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Hydrograph Analysis and Baseflow Separation

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15.1 Introduction

While for such engineering design problems as dykes, river training, bridges, and stormwater drainage systems peak discharge rates are sufficient, they are inadequate for the design of hydraulic structures where storage is involved. A spillway of a dam, for example, is hit not by the natural hydrograph with its peak discharge of the catchment but by a design discharge significantly attenuated by the retention effect of the reservoir: flood volume counts, and therefore, the design work is usually based on the hydrograph rather than the peak discharge rate.

The streamflow hydrograph is the graphical representation of the variation of discharge through the cross section of a water course over time. It is the superposition of responses of the contributing watershed to precipitation and evapotranspiration according to the properties such as area, topography, morphology, geology, storage capacity, soil moisture, vegetation, and land use.

A typical hydrograph has three parts (Figure 15.1). The rising of the hydrograph from B to C (ascension curve, rising limb, or concentration curve) is due to rainfall generating mainly direct runoff (quick flow). Peak time (B to C in Figure 15.1) shows the time when the maximum flow resulting from the input occurs. Depending on the concentration time of the watershed and the rainfall duration, this can happen as a crest segment [55]. After peaking, direct flow decreases along the recession curve also called depletion curve from C to E corresponding to the discharge of water from the basin after the rainfall ceases. A recession curve can be separated into two parts: the falling limb from C to D and the baseflow recession from D to E in Figure 15.1. The shape of the recession curve does not depend on the input, while that of ascension curve does. When an intermittent stream is concerned, zero-flow portions from H to I arise too.

A flow or flood hydrograph that is caused by a single heavy rainfall event can be represented by three functions: input function, transfer function, and output function. Normally, a rainfall event (hyetograph) is the input, while the total runoff discharge hydrograph is considered as the output function. The watershed itself represents the transfer function, converting parts of the rainfall hyetograph into direct runoff, while the rest is “lost,” caught by vegetation (interception), as soil moisture and infiltration, and leaves the catchment later by evapotranspiration or as groundwater outflow (baseflow).
This event-based philosophy is mainly applied in flood analysis and the simulation of design flood hydrographs. A classical and basic transfer or response function is the unit hydrograph method [57]. The unit hydrograph of a catchment is its typical reaction on 1 mm (one unit) of effective rainfall occurring in a defined time step. Once the unit hydrograph is derived, a flood hydrograph caused by different rainfall heights in consecutive time intervals (design hyetograph) is computed by convolution (multiplication and superposition).

The unit hydrograph as the transfer function or response function of a watershed can be determined from measured rainfall and runoff during a flood event. Before processing the observed data, the slow-flow "baseflow" component is separated from the total hydrograph. Likewise, the "losses," that is, the part of rainfall that does not become direct flow, must be separated from the hyetograph so that volume continuity is achieved. The method is only applicable for smaller- or middle-sized watersheds where a fairly equal or typical rainfall distribution during heavy rainfall events can be expected. For larger catchments or with different spatial rainfall patterns, distributed hydrological models are needed.

Runoff is generated either by rainfall or by snowmelt. Glaciers can also contribute to the surface runoff of watersheds. However, it should be kept in mind that not all rainfall contributes runoff due to the absorption rate of the soil changing with water demand of soil storage. Surface flow interacts with atmosphere and subsurface water systems. At the initial stage of precipitation, a large portion of it is devoted to the surface storage to fill the retention and detention capacities of the soil. Retention is depleted by evaporation in a long period of time, while detention has a short period of time to be swept out by surface runoff or infiltration. Subsurface flow takes place beneath the soil surface. It originates from infiltrated precipitation that is diverted from its vertical movement by impermeable layers in the unsaturated zone (interflow). Groundwater is located in the saturated zone under the surface within spaces in gravel, sand, and soil pores and in fractures and fissures of rock formations. Groundwater can be mobile or immobile depending on the soil formation and the gradient. Flow velocity is proportional to the gradient and the permeability of the soil formation (Darcy’s law). Under low-permeability conditions, groundwater flow becomes slow or stays immobile within the soil formation.

It was indicated previously that the flow can be separated into two parts, direct runoff born from surface flow and shallow subsurface drainage and baseflow consisting mainly of exfiltrating groundwater. Groundwater-fed baseflow is the largest component of the discharge of most rivers. Groundwater recharge by precipitation is thus an important process. During the initial stage of a
rainfall event, the surface layers of the soil are moisturized and little depressions filled. Soon infiltration starts and high portions of rain find their way to the saturated zone, the upper aquifer. Besides the permeability of the unsaturated (vadose) zone, macropores play an important role in vertical water transport and fast groundwater recharge. Layers of lower permeability in the vadose zone may divert the vertical infiltrating water and cause subsurface flow, interflow. When the rate of rainfall exceeds the infiltration rate, infiltration excess overland flow occurs, which is also called Hortonian overland flow or saturated overland flow. Such flows are usual in arid and semi-arid regions, where rainfall intensities are high and soil infiltration capacity is low due to soil surface characteristics. In the occurrence of this type of flow, the antecedent soil moisture plays an important role whether or not saturation excess overland flow is observed.

### 15.2 Recession Curve

Many shortcomings of recession analysis and the large number of methods that exist are due to the high variation in recession behavior, both within and between catchments [74]. Baseflow literature reveals that many problems still remain in recession analysis. However, modern computers have allowed the development of automatic and more objective methods, which eliminate some of the subjective elements of recession analysis [74].

The recession curve can be expressed analytically. However, there is no unique expression due to the high variability encountered in the recession behavior of individual segments. Even when the expression is set, there is no unique parameter set to use; hence, calibration becomes another issue to deal with.

During dry weather, water stored in the catchment is removed by soil and groundwater drainage and by evapotranspiration. The gradual depletion of discharge during periods with little or no precipitation constitutes the drainage or recession rate, graphically presented as the recession curve. The recession curve tells, in a general way, about the natural storages feeding the stream. The recession curve of the streamflow hydrograph contains valuable information related to the storage and aquifer characteristics of a hydrological basin. Information on low-flow characteristics is required for such water resource management issues as water supply, irrigation, hydropower, and water quality and quantity estimation. The understanding of the flow process from groundwater or other delayed sources is also essential in studies of water budgets and catchment response [74].

The recession curve analysis techniques are basic flow equations, linear reservoir models, autoregressive processes, and empirical relations [74]. Also basic flow equations were used to define the recession curve of the hydrograph [32,60]. The recession curve is widely characterized by an exponential equation, which corresponds to the linear reservoir concept in which the discharge is directly proportional to the storage in the reservoir. The reservoir here points the groundwater system. Among others, studies in [34,35] using the linear reservoir model in modeling daily intermittent hydrological processes should be mentioned. The Tank model [45,66,67] is another example of this approach.

Hall [26] and Tallaksen [74] report that the mathematical background of this kind of analysis goes back to the work by Barnes [11] who found that flow is scattered as a straight line on a semilogarithmic paper, even to that by Maillet [42], and originates from the Boussinesq nonlinear differential equation given for aquifers [30,68,70]. Based upon this analysis, the well-known exponential recession equation is obtained as

\[ Q_t = Q_0 e^{-\alpha t} \]  

where

- \( \alpha \) is the recession coefficient
- \( t \) is the time
- \( Q_0 \) is the start or initial value
- \( Q_t \) flow \( t \) days after the peak
During the period when the hydrograph recesses, $Q_t$ can also be expressed as the product of a value $K$, smaller than one, and flow on the previous day, $Q_{t-1}$, as

$$Q_t = KQ_{t-1}$$  \hspace{1cm} (15.2)

Due to inflows originating from various storage systems, that is, flow components, it should be kept in mind that $K$ is not constant throughout the recession curve but is smaller at the beginning than at the end part [7], which mainly consists of baseflow. The $K$ values vary seasonally too [73]. They are therefore of random structure and have their own probability distribution functions. As an alternative to $K$, the half-life ($t_{0.5}$), the time required for streamflow to fall down its half value, was introduced [17,18]. The half-life has the advantage of having the dimension of time and hence a physical meaning.

Equation 15.2 can be written as

$$Q_t = KQ_{t-1} + \varepsilon_t$$  \hspace{1cm} (15.3)

where $\varepsilon$ is a normally distributed independent random variable with zero mean and constant variance. In that case, the recession part of the hydrograph is considered a first-order autoregressive model [76]. Relationships between the recession curve parameters and the ARMA model parameters were developed as another example for this approach [63].

Empirical relations are among the most commonly used approaches. For example, in [15,52], the exponential recession function in the form of

$$Q_t = (Q_0 - Q_b) e^{-mt} + Q_b$$  \hspace{1cm} (15.4)

was used for data from Poland and Denmark, respectively. The same technique was used in [36]. Here, $Q_b$ is the minimum flow in the river that changes from year to year [88]. In [37], Equation 15.1 was used in the double exponential form of

$$Q_t = Q_0 e^{-mt}$$  \hspace{1cm} (15.5)

in which $m$ and $n$ are constants. An approach was given in [53], splitting the complete recession curve into two stages, the upper and lower recessions, to take, respectively, the forms of

$$Q_t = Q_{0*} e^{-at}$$  \hspace{1cm} (15.6)

$$Q_t = Q_{0*} e^{b+c*}$$  \hspace{1cm} (15.7)

where

- $t$ is the time measured from the start of the upper recession, the peak value, $Q_0$, of the total hydrograph
- $t^*$ is the time from the start of the lower recession
- $Q_{0*}$ is the initial flow discharge at the beginning of the lower portion of the curve
- $a$, $b$, and $c$ are parameters

An experimental/arbitrary procedure was adopted. Surface runoff is assumed to occur and Equation 15.6 is therefore used as long as $Q_t/Q_{t-1} \leq 0.9$, while the lower recession curve (Equation 15.7) is used in case that the ratio takes values greater than the river basin-specific value, 0.9 in [53]. A similar approach splitting the recession curve was given in [1–4]. The observed monthly mean streamflow discharge was used in splitting the curve into the upper and lower parts. Both parts were calculated by using Equation 15.1 with different parameters determined at monthly time resolution from the observed recession curves of the daily streamflow hydrographs. Such an algorithm increases the number of parameters dramatically. Using the exponential equation to define the point on the recession...
where the baseflow starts was another attempt [49]. By this approach, a series of recession constants are calculated by regressing flow on time after the flow nearest to the peak value of the hydrograph is successively deleted. Progressively higher values of recession constants are obtained as the number of time units deleted increases, and the constant stabilizes thereafter. The day on which the constant stabilizes is taken as the beginning of the baseflow component. A review on the exponential decay function was supplied [5].

To computerize the recession curve analysis, a number of softwares were developed. For instance, DIFGA [56] and RCA [65] both use the exponential recession curve equation. In the United States, a computer program, HYSEP, was developed [61] for the purpose of baseflow separation in which three methods of hydrograph separation that are referred to in the literature as the fixed-interval, sliding-interval, and local minimum methods were employed. BFI, another computer program implementing the deterministic procedure of the Institute of Hydrology [31], was released at http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi. Using digital filter-based separation modules, a Web-based Hydrograph Analysis Tool (WHAT) system was developed [40]. The user-friendly software, AdUKIH [8], is the most recent. Instead of the linear reservoir theory, the nonlinear reservoir theory can also be applied. The nonlinear concept is detailed later.

15.3 Master Recession Curve

Given a number of hydrographs, they can be combined to give a master recession curve. A master recession curve can be obtained by simply averaging many recession curves. Different techniques are used to obtain the master recession curve of the basin.

The correlation method is based on the plotted logarithms of flow values \( \log Q_t \) against \( \log Q_{t+N} \) some fixed time \( N \) later. The slope of the straight line indicated by the data corresponds to the recession constant of the basin.

The matching strip method is based on the simple exponential model. The plot of logarithms of the flows against time result is a straight line. The slope of that line gives the recession constant. Observed individual recession curves are plotted on the same graph, and the recession is then superimposed and adjusted horizontally. A mean line through the set of individual lines represents the master recession curve [48]. A composite recession curve can be similarly developed by piecing together sections of individual recessions or a modified method can be proposed for development of the master recession curve of the basin [17,25].

Data used for the development of a master recession curve should be carefully selected; otherwise, the points will scatter widely and will be difficult to construct a master recession curve [41]. Since the development of master recession curve of the basin is of significant subjectivity, it should be careful in the development of the curve, although it was concluded that the correlation method was less subjective than the matching strip method [48].

The graphical methods of matching strip, correlation, and tabulation, which are all arbitrary methods, are traditionally used in constructing the master recession curve. In the nowadays rarely used tabulating method [33], the recession periods are tabulated and shifted until the discharges agree approximately, and mean discharge is calculated for each time step in the period. In the matching spring method [75], individual recession segments are plotted and adjusted horizontally until they overlap in the main parts. The master recession curve is then constructed as the mean line by eye fitting. In the correlation method [39], the discharge at one time \( Q_t \) is plotted against the discharge one time interval later \( Q_{t+\Delta t} \) in the recession period, and a curve is fitted. The time step is determined in such a way that the fitted curve is exponential, for example, a straight line in a semilogarithmic paper (Figure 15.2).

Recession characteristics can be found either from the master recession curve or from the individual recession segments separately. When the latter case is used, a mean value can be considered representative for the catchment.
15.4 Baseflow Separation

An engineering use of the recession curve allows users to separate the flow into its three main components, surface flow, interflow (subsurface flow), and baseflow. Of these, the baseflow is that component of the flow in a river that is not the direct consequence of the rainfall event but is considered as the outflow of the groundwater reservoir feeding the river entirely during rainless periods [21]. It is defined as the net flow from the groundwater storage to the river under the effect of diverse geological, climatologic, and morphological factors, resulting in considerable variations both in time and space [58]. Land use and land cover characteristics such as forestation in the hydrological basin affect the groundwater storage and hence the baseflow [85]. A better understanding of baseflow can help in controlling irrigation withdrawals during low-flow periods, making water supply estimates and forecasts, and determining storage requirements for maintenance of adequate flow for waste dilution [59]. Especially, however, separated baseflow allows the quantification of groundwater recharge in the river basin.

In the planning and management studies of water resources, total flow is separated into baseflow and direct flow where direct flow is considered the sum of surface flow and interflow. As the baseflow and direct flow hydrographs are not measured separately but instead only the total flow is measured, the following question arises: How can the measured hydrograph be separated? In practice, graphical separation techniques to be detailed later are commonly employed for this purpose.

Analytical methods are available as well [30, 68, 70]. With the help of these methods, subjective points associated with baseflow separation can be reduced by using the analytical solution of the Boussinesq equation.

A certain kind of filter disintegrating the daily streamflow into quick flow and baseflow components was made available by many researchers. A well-known one is the UK smoothed minima approach [31]. This is a widely used method [43, 77, 78] recently revised [51] and adopted to intermittent streams [8, 50]. Another approach is the so-called recursive digital filter algorithm used, among others, in [10, 13, 19, 29, 48, 62, 69, 71, 72]. The recursive digital filter technique was coupled to the smoothed minima
approach [9,38]. Physically based filters were made available [22,23,46] for separating baseflow from the total streamflow. Spectral analysis of baseflow separation [16,64] should also be mentioned.

Baseflow Index (BFI) is calculated as the ratio of baseflow volume to total streamflow volume. Baseflow usually occurs in times of sustained and regionally extensive periods of low precipitation and snowmelt, when streamflow is fed from groundwater. A number of studies highlighted the importance of BFI and automatic calculation procedures have been developed. A procedure for calculating the BFI is described in detail in [25]. The BFI is originally related to the geology of the catchment area and is applied for soil classification and geological regionalization.

Having in mind the definitions mentioned earlier, the BFI over some time period $dt = t_2 - t_1$ can be presented as the ratio of baseflow volume to the total streamflow volume:

$$BFI = \frac{\int_{t_1}^{t_2} Q_{\text{baseflow}}(t)\,dt}{\int_{t_1}^{t_2} Q_{\text{total}}(t)\,dt} \quad (15.8)$$

where $dt$ could be $n$ consequent days.

### 15.5 Baseflow Separation Techniques

In applied hydrology, the term “baseflow” has two different meanings that are often confused. By neglecting these differences, unsuited approaches might be applied with unrealistic results. The first and more classical definition of baseflow comes from flood hydrology and aims simply to separate the slow component “baseflow” from the quick “direct flow.” This concept of quick flow eases the determination of flood hydrographs for the design of hydraulic structures, for example, spillways of dams. It does not describe physical processes. The second concept aims to separate groundwater flow from total flow. This outflow from the shallow aquifers of the catchments is the main flow component and makes up to more than 80% in the average rivers of the world. Its proper separation enables a reliable determination of groundwater recharge.

Separation of flow into two components, direct flow and baseflow, is sufficient in most of the engineering practices. In this context, direct flow is understood as the total of surface flow and subsurface flow (interflow) reaching the stream with little delay, whereas baseflow is groundwater outflow together with the delayed subsurface flow. For this aim, graphical baseflow separation techniques are commonly used to be detailed as follows.

#### 15.5.1 Graphical Techniques

Graphical separation techniques in Figure 15.3, adapted from [14,44], are used extensively only to separate quick flow from slow flow. These methods detailed later are not apt for the separation of groundwater baseflow and they do not consider flow recession. Instead, these approaches were developed for flood hydrology and do not separate the entire groundwater baseflow but only slow flow from quick flow. They are called the straight-line constant-discharge method (line 1), constant-slope method (line 2), the fixed-base/concave method (line 3), and the variable slope (line 4) (Figure 15.3). Aiming at separating quick flow from the slow flow for the purposes of flood analysis and flood forecasting, these approaches are all based on empirical background yet seem reasonable for using in the unit hydrograph computation to route the portion of precipitation that goes through the quick flow reservoir to the stream. In reality, however, groundwater outflow is considerably higher than slow flow. In many cases, baseflow is the dominant discharge component even during flood events [28]. In this sense, Figure 15.3 appears to be problematic as baseflow is very low and does not follow the recession. The nonlinear baseflow separation technique (line 5) in Figure 15.3 aims to consider the groundwater-fed baseflow and therefore results in much more baseflow than aforementioned graphical baseflow separation techniques.
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a. **Constant-Discharge/Straight-Line Method (line 1 in Figure 15.3)**

In the straight-line method, a horizontal line is drawn from the beginning of the ascension curve of the hydrograph to the intersection with the recession limb. This is applicable to ephemeral streams.

This is the easiest method commonly used for practical purposes. It is simply the horizontal line A–D in Figure 15.3 starting with the lowest point of the hydrograph before the ascension curve starts. The line is extended until it intersects the recession curve of the hydrograph. Flow under that line is considered baseflow, while flow above it is direct flow. This method is applicable to ephemeral streams. It can easily be argued that the baseflow will continue to decrease beyond the start of the flood runoff, possibly to the time when the flood runoff is maximum. It could also be argued that flow from groundwater storage begins before the time when the total runoff equals the baseflow rate prior to the start of flood runoff. Such arguments have led to proposals of other methods.

b. **Constant-Slope Method (line 2 in Figure 15.3)**

In the fixed-base method (line 2 in Figure 15.3), the surface runoff can be assumed to end a fixed time $N$ days after the hydrograph peak. A line is obtained by projecting the baseflow before the beginning of surface runoff ahead to the time of the peak. This line is connected to the point on the recession limb at the time $N$ days after the peak.

c. **Fixed-Base/Concave Method (line 3 in Figure 15.3)**

For the concave method, the starting and ending points for the line separating baseflow and direct runoff are the same as for the constant-slope method. However, for the concave method, baseflow continues to decrease until the time of the peak discharge of the storm hydrograph.

At that time, the separation line is straight between that point and the inflection point on the recession. This is shown in Figure 15.3. While the concave method may require a little more effort to define than the other two methods, it is probably a more realistic representation of the actual separation of flow as determined by the physical processes that control flow during storm events. The distribution of direct runoff equals the difference between the total discharge and the baseflow.

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**FIGURE 15.3** Graphical methods (1–4) for the separation of slow-flow “baseflow” for flood analysis and synthesis. (Adapted from Chow et al., *Applied Hydrology*, 1988.) The groundwater baseflow hydrograph could be as high as to follow the recession.

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d. **Variable Slope Method (line 4 in Figure 15.3)**

A line is obtained by extrapolating the baseflow curve of the previous hydrograph forward to the time of the peak discharge. A second line is obtained by extrapolating the baseflow of the current hydrograph backward to the inflection point on the recession curve. By connecting the end points of the lines, direct flow is separated from the baseflow.

### 15.5.2 Manual/Empirical Separation

In hydrological engineering practice, baseflow is often separated manually by intuition and experience, however, following strictly the recessions of the hydrographs. Though subjectivity has an impact, the results are certainly closer to physical reality than the straight-line approaches.

### 15.5.3 Analytical (Parametric) Techniques

In order to reduce subjectivity and to ease separation, also analytical methods were developed to separate baseflow from the total flow hydrograph. For instance, two automated methods (the smoothed minima and recursive digital filter) were compared to separate baseflow [48]. Use of the digital filter with the parameter set to 0.925 was found to be a fast and objective method of continuous baseflow separation. Another attempt based on exponential recession equation was made [49]. A series of recession constants are calculated by regressing the logarithms of the flow on time by successively deleting the flow nearest the peak of the hydrograph. Progressively higher values of recession constants are obtained as the number of time units deleted increases, and the constant stabilizes thereafter. They day on which the constant stabilizes is taken as the beginning of baseflow. A baseflow separation technique based on analytical solutions of the Boussinesq equation was given in [70]. The technique reduces some of the subjectivities associated with the baseflow separation techniques.

### 15.5.4 Linear Conceptual Techniques

In these techniques, baseflow is determined as the outflow of one or more linear reservoirs starting at the last recession of the time series and going backward on the time axis. At each recharge phase, normally coincident with direct runoff, the recession curve restarts at a lower point. A transition curve links both recession curves. Separated baseflow allows the determination of groundwater storage and recharge that is computed as inflow.

### 15.5.5 Separation of Flow into Three Components

The procedure adapted from [12] and illustrated in Figure 15.4 where the hydrograph was plotted on a semilogarithmic paper is used to separate the flow into three components, surface flow, subsurface flow, and baseflow. The baseflow recession is approximated by a straight line and is extended backward. The difference between the total flow and the value on the extended line represents the combined surface and subsurface flow. The combined flow is plotted on the semilogarithmic paper and a straight line extended backward is fitted to the subsurface flow recession.

### 15.5.6 Separation of a Complex Hydrograph

It is relatively easy to separate baseflow from a simple (one-peak) hydrograph. In most cases, however, baseflow shall be separated from long time series of flows, for example, from a hydrograph of a year with 365 daily values and many peaks. Automated computer-supported methods are used in this case.
15.6 Nonlinear Method

The exponential decay function implying that the groundwater aquifer reacts like a single linear reservoir has, as detailed earlier, been used widely in hydrological literature. Here, the nonlinear reservoir approximation is introduced in order to separate groundwater flow from total flow. Studies [24,47,80–83,86] are all based on the nonlinear theory although there still are such studies as [20] insisting in the use of the linear theory. Later, the nonlinear theory was applied on the data from Australia [87]. A case study for an intermittent streamflow data set in the Thrace region in the European part of Turkey was studied by using the nonlinear algorithm [6]. Another application was performed on the streamflow data from Texas, United States [84]. A recent study [27] tried to understand how applicable the theory is in separating flow into its components during storm events.

In this theory, the storage–discharge relationship was modified by adding a dimensionless exponent \( b \), such that

\[
S = aQ^b
\]  

where

- \( S \), the storage, is in m\(^3\)
- \( Q \), the discharge, in m\(^3\)/s
- the factor \( a \) in m\(^{3(1-b)} \), whereas the exponent \( b \) has no unit

If volumes are expressed as heights over unit area and the time step is a day (\( S \) in mm, \( Q \) in mm/d), then \( a \) is in mm\(^{-b} \) d\(^b\). It is seen that the linear reservoir algorithm is reached for \( b = 1 \).

\[
\frac{dS}{dt} = -Q
\]
can be written for periods with no flow into the reservoir (no groundwater recharge), during the recession curve of the hydrograph. Combining Equations 15.9 and 15.10 for a recession period starting at an initial discharge $Q_0$ yields, after mathematical transformation, in

$$Q_t = Q_0 \left[ 1 + \frac{(1-b)Q_0^{b+1}}{ab} t \right]^{1/b-1} \quad \text{(15.11)}$$

The parameter values $a$ and $b$ are calibrated using observed recession discharges on the base of an iterative least-squares method. From Equations 15.9 and 15.10,

$$a = \frac{\sum (Q_{i-1} + Q_i) \Delta t}{2 \sum (Q_i - Q_{i-1})} \quad \text{(15.12)}$$

is obtained to calibrate the parameter $a$ for the systematically varying parameter $b$ such that the computed outflow volume during the considered time period is equal to that in the given recession curve. The couple of $(a,b)$ with the minimum sum of squared deviation from the observation represents the properties of the aquifer. Analysis of observed flow recession of numerous rivers in different hydrological regimes [6, 80–83, 87] yielded values $b < 1$ with a typical value of $b = 0.5$, which is a finding confirmed by theoretical derivations [54, 79] for unconfined aquifers. For practical purposes, such as regionalization, it is more practical to fix the exponent $b$ and calibrate the parameter $a$. A value of $b = 0.5$ as found typical previously can be suggested for average conditions.

The procedure for computation of the baseflow recession starts at the last value of the recession and proceeds backward along the time axis of the hydrograph. Baseflow at the time $t - \Delta t$ is determined by

$$Q_{t-\Delta t} = Q_0^{b-1} + \frac{t(b-1)}{ab} \quad \text{(15.13)}$$

that can be derived easily by inverting Equation 15.11. The procedure is applicable to daily time series and $\Delta t$ therefore corresponds to one day. The computation of baseflow recession is adopted from [82] as follows (Figure 15.5).

When the backward computed baseflow recession curve intersects the rising limb of the hydrograph of the total flow, a one-step transition point is adopted as the peak of baseflow hydrograph. The rising limb of the baseflow hydrograph is then computed from the recession curve computed one step forward for each given total flow value.

The effective groundwater recharge (percolation to the aquifer) can be computed by using the water balance of

$$\text{Storage at time } (i-1) + \text{Input to the storage at time } i \left( GWR_i \right) = \text{Storage at time } i + \text{Outputs from the storage (baseflow, ET, abstraction) at time } i \quad \text{(15.14)}$$

that mathematically can be written as

$$GWR_i = S_i - S_{i-1} + \int_{t_{i-1}}^t (Q + A + ET) \, dt \quad \text{(15.15)}$$

where

- $GWR$ is the groundwater recharge
- $A$ is the abstraction
- $ET$ is the evapotranspiration, while others stand the same as previously defined.

15.7 Application of Nonlinear Method to Real Data

Figure 15.6 shows baseflow separation for a 1-year hydrograph of a little river in East Germany. Two automated methods were applied, the model DIFGA, describing flow recession as the outflow of two parallel reservoirs [56], and BNL [82] using the nonlinear reservoir algorithm. Results are similar though the nonlinear recession fits slightly better during higher flows.

As lined out earlier, groundwater storage and groundwater recharge can be computed from separated baseflow. Figure 15.7 shows separation by the nonlinear reservoir algorithm for the little river.

Eisenbach in North Germany. The computed storage shows a high correlation and similarity to the observed groundwater level and its variation, confirming thus the aptitude of the method.

15.8 Summary and Conclusions

Baseflow separation is used in hydrology for two different purposes that should not be confused. The older approach is applied in flood hydrology to separate the slow-flow component from quick flow during a flood event. It is a practical but hardly physically based method. The separated flood hydrograph is used in rainstorm-flood modeling, ranging from unit hydrograph up to more sophisticated methods.

The second method aims to separate the groundwater component from total flow not only during floods but for the entire time series. The separated baseflow hydrograph allows computing of groundwater storage and recharge in watersheds, which are important components of water balances. Separation methods take into account the shapes of flow recessions, which reflect indeed the geohydrological conditions of the basin. Recession analysis is therefore an important prerequisite for baseflow separation. Different approaches are applied to model flow recessions, such as digital filters and reservoir algorithms, that is, relationships between storage and outflow of the aquifers and parallel linear and nonlinear reservoirs. Extensive studies of observed recessions at many rivers suggest that the nonlinear reservoir is the most physically based and best-fitting equation.

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