Response to Reviewer #1

I have responded to all of the very useful comments of the reviewer.

Major Comments

1 The continuous application of the BRM requires that the calibrated algorithm (Equations 7 and 8) be known, i.e. that the values of the parameters f and k be known. These parameters are determined from tracer studies on events, or recession events.

2 Ok. I have moved the catchment description (previously was Section 3.1) to the end of Methods (now Section 2.4). The heading "Methods" is now "Methods and Study Site".

3 Ok. Unless the text followed closely after the direction "below", I have now added Section numbers to make the directions clearer.

4 L97-101: Ok. The words "in the light of surprising effects of first separating the baseflow" have been deleted.

5 L259-261:The words "an unusual" have been changed to "a particular". It seems to me that Brutsaert and Nieber, 1977 did not introduce a separation of different baseflow responses, because they were talking about recession analysis in the example given not baseflow separation.

6 BFI_{max} estimation using FDCs (Collischonn and Fan, 2013) is based on relatively moist catchments in Brazil like that at Glendhu, so it seemed worth comparing them. This method is not important for the paper.

7 Fig 5d: I agree that this is a comment worth making and have added the sentence "Note that the temporal connection between the streamflow and components is not the same, each has been sorted separately to produce the relevant FDC."

8 L614-617: I have inserted "e.g." before the Pfister et al. (2014) reference.

9 In the discussion, sections 4.1 and 4.2 are concerned with the BRM baseflow separation, and sections 4.3 and 4.4 with the new approach to recession analysis. I think it would be confusing to mix these up.

10 L437-438 and L721-723: When using the BFI as a constraint, one of the parameters (f) is varied in a systematic manner across its full range and the second parameter (k) found as the value required to produce the constrained value of the BFI. The goodness of fit between the sum and the streamflow is different for each pair of parameters and the best fitting pair can easily be found. If BFI is not used as a constraint, the optimum fit can occur for the trivial case when f=1 (and BFI=1) and the baseflow exactly matches the streamflow without any quickflow.

11 L762-772: Ok. I have added the words "Note that Kirchner's method is often used for recession analysis."

12 L785-789: I have included oxygen-18 and deuterium here (item (3)) as part of the more general term "conservative tracers".

13 L813-865: I have removed the word "limited" from the first sentence. I think "observations" is a good word here, being stronger than "considerations" and weaker than "conclusions".

14 L689 and L887: I have added the words critical "(i.e. the precise value is not important)"

15 Additional comment L917: I consider that soil water contributing to the stream (i.e. directly not via groundwater) is pre-event water that is mobilised by the rainfall (event water). Consequently it drops to zero between rainfall events while baseflow does not (in perennial streams).

16 L919-924: This part refers to the second main message: that recession analysis of streamflow alone can give misleading information on catchment storages. I think it needs to be brief or else it will overweight the second of the two main messages in the Conclusions.

Minor Comments

1-5 Ok, changes made

6 Ok. Word “schematically” inserted

7-8 Ok

9 I prefer the word “also” being there

10 “a” had to be changed to “e” here, because “a” is used as one of the Eckhardt parameters. I found and corrected an error in Eqn 13

11 I have rewritten Section 2.2.1

12 I think this is necessary. It is relatively brief.

13-15 Ok

16 I can’t see what is confusing about this. I would change it if I knew what was confusing about it.

17 Good idea, but I am travelling and can’t change the figures.

18 These words are in those of the original authors (Pearce et al.)

19-21 Ok

22 Ok Words deleted.

Response to Reviewer#2

The reviewer takes issue with four broad aspects of the paper. These are headed by what he/she considers are problematical assertions in the paper, which I believe I have now toned down to quite an extent:

(1) "That there is no general concensus on how to approach the problem of baseflow and recession analysis, even though there are many different methods for each"

Changes made:
L22 (abstract): The words "and no consensus on how best to apply them" have been deleted.
L59-62: Sentence "However, the many baseflow separation methods have been regarded with suspicion for a long time because they were often associated with "the Hortonian view of catchments" (Beven, 1991) or were considered "to a large extent, arbitrary" (Hewlett and Hibbert, 1967)." has been deleted.
L86: Words "the general technique itself is in some disarray, and that" have been deleted
L97: Words "in the light of surprising effects of first separating the baseflow." have been deleted.

Regarding baseflow separation I quoted Beven (1991) and Hewlett and Hibbert (1967) (L59-62) and yes these were written 20 and 50 years ago, but I went on to say that "nevertheless, arbitrary as they may be, most of the methods yield results that are quite similar" (L62-63) as shown by Gonzales et al. (2009) (written 6 years ago). I do not think (or say) that the field of baseflow separation is in disarray, but I have now deleted this sentence.

Regarding recession analysis, I was influenced by Stoelzle et al. (2013) who very "recently highlighted discrepancies between methods of extracting recession parameters from empirical data by contrasting results from three established methods (...). They questioned whether such parameters are really able to characterise catchments ...because specific catchment characteristics derived by different recession analysis methods were so different." (L80-87 and L265-271). I do think that the field of recession analysis is in disarray (and obviously others do too, e.g. Stoelzle et al., 2013), but I have now deleted the words.

(2) "That performing recession analysis prior to baseflow separation can be highly misleading"

I believe that I did qualify this statement with the proviso that it applies when the recession analysis includes some of the early part of the recession. There is not expected to be any problem when the analysis is applied only to the late part of the recession. The reasons and reasoning for the quoted assertion (2) are demonstrated for Glendhu. Citations are given to the literature where misleading information on catchment storages may have been drawn from recession analysis on streamflow during the early part of the recession.

In regard to whether performing recession analysis prior to baseflow separation can be highly misleading, the reviewer asks "Can it – I am sure it can, but under what conditions, in what sorts of watersheds, for what kind of events?". The answers follow from the proviso that it only applies if the analysis includes some of the early part of the recession. The conditions are during the transition from the early to the late part of the

recession as stated. Sorts of watersheds are those which have both early and late recessions (i.e. not purely baseflow watersheds or purely quickflow watersheds). The kinds of events are those which produce early recessions followed by late recessions in the stream (i.e. quickflow + baseflow becoming just baseflow as quickflow falls to zero). This is not meant to be flippant – I don't understand what else the reviewer wants. I truly believe that the choice of Glendhu is not important – many catchments would do.
The statement "whilst this may be considered obvious by some" seems to have been misinterpreted by the reviewer. It does not mean that I necessarily think it is obvious, it simply was a response to a previous reviewer who asserted that there was nothing new in the paper.
This assertion is not at all an attack on baseflow separation practitioners, or the procedure of Eckhardt (2005) in using the parameter a derived from the late part of the streamflow recession; indeed I think that derivation is perfectly valid. It is the many recession analysis studies in the literature (some of which I have cited) that apply recession analysis to the early part of the baseflow recession as well as to the late part that I believe may have produced misleading information on catchment storages.

(3) "That applying baseflow separation analysis before recession analysis can resolve some problems with recession analysis and provide new and important insights into catchment water storages"

Again this needs to be tempered with the proviso that it only applies when the recession analysis includes some of the early part of the recession. In particular, the artifactual high power-law slopes on the recession plot that occur especially when quickflow and baseflow are approximately equal give misleading information on catchment storages. By plotting quickflow and baseflow (although there are reservations with plotting baseflow as explained in L447-449) as well as streamflow, information which actually refers to those components is gained and this has not been done before. This must give insights into catchment water storages compared to the misleading information given by the streamflow when the analysis includes some of the early part of the recession. Citations are given to papers (both ancient and modern) which report such artifactual high power-law slopes. This represents a solid body of evidence to support the statement.

(4) "That the new "bump and rise" baseflow separation method provides "more accurate" baseflow separations than previous methods"

Changes made:

Lines 24, 91, 731: The description as "more accurate" has been toned down. The words "more accurately than previous methods" have been removed from everywhere they occur in the paper, and "aims to accurately simulate the shape of tracer-determined baseflow or pre-event water." used instead.
L249: Words changed from "simply, but as accurately as possible" to "simply, but accurately".
L933: (Conclusions) Words changed from "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." to "The advantage of the BRM is that it specifically simulates the shape of the baseflow or pre-event component as shown by tracers."

The BRM baseflow separation method aims to reproduce the component separations determined by tracer separations. It appears well accepted that tracer separations are the most objective way of separating streamflow components. Because they are quite work intensive, tracer separations generally only cover a few events or short periods of up to a few months. Nevertheless the observations from a considerable number of tracer investigations give unequivocal evidence of rapid response of baseflow to rainfall (the “bump”), which Kirchner (2003) describes in one of his apparent paradoxes as “prompt discharge of old water during storm events” (e.g. Hooper and Shoemaker, 1986; Bonell et al., 1990; Buttle, 1994; Bazemore et al., 1994; Hangin et al., 2001; Joerin et al., 2002; Iorgulescu et al., 2005; Gonzales et al., 2009; Iwagami et al., 2010; Zhang et al., 2013). Although the paper gives data for only one catchment, the BRM was found to be compatible with all of these separations (work to be reported). If I had given data for three catchments, it would not have increased the total much compared with what was already there in the tracer studies.

In addition, to the extent that tracer studies represent the best estimate of baseflow separation, then the BRM has the best chance of representing that separation when calibrated by fitting to tracer separation data. When calibrated by the optimization method in the absence of tracer data, the general shape of the baseflow should be close to that shown by tracers but some arbitrariness comes into the amount of baseflow (i.e. the BFI).

Obviously, using studies using tracers to determine component separations can have their own limitations. Tracer separations can in reality be event/pre-event water separations (e.g. Glendhu). Three component separations using two tracers (e.g. Haute Mentue Catchment) seem to be the best way of determining groundwater contributions.

Response to Editor

Thanks again for your work on this Jim.

I have responded to all of the comments of Reviewer#1 and made the suggested change in most cases.

I have responded to the four broad concerns of Reviewer#2 and have read the paper again to see how I can change the paper to tone it down. The changes I have made are listed in the response to Reviewer#2. In particular the main changes to tone the paper down have been made in response to his items 1 and 4, and I think resulted in quite a big change to the tone of the paper. I hope it is now acceptable for publication in HESS.

This round of revisions arrived just before I left New Zealand and I am away from 9 April to 19 May, so may not be able to do further work on this until after 19 May.

Mike Stewart
16 April 2015

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

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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~~. The new baseflow separation method presented here (the bump and rise method or BRM) aims to accurately simulate~~s~~ 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 BRM algorithm is then applied to the Glendhu streamflow record. 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. Applying baseflow separation before recession analysis could therefore shed new light on water storage reservoirs in catchments and possibly resolve some current problems with recession analysis. Among other things it shows that both quickflow and baseflow reservoirs in the studied catchment have (non-linear) quadratic characteristics.

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 because they were often associated with "the Hortonian view of catchments" (Beven, 1991) or were considered "to a large extent, arbitrary" (Hewlett and Hibbert, 1967). Nevertheless,~~ Although considered to some extent arbitrary by some (e.g. Hewlett and Hibbert, 1967; Beven, 1991)~~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 specifically considered during ~~middle~~ intermediate and high flows, because streamflow during such events is composed of comparable amounts of both quickflow and baseflow (e.g. Sklash and Farvolden, 1979) and they are produced by very different mechanisms. Consequently, ~~I~~it is believed that process descriptors such as hydrograph recession constants (or transit time distribution parameters) should be determined on separated components~~,~~ as well as ~~not~~ total streamflow during such flows, because ~~the latter~~streamflow is a mixture and therefore can give~~s~~ 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 early streamflow recession 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) 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) which aims to accurately simulate~~s~~ 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. ~~.~~ The paper 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 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.

2 Methods and Study Site

2.1 Baseflow Separation

Justification for making baseflow separations rests on the dissimilarity of quickflow and baseflow generation processes in catchments (e.g. Hewlett and Hibbert, 1967). 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 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 (mainly 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 as an example showing schematically 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

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

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

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). 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 characteristic 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., 2013). 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

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

which approximately matched the tracer separations. m and C are parameters identified by fitting to the pre-event hydrograph identified by tracers. 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

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

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

$$B_t = aB_{t-1} \tag{6}$$

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 (e.g. 0.8 for perennial streams in catchments with permeable bedrock). 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~~. Tracer separations 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 parameters of the recursive digital filter that can be applied to the streamflow record. The separation procedure is described by the equations:

$$B_t = B_{t-1} + k + f(Q_t - Q_{t-1}) \qquad \text{for} \qquad Q_t > B_{t-1} + k \qquad (7)$$

$$B_t = Q_t \qquad \text{for} \qquad Q_t \leq B_{t-1} + k \qquad (8)$$

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). A~~n unusual~~particular 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.

2.2 Recession Analysis

Recession analysis also has a long history. Stoelzle (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

$$V = Q/\beta \tag{9}$$

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

$$Q_t = Q_o exp(-\beta t) \tag{10}$$

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

$$V = eQ^b \tag{11}$$

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

$$Q_t = Q_o[1 + \frac{(1-b)Q_o^{(1-b)}}{eb} t]^{1/(b-1)} \tag{12}$$

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

$$Q_t = Q_o\left[1 + \frac{1}{\alpha e}.Q_o^{0.5}.t\right]^{-2} \tag{13}$$

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

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

where α is

$$\alpha = KB/PL^2 \tag{15}$$

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:

$$\frac{dV}{dt} = R - E - Q \tag{16}$$

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

$$\frac{dV}{dt} = -Q \tag{17}$$

from whence equation 10 leads to

$$-\frac{dQ}{dt} = \frac{1}{eb} Q^{2-b} = cQ^{d} \tag{18}$$

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 often found d averaging close to 1.5 (e.g. Brutsaert and Nieber, 1977; Wittenberg, 1999; Dewandel, 2005; Stoelzle et al., 2013). 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 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. different selection criteria for data points), and 2) different parameter-fitting methods to the power-law storage-outflow model (equation 17). There is generally a very broad scatter of points on the plots, which makes parameter-fitting difficult. Clearly evapotranspiration is likely to play a role in producing some of the scatter because evapotranspiration was neglected from equation 16. However, it is also believed that part of the scatter ~~as well as the steep slopes of recession curves often observed at intermediate flows in recession plots are~~ is due to recession analysis being applied to streamflow rather than to its separated components (see below).

2.2.1 The New Recession Analysis Approach

The new approach proposed here consists of applying recession analysis via the recession plot to separated quickflow and baseflow components as well as to the streamflow. The rationale for this is that quickflow and baseflow derive from different storages within the catchment. ~~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 recession analysis being applied to streamflow rather than to its separated components.~~ ~~As shown below,~~In particular, 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, as demonstrated for Glendhu Catchment below. ~~because the storage for each component is very different.~~ This ~~has probably~~is expected to have led to some previous recession analysis studies giving misleading results in regard to catchment storage in cases where early recession streamflow has been analysed.

2.3 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 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.

2.4 Hydrogeology of Glendhu Catchment

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". 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 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-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 belowSection 3.1). 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 in the early part of the recession the baseflow is a subdued reflection of the streamflow because of its calculation procedure (equations 6 and 7) in the early part of the recession,. while In 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~~

~~3.1 Hydrogeology of Glendhu Catchment~~

~~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.~~

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3.21 Application of Baseflow Separation Methods

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,

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

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 this section 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

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

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

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 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).

3.32 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. Discharge data less than two hours after rainfall has been excluded. 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 line at high flows when baseflow makes up only a small proportion of the streamflow, and diverging from it 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 quickflow points at flows above about 1 mm/d fall on the quickflow line with slope of 1.5. Errors 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 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 accurate enough to show this (see Section 3.4).

Flow duration curves for streamflow, baseflow and quickflow are given in Fig. 5d. The streamflow FDC has a -very shallow slope indicating groundwater dominance over the higher exceedance percentages. Streamflow diverges noticeably from baseflow below about 17% exceedence (when quickflow reaches about 10% of streamflow). Note that the temporal connection between the streamflow and components is not the same, each has been sorted separately to produce the relevant FDC. Theis figure 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 (e.g. Pfister et al., 2014).

3.43 “Master” recession curve for Glendhu

Fig. 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. 6b). The baseflow was calculated using the parameters identified by the fitting to the pre-event hydrograph above (f = 0.40, k = 0.009 mm d^{-1} h^{-1}, Table 2). These parameters give a BFI of 0.828. During the late part of the recession, when the baseflow dominates the streamflow, a slow recession curve was fitted to the streamflow. The data are given in Table 2. 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. 6b).

It is also instructive to see the recession plot of the data (Fig. 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 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 streamflow (which is the same as the late-recession baseflow) have meaning in terms of storage types.

Fig. 6d shows the fraction of baseflow in the streamflow versus time according to the tracer-based BRM. Baseflow makes up 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.

4 Discussion

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 aims to accurately 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").

(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).

(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, specification of f and k depends on an initial estimate of the BFI, although the optimisation procedure means that the precise value estimated for the BFI is important, but not critical to the procedure.~~this is not critical.~~

(2) The method produces an ~~avergae~~averaged representation of the baseflow hydrograph when applied to long-term data, so seasonal or intra catchment variations are likely.

(3) Separation 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.

4.3 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 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. Lack of separation has probably led to misinterpretation of the slopes in terms of catchment storage reservoir types.

Kirchner's (2009) 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 in (Fig. 6c)). Note also that Kirchner's method is often used for recession analysis. Likewise Lamb and Beven's (1997) approach may have been fit-for-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).

4.4 A new approach to recession analysis

It appears that streamflow recession analysis is a technique in disarray (Stoelzle et al., 2013). Different methods give different results and there is "a continued lack of concensus on how to interpret the cloud of data points" (Brutsaert, 2005). This work asserts that recession studies may have been giving misleading results in regard to catchment functioning because streamflow is a varying mixture of components (unless the studies were applied to late recessions only). The new approach of applying recession analysis to the separated quickflow component 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 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-~~ intermediate flow range) instead of separated components. This may have 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 dominated by quickflow, and baseflow contributes almost all of the flow at low flows, so these parts 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, contributions from snowmelt or wetlands or deeper groundwater systems, and drainage from different aquifers in different dryness conditions (McMillan et al., 2011). 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. 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, the inflexion point 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 mostly groundwater, and quickflow is also starting to look distinctly groundwater-influenced (or saturation-influenced). The success of groundwater models (Gusyev et al., 2013, 2014) in simulating tritium concentrations and baseflows in streams while being calibrated to 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).

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~~ specifically simulates~~ion of~~ the shape of the baseflow or pre-event component as shown ~~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 relatively 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~~the precise value estimated for the BFI is important but not critical to the procedure, (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 intermediate~~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 to separated components in this paper are: (1) Many cases of high power-law slopes ($d>1.5$) in recession plots reported in the literature are likely to be artifacts due to plotting early recession streamflow instead of quickflow. 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. (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.

6 Acknowledgements

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7 References

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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.

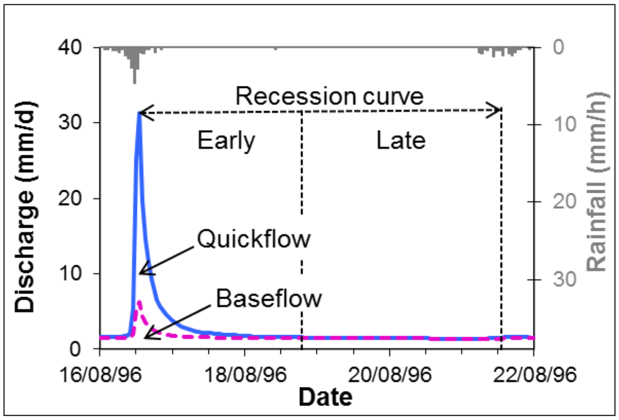
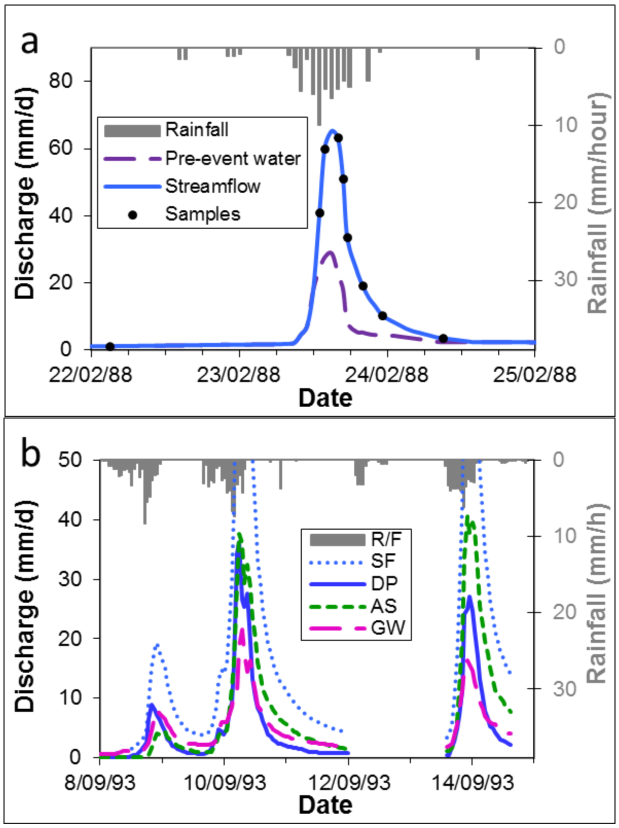


Figure 1 Quickflow and baseflow components of streamflow, and the early and late parts of the recession curve. Quickflow is represented by the area between the streamflow and baseflow curves, and baseflow is the area under the baseflow curve.



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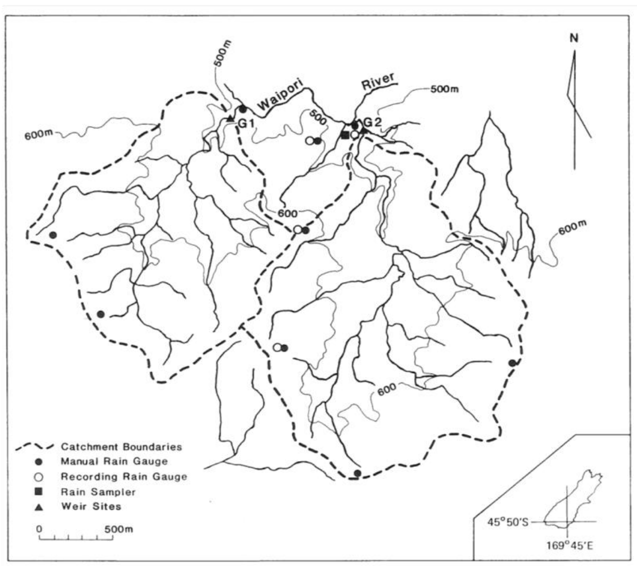

Figure 3 Map of Glendhu catchments (GH1 and GH2). The inset shows their location in the South Island of New Zealand.

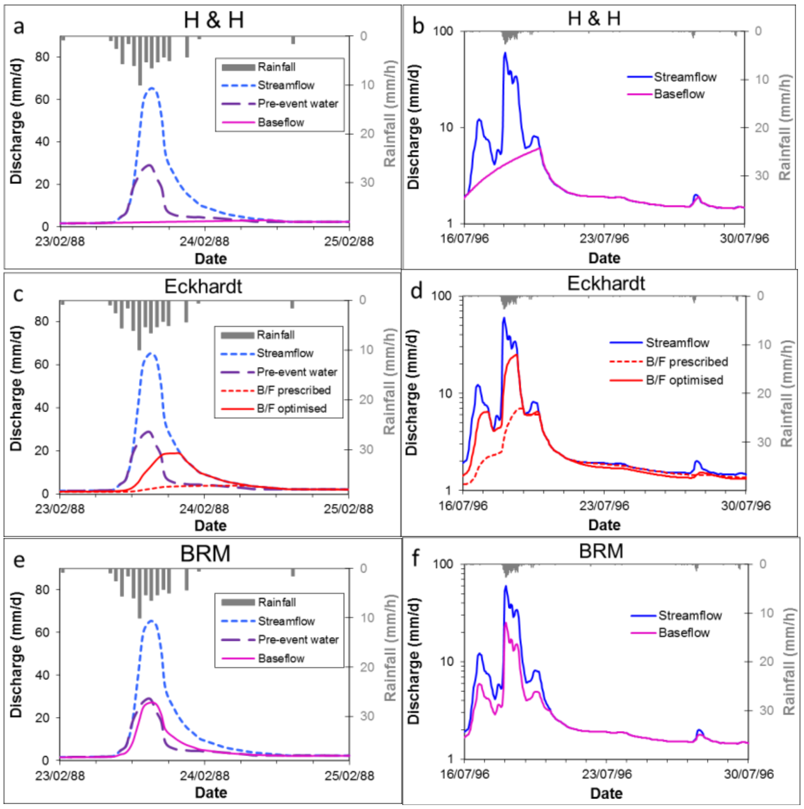

Figure 4 (a, c, e) Fits of the three baseflow separation methods to pre-event water determined by deuterium measurements at Glendhu GH1 Catchment for an event on 23/2/88. The parameters determined by fitting are given in Table 1. (b, d, f) Baseflows resulting from the best-fit parameters for a two-week period in 1996. Note the logarithmic vertical scales.

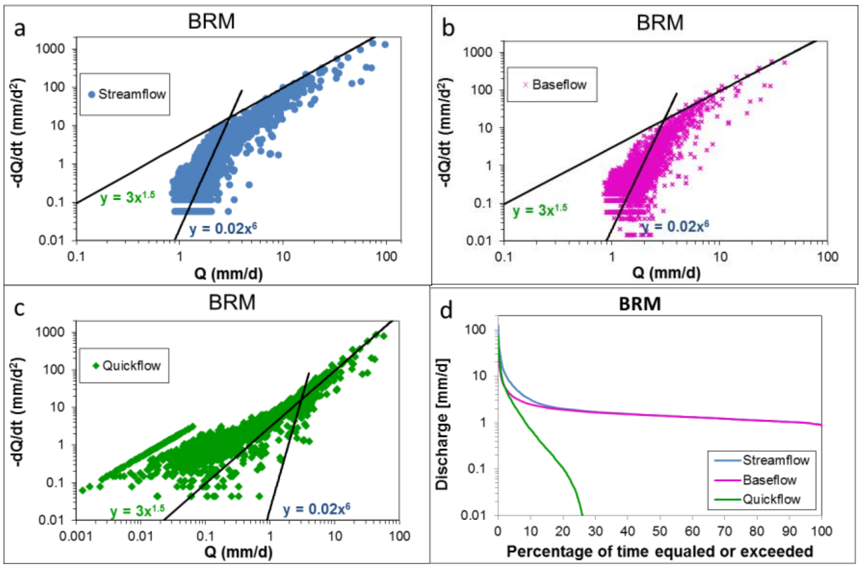

Figure 5 (a-c) Recession plots showing streamflow, baseflow and quickflow from the 1996 GH1 flow record using the BRM method. The line through the mid-flow streamflow and baseflow points has slope of 6.0, and that through the higher flow quickflow points (flows greater than 1 mm/d) has slope of 1.5.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

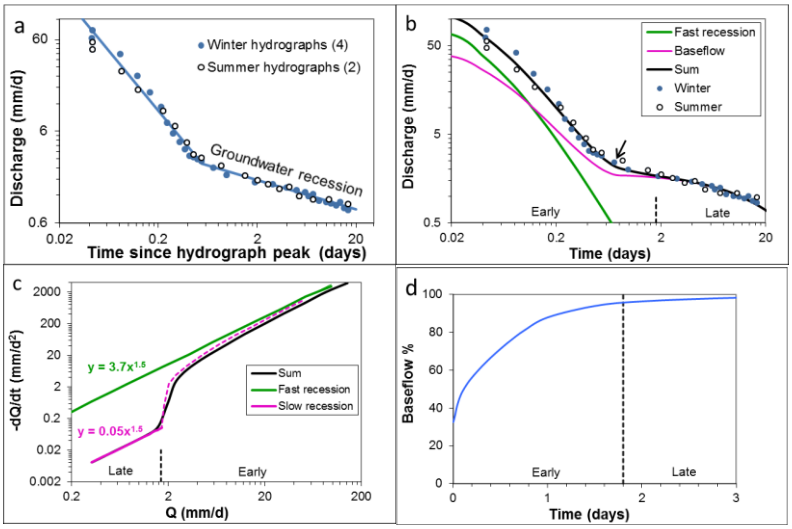

Figure 6 (a) "Master" recession curve for Glendhu GH1 catchment (redrawn from Pearce et al., 1984). (b) Master recession data matched by the sum of the BRM baseflow and fast recession curve. The arrow shows the inflexion point. Early and late parts of the master recession curve are shown. (c) Recession 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 curve shows the "bump" in the baseflow. (d) Variation of the baseflow contribution to streamflow with time during the master recession curve.

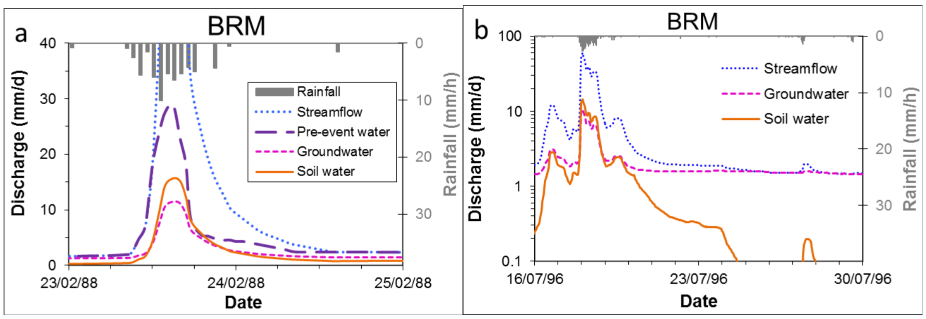

Figure 7 (a, b) Plots showing groundwater and soil water components of the baseflow matched to the pre-event hydrograph. Streamflow is pre-event water plus event water.