A REVIEW OF TECHNIQUES FOR ANALYSING BASEFLOW FROM STREAM HYDROGRAPHS

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Abstract: Understanding the groundwater contribution to streams is critical when dealing with a wide range of water management issues. Analysis of the streamflow hydrograph, specifically separating and interpreting baseflow (the longer-term delayed flow from storage) from quickflow (the short-term response to a rainfall event) is a well-established strategy in understanding the magnitude and dynamics of groundwater discharge. A multitude of methods have evolved and these can be conveniently categorised into three basic approaches of baseflow separation, frequency analysis and recession analysis.

Baseflow separation uses the time-series record of stream flow to derive the baseflow signature. Graphical separation methods tend to focus on defining the points where baseflow intersects the rising and falling limbs of the quickflow response Filtering methods process the entire stream hydrograph to derive a baseflow hydrograph. Recursive digital filters, which are routine tools in signal analysis, are commonly used to remove the high-frequency quickflow signal to derive a low-frequency baseflow signal. Such filters are simple and robust but the results are very sensitive to the filter parameter, which needs calibration before the results can be considered to be numerically valid. Also, many of the filters have no hydrological basis.

Frequency analysis takes a different approach by deriving the relationship between magnitude and frequency of streamflow discharges. In its most common application, a flow duration curve (FDC) is generated showing the percentage of time that a given flow rate is equalled or exceeded. As well as the general shape of the FDC, various indices have been developed to characterise baseflow. Many of these indices are strongly intercorrelated and limited work has been undertaken to link these indices to groundwater processes.

Recession analysis focuses on the recession curve which is the specific part of the hydrograph following the stream peak (and rainfall event) when flow diminishes. Recession segments are selected from the hydrographic record and can be individually or collectively analysed to gain an understanding of the processes that influence baseflow. Graphical methods, such as correlation or matching strip techniques involve plotting multiple recession curves to derive a master recession curve representing a composite of baseflow conditions. In analytical methods, equations are applied to fit the recession segments. A storage-outflow model is developed to represent discharge from one or more natural storages during the recession phase. In its simplest form, the classic exponential decay function as used to represent heat flow, diffusion or radioactivity is applied. This assumes a linear relationship between storage and outflow which is commonly not applicable, so more complex functions have had to be developed.

Baseflow analysis, with a wide availability of methodologies, is a valuable strategy in understanding the dynamics of groundwater discharge to streams. Streamflow data is commonly collected and made publicly available, so is amenable to desktop analysis prior to any detailed field investigations. However, it is important to remember that the assumption that baseflow equates to groundwater discharge is not always valid. Water can be released into streams over different timeframes from different storages such as connected lakes or wetlands, snow or stream banks. As the hydrographic record represents a net water balance, baseflow is also influenced by any water losses from the stream such as direct evaporation, transpiration from riparian vegetation, or seepage into aquifers along specific reaches. Water use or management activities such as stream regulation, direct water extraction, or nearby groundwater pumping can significantly alter the baseflow component. Hence, careful consideration of the overall water budget and management regime for the stream is required.

Keywords: stream hydrograph, baseflow, recession analysis, seepage flux

INTRODUCTION

Historically, groundwater and surface water in Australia have been perceived and managed as isolated resources. There is however growing recognition that rivers can receive groundwater from underlying aquifers, and this can have significant implications for river water quantity and quality. The analysis of groundwater inputs into streams is critical when dealing with issues such as reliability of water supply, water allocation and trading, design of water storages, hydroelectric power generation, ecosystem water requirements, waste dilution, contamination impacts or predicting peak stream salinities.

A stream hydrograph is the time-series record of stream conditions (such as water level or flow) at a gauging site. The hydrograph represents the aggregate of the different water sources that contribute to stream flow. These components can be subdivided into:

(i.) *Quickflow* – the direct response to a rainfall event including overland flow (*runoff*), lateral movement in the soil profile (*interflow*) and direct rainfall onto the stream surface (*direct precipitation*), and;

(ii.) *Baseflow* – the longer-term discharge derived from natural storages.

The relative contributions of quickflow and baseflow components changes through the stream hydrographic record. The *flood or storm hydrograph* is the classic response to a rainfall event and consists of three main stages (Figure 1):

(i.) Prior low-flow conditions in the stream consisting entirely of baseflow at the end of a dry period;

(ii.) With rainfall, an increase in streamflow with input of quickflow dominated by runoff and interflow. This initiates the rising limb towards the crest of the flood hydrograph. The rapid rise of the stream level relative to surrounding groundwater levels reduces or can even reverse the hydraulic gradient towards the stream. This is expressed as a reduction in the baseflow component at this stage;

(iii.) The quickflow component passes, expressed by the falling limb of the flood hydrograph. With declining stream levels timed with the delayed response of a rising watertable from infiltrating rainfall, the hydraulic gradient towards the stream increases. At this time, the baseflow component starts to increase. At some point along the falling limb, quickflow ceases and streamflow is again entirely baseflow. Over time, baseflow declines as natural storages are gradually drained during the dry period up until the next significant rainfall event.

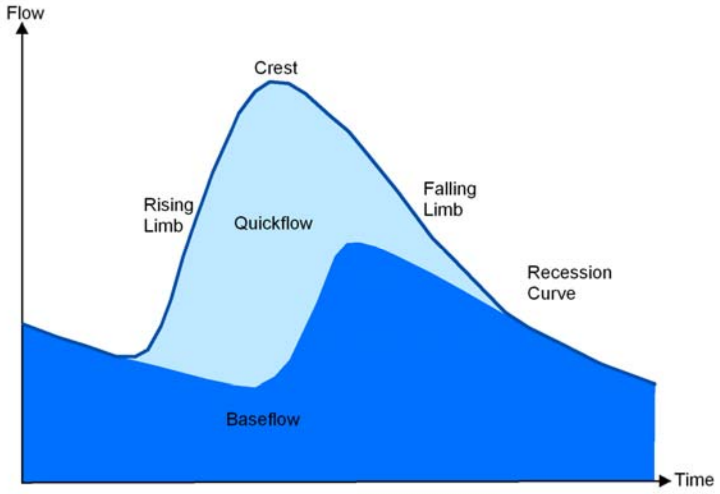

Figure 1: Components of a typical flood hydrograph

Analysing the stream hydrograph to separate out the baseflow component provides information on the characteristics of the natural storages feeding the stream. Groundwater discharge from the shallow unconfined aquifer is commonly assumed to be the main contributor to baseflow. For this to be a significant process, the unconfined aquifer needs to be adequately replenished (typically on a seasonal basis), have a shallow watertable that is higher than the stream water level, and have adequate water storage and transmission properties to maintain flow to the stream (Smakhtin 2001). For a gaining stream, where the underlying aquifer satisfies this criteria and groundwater contributes to stream flow, analysis of the stream hydrograph can indicate the magnitude and timing of this contribution.

However, in certain catchments baseflow may not be dominated by groundwater discharge from the shallow unconfined aquifer. Other storages such as connected lakes or wetlands, snow, glaciers, caverns in karst terrains, or temporary storage within the river bank following the passage of high-flow events (*bank storage*) can also contribute to the baseflow regime of a stream (Griffiths and Clausen 1997).

Another complication is that baseflow is also influenced by any water losses from the stream. The hydrographic record essentially represents the net balance between gains to and losses from the stream. These losses include direct evaporation from the stream channel or from any connected surface water features such as lakes and wetlands, transpiration from riparian vegetation, evapotranspiration from source groundwater seepages, leakage to the underlying aquifer, or rewetting of stream bank and alluvial deposits (Smakhtin 2001). These processes are often aggregated into a *transmission loss* for the reach of the stream.

Also, water use or management activities can significantly affect the baseflow regime. Many streams have highly modified flows due to the development and use of water resources. Overextraction can mean that streams that were naturally perennial due to prolonged baseflow, can become intermittent. Major regulated systems such as the River Murray have artificially high flows during the summer due to releases to supply irrigation and urban users. Specific activities that can influence baseflow include:

(i.) Stream *regulation* where flow is controlled by infrastructure such as dams, locks or weirs. Releases from surface water storages for downstream users can make up the bulk of streamflow during dry periods. Baseflow analysis should be undertaken in unregulated reaches, or at least the regulated catchment area should be no more than 10% of the catchment area of the streamflow gauge (Neal et al. 2004);
(ii.) Direct pumping of water from the stream for consumptive uses such as irrigation, urban supply or industry;
(iii.) Artificial diversion of water into or out of the stream as part of inter-basin transfer schemes;
(iv.) Direct discharges into the stream, such as from sewage treatment plants, industrial outfalls or mine dewatering activities;
(v.) Seasonal return flows from drainage of irrigation areas;
(vi.) Artificial drainage of the floodplain, typically for agricultural or urban development, which can enhance rapid runoff and reduce delayed drainage;
(vii.) Changes in land use, such as clearing, reafforestation or changes in crop type, which can significantly alter evapotranspiration rates;
(viii.) Groundwater extraction, sufficient to lower the watertable and decrease or reverse the hydraulic gradient towards the stream.

Careful consideration of the overall water budget and management regime for the stream is required before the assumption that baseflow equates to groundwater discharge can be made.

BASEFLOW ANALYSIS TECHNIQUES

Analysing the baseflow component of the stream hydrograph has had a long history of development since the early theoretical and empirical work of Boussinesq (1904), Maillet (1905) and Horton (1933). Several useful reviews have been written including Hall (1968), Nathan and McMahon (1990), Tallaksen (1995) and Smakhtin (2001) to map this development. The multitude of methods that have evolved can be conveniently categorised into three basic approaches of *baseflow separation*, *frequency analysis* and *recession analysis.*

Baseflow Separation

Baseflow separation techniques use the time-series record of stream flow to derive the baseflow signature. The common separation methods are either *graphical* which tend to focus on defining the points where baseflow intersects the rising and falling limbs of the quickflow response, or involve *filtering* where data processing of the entire stream hydrograph derives a baseflow hydrograph.

Graphical Separation Methods

Graphical methods are commonly used to plot the baseflow component of a flood hydrograph event, including the point where the baseflow intersects the falling limb (Figure 2). Stream flow subsequent to this point is assumed to be entirely baseflow, until the start of the hydrographic response to the next significant rainfall event. These graphical approaches to partitioning baseflow vary in complexity and include:

(i.) An empirical relationship for estimating the point along the falling limb where quickflow has ceased and all of the stream flow is baseflow;

$$D = 0.827A^{0.2} \qquad \text{(Equation 1)}$$

where D is the number of days between the storm crest and the end of quickflow, and A is the area of the catchment in square kilometres (Linsley et al. 1975). The value of the exponential constant (0.2) can vary depending on catchment characteristics such as slope, vegetation and geology.
(ii.) The *constant discharge method* assumes that baseflow is constant during the storm hydrograph (Linsley et al. 1958). The minimum streamflow immediately prior to the rising limb is used as the constant value.
(iii.) The *constant slope method* connects the start of the rising limb with the inflection point on the receeding limb. This assumes an instant response in baseflow to the rainfall event.
(iv.) The *concave method* attempts to represent the assumed initial decrease in baseflow during the climbing limb by projecting the declining hydrographic trend evident prior to the rainfall event to directly under the crest of the flood hydrograph (Linsley et al. 1958). This minima is then connected to the inflection point on the receeding limb of storm hydrograph to model the delayed increase in baseflow.
(v.) Using the trends of the falling limbs before and after the storm hydrograph to set the bounding limits for the baseflow component (Frohlich et al. 1994).
(vi.) Use the Boussinesq equation as the basis for defining the point along the falling limb where all of the streamflow is baseflow (Szilagyi and Parlange 1998).

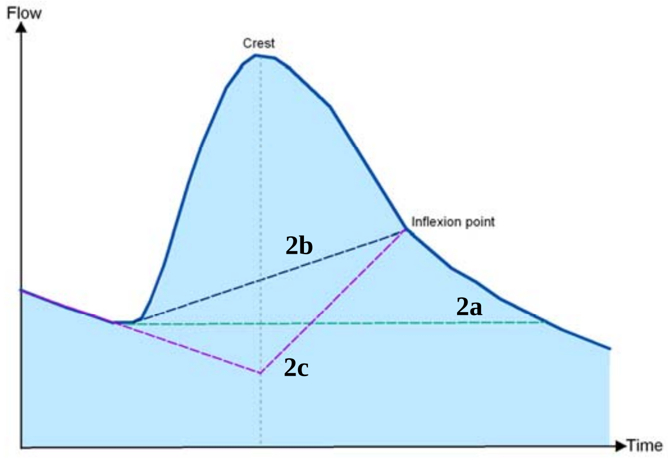

Figure 2: Graphical baseflow separation techniques including **(2a)** constant discharge method **(2b)** constant slope method and **(2c)** concave method (Linsley et al. 1958)

Filtering Separation Methods

The baseflow component of the streamflow time series can also be separated using data processing or filtering procedures. These methods tend not to have any hydrological basis but aim to generate an objective, repeatable and easily automated index that can be related to the baseflow response of a catchment. The *baseflow index* (BFI) or *reliability index*, which is the long-term ratio of baseflow to total streamflow, is commonly generated from this analysis. Other indices include the *mean annual baseflow volume* and the long-term *average daily baseflow* (Smakhtin 2001). Examples of continuous hydrographic separation techniques based on processing or filtering the data record include:

(i.) increasing the base flow at each time step, either at a constant rate or varied by a fraction of the runoff (Boughton 1988)

(ii.) The *smoothed minima technique* which uses the minima of 5-day nonoverlapping periods derived from the hydrograph. (Institute of Hydrology 1980; FREND 1989). The baseflow hydrograph is generated by connecting a subset of points selected from this minima series. The HYSEP hydrograph separation program (http://water.usgs.gov/software/hysep.html) uses a variant of this called the *local-minimum method* (Sloto and Crouse 1996)

(iii.) The *fixed interval method* discretises the hydrographic record into increments of fixed time (Pettyjohn and Henning 1979). The magnitude of the time interval used is calculated by doubling (and rounding up) the duration of quickflow calculated empirically from Equation 1. The baseflow component of each time increment is assigned the minimum streamflow recorded within the increment.

(iv.) The *sliding-interval method* assigns a baseflow to each daily record in the hydrograph based on the lowest discharge found within a fixed time period before and after that particular day (Pettyjohn and Henning 1979).

(v.) *Recursive digital filters*, which are routine tools in signal analysis and processing, are used to remove the high-frequency quickflow signal to derive the low-frequency baseflow signal (Nathan and McMahon 1990). Table 1 outlines some of the digital filters that have been applied to smooth hydrographic data. Eckhardt (2005) has developed a general formulation that can devolve into several of the commonly used one-parameter filters;

$$q_{b(i)} = \frac{(1 - BFI_{\max})aq_{b(i-1)} + (1-a)BFI_{\max} q_i}{1 - aBFI_{\max}} \qquad \textit{(Equation 2)}$$

Where $q_{b(i)}$ is the baseflow at time step i, $q_{b(i-1)}$ is the baseflow at the previous time step i-1, q_i is the stream flow at time step i, a is the recession constant and BFI_{max} is the maximum value of the baseflow index that can be measured.

(vi.) The *streamflow partitioning method* uses both the daily record of streamflow and rainfall (Shirmohammadi et al. 1984). Baseflow equates to streamflow on a given day, if rainfall on that day and a set number of days previous, is less than a defined rainfall threshold value. Linear interpolation is used to separate the quickflow component during high rainfall events.

Table 1: Recursive digital filters used in baseflow analysis (Grayson et al. 1996; Chapman 1999; Furey and Gupta 2001)

Filter Name	Filter Equation	Source	Comments
One-parameter algorithm	$q_{b(i)} = \frac{k}{2-k} q_{b(i-1)} + \frac{1-k}{2-k} q_{(i)}$	Chapman and Maxwell (1996)	$q_b(i) \leq q(i)$ Applied as a single pass through the data.
Boughton two-parameter algorithm	$q_{b(i)} = \frac{k}{1+C} q_{b(i-1)} + \frac{C}{1+C} q_{(i)}$	Boughton (1993) Chapman and Maxwell (1996)	$q_b(i) \leq q(i)$ Applied as a single pass through the data Allows calibration against other baseflow information such as tracers, by adjusting parameter *C*
IHACRES three-parameter algorithm	$q_{b(i)} = \frac{k}{1+C} q_{b(i-1)} + \frac{C}{1+C} (q_{(i)} + \alpha_q q_{(i-1)})$	Jakeman and Hornberger (1993)	Extension of Boughton two-parameter algorithm
Lyne and Hollick algorithm	$q_{f(i)} = \alpha q_{f(i-1)} + (q_{(i)} - q_{(i-1)}) \frac{1+\alpha}{2}$	Lyne and Hollick (1979) Nathan and McMahon, (1990)	$q_f(i) \geq 0$ α value of 0.925 recommended for daily stream data filter recommended to be applied in three passes Baseflow is $q_b = q - q_f$
Chapman algorithm	$q_{f(i)} = \frac{3\alpha - 1}{3-\alpha} q_{f(i-1)} + \frac{2}{3-\alpha} (q_{(i)} - \alpha q_{(i-1)})$	Chapman (1991) Mau and Winter (1997)	Baseflow is $q_b = q - q_f$
Furey and Gupta filter	$q_{b(i)} = (1-\gamma) q_{b(i-1)} + \gamma \frac{c_3}{c_1} (q_{(i-d-1)} - q_{b(i-d-1)})$	Furey and Gupta (2001)	Physically-based filter using mass balance equation for baseflow through a hillside

$q_{(i)}$ is the original streamflow for the i^{th} sampling instant
$q_{b(i)}$ is the filtered baseflow response for the i^{th} sampling instant
$q_{f(i)}$ is the filtered quickflow for the i^{th} sampling instant
$q_{(i-1)}$ is the original streamflow for the previous sampling instant to i
$q_{b(i-1)}$ is the filtered baseflow response for the previous sampling instant to i
$q_{f(i-1)}$ is the filtered quickflow for the previous sampling instant to i
k is the filter parameter given by the recession constant
α, α_q are filter parameters
C is a parameter that allows the shape of the separation to be altered
γ, c_1, c_3 are physically based parameters

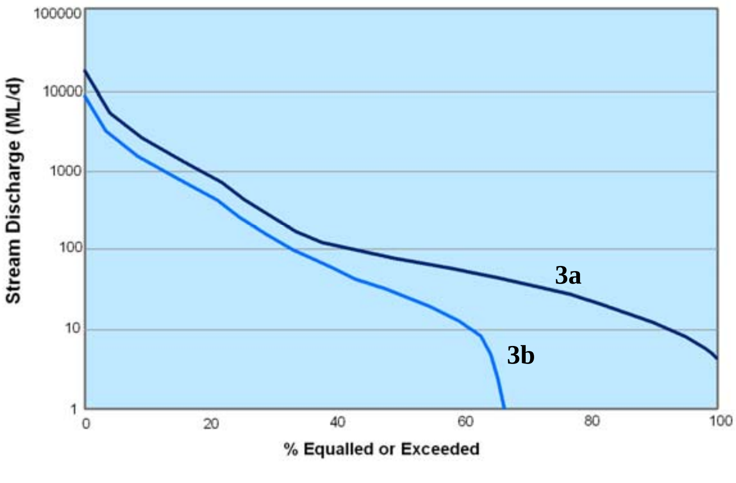

Figure 3: Flow distribution curves for examples of **(3a)** high baseflow and **(3b)** low baseflow streams

Frequency Analysis Methods

Frequency analysis takes a different approach in characterising baseflow by deriving the relationship between the magnitude and frequency of streamflow discharges from the hydrographic record. In its most common application, a flow duration curve (FDC) is generated. Instead of plotting as a time series, a flow duration curve shows the percentage of time that a given flow rate is equalled or exceeded. The FDC is constructed from flow data of fixed time period (eg daily, monthly, annual) by:

(i.) Sorting the flow data in order of decreasing flow

(ii.) Assigning a unique ranking number *m* to each flow, starting with 1 for the maximum flow to *n* for the minimum flow, where *n* is the number of flow measurements.

(iii.) The probability P that a given flow will be equalled or exceeded is defined by:

$$P = 100\frac{m}{n+1} \qquad \textit{Equation 3}$$

(iv.) The flow-probability relationship is typically presented as a log-normal plot (Fetter 1994)

Flow duration curves can be constructed for the entire record of flow measurement, or for specific time periods such as similar calendar months or seasons.

The FDC provides information on the baseflow component of stream flow. The method relies on the statistics of measured flows, rather than any analysis of hydrological processes as such. The *median flow* (Q50) is the discharge which is equalled or exceeded 50% of the time. The part of the curve with flows below the median flow represents low-flow conditions. Baseflow is interpreted to be significant if this part of the curve has a low slope, as this reflects continuous discharge to the stream. A steep slope for these low-flows suggests relatively small contributions from natural storages like groundwater (Figure 3). These streams may cease to flow for relatively long periods. In this way, the shape of the FDC can indicate the hydrogeological characteristics of a catchment (Smakhtin 2001).

Various indices are used to represent the characteristics of the low-flow regime for a stream. The ratio of the discharge which is equalled or exceeded 90% of the time, to that of 50% of the time (Q90/Q50) is commonly used to indicate the proportion of streamflow contributed from groundwater storage (Nathan and McMahon 1990). Other low-flow indices include:

(i.) One- or *n*-day discharges that are exceeded at defined percentages of time, say 75, 90 or 95 % eg Q75(7), Q75(10), Q95(10)

(ii.) The percentage of time the stream is at zero-flow conditions

(iii.) The longest recorded period of consecutive zero-flow days (Smakhtin 2001)

A *Low-flow Frequency Curve* (LFFC) shows the proportion of years when a low-flow rate is exceeded. This depicts the *recurrence interval* which is the average interval (in years) that the stream discharge falls below a given rate, and can also be used to represent baseflow conditions. The curve is generated from the series of annual minimum flow values extracted from the stream monitoring data. Like the flow duration curve, various indices can be used to indicate baseflow conditions including:

(i.) The slope of the LFFC, as the larger the slope indicates more variability in low-flows

(ii.) Breaks in the curve near the modal value have been interpreted as representing when streamflow is exclusively from groundwater storage

(iii.) Lowest average flows that occur over a set number of consecutive days (eg 3, 7 days) at defined recurrence intervals (eg 2, 10 years), for example 7-day 10-year low flow (7Q10) or 7-day 2-year low flow (7Q2)

(iv.) The average of the annual series of minimum 7-day average flows, MAM7 or also known as *dry weather flow*

(v.) Indices of seasonal low flows such as mean 30-day summer low flows (Smakhtin 2001)

Recession Analysis Methods

The *recession curve* is the specific part of the flood hydrograph after the crest (and the rainfall event) where streamflow diminishes (Figure 1). The slope of the recession curve flattens over time from its initial steepness as the quickflow component passes and baseflow becomes dominant. A *recession period* lasts until stream flow begins to increase again due to subsequent rainfall. Hence, recession curves are the parts of the hydrograph that are dominated by the release of water from natural storages, typically assumed to be groundwater discharge. *Recession segments* are selected from the hydrograph and can be individually or collectively analysed to gain an understanding of the discharge processes that make up baseflow. Graphical approaches have traditionally been taken but more recently analysis has focussed on defining an analytical solution or mathematical model that can adequately fit the recession segments.

Each recession segment is often considered as a classic exponential decay function as applied in other fields such as heat flow, diffusion or radioactivity, and expressed as:

$$Q_t = Q_0 e^{-\alpha t} \quad \text{or} \quad Q_t = Q_0 e^{-\frac{t}{T_c}} \qquad \textit{(Equation 4)}$$

where Q_t is the stream flow at time t, Q_0 is the initial stream flow at the start of the recession segment, α is a constant also known as the *cut-off frequency* (f_c) and T_c is the *residence time or turnover time* of the groundwater system defined as the ratio of storage to flow.

The term $e^{-\alpha}$ in this equation can be replaced by k, called the *recession constant* or *depletion factor*, which is commonly used as an indicator of the extent of baseflow (Nathan and McMahon 1990). The typical ranges of daily recession constants for streamflow components, namely runoff (0-2-0.8), interflow (0.7-0.94) and groundwater flow (0.93-0.995) do overlap (Nathan and McMahon 1990). However, high recession constants (eg > 0.9) tend to indicate dominance of baseflow in streamflow. Another parameter interpreted from the recession segment is the *recession index (K)* which is the time (in days) required for baseflow to recede by one log-cycle ie Q_0 to $0.1Q_0$. A similar index called the *half-flow period* or *half-life*, which is the time (in days) for flow to halve can also be calculated. For streams with low baseflow inputs the half-life may be in the range of 7-21 days, while discharge from large stable natural storages can result in a half-life exceeding 120 days (Smakhtin 2001).

The integrated form of the classic recession function of Equation 4 is;

$$Q_t = \alpha S_t \qquad \textit{(Equation 5)}$$

where S_t is the storage in the reservoir that is discharging into the stream at time t. This relationship is called a linear *storage-outflow model* and implies that the recession will plot as a straight line on a semi-logarithmic scale. However, semi-logarithmic plots of individual recessions are commonly curved rather than linear. This is because other natural storages (eg bank storage, wetlands, deeper confined aquifers) can also contribute to baseflow, and these have different regimes of water release to the stream than that of the groundwater stored in the shallow aquifer (Sujono et al. 2004). The recession curve is effectively a composite of water discharged into the stream from multiple natural storages. This coincides with the concept that a catchment is a series of interconnected reservoirs (such as rainfall, snow, aquifers, soil, biomass etc), each having distinct characteristics in terms of recharge, storage and discharge (Smakhtin 2001).

A curved semi-logarithmic plot for recessions means that the storage-outflow relationship is non-linear. For groundwater discharge from a shallow unconfined aquifer, there are three main reasons for this non-linearity (Van de Griend et al. 2002):

(i.) A falling watertable continually decreases the effective thickness of the aquifer and decreases the ability to drain. Declining watertables can also be attributed to other processes other than stream discharge, such as evapotranspiration or groundwater extraction.
(ii.) The hydraulic conductivity tends to decrease with depth. This is attributed to increased compaction with depth in unconsolidated sediments, and decreased fracturing with depth in hard rock formations.
(iii.) With prolonged drainage, the lower order stream channels can run dry, leaving only the highest order reaches receiving baseflow.

Another complication is that the recession behaviour for a stream can change through time. This is reflected in variations in the shape of the recession segments found in a stream hydrograph. This is due to variability in such factors as the areal distribution of rainfall, residual storage in connected surface water bodies, catchment wetness, saturated aquifer thickness or depth of stream penetration into the aquifer. Baseflows are also influenced by seasonal effects such as variations in rainfall and evapotranspiration. High evapotranspiration rates during warm weather or active growing seasons can significantly reduce the baseflow component, particularly in shallow watertable areas.

Different approaches have been used in recession analysis to address this non-linearity and variability in recession:

(i.) Approximating the semi-logarithmic plot of the recession curve as three straight lines of different slope (Barnes 1940). The gradients of these three lines are inferred to be the recession constants for the main streamflow components of runoff, interflow and groundwater flow. The plotting of the three lines is difficult because of the gradual nature of the change in curvature in the recession.
(ii.) Plotting flow ratios (Q_0/Q_t) instead of flow (Q_t) on the semi-logarithmic plot (Hino and Hasebe 1984) to facilitate better interpretation of the recession.
(iii.) Using a double logarithmic plot of streamflow against time (Hewlett and Hibbert 1963). Any abrupt change in slope is interpreted to mark the transition from quickflow to baseflow.
(iv.) The *correlation method* where the current flow Q is plotted on a natural scale against the flow (Q_t) at some fixed time interval t previously (eg 2 days before) for each of the recession curves evident in the hydrograph (Langbein 1938). A line enveloping the traces of these multiple recessions is drawn through the origin to derive the *master recession curve.* By rearranging the exponential decay (Equation 4) the recession constant k can be derived from the slope of this master recession curve and the lag time interval t.

$$k = (\frac{Q}{Q_0})^{1/t}$$ *(Equation 6)*

(v.) The *matching strip method* involves plotting multiple recession curves derived from the hydrograph on the one semi-logarithmic plot in order of increasing minimum discharge (Toebes and Strang 1964). Each recession curve is superimposed and adjusted horizontally to produce an overlapping sequence. The master recession curve is interpreted as the envelope to this sequence, and the recession constant *k* derived from its slope (Equation 6).

(vi.) The *tabulation method* where data from the multiple recession curves are used to derive the master recession curve and average discharges calculated for the period of the hydrographic record (Johnson and Dils 1956). Recession periods are tabulated and sorted, and mean discharges calculated for each timestep. This is either done computationally (Boughton 1995) or by an analytical solution (Singh 1989).

(vii.) The *recession ratio* method which analyses the ratios of current flow (Q) to the flow (Q_t) at some fixed time interval t previously (eg 2 days before). A cumulative frequency diagram is plotted to estimate indices such as the *median recession ratio* (REC50) as a substitute for the recession constant, *k* (Smakhtin 2001).

(viii.) The *parameter averaging method* where the recession function (Equation 4) is fitted for each of the recession segments in the hydrograph. The recession constants that are derived are then averaged (James and Thompson 1970)

(ix.) *Wavelet transform analysis* is a technique to break down a signal into its components and applied in such fields as image processing and geophysics. The technique can also be used in hydrograph recession analysis in terms of separating out the low frequency signature of the baseflow. Plots of frequency against time called *mean-square wavelet maps* are used to derive recession constants (Sujono et al. 2004).

(x.) Using different storage-outflow models or combinations of storage-outflow models to obtain a better fit to the recession curve. The classic exponential decay function (Equation 4) represents a linear relationship between storage and outflow. Other equations have been developed to model discharge from different types of natural storages (Table 2). By combining these equations, discharge from the various natural storages can be better accounted for. For example, a simple option is to add a constant (*b*) to the linear reservoir equation:

$$Q = Q_0 e^{-\alpha t} + b$$ *(Equation 7)*

This provides a better fit to recession curves that stabilise to a constant streamflow over time. This constant flow may represent discharge from a large groundwater storage or from ice or snow reserves. A model based on combining two linear storages has also been used to provide a better fit to the recession curves for a small forested catchment (Moore 1997). These two storages were interpreted to represent different residence times for water in footslope and upslope zones in the catchment.

(xi.) The *Meyboom* method uses stream hydrograph data over two or more consecutive years (Meyboom 1961). The baseflow is assumed to be entirely groundwater discharged from the unconfined aquifer. An annual recession is interpreted as the long-term decline during the dry season following the phase of rising streamflow during the wet season. The total potential groundwater discharge (V_{tp}) to the stream during this complete recession phase is derived as:

$$V_{tp} = \frac{Q_0 K}{2.3}$$ *(Equation 8)*

where Q_0 is the baseflow at the start of the recession and K is the recession index, the time for baseflow to decline from Q_0 to $0.1Q_0$.

(iv.) The *recession-curve-displacement* method is based on the upward displacement of the recession curve during the rainfall event (Rorabaugh 1964; Rutledge and Daniel 1994; Rutledge 1998). The method assumes that baseflow is entirely groundwater discharge from an unconfined aquifer of uniform thickness and hydraulic properties, with the stream fully penetrating the aquifer. On the basis of the algorithms developed, the total recharge to the groundwater system during the rainfall event has been shown to be about twice the total potential discharge to the stream at a critical time (T_c) after the hydrographic peak. Hence, the total volume of groundwater recharge due to the rainfall event (R) can be estimated from the stream hydrograph by:

$$R = \frac{2(Q_2 - Q_1)K}{2.3026}$$ *(Equation 9)*

where Q_1 is the baseflow at the critical time (T_c) extrapolated from the pre-event recession curve, Q_2 is the baseflow at the critical time (T_c) extrapolated from the post-event recession curve, and K is the recession index (Figure 4).

Table 2: Different storage-outflow models used in recession analysis (Moore 1997; Griffiths and Clausen 1997; Dewandel et al 2003)

Conceptual Model	Storage-Outflow Relation	Recession Function	Storage Types	Source	Comments
Linear reservoir	$Q = kS$	$Q = Q_0 e^{-kt}$	General storage	Boussinesq (1877) Maillet (1905)	Linearised Depuit-Boussinesq equation. Approximation for short time periods
Horton double exponential		$Q = Q_0 e^{-\alpha_2 t^m}$	General storage	Horton (1933)	Transformation of linear reservoir model
		$Q = Q_0 (1 + (n-1)\alpha_0 t)^{n(1-n)}$		Coutagne (1948)	
		$Q = Q_0 - Q_c (1 + (n-1)\alpha_0 t)^{n(1-n)} +$	Karstic aquifers	Padilla et al. (1994)	Qc is discharge from low-transmissivity components of karst
Channel Bank Storage		$Q = \alpha e^{-kt}$	Channel banks	Cooper and Rorabaugh, (1963)	Variant of linear reservoir. Also used to model evapotranspirative losses
Exponential reservoir	$Q = Q_B e^{-\phi SD}$	$Q = Q_0 /(1 + \phi Q_0 t)$	Throughflow in soil		hydraulic conductivity assumed to exponentially decrease with depth
Power-law reservoir	$Q = \alpha S^{\beta}$	$Q = Q_0 (1 + \mu t)^p$ $p = \beta /(1 - \beta)$ $\mu = \alpha^{1/\beta} (\beta - 1) Q_0^{(\beta-1)\beta}$	Springs and unconfined aquifers (p = -2) Soil moisture	Hall (1968) Brutsaert and Nieber (1977)	Recessions modelled using p ~ 1.67 (Wittenberg 1994)
Depuit-Boussinesq aquifer storage		$Q = Q_0 (1 + a_3 t)^{-2}$	Shallow unconfined aquifer	Boussinesq (1904)	Special case of power-law reservoir for Depuit-Boussinesq aquifer model
Depression Storage Detention Storage		$Q = \alpha_1 /(1 + \alpha_2 t)^3$	Surface depressions such as lakes and wetlands, Overland flow	Griffiths and Clausen (1997)	variant of power-law reservoir
Two parallel linear reservoirs	$Q = k_1 S_1 + k_2 S_2$	$Q = Q_1 e^{-k_1 t} + Q_2 e^{-k_2 t}$	Independent aquifers	Barnes (1939)	
Two serial linear reservoirs	$Q = k_2 S_2$ $\frac{dS_2}{dt} = Q_1 e^{-k_1 t} - k_2 S_2$	$Q = Q_0 e^{-k_2 t} + \frac{k_2 Q_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t})$			
Cavern Storage		$Q = \alpha_1 - \alpha_2 t$	Underground caverns in karst terraine	Griffiths and Clausen (1997)	
Hyperbola reservoir		$Q = \alpha_1 t^{-r} + b$	Ice melt, lakes	Toebes and Strang (1964)	
Constant reservoir		$Q = \alpha$	Permanent snow and ice pack, large groundwater storages		Constant stream flow over a finite time period

Q - discharge
S, S_1, S_2 – reservoir storages
SD – catchment storage deficit
t– time since beginning of recession
Q_0 – discharge for t = 0
Q_B, Q_1, Q_2, k, k_1, k_2, α, β, φ - parameters to be determined by calibration

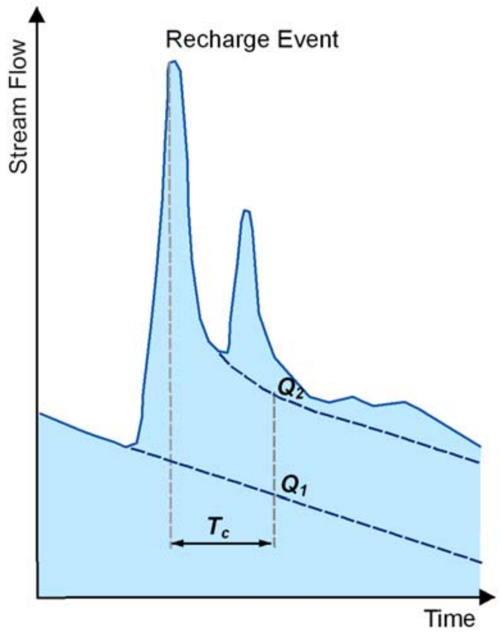

Figure 4: Procedure for recession curve displacement method (after Rutledge and Daniel 1993)

(1) Estimate the recession index (K) from the stream hydrograph record
(2) Calculate the critical time (T_c), using the relationship $T_c = 0.2144K$
(3) Locate the time on the hydrograph which is T_c days after the peak, where streamflow recessions will be extrapolated to
(4) Extrapolate the pre-event recession curve to derive Q_1
(5) Extrapolate the post-event curve to derive Q_2
(6) Calculate total potential groundwater recharge using these parameters

DISCUSSION AND CONCLUSIONS

A wide variety of approaches have evolved to analyse the hydrographic record to derive the baseflow component and gain an understanding of underlying discharge processes. These approaches have been conveniently categorised into baseflow separation, frequency analysis and recession analysis. In baseflow separation, the early development of graphical methods has been largely replaced by data processing techniques. In particular, the application of recursive digital filters has played a significant role. Many of these filters have been adopted from signal processing and involve the separation of high frequency events. The major challenge is to develop algorithms that have a hydrological basis and can derive hydrogeological parameters. Such physically based filters are being developed, some based on mass balance equations for baseflow from hillsides (Furey and Gupta 2001 2003). In contrast, frequency analysis takes a statistical approach to describe the general low-flow regime. There has been a focus on the development of various low-flow indices but many of these are strongly intercorrelated (Smakhtin 2001). Also limited work has been done to link these indices directly to groundwater processes. To this end, some studies have combined low-flow frequency analysis with recession analysis (Loganathan et al 1986; Gottschalk et al 1997). As in baseflow separation, the traditional approach to recession analysis has been graphical. Early analytical solutions assumed exponential decay of baseflow recession, reflected in a linear relationship between storage and outflow. However, recession behaviour can be complex, variable and non-linear so more complex storage-outflow models have had to be developed. There is now the opportunity to tailor a storage-outflow model that better reflects the natural storages in a catchment. On this basis, it appears that recession analysis holds the most promise in deriving hydrogeological understanding from interpretation of the stream hydrograph.

Baseflow analysis of stream hydrographs can provide valuable insights into how groundwater contribution to stream flow changes through time. A distinct advantage of the approach is that it uses stream flow data that is routinely collected and placed in the public domain. This means that baseflow analysis can be readily undertaken as a desktop study prior to any detailed field investigations. In terms of data availability, Table 3 outlines the significant surface water monitoring databases in Australia, highlighting the State and Territory agencies involved in water management as the main data custodians. To better coordinate the access to these databases, the Executive Steering Committee for Australia's Water Resources Information has been established to build the Australian Water Data Infrastructure (ESCAWRI 2005). The infrastructure will be designed to allow access to the many hydrological databases maintained by different custodians. Currently, the Water Resources Station Catalogue developed by the Bureau of Meteorology provides a national inventory of the river gauging stations, as well as rainfall and evaporation stations, across the country (BOM 2005).

However, baseflow analysis is only applicable for gaining streams, although frequency analysis can provide insights into losing conditions. Baseflow analysis can provide information on the temporal changes but not the spatial distribution of groundwater inputs along a stream between gauging stations. Baseflow conditions are commonly assumed to be entirely groundwater discharge, which may not always be valid. The method cannot be applied in rivers that are regulated or have significant diversions or extractions, or have large natural storages such as lakes or wetlands. The overall water budget and management regime for the river needs to be considered when evaluating the significance of groundwater to the baseflow signal. This may mean that other methods such as environmental tracers (like major ions, stable isotopes or radon) or hydrometric analysis (comparing river levels with nearby groundwater levels to define hydraulic gradients) may need to be used to confirm groundwater discharge to the river.

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Table 3: Significant surface water monitoring databases in Australia (after Brodie et al. 2003)

Database Name	Area	Custodian	Water Features	Data Access	Data Themes	Sites
Water Resource Information System	ACT	Environment ACT http://www.environment.act.gov.au/airandwater/airandwater.html				360
Surface Water Data	NSW	NSW Dept Infrastructure, Planning & Natural Resources http://www.dipnr.nsw.gov.au/water/index.shtml	streams, channels reservoirs	http://waterinfo.dlwc.nsw.gov.au/	water flow water level rainfall water quality	1,700
	NSW	Manly Hydraulics Laboratory http://www.mhl.nsw.gov.au/	streams, estuaries	http://www.mhl.nsw.gov.au/www/dcol.htmlx	water level water quality tides rainfall	200
Surface Water and Water Quality	NT	NT Dept Planning & Infrastructure http://www.ipe.nt.gov.au/whatwedo/water-resources/index.html	streams rainfall	http://www.ipe.nt.gov.au/whatwedo/water-resources/surface/telemeteredsites/index.html	water flow water level	
Surfacewater Resource Information	Qld	Qld Dept Natural Resources and Mines http://www.nrm.qld.gov.au/resources/index.html	streams	http://www.nrm.qld.gov.au/watershed/index.html	water level, water flow temperature conductivity water quality	5,000
State Surface Water Archive	SA	SA Dept of Water, Land and Biodiversity Conservation http://www.dwlbc.sa.gov.au/	streams rainfall	http://www.dwlbc.sa.gov.au/subs/surface_water_archive/a1pgs/index.htm	water flow water level velocity	1035
Tasmanian Water Information Database	Tas	Tas Department Primary Industries, Water and Environment http://www.dpiwe.tas.gov.au	streams rainfall	http://wired.dpiwe.tas.gov.au/hoo/WaterManagement	water level water flow water quality	17,000
Victoria Water Resources Data Warehouse	Vic	Vic Dept Sustainability and Environment http://www.dse.vic.gov.au/dse/index.htm	streams	http://www.vicwaterdata.net/	water flow water levels water quality	90,000
WIN, Water Information System and HYDSTRA	WA	WA Department of Environment http://www.environment.wa.gov.au	streams wetlands rainfall	http://203.20.251.100/waterinformation/telem/table.htm	water flow water level water quality rainfall	15,000
Water Resources Station Catalogue	Aus	Bureau of Meteorology http://www.bom.gov.au/hydro/	streams	http://www.bom.gov.au/hydro/wrsc	Metadata	2.050

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RELEVANT LINKS

ASTHyDA Project (http://www.geo.uio.no/drought/) – European project focussing on tools for assessing low surface water and groundwater flows

Australian Hydrographers Association (http://www.aha.net.au/)

BFI (http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/index.html) US Bureau of Reclamation software for determining a Base Flow Index using a *local minimum* approach

HYSEP (http://water.usgs.gov/software/hysep.html) – USGS hydrographic separation program based on the fixed-interval, sliding-interval and local-minimum methods

Low Flows 2000 (http://www.nwl.ac.uk/ih/www/products/iproducts.html)- Decision support tool for estimating low flows in the United Kingdom

PART (http://water.usgs.gov/ogw/part/) - USGS program for estimating baseflows using a stream partitioning method

RAP (http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit.woa/wa/productDetails?productID=1000002) – CRC Catchment Hydrology River Analysis Package including baseflow analysis

RECESS (http://water.usgs.gov/ogw/recess/) USGS method for analysing streamflow recession to determine the master recession curve

RORA (http://water.usgs.gov/ogw/rora/): USGS program for estimating groundwater recharge using the recession-curve-displacement method