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# New baseflow separation and recession analysis approaches for streamflow

**M. K. Stewart**

Aquifer Dynamics & GNS Science, P.O. Box 30368, 5010 Lower Hutt, New Zealand

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Correspondence to: M. K. Stewart (m.stewart@gns.cri.nz)

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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. A new baseflow separation method is presented, which is justified by being based generally on the more objective tracer separation methods and by being optimised by fitting to the recession hydrograph. 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 sheds new light on water storage in catchments and may 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 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). 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 the many baseflow separation methods were often associated with the Hortonian view of catchments, and are 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, arbitrary as they may be, most of the methods yield results that are quite similar (e.g. Gonzales et al., 2009 obtained baseflow fractions 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 high flows, because streamflow during high flow events is composed 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) 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), Kirchner (2009). Stoelzle et al. (2013) 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 BRM method) which is optimised by fitting to the recession hydrograph and based generally on the results of tracer hydrograph separations. 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. The same procedure is applied to flow duration curves. 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

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 waters 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 stream 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 ($B_t$)

$$Q_t = A_t + B_t \tag{1}$$

where time steps are indicated by the sequences $\ldots\ Q_{t-1},\ Q_t,\ Q_{t+1}\ \ldots$ etc. The time increment is normally one hour in the examples given below. 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. Figure 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)

(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 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 $\mathrm{ft^3\,s^{-1}\,mile^{-2}\,h^{-1}}$ (0.000546 $\mathrm{m^3\,s^{-1}\,km^{-2}\,h^{-1}}$ or 0.0472 $\mathrm{mm\,d^{-1}\,h^{-1}}$). Other authors have adapted the method by changing the value of the constant ($k$) to be more suitable for their 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 aspect 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”. 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., 2012). In the case of groundwater, the rapid response is believed to be 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, p. 349; Stewart et al., 2007, p. 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 trial and error. Wittenberg (1999) and Wittenberg and Sivapalan (1999) used their inverted nonlinear reservoir algorithm which describes baseflow as a sequence of recessions of groundwater recharges

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

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 Eq. (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.

The new baseflow separation method proposed in this paper (hereafter called the "bump and rise" method or BRM) is also based on the evidence from tracer separations. These 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 as parameters that can be optimised in particular catchments by fitting to the hydrograph recession. The separation procedure is described by the equations:

$$B_t = B_{t-1} + k + f(Q_t - Q_{t-1}) \quad \text{for} \quad Q_t > B_{t-1} + k \tag{6}$$

$$B_t = Q_t \quad \text{for} \quad Q_t \le B_{t-1} + k \tag{7}$$

where $f$ is a constant fraction of the increase or decrease of streamflow during an event. 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 method is that two types of baseflow response are included, short-term response via the bump and longer-term response via the rise.

## 3 Recession analysis

Recession analysis also has a long history. Stoelzle et al. (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; 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; 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

$$V = Q/\beta \tag{8}$$

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

$$Q_t = Q_0 \exp(-\beta t) \tag{9}$$

where $Q_0$ 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

$$V = aQ^b \tag{10}$$

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

$$Q_t = Q_0 \left[ 1 + \frac{(1-b)Q_0^{(1-b)}}{ab} t \right]^{1/(b-1)}. \tag{11}$$

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 (Eqs. 8 and 9). For $b = 0.5$, Eq. (11) reduces to the quadratic equation

$$Q_t = Q_0 \left[ 1 + \frac{1}{a} \cdot Q_0^{0.5} \cdot t \right]^{-2}. \tag{12}$$

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

$$Q_t = Q_0(1 + \alpha t)^{-2} \tag{13}$$

where $\alpha$ is

$$\alpha = KB/PL^2. \tag{14}$$

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 only 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 (following Kirchner, 2009). To keep the timing right, the method pairs streamflow $Q = (Q_{t-1} + Q_t)/2$ with negative streamflow recession rate $-\mathrm{d}Q/\mathrm{d}t = Q_t - Q_{t-1}$.

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

$$\frac{\mathrm{d}V}{\mathrm{d}t} = R - E - Q \tag{15}$$

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

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -Q \tag{16}$$

from whence Eq. (10) leads to

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{1}{ab}Q^{2-b} = cQ^{d}. \tag{17}$$

The exponent $d$ allows for both linear ($d = 1$) and non-linear ($d \neq 1$) storage outflow relationships, with $d = 1.5$ giving the frequently observed quadratic relationship (Eq. 12). Authors who have investigated the dependence of $-\mathrm{d}Q/\mathrm{d}t$ on $Q$ for late recessions (low flows) have generally 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 at higher flows, e.g. Brutsaert and Nieber (1977) found values of $d = 3$ for the early parts of recessions.

Current problems in determining recession parameter values from streamflow data on recession plots are due to (1) different recession extraction methods (i.e. different selection criteria for data points), and (2) different parameter fitting methods to the power-law storage-outflow model (Eq. 17). Depending on (1) there is generally a very broad scatter of points, which makes parameter fitting difficult in (2). However, as shown below applying recession analysis to streamflow (during early parts of recessions) rather than to its separated components has probably led to some previous recession analysis studies giving misleading results.

## 4 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 (Figs. 4e and 5e). 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 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

$$C_{\text{out}}(t) = \int_{0}^{\infty} C_{\text{in}}(t-\tau)h(\tau)\mathrm{d}\tau \tag{18}$$

where $C_{\text{in}}$ and $C_{\text{out}}$ 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 $\tau$. $h(\tau)$ 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 Eq. (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.

## 6 Glendhu catchment

The Glendhu catchments display rolling-to-steep topography, and range in elevation 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 of both GH1 and GH2. They frequently exhibit central wetlands that extend downstream as riparian bogs. Snow tussock (Chionochloa rigida) is the dominant vegetation cover in the control catchment (GH1); Monterey pine (pinus radiata) extends over 67 % of GH2. 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 7.6 °C, and the mean annual rainfall is 1350 mm $a^{-1}$. Annual runoff is measured at all weirs to an accuracy of ±5 % (Pearce et al., 1984).

## 7 Application of the BRM baseflow separation method to Glendhu streamflow

### 7.1 Winter and summer events

Application of the BRM method is illustrated in Figs. 4 and 5 for streamflow events in winter (August 1996) and summer (February 1996) at Glendhu Catchment (GH1) based on hourly streamflow data. August 1996 had one large streamflow event and a number of medium to small events (Fig. 4a), while February was dry with only two small events (Fig. 5a). The baseflow estimated with the BRM method has small peaks (the bumps) underlying the streamflow peaks which comprise 16 % of the streamflow increase during the events (Figs. 4b and 5b). The baseflow fractions estimated were 71.5 % in August and 95 % in February.

To determine the BRM parameters (bump fraction, $f$, and slope, $k$), the streamflow recessions are fitted with the *sums* of the baseflow (calculated using Eqs. 6 and 7) and fast quadratic recessions (Eq. 13) as illustrated in Figs. 4b and 5b. The choice of the fast quadratic recession is justified in Sect. 7.2 below. The baseflow fractions during the periods tested were first estimated based on examination of the streamflow and previous experience with the catchment, and were kept constant during the optimisation process to give a constraint on $f$ and $k$. A well-chosen estimate of baseflow fraction appears to be sufficient, as the actual value was not critical. The best match of the sum to the streamflow was determined using least squares,

$$\mathrm{sd} = \sum \left( (Q_i - S_i)^2 / N \right)^{0.5} \tag{19}$$

where $S_i$ are the sums of the baseflow and recession values, and $N$ is the number of values. The very small peak in streamflow on the receding flank of the second peak due to a small amount of rainfall in Fig. 5b was excluded. The full range of $f$ values was examined with $k$ being adjusted from its maximum value (for $f = 0$) to zero (for $f = f_{\max}$). For each value of $f$, the recession parameters ($Q_0$ and $\alpha$) were adjusted to give the best match using Excel Solver. Figures 4c and 5c show the variation of goodness of fit with $f$ for each case. The curves show minima around $f$ values of 16–20 %. The optimum values in each case are given in Table 1. One might expect that $f$ would be higher in winter when wet conditions could make the baseflow more responsive, and smaller in summer, but this is not shown by the results (in fact slightly the reverse). The slopes ($k$) for $f = 0$ (winter 0.0077 and summer 0.0038 mm d$^{-1}$ h$^{-1}$) can be compared with the constant slope proposed by Hewlett and Hibbert (1967) (0.0472 mm d$^{-1}$ h$^{-1}$). If the Hewlett and Hibbert $k$ value had been used (for $f = 0$) the baseflow fractions would have been higher (e.g. 77.4 % for the winter peak (16 August 1996) instead of 71.5 %). The slopes at the optimum $f$ values are considerably less than those at $f = 0$.

Quickflow is determined by subtracting baseflow from streamflow. 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 h unless there is further rain. The recession behavior of the streamflow and quickflow can be examined on a recession plot (i.e. $-\mathrm{d}Q/\mathrm{d}t$ vs. $Q$, Figs. 4d and 5d). Figure 4d shows the plot for the month of August 1996. Discharge data has been excluded if less than four hours after rainfall. The streamflow points define a curve approaching the quickflow points at high flows when baseflow makes up only a small proportion of the streamflow, and diverging from them when baseflow becomes more important (the line shown on the lower part of the streamflow points has a slope of 4). The quickflow points fall on a line with slope about 1.5, but errors become much larger as quickflow becomes very small (i.e. as baseflow approaches streamflow). 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 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 are not accurate enough to show this (see Sect. 7.3).

Figure 5d shows the recession plot for 12 to 15 February 1996 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 and 5e. The streamflow FDCs have relatively shallow slopes indicating groundwater dominance at lower exceedance percentages. In the winter period (Fig. 4e, August 1996), streamflow began to diverge noticeably from baseflow at about 40 % exceedence (when quickflow had reached about 10 % of streamflow). In the summer period (Fig. 5e, February 1996), streamflow began to diverge from baseflow at around 90 % exceedence. These figures reveal 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 Eq. (9). Figure 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 (Fig. 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 Eq. (17) gives the reciprocal equation

$$Q_t = Q_0(1 + \gamma t)^{-1} \qquad (20)$$

whose parameters are $Q_0$ and $\gamma$. Figure 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.

### 7.3 “Master” recession curve for Glendhu

Figure 7a 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). 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 $d^{-1}$). 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). The early part of the baseflow was determined using the methods outlined above (with $f = 16\,\%$ and $k = 0.000876\,\mathrm{mm\,d^{-1}\,h^{-1}}$), and the late part by a slow recession curve fitted to the streamflow. The data are given in Table 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. 7b).

It is also instructive to see the recession plot of the data (Fig. 7c). 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 dashed. 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 the point that the slope of the streamflow points on a recession plot is meaningless at medium flows. Only the quickflow and low baseflow slopes have meaning.

Figure 7d shows the fraction of baseflow in the streamflow vs. time. The baseflow makes up 17 % of the streamflow at the highest flows, then starts gradually increasing from two hours (0.1 d) to 50 % at 12 h (0.5 d) and then to 95 % at 60 h (2.5 d). The change from early to late recession is shown at 2.5 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.

Figure 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 August 1996 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 $f = 42\,\%$, $k \sim 0\,\mathrm{mm\,d^{-1}\,h^{-1}}$, and would not be compatible with the previous results (Sects. 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 December 2001, 21 February 2005 and 26 February 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 ($\tau_m$), according to the equation

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

where $\tau_{m1}$, $\tau_{m2}$ are the mean transit times of the baseflow components. Thus $\tau_m$ 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).

## 8 Discussion

### 8.1 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 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 effects of rainfall. 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 sum of the baseflow and a fast recession to the recession hydrograph. This is applied to the early (fast recession influenced) part of the recession.
3. The method can be applied using streamflow data alone.
4. The method is easy to implement mathematically.

Current limitations or areas where further research may be needed are: (1) specification of $f$ and $k$ depends on an initial estimate of the baseflow fraction, although the optimisation procedure means that this is not critical, (2) the method produces a generalised representation of the baseflow hydrograph, so seasonal or inter/intra catchment variations are likely, and (3) separation of the hydrograph into three components (as shown by some tracer studies) could be explored.

## 8.2 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 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.

Kirchner’s (2006) 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 baseflow in Figs. 4d, 5d and 7c). Likewise Lamb and Beven’s (1997) approach was fit-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.

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).

### 8.3 A new approach to recession analysis

It appears that recession analysis is a technique in disarray (Stoelzle et al., 2012). Different methods give different results and there is little consensus on how best to apply recession analysis to streams. And in fact the recession studies have been giving misleading results in regard to catchment functioning because baseflow separation has not been applied before analysis (unless the studies were exclusively on late recessions or stringent conditions have been applied). The new approach of applying recession analysis to separated quickflow and baseflow components as well as streamflow may help to resolve this confusion. In particular, recession analysis on quickflow and baseflow 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 (Sect. 7.2). This may result from a variety of processes such as 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 other catchments by other authors. 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 instead of separated components. This 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 all of the flow at low flows, so these parts are less confusing.

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). The 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 groundwater, and quickflow is also starting to look distinctly groundwater-influenced (or saturation-influenced). The success of a groundwater model (Gusyev et al., 2013) in simulating tritium concentrations and baseflows in streams 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.

### 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 ($^3$H/$^3$He, 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 and 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 years) 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 Conclusions

The main message of this paper is that it is necessary to apply baseflow separation before recession analysis because analysing streamflow alone can give very misleading results. This is because streamflow is a mixture of quickflow and baseflow components, and they have very different characteristics. It is necessary to actually plot quickflow as well as streamflow on a recession plot to really appreciate this fact. 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).

A new baseflow separation method (called the BRM method) is presented, generally based on the results of tracer separations reported in the literature. Advantages of the method are: (1) it is evidence-based, (2) the parameters ($f$ and $k$) can be optimised by fitting to recession hydrographs, (3) it can be applied using streamflow data alone, and (4) it is easy to implement mathematically. Current limitations or areas where further research may be needed are: (1) specification of $f$ and $k$ depends on an initial estimate of the baseflow fraction, although the optimisation procedure means that this is not critical, (2) the method produces a generalised representation of the baseflow hydrograph, so seasonal or inter/intra catchment variations are likely, and (3) separation of the hydrograph into three components (as shown by some tracer studies) could be explored.

The new approach of applying recession analysis to separated quickflow and baseflow components as well as streamflow may be shedding new light on catchment storage. In particular, recession analysis on quickflow and baseflow gives 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. Flow duration curves can also be determined for 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) the many cases of high power-law slopes ($d > 1.5$) in recession plots reported in the literature are revealed as 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 (groundwater aquifers, riparian zones, perched zones in the soil) 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, 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.** Parameters of the baseflows ($f$ and $k$) and fast recessions ($Q_0$ and $\alpha$) giving the best fits (i.e. smallest standard deviations, sd) for various streamflow recessions at catchment GH1, Glendhu, New Zealand.

| Recession Type | $\mathrm{BF}^a$ % | $f^a$ % | $k^a$ $\mathrm{mm\,d^{-1}\,h^{-1}}$ | $Q_0^a$ $\mathrm{mm\,d^{-1}}$ | $\alpha^a$ $\mathrm{h^{-1}}$ | $\mathrm{sd}^a$ $\mathrm{mm\,d^{-1}}$ |
|---|---|---|---|---|---|---|
| Hewlett and Hibbert (1967) | | | 0.0472 | | | |
| Winter peak (16 Aug 1996) | | | | | | |
| Quadratic | 71.5 | 0 | 0.00766 | 29.4 | 6.16 | 0.31 |
| Quadratic | ” | 16 | 0.000864 | 24.7 | 5.77 | 0.18 |
| Exponential | ” | 6 | 0.00366 | 25.6 | $7.35^b$ | 0.84 |
| Reciprocal | ” | 30 | 0 | 21.5 | $19.1^c$ | 0.50 |
| Summer peak 1 (12 Feb 1996) | | | | | | |
| Quadratic | 95.0 | 0 | 0.00376 | 0.96 | 3.02 | 0.020 |
| Quadratic | ” | 20 | 0.00215 | 0.74 | 2.62 | 0.018 |
| Summer peak 2 (13 Feb 1996) | | | | | | |
| Quadratic | 95.0 | 0 | 0.00376 | 2.15 | 5.00 | 0.0086 |
| Quadratic | ” | 17 | 0.00236 | 1.79 | 4.74 | 0.0023 |
| Master recession curve | | | | | | |
| Fast | 72.1 | 16 | 0.000876 | 147.6 | 18 | – |
| Slow | ” | 16 | 0.000876 | 1.81 | 0.031 | – |
| Deuterium separation (23 Feb 1988) | | | | | | |
| Quadratic | 28.7 | 0 | 0.1035 | 22.3 | 5.93 | 0.974 |
| Quadratic | ” | 16 | 0.000864 | 19.5 | 3.38 | 0.235 |

[a] BF is baseflow fraction, $f$ bump fraction, $k$ slope parameter, $Q_0$ initial flow and $\alpha$ quadratic recession parameter.

[b] $\beta$ (exponential recession parameter, Eq. 9).

[c] $\gamma$ (reciprocal recession parameter, Eq. 20).

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New baseflow separation and recession analysis approaches for streamflow

M. K. Stewart

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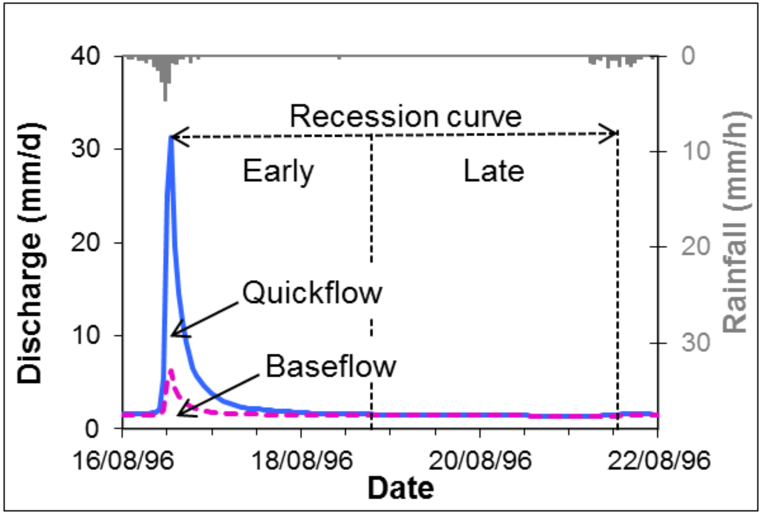

**Figure 1.** Quickflow and baseflow components of streamflow, and the early and late parts of the recession curve.

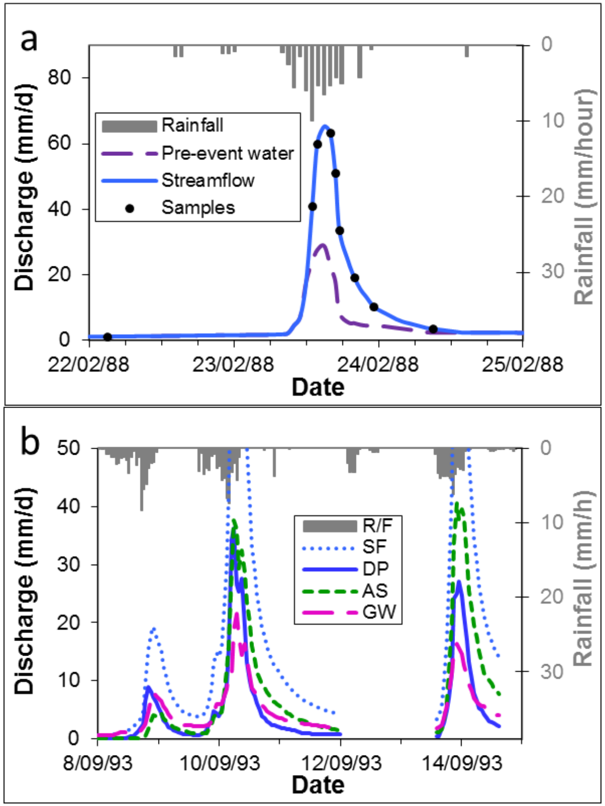

**Figure 2.** Tracer hydrograph separation results. **(a)** Event/pre-event water separation from catchment GH1, Glendhu, New Zealand using deuterium (replotted from Bonell et al., 1990). **(b)** Three component separation from Haute–Mentue research catchment, Switzerland using silica and calcium (replotted 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.

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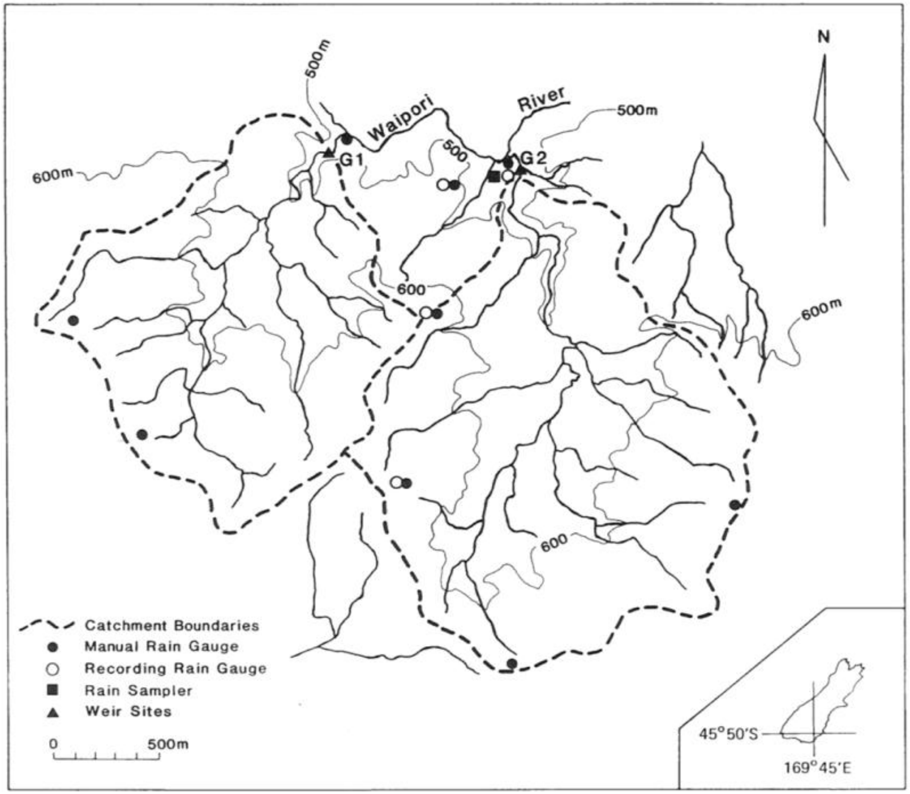

**Figure 3.** Map of Glendhu catchments showing catchment boundaries, stream courses and altitude contours (GH1 sampled at G1 weir, and GH2 at G2 weir). The inset shows their location in the South Island of New Zealand.

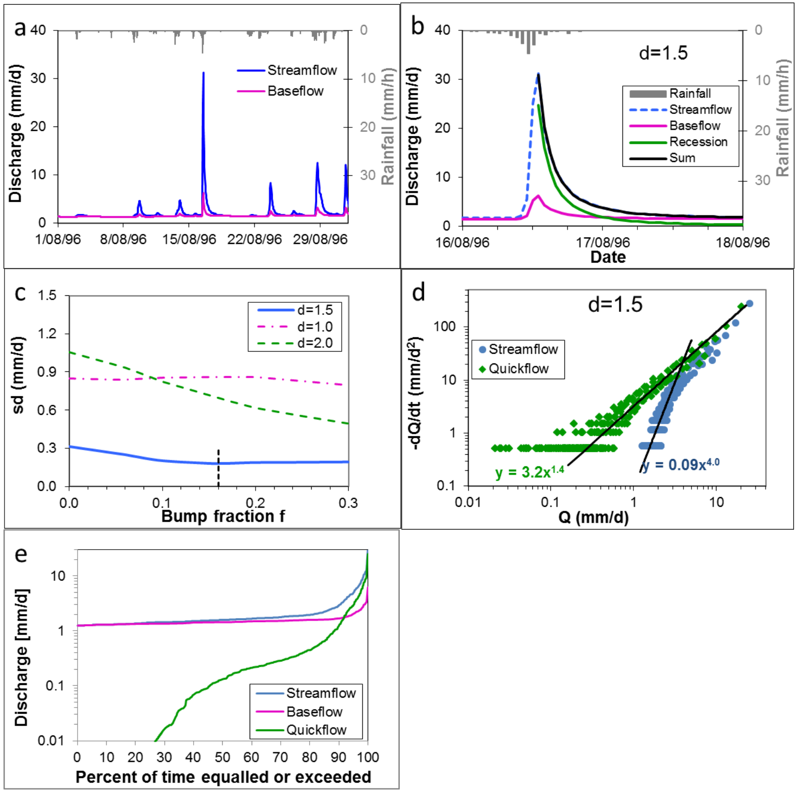

**Figure 4.** Application of the BRM baseflow separation method to Glendhu in winter. **(a)** Discharge during August 1996 showing streamflow, baseflow and rainfall, **(b)** 16 August 1996 event showing the sum of the baseflow and fast recession matched to the streamflow recession. **(c)** Variation of goodness of fit measure (sd) with bump fraction **(f)** for quadratic ($d = 1.5$) fast recession. Curves for $d = 1.0$ and 2.0 are also shown. **(d)** Recession plot (i.e. $Q$ vs. $-\mathrm{d}Q/\mathrm{d}t$) showing streamflow and quickflow recession data. **(e)** Flow duration curves for streamflow, baseflow and quickflow in August 1996.

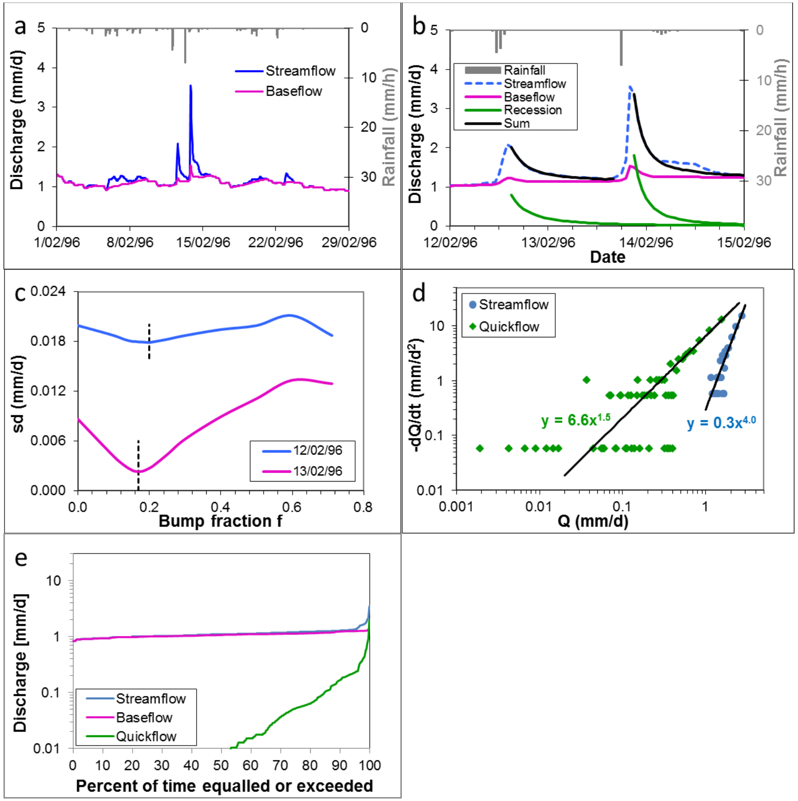

**Figure 5.** Application of the BRM baseflow separation method to Glendhu in summer. **(a)** Discharge during February 1996 showing streamflow, baseflow and rainfall, **(b)** 12 and 13 February 1996 events showing the sums of the baseflow and fast recessions matched to the streamflow recessions. **(c)** Variation of goodness of fit measure (sd) with bump fraction **(f)** for quadratic ($d$ = 1.5) fast recession. **(d)** Recession plot showing streamflow and quickflow recession data. **(e)** Flow duration curves for streamflow, baseflow and quickflow in February 1996.

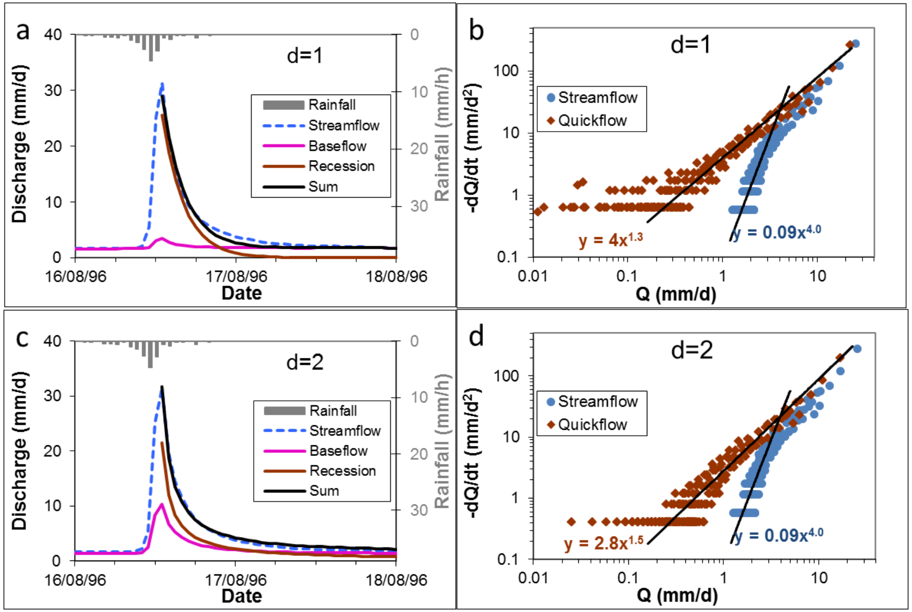

**Figure 6.** Effects of choice of fast recession type on the match between the sum and the streamflow, and quickflow recession plot character (see Sect. 7.2). **(a, b)** Exponential recession ($d = 1$). **(c, d)** Reciprocal recession ($d = 2$).

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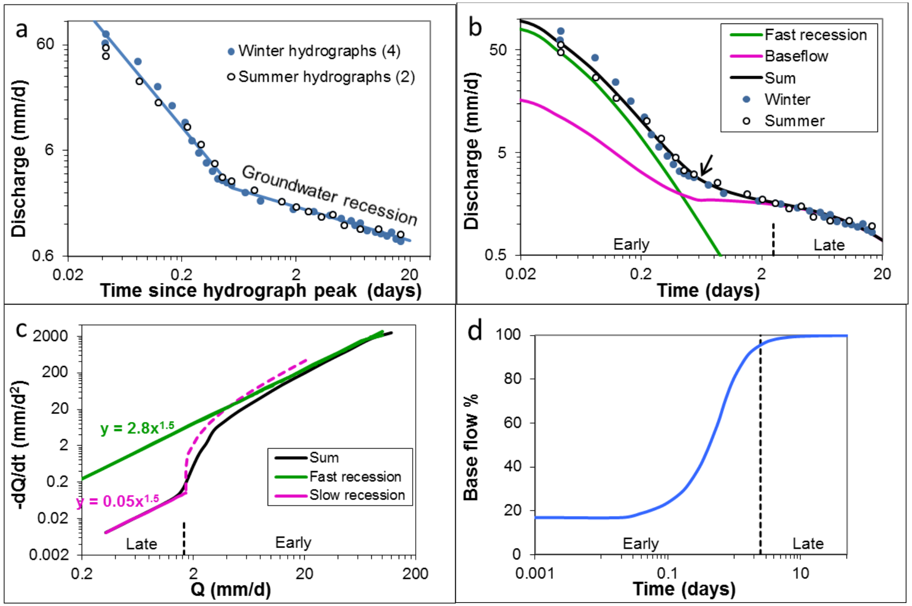

**Figure 7. (a)** “Master” recession curve for Glendhu catchment (redrawn from Pearce et al., 1984). **(b)** Master recession data matched by the sum of the baseflow and fast recession curve. The arrow shows the inflexion point. Early and late parts of the master recession curve are shown. **(c)** Recession 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.

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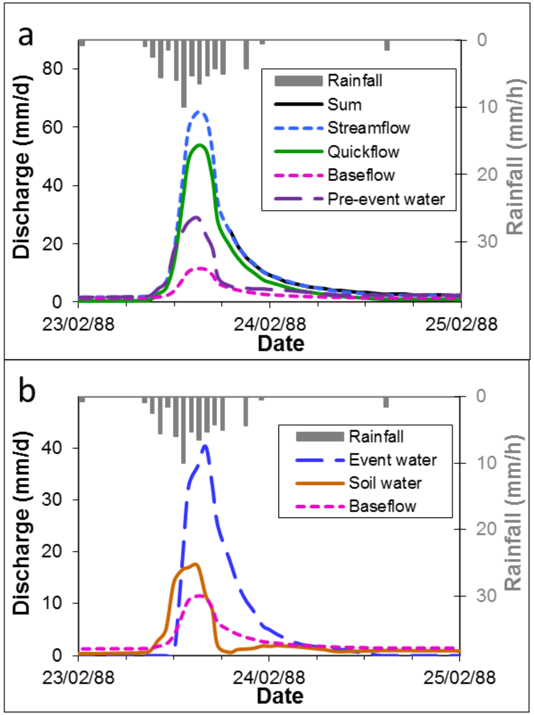

**Figure 8.** Deuterium separation event. **(a)** The sum of the baseflow and fast recession (quickflow) matched to the streamflow recession. Pre-event water is shown. **(b)** The three components in streamflow in the event: event water, soil water and baseflow.

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