtained by finding the best-fits of the sum (i.e. baseflow plus fast recession) to the streamflow were similar at 0.16, while the slopes (k) were different. The fast recession was assumed to have a quadratic form (i.e. d = 1.5, equation 14) when fitting the sum to the streamflow, but the exponential (d = 1) and reciprocal (d = 2) forms were also tested and found to give the same quadratic result for the quickflow (i.e. slope of d = 1.5 on Fig. 5c) (Stewart 2014a). This optimizing process was also applied to the Eckhardt method in Stewart (2014b).

3.3 Application of New Approach to Recession and Flow Duration Curve Analysis

The recession behavior of the streamflow, BRM baseflow and BRM quickflow from the hourly streamflow record during 1996 are examined on recession plots (i.e. -dQ/dt versus Q) in Figs. 5a-c. ~~Quickflow is determined by subtracting baseflow from streamflow.~~ Discharge data less than two hours after rainfall has been excluded. ~~Quickflow is determined by subtracting baseflow from streamflow.~~ The three figures have the same two lines on each. The first is a line through the lower part of the streamflow data with slope of 6 (this is called the streamflow line, see Fig. 5a). The second is a line through the quickflow points with slope of about 1.5 (this is called the quickflow line, see Fig. 5c). The streamflow points define a curve approaching the quickflow ~~points~~ line at high flows when baseflow makes up only a small proportion of the streamflow, and diverging from it~~them~~ when baseflow becomes more important. The slope of a line through the points becomes much steeper in this lower portion (as shown by the streamflow line), The baseflow points (Fig. 5b) have a similar pattern to the streamflow points because the BRM baseflow shape mimics the streamflow shape at high to medium flows because of the form of equations 7 & 8. At low flows the baseflow plots on the streamflow and hence shows the same low flow pattern as the streamflow.

Quickflow is determined by subtracting baseflow from streamflow (Equation 1). It rises rapidly from zero or near-zero at the onset of rainfall to a peak two to three hours after rainfall, then falls back to zero in around 24 to 48 hours unless there is further rain. ~~(the line shown on the lower part of the streamflow points has a slope of 4).~~ The quickflow points at flows above about 1 mm/d fall on the~~a~~ quickflow line with slope ~~about~~ of 1.5. E~~e~~rrors become much larger as quickflow becomes very small (i.e. as baseflow approaches streamflow and quickflow is the small difference between the two). As Rupp and Selker (2006) have noted "time derivatives of Q amplify noise and inaccuracies in discharge data". Nevertheless the quickflow points show a clear pattern supporting near-quadratic fast recessions. The streamflow points might~~would~~ be expected to show a recession slope of 1.5 at very low flows as the streamflow becomes dominated by baseflow, but the data may not be ~~are not~~ accurate enough to show this (see Section ~~7.3~~3.4).

Fig. 5d shows the recession plot for 12/2/96 to 15/2/96 when there were the highest flows in the month, although they were still quite small. The rest of the month had very low flows so is not plotted in Fig. 5d. Again, the lower streamflow points show a slope of about four, and the quickflow points a slope of about 1.5 (i.e. near-quadratic recession behavior).

Flow duration curves for streamflow, baseflow and quickflow are given in Figs. 4e 5dand 5e. The streamflow FDCs has a ve relatively very shallow slopes indicating groundwater dominance over the higher at lower exceedance percentages. In the winter period (Fig. 4e, August 1996), Sstreamflow began to diverges noticeably from baseflow at about 40%below about 17% exceedence (when quickflow had reached reaches about 10% of streamflow). In the summer period (Fig. 5e, February 1996), streamflow began to diverge from baseflow at around 90% exceedence. Thisese figures reveals the reasons for breakpoints (i.e. changes of slope) in streamflow FDCs, which have been related to contributions from different sources/reservoirs in catchments (Pfister et al., 2014).

7.2 Choice of fast recession curve

It is not immediately apparent what type of recession curve would be appropriate to describe drainage from the fast water stores. Linear reservoirs (d=1) will have the exponential recession equation given by equation (9). Fig. 6a shows the fit between the streamflow recession and the sum using the exponential form. The simulation does not bend enough to match the streamflow and gives a relatively poor fit as shown by the standard deviation plotted in Fig. 4c. The quickflow was calculated using the best fit (f=0.06, Table 1) and is shown in a recession plot in Fig. 6b. The line through the quickflow points has power-law slope around 1.3 so is quite similar to that expected for a quadratic aquifer (1.5).

The result of using the quadratic form (d=1.5) has already been demonstrated (Figs. 4b-d). This gives a more accurate fit between the sum and the streamflow, and yields a power-law slope of around 1.4 which is close to that expected for a quadratic aquifer.

For d=2, substituting in equation 17 gives the reciprocal equation

$$Q_t = Q_o(1+\gamma t)^{-1} \qquad (20)$$

whose parameters are Q_o and γ. Fig. 6c shows the fit between the sum and the streamflow using this equation. In this case, the simulation bends too much and the fit to the streamflow is relatively poor. The quickflow has been calculated using the best fit (f=0.3) and is plotted in Fig. 6d. The power-law slope of the line through the quickflow points is 1.5, again close to that expected for a quadratic aquifer.

These comparisons show that quickflow drains from approximately quadratic reservoirs and the conclusion is not affected by what type of fast recession is assumed. But the fit is best when quadratic recessions are assumed so that is a good reason to use the quadratic equation for fast recessions.

7.33.4 "Master" recession curve for Glendhu

Fig. ~~7a~~ 6a shows the master recession curve not involving snowmelt or additional rainfall, derived by Pearce et al. (1984) from the longest recessions observed during a three year study period in GH1 and GH2 (before afforestation of GH2). The data for the curve come from four storm events during winter and six during summer. These authors reported that “This recession curve is typical of high to medium runoff events. The plot shows that there is a marked change of slope between the early and late parts of the recessions (at a flow of about 2.6 mm/d). Quickflow, as defined by the method of Hewlett and Hibbert (1967), comprises 30% of the annual hydrograph and ceases shortly after the change in recession rate in most hydrographs.”

The streamflow points from the master curve have been fitted by the sum of a quadratic fast recession curve and the baseflow (Fig. ~~7b~~6b). The ~~early part of the~~ baseflow was ~~determined~~ calculated using the parameters identified by the fitting to the pre-event hydrograph above ~~the methods outlined above (with~~(f = 0.40~~, and~~ k = 0.009~~0876~~ mm d^{-1} h^{-1}, Table 2)~~. , and~~ These parameters give a BFI of 0.828. During the late part of the recession, when the baseflow dominates the streamflow, ~~by~~ a slow recession curve was fitted to the streamflow. The data are given in Table 2~~1~~. The sum fits all of the points well and there is a smooth transition between the early and late parts of the recession. The inflexion point (Fig. 7b) occurs when the baseflow stops falling and begins to rise. The inflexion point is therefore an expression of the change from the bump to the rise in the baseflow and supports the BRM baseflow separation method. The change from early to late recession when baseflow begins to dominate the recession comes considerably after the inflexion point (Fig. 6~~7~~b).

It is also instructive to see the recession plot of the data (Fig. ~~7c~~6c). The quickflow (i.e. fast) and baseflow (i.e. slow) recessions are shown, both with slopes of 1.5. The early part of the baseflow (i.e. the bump) is shown by the dashed curve. The sum of the fast recession and the baseflow, which fits the streamflow points, is close to the fast recession at high flow and matches the slow flow recession at low flows, as expected. The slope is steeper at the medium flows between these two end states (the slope is about 6). This ~~reiterates~~ emphasises the point that the slope of the streamflow points on a recession plot is meaningless in terms of catchment storages at medium flows. Only the slopes of the quickflow and the late-recession~~ow~~ streamflow~~baseflow~~ (which is the same as the late-recession baseflow) ~~slopes~~ have meaning in terms of storage types.

Fig. ~~7d~~ 6d shows the fraction of baseflow in the streamflow versus time according to the tracer-based BRM. B~~The b~~aseflow makes up ~~17~~32% of the streamflow at the highest flow, then rises to 50% in about three hours (0.12 d), 75% at 14 hours (0.6 d) and 95% at 43 hours (1.8 d). The change from early to late recession is shown at 1.8 d.

~~7.4 Deuterium separation flow event~~

~~Bonell et al. (1990) carried out separation of event and pre-event waters using deuterium and chloride concentrations to investigate the runoff mechanisms operating in GH1 and GH2 at Glendhu (Fig. 2a). The results showed that for quickflow volumes greater than 10 mm (over the catchment area), the early part of the storm hydrograph could be attributed to two sources, pre-event water from a shallow unconfined groundwater aquifer, and event water from “saturated overland flow” (Bonell et al., 1990). The pre-event water responded more rapidly to rainfall than event water. The late part of the storm hydrograph consisted of pre-event water only.~~

Fig. 8a shows their results for the large storm on 23 February 1988. Their pre-event water hydrograph is compared with quickflow and baseflow hydrographs determined by the BRM method (using the same baseflow constants as for the 16/8/96 storm, Table 1). However, note that rainfall continued for several hours after the peak of the flow event so the sum could only be matched to the streamflow several hours after the peak. All of the component hydrographs have similar shapes, but the pre-event water peak is higher than the baseflow peak (Fig. 8a). The baseflow could be adjusted to fit the pre-event water peak, but this would require f = 42%, k ~ 0 mm d^{-1} h^{-1}, and would not be compatible with the previous results (sections 7.1 and 7.2), as it would necessitate much higher baseflow fractions over all events in Glendhu Catchment. Instead, it is believed that "pre-event water" is a more encompassing term than "baseflow", and in particular includes a component here called "soil water". Since baseflow is considered to be slow storage water, then the pre-event component logically contains both slow storage and fast storage (i.e. soil) waters.

The soil water hydrograph is shown in Fig. 8b along with the event water and baseflow hydrographs. Soil water was computed by subtracting baseflow from pre-event water. All three components show similar shapes. This "three component hydrograph separation" can be compared with that reported by Joerin et al., 2002 and Iorgulescu et al., 2005 (see Fig. 2b) for the Haute-Mentue Catchment in Switzerland based on the chemicals silica and calcium. Their three components were called direct precipitation (equivalent to event water here), acid soil (soil water), and deep groundwater (baseflow).

7.5 Tritium measurements as probes of the baseflow

Tritium measurements were reported by Stewart and Fahey (2010) for GH1 stream at Glendhu. Samples were collected on three occasions (5/12/2001, 21/2/2005 and 26/2/2009) in moderate streamflow conditions in summer. The present analysis shows that the samples were all collected when baseflow was dominant (not shown). The results were interpreted as showing the presence of two components in the baseflow. One component was young groundwater (with mean transit time of a few months) from loess horizons and weathered colluvium mantling the slopes and connected to the stream by a shallow groundwater system making up 84% of the baseflow. The other was old groundwater (with mean transit time of 26 years) from aquifers in the crystalline schist bedrock connected to the stream via a wetland. It is expected that the fraction of the young component (b) would tend to be greater at higher baseflow giving the streamwater a younger overall mean transit time (τ_m), according to the equation

$$\tau_m = b\tau_{m1} + (1 - b)\tau_{m2} \qquad (21)$$

where τ_{m1},τ_{m2} are the mean transit times of the baseflow components. Thus τ_m may vary inversely with streamflow. Further tritium measurements are needed to show this at Glendhu, but measurements at Toenepi (which has similar rainfall and is situated near Hamilton in the North Island of New Zealand) have demonstrated such variations (Morgenstern et al., 2010).

84 Discussion

~~8~~4.1 A new baseflow separation method: Advantages and limitations

A new baseflow separation method (the BRM method) is presented. Advantages of the method are:

(1) It simulates the shape of the baseflow or pre-event component determined by tracers more accurately than previous baseflow separation methods. This should mean that it gives more accurate baseflow separations and BFIs, because tracer separation of the hydrograph is regarded as the only objective method. The BRM method involves a rapid response to rainfall (the "bump") and then a gradual increase with time following rainfall (the "rise"). ~~is based on evidence from tracer separations, which show that all components of streamflow including groundwater show rapid responses to rainfall (the "bump"). In the case of groundwater it is attributed to celerity in the unsaturated zone. The method also includes a gradual increase with time following rainfall (the "rise") which is attributed to slow recharge of the groundwater aquifer. Such recharge must occur, otherwise the aquifer would run dry.~~

(2) The parameters (f and k) quantifying the baseflow can be determined by fitting the baseflow to tracer hydrograph separations (as illustrated in Section 3.2) or by fitting the sum of the baseflow and a fast recession to the recession hydrograph under the constraint of a BFI determined by flow considerations (as illustrated in Stewart, 2014a). ~~This is applied to the early (fast recession influenced) part of the recession.~~

(3) The method can be applied using tracer data or streamflow data alone, and

(4) The method is easy to implement mathematically.

Current limitations or areas where further research may be needed are:

(1) Where there is no tracer data, s~~S~~pecification of f and k depends on an initial estimate of the ~~baseflow fraction~~BFI, although the optimisation procedure means that this is not critical.

(2) T~~t~~he method produces an avergaed ~~generalised~~ representation of the baseflow hydrograph when applied to long-term data, so seasonal or ~~inter/~~intra catchment variations are likely.

(3) S~~s~~eparation of the hydrograph into three or more components (as shown by some tracer studies) could be explored. The next section considers three components.

4.2 Calibration of the BRM Algorithm

This paper describes and demonstrates two ways of calibrating the BRM method (i.e. determining its parameters f and k). These were also applied to the H & H and Eckhardt methods. These are (1) fitting the methods to tracer separations, and (2) applying an optimizing or other procedure. The tracer-based (first way) is demonstrated in this paper, the optimizing procedure (second way) was demonstrated in the early (unreviewed) version of this paper (Stewart, 2014a) and applied to the Eckhardt method in Stewart (2014b). Additional procedures put forward by Collischon and Fan (2013), based on characteristic flow duration curve flows (Q_{90}/Q_{50}) and a backwards filter, are also compared with the other methods in this paper, but are not considered in detail.

Tracer separation of streamflow components depends on the tracer or tracers being used and the experimental methods, etc. Klaus and McDonnell (2013) recently reviewed the use of stable isotopes for hydrograph separation and restated the five underlying assumptions. In the present case, deuterium was used by Bonell et al. (1990) to separate the streamflow into event and pre-event components (Fig. 2a). The pre-event component includes all of the water present in the catchment before the recorded rainfall event. The pre-event component therefore includes soil water mobilized during the event as well as groundwater. Three-component tracer separations have often been able to identify soil water contributions along with direct precipitation and groundwater contributions in streamflow (e.g. Iorgulescu et al. (2005) identified direct precipitation, acid soil and groundwater components, Fig. 2b).

The second way of calibrating the BRM assumes a value for the BFI and then uses this as a constraint to enable the sum (baseflow plus a fast recession) to be fitted to a streamflow recession (winter and summer events were examined in Stewart, 2014a). It is assumed that when the best-fit occurs (i.e. the baseflow has the optimum shape to fit to the streamflow) that the baseflow shape will be most similar to the "true" groundwater shape. The winter event BFI assumed is approximately in agreement with the BFIs given by the H & H and prescribed Eckhardt methods when applied to the 1996 streamflow record (the BFIs given by the H & H, prescribed Eckhardt and winter BRM methods are 0.679, 0.617 and 0.622 respectively). If this represents groundwater alone, then the difference with the pre-event water (or the BRM baseflow matched to it) is the soil water component as explained in Stewart (2014a). The groundwater and soil water components derived are shown in Fig. 7 for the 23/2/88 event and two-week period in 1996. The soil water component responds to rainfall more than the groundwater during events, then falls more rapidly after them. In the absence of tracers, it is not generally possible to identify the true groundwater component, but some BFI results appear to be "hydrologically more plausible" than others (quoted phrase from Eckhardt, 2008). The BFI assumed for the groundwater here is considered to be hydrologically plausible.

~~8~~4.~~2~~3 Why is it necessary to apply baseflow separation to understand the hydrograph?

The answer is straightforward:

Because streamflow is a mixture of quickflow and baseflow components, which have very different characteristics and generation mechanisms and therefore give very misleading results when analysed as a mixture.

Previous authors (e.g. Hall, 1968, Brutsaert and Nieber, 1977, Tallaksen, 1995) addressed "baseflow recession analysis" or "low flow recession analysis" in their titles, but nevertheless included both early and late parts of the recession hydrograph in their analyses. Kirchner (2009, P. 27) described his approach with the statement "the present 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, and makes the analysis simple, general and portable". This

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work contends that catchment runoff is *not* a single continuum, and the varying contributions of two or more very different components need to be kept in mind when the power-law slopes of the points on recession plots are considered.~~can and should be separated into its two components for analysis.~~ Lack of separation has probably led to misinterpretation of the ~~results of recession analysis in many previous studies, and may have distorted scientific understanding of catchment functioning and hindered rainfall-runoff modelling~~slopes in terms of catchment storage reservoir types.

Kirchner's (2009~~6~~) approach may be appropriate for his main purpose of "doing hydrology backwards" (i.e. inferring rainfall from catchment runoff), but the current author suggests that it gives misleading information about catchment storage reservoirs (as illustrated by the different slopes of streamflow, quickflow and probably baseflow (Fig. 6c).~~in Figs. 4d, 5d and 7c).~~ Likewise Lamb and Beven's (1997) approach ~~was~~ may have been fit-for~~to~~-purpose for assessing the "catchment saturated zone store", but by combining parts of the early recession with the late recession may give misleading information concerning catchment reservoir type (and therefore catchment response). Others have used recession analysis on early and late streamflow recessions for diagnostic tests of model structure at different scales (e.g. Clark et al., 2009; McMillan et al., 2011) and it is suggested that these interpretations may have produced misleading information on storage reservoirs.

Evidence of the very different characteristics and generation mechanisms of quickflow and baseflow are provided by:

(1) The different timings of their releases to the stream (quick and slow) as shown by the early and late parts of the recession curve. (Note: The rapid response of slow storage water to rainfall (the "bump" in the BRM baseflow hydrograph) does not conflict with this because the bump is due to celerity not to fast storage.)

(2) Many tracer studies (chemical and stable isotope) have shown differences between quickflow and baseflow, and substantiated their different timings of storage.

(3) Transit times of streamwaters show great differences between quickflow and baseflow. While quickflow is young (as shown by the variations of conservative tracers and radioactive decay of tritium), baseflow can be much older with substantial fractions of water having mean transit times beyond the reach of conservative tracer variations (4 years) and averaging 10 years as shown by tritium measurements (Stewart et al., 2010).

These considerations show that quickflow and baseflow are very different and in particular have very different hydrographs, so their combined hydrograph (streamflow) does not reflect catchment characteristics (except at low flows when there is no quickflow).

~~8~~4.~~3~~4 A new approach to recession analysis

It appears that streamflow recession analysis is a technique in disarray (Stoelzle et al., 2013~~2~~). Different methods give different results and there is "a continued lack of concensus on how to interpret the cloud of data points" (Brutsaert, 2005). ~~little consensus on how best to apply recession analysis to streams. And in fact~~ This work asserts that ~~the~~ recession studies have been giving misleading results in regard to catchment functioning because streamflow is a varying mixture of components ~~baseflow separation has not been applied before analysis~~ (unless the studies were ~~exclusively~~ applied to~~on~~ late recessions only~~or stringent conditions have been applied~~). The new approach of applying recession analysis to the separated quickflow ~~and baseflow~~ component~~s~~ as well as streamflow may help to resolve this confusion, by demonstrating the underlying structure due to the different components in recession plots (as illustrated in Fig. 6c). Plotting baseflow from the late part of the recession may also be helpful. In particular, it is believed that recession analysis on quickflow, and late recession baseflow as well as streamflow will give information that actually pertains to those components, giving a clearer idea than ever before on the nature of the water storages in the catchment, and contributing to broader goals such as catchment characterisation, classification and regionalisation.

Observations from the limited data set in this paper and from some other catchments to be reported elsewhere are:

(1) Quickflow appears to be quadratic in character (Section 7.2). This may result from a variety of processes such as surface detention, passage through saturated zones within the soil (perched zones) or within riparian zones near the stream. Whether this is true of catchments in a wider variety of climatic regimes remains to be seen.

(2) The baseflow reservoirs at Glendhu appear to be quadratic in character, as has been previously observed at ~~some~~ many other catchments by other authors (Brutsaert and Nieber, 1977; Wittenberg, 1999; Dewandel, 2005; Stoelzle et al., 2013). Hillslope and valley groundwater aquifers feed the water slowly to the stream.

(3) The many cases of high power-law slopes (d>1.5) in recession plots reported in the literature appear to be artifacts due to plotting early recession streamflow (particularly in the mid-flow range) instead of separated components. This may have ~~has~~ also contributed to the wide scatter of points generally observed in recession plots (referred to as “high time variability in the recession curve” by Tallaksen, 1995).

(4) The most problematic parts of streamflow recession curves are those at intermediate flows when quickflow and baseflow are approximately equal. This is where steep power-law slopes are found. Data at high flows ~~are often removed because they are shortly after rainfall or~~ are dominated by quickflow, and baseflow contributes almost all of the flow at low flows, so these parts ~~are less confusing~~do not have high power-law slopes.

(5) Some other causes of scatter in recession plots are: insufficient accuracy of measurements at low flows (Rupp and Selker, 2002), effects of rainfall during recession periods (most data selection methods try to exclude these), different rates of evapotranspiration in different seasons, different effects of rainfall falling in different parts of the catchment, and drainage from different aquifers in different dryness conditions. These effects will be able to be examined more carefully when the confounding effects of baseflow are removed from intermediate flows.

(6) Splitting the recession curve into early and late portions based on baseflow separation turns out to be a very useful thing to do. The early part has quickflow plus the confounding effects of baseflow, while the late part has only baseflow. The late part starts when baseflow becomes predominant (>95%, Fig. ~~7d~~6d), this can be calculated by identifying the point where $B_t/Q_t = 0.95$ during a recession. The separation can be made

It appears that at Glendhu, t~~T~~he inflexion point~~, when visible,~~ records a change of slope *in the baseflow* and lies within the early part of the recession.

(7) The close links between surface water hydrology and groundwater hydrology are revealed as being even closer by this work. Baseflow is ~~almost entirely~~mostly groundwater, and quickflow is also starting to look distinctly groundwater-influenced (or saturation-influenced). The success of ~~a~~ groundwater models (Gusyev et al., 2013, 2014) in simulating tritium concentrations and baseflows in streams while being calibrated to groundwater levels in wells ~~and groundwater levels in wells~~ shows the intimate connection between the two. The feeling that catchment drainage can be treated as a single continuum of hydrological behavior has probably prevented recognition of the disparate natures of the quick and slow drainages. This may be a symptom of the fact that surface water hydrology and groundwater hydrology can be regarded as different disciplines (Barthel, 2014). Others however are crossing the divide by examining geological controls on BFIs (Bloomfield et al., 2009) and relating baseflow simulation to aquifer model structure (Stoelzle et al., 2014).

~~8.4 Transit time analysis and chemical-discharge relationships~~

~~In line with the thesis of this work, it is contended that transit time analysis should also take account of the flow components being analysed. Transit time analysis applied to undifferentiated streamflow has similar problems to recession analysis being applied to streamflow. At first sight, it appears that transit time analysis looks through the mix of waters that is streamflow by assigning a distribution of transit times to the water in the stream. However, Stewart et al. (2010, 2012) have pointed out that the most-used technique (smoothing of stable isotope or chemical variations) does not "see" water older than about four years. The unseen older water ("hidden streamflow") is a problem because incorrect conclusions are then drawn about the flowpaths through the catchment, in particular the amount of deep (bedrock) paths are underestimated. When the stable isotope/chemical variation method is used, an effort should be made to quantify the amount of old baseflow water (by modelling or using tritium or gas tracers ($^3H/^3He$, CFCs, SF_6)). When tritium alone is used, only baseflow should be sampled as tritium measurements reveal old water but are not effective for dating young water.~~

~~As with recession and transit time analysis, results of regular measurements of chemicals and environmental isotopes in streams should also be considered in relation to the flow components. Correlations of chemicals with discharge (e.g. Godsey et al., 2009) based on regularly spaced sampling intervals may be most strongly influenced by baseflow, because baseflow conditions apply for a much greater proportion of the time than quickflow conditions and even when quickflow is present there is also baseflow. Only rarely is quickflow dominant in the stream. Of course, many other chemical and isotopic studies in streams have taken explicit notice of different stream components (e.g. by applying mixing models such as EMMA - end member mixing analysis, e.g. Christophersen and Hooper, 1992).~~

~~8.5 Nature of quickflow and baseflow stores at Glendhu~~

~~Although Glendhu data has been used, this study has not primarily been about Glendhu. Nevertheless some observations can be made about the water stores and functioning of Glendhu Catchment (GH1).~~

~~Quickflow is composed of water stored in wetlands near the stream fed by regolith on the surrounding hillslopes (soil water) plus event water. Bowden et al. (2001) showed that lateral flow in the thin Organic and A Horizon layers in the lower hillslopes was substantial and probably often emerged as flow over the wetland surface in large events (identified as the soil water component in Fig. 8). To this was added direct rainfall (event water). The quickflow reservoirs have a quadratic signature reflecting near-stream groundwater involvement (Figs. 4d, 5d).~~

~~Most of the baseflow (84%) is slow drainage from deep loess horizons (layers B and C) and weathered bedrock colluvium mantling the slopes which connect through a shallow groundwater system to the stream. This has relatively young MTTs of a few months to years. A small proportion (16%) is much older water (MTT=26 yrs) that drains through the schist bedrock and emerges in or around the wetland and stream (Stewart and Fahey, 2010). Both have the quadratic signature (Fig. 7c).~~

~~Four flow components have been identified at Glendhu based on the previous tracer studies (Bonell et al., 1990; Stewart and Fahey, 2010). Nevertheless, my approach here has been to separate the streamflow into two components, because 1) the older baseflow component is small in volume compared to the younger baseflow component so the younger component dominates baseflow, and 2) the quickflow components do not appear to differ greatly in their transit time responses. However, if three components with different transit times can be justified based on tracer studies (e.g. Iorgulescu et al., 2005) then recession analysis can be performed just as easily on three components as on two.~~

~~9~~5 Conclusions

This paper has two main messages. The first is the introduction of a new baseflow separation method (the bump and rise method or BRM). The advantage of the BRM is that it enables simulation of the shape of the baseflow or pre-event component determined by tracers more accurately than previous methods. Tracer separations are regarded as the only objective way of determining baseflow separations and BFIs, so the BRM method should give more accurate baseflow separations and BFIs. The BRM parameters are determined by either fitting them to tracer separations (which are usually determined on a small number of events) as illustrated in this paper, or by estimating the BFI and using it as a constraint which enables determination of the BRM parameters by an optimization procedure on an event or events as illustrated in an earlier version of this paper (Stewart, 2014a). The BRM algorithm can then be simply applied to the entire streamflow record.

Current limitations or areas where further research could be needed are: (1) specification of f and k depends on tracer information or an initial estimate of the BFI, although the optimisation procedure means that this is not critical, (2) the method applied to long-term data produces an averaged representation of the baseflow hydrograph, so seasonal or intra catchment variations are likely, and (3) separation of the hydrograph into three components (as shown by some tracer studies) could be explored (and has been for the Glendhu Catchment).

The second main message is that recession analysis of streamflow alone on recession plots can give very misleading results regarding the nature of catchment storages because streamflow is a varying mixture of components. Instead, plotting separated quickflow gives insight into the early recession flow sources (high to mid flows), and separated baseflow (which is equal to streamflow) gives insight into the late recession flow sources (low flows). The very different behaviours of quickflow and baseflow are evident from their different timings of release from storage (shown by the early and late portions of the recession curve, by tracer studies, and by their very different transit times). Clearer ideas on the nature of the storages in the catchment can contribute to broader goals such as catchment characterisation, classification and regionalization, as well as modelling. Flow duration curves can also be determined for the separated stream components, and these help to illuminate the makeup of the streamflow at different exceedance percentages.

Conclusions drawn from applying recession analysis ~~curves~~ to separated components in this paper are: (1) M~~The m~~any cases of high power-law slopes (d>1.5) in recession plots reported in the literature are ~~revealed as~~likely to be artifacts due to plotting early recession streamflow instead of quickflow ~~or baseflow~~. The most problematic parts of streamflow recession curves are those at intermediate flows when quickflow and baseflow are approximately equal. This is where steep power-law slopes are found. ~~This has also contributed to the wide scatter of points generally observed in recession plots.~~ (2) Both quickflow and baseflow reservoirs appear to be quadratic in character, suggesting that much streamwater passes through saturated zones (perched zones in the soil, riparian zones, groundwater aquifers) at some stage. (3) Other causes of scatter in recession plots will be able to be examined more carefully when the confounding effects of baseflow are removed from intermediate flows. (4) Splitting the recession curve into early and late portions is very informative, because of their different makeups. The late part starts when baseflow becomes predominant.

Some suggestions for the way forward in light of the findings of this paper are: (1) Recession analyses (and ~~,~~ transit time analyses and chemical/discharge relationships) should be qualified with the component being analysed. This will make the significance of the results clearer. (2) Rainfall-runoff models should make more use of (non-linear) quadratic storage systems for simulating streamflow. (3) Much more data on many other catchment areas needs to be examined in this way to develop and refine these concepts.

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Table 1. Tracer calibration of the baseflow separation methods by comparison with pre-event water determined using deuterium for a streamflow event on 23 February 1988 at Glendhu GH1 Catchment (Bonell et al., 1990). The listed parameters were determined as described in the text. The standard deviations (sd) show the goodness of fit between the various baseflows and the pre-event water.

Separation Method	BFI[a]	f[a]	k[a] $mmd^{-1}h^{-1}$	BFI_{max}[a]	a[a] h^{-1}	sd mmd^{-1}
Pre-event water	0.529	--	--	--	--	--
H & H	0.255	--	0.0472	--	--	6.41
Eckhardt (prescribed)	0.272	--	--	0.8	0.9982	6.34
Eckhardt (optimised)	0.524	--	--	0.886	0.991	5.40
BRM	0.526	0.4	0.009	--	--	1.98

[a]BFI is baseflow index, f bump fraction, k slope parameter, BFI_{max} maximum value of the baseflow index that can be modelled by the Eckhardt algorithm, and a recession constant.

Table 2. BFIs and parameters of the baseflow separation methods applied to the hourly streamflow record in 1996, and to the master recession curve. The Q_{90}/Q_{50} ratio is from the flow duration curve for 1996, and the FDC BFI_{max} and FDC BFI are from equations 20 and 21 in the text.

Separation Method	BFI[a]	f[a]	k[a] $mmd^{-1}h^{-1}$	BFI_{max}[a]	a[a] h^{-1}
Q_{90}/Q_{50}	0.728	--	--	--	--
FDC BFI_{max} (eqn 20)	--	--	--	0.824	--
FDC BFI (eqn 21)	0.779	--	--	--	--
H & H	0.679	--	0.0472	--	--
Eckhardt (prescribed)	0.617	--	--	0.8	0.9982
Eckhardt (back filter)	0.521			0.593	0.9982
Eckhardt (optimised)	0.754	--	--	0.886	0.991
Eckhardt (back filter)	0.580	--	--	0.668	0.991
BRM	0.780	0.4	0.009	--	--
Master recession curve	0.828	0.4	0.009	--	--

[a]BFI is baseflow index, f bump fraction, k slope parameter, BFI_{max} maximum value of the baseflow index that can be modelled by the Eckhardt algorithm, and a recession constant.

Figure Captions

Figure 1 Quickflow and baseflow components of streamflow, and the early and late parts of the recession curve. Quickflow is represented by the area between the streamflow and baseflow curves, and baseflow is the area under the baseflow curve.

Figure 2 Tracer hydrograph separation results. (a) Event/pre-event water separation from catchment GH1, Glendhu, New Zealand using deuterium (replotted from Bonell et al., 1990). (b) Three component separation from Haute-Mentue research catchment, Switzerland using silica and calcium (replotted from Iorgulescu et al., 2005). R/F is rainfall, SF streamflow and the flow components are DP direct precipitation, AS acid soil and GW groundwater.

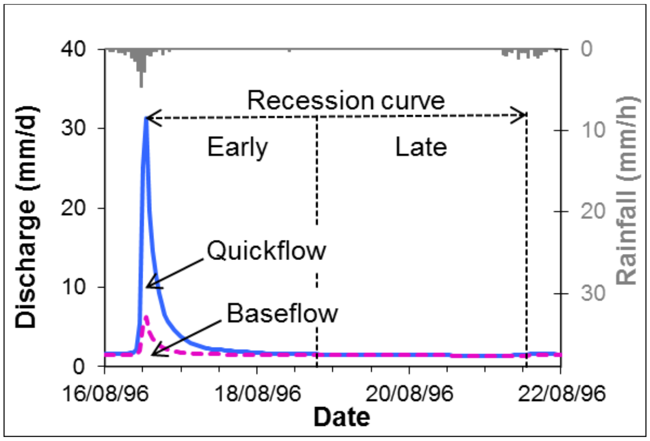
Figure 3 Map of Glendhu catchments (GH1 and GH2). The inset shows their location in the South Island of New Zealand.

Figure 4 (a, c, e) Application of the three baseflow separation methods to fit the pre-event component determined by deuterium measurements at Glendhu GH1 Catchment for an event on 23/2/88. The parameters determined by fitting are given in Table 2. (b, d, f) Baseflows resulting from the best-fit parameters for a two-week period in 1996. Note the logarithmic scales.

Figure 5. (a-c) Recession plots showing streamflow, baseflow and quickflow from the 1996 GH1 hourly flow record. The line through the mid-flow streamflow and baseflow points has slope of 6.0, and that through the higher flow quickflow points (flows greater than 1 mm/d) has slope of 1.5. (d) Flow duration curve showing streamflow, baseflow and quickflow.

Figure 6. (a) “Master” recession curve for Glendhu GH1 catchment (redrawn from Pearce et al., 1984). (b) Master recession data matched by the sum of the baseflow and a fast recession curve. The arrow shows the inflexion point. Early and late parts of the master recession curve are shown. (c) Recession plot of master recession curve (sum), baseflow and fast recession. The sum is close to the fast recession curve at high flows and close to the baseflow (slow recession curve) at low flows. The dashed part of the curve shows the ”bump” in the baseflow. (d) Variation of the baseflow contribution to streamflow with time during the master recession curve.

Figure 7 (a, b) Plots showing groundwater and soil water components of the baseflow matched to the pre-event hydrograph. Streamflow is pre-event water plus event water.



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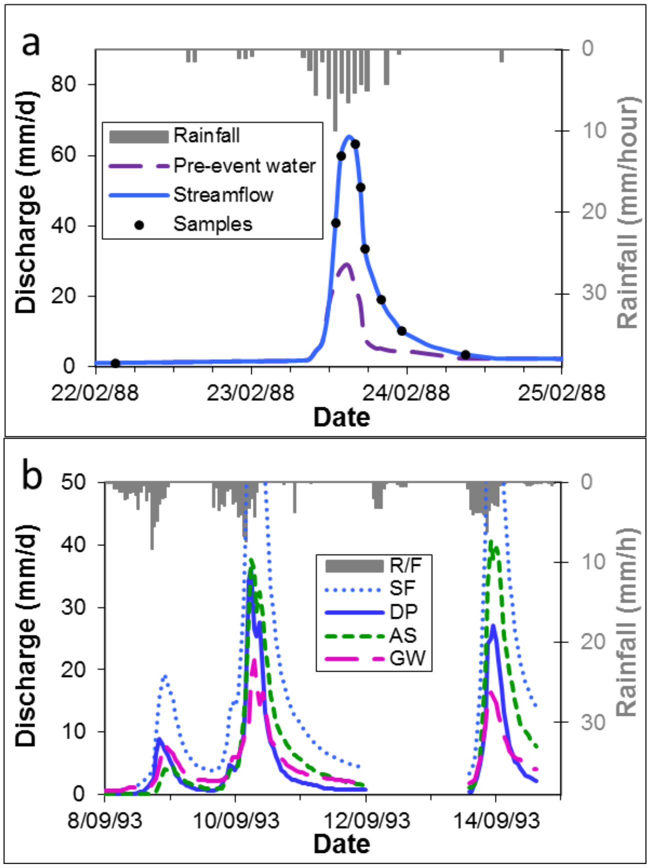

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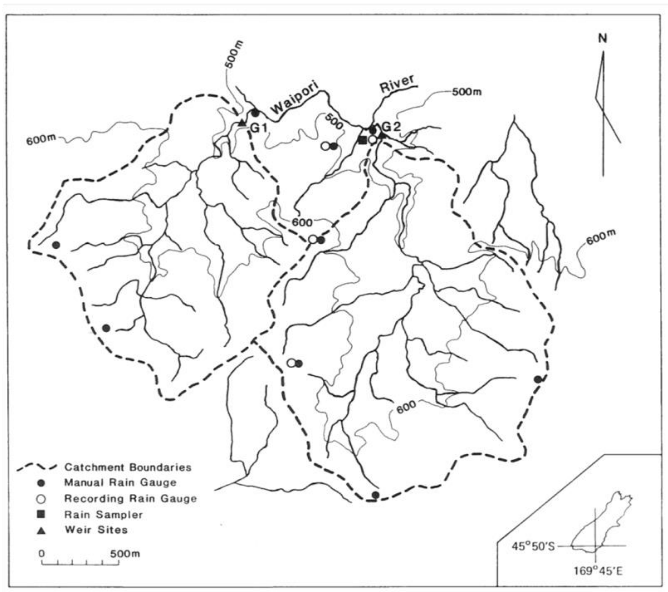

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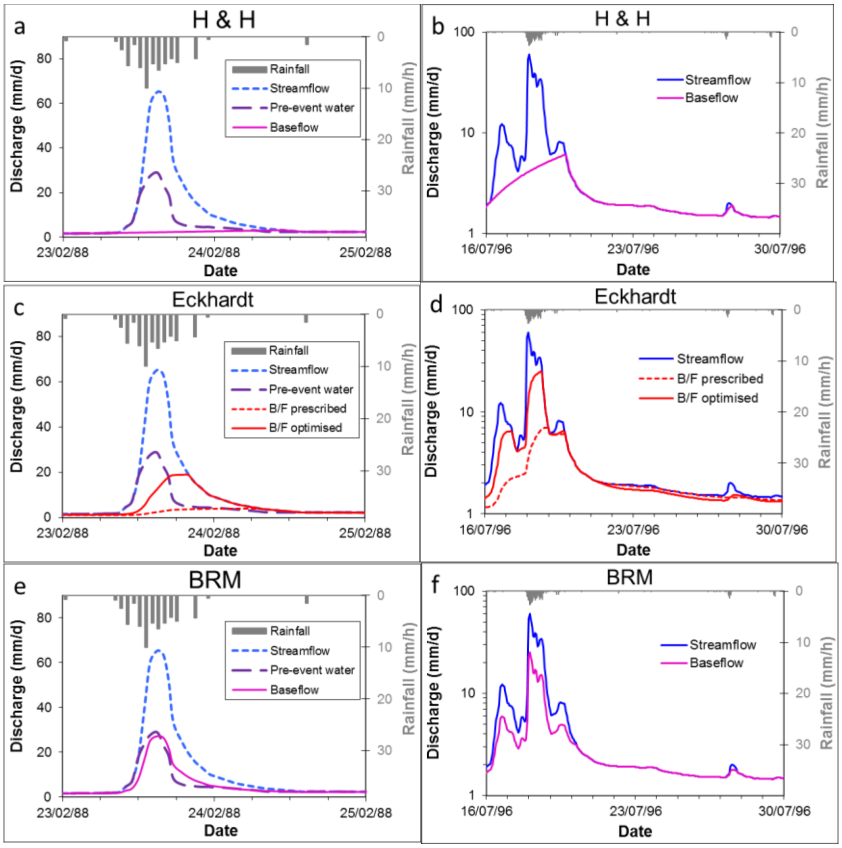
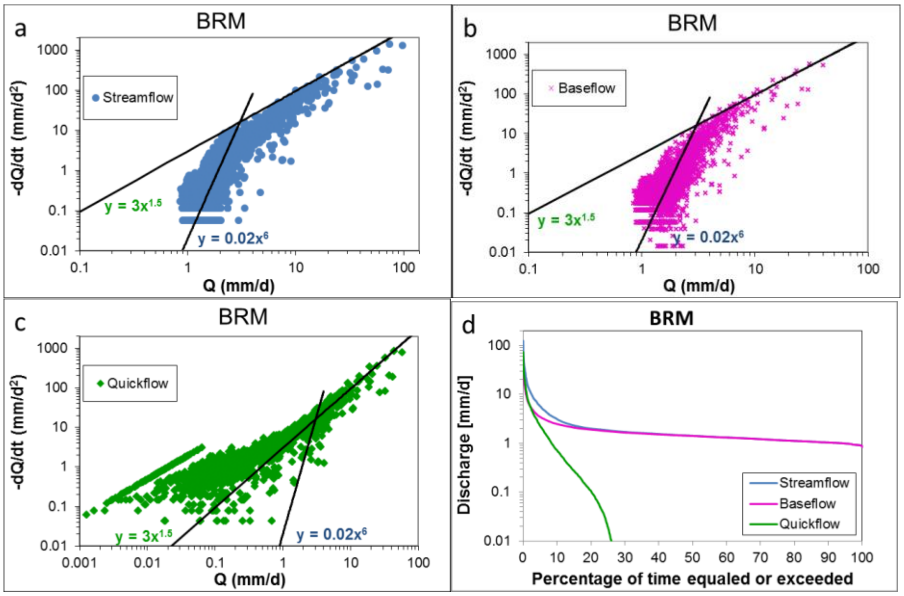


Figure 4 (a, c, e) Fits of the three baseflow separation methods to pre-event water determined by deuterium measurements at Glendhu GH1 Catchment for an event on 23/2/88. The parameters determined by fitting are given in Table 12. (b, d, f) Baseflows resulting from the best-fit parameters for a two-week period in 1996. Note the logarithmic vertical scales.



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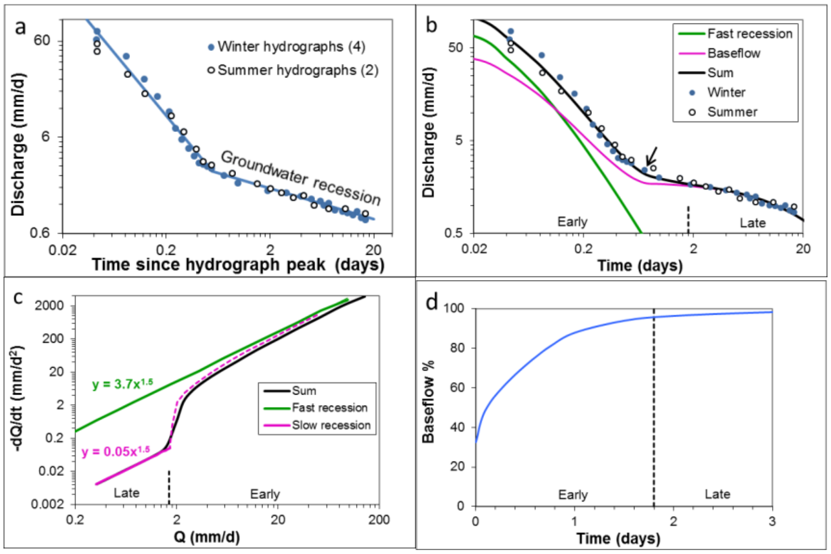

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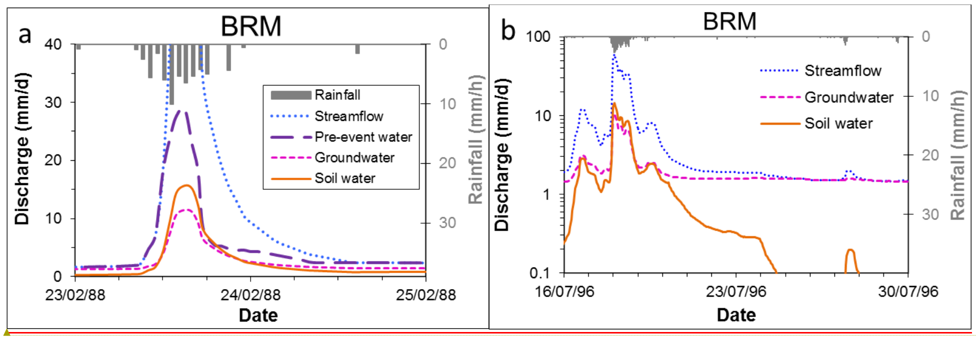

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