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Research Article

A review on baseflow separation methods

Nguyen Y Nhu[1]*

[1] Vietnam National University, University of Science; nguyenynhu@hus.edu.vn

*Corresponding author: nguyenynhu@hus.edu.vn; Tel.: +84–869110757

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Abstract: Baseflow separation is essential for effective water management, drought assessment, and groundwater resources protection. Despite its importance, baseflow observations are often limited to small-scale studies. To address this limitation, researchers have developed various baseflow separation methods. This paper reviews and analyzes existing studies which have developed or used the baseflow separation methods. A total of 43 studies are described, with a detailed review of 26 of them, focused on baseflow separation methods. Even if existing methods have already focused on baseflow separation, however, various methods produce divergent outcomes, primarily due to the inherent challenges in directly observing the flow process associated with each technique. A minority of methods are anchored in physical science, particularly noticeable during waning streamflow periods. Notably, certain methods dynamically adjust baseflow estimates in response to precipitation intensity, an approach that, while intuitive, lacks a physical rationale and introduces subjectivity, especially when precipitation events conflate. Filter methods, despite their apparent rigor compared to graphical techniques, they suffer from a lack of physical underpinning regarding their operational frequency and orientation and are often constrained by arbitrary limits to avert baseflow estimates from surpassing total streamflow or descending into negative values. While the process-based methodology enhances accuracy by employing physical principles to gauge baseflow across both arid intervals and rainy spells, the veracity of hydrological models is intimately tied to the data's availability and integrity. The main recommendations resulting from this review are that combining the strengths of different baseflow separation methods can lead to more robust results. For example, starting with a digital filter method for initial separation and refining it with physical-based approaches. Leveraging advancements in computational power and algorithms can help in handling complex calculations and iterative processes more efficiently, leading to more accurate baseflow estimations.

Keywords: Baseflow separation; Graph separation; Isotope; Digital filters; Process-based; Subsurface flow.

1. Introduction

In the context of precipitation within a watershed, the flow pathway is established at the outlet of the basin, encompassing various water sources. Distinguishing the proportions of these different flow components necessitates dividing the flow into surface flow and base flow [1–2]. Studying baseflow characteristics is crucial for understanding runoff processes, streamflow interactions, and groundwater significant. Researchers also examine baseflow recession, spatial and temporal scale, to estimate aquifer parameters from streamflow data [3–6]. Specifically, the base flow separation, also known as the hydrological flow component or groundwater component, represents a fundamental problem in both technical hydrology and applied hydrology. It involves analyzing terrain slopes and calculating convergence, which significantly influences the overall hydrological behavior.

Generally, base flow constitutes the lower portion of the hydrograph with minimal variability. It finds application in industrial and agricultural water supply, water resource security, non-point source pollution assessment, water resource evaluation, and flow regime modeling [7]. During dry seasons, base flow serves as the primary contributor to river flow, maintaining the baseflow regime and playing a crucial role in sustaining ecosystems, providing stable water supply for livelihoods, and safeguarding ecological environments. Furthermore, the separation of base flow has substantial implications for regional water resource planning and protection of stream ecosystems.

Base flow separation methods are tools used to distinguish between base flow and stormflow within a river's discharge. These methods are crucial for hydrological studies because they allow us to understand and quantify the contribution of groundwater to river flow, which is vital for managing water resources sustainably. However, our understanding of base flow dynamics remains incomplete. The separation of base flow remains a challenge in hydrological and ecohydrological research. Scholars both within and beyond national borders have shown widespread interest in this topic in recent years, resulting in notable advancements and breakthroughs. While various separation methods exist, most of them rely on empirical approaches based on flow characteristics. These methods often use graphical techniques or mathematical formulas to separate the hydrograph, the graphical representation of streamflow over time, into its different components. Achieving a consensus on base flow separation is challenging due to the interdisciplinary nature, involving climatology, physical geography, hydrogeology, and other scientific domains. The scarcity of experimental data further complicates the development of universally accepted methods. Despite extensive discussion and development of separation methods, comprehensive analysis comparing these available methods is lacking. This gap hinders the ability of hydrologists and water managers to select the most appropriate method for their specific context. Our research is the first attempt to address this gap by providing a systematic review of base flow separation methods. We evaluate their development and assess their application in contemporary hydrological studies. By highlighting the strengths and limitations of each method, we offer guidance for researchers to choose suitable techniques for their unique environmental and hydrological conditions. This work has the potential to significantly influence hydrology, ecology, hydrogeology, and water management by providing a clearer understanding of base flow dynamics and improving the selection process for separation methods.

2. Baseflow component

Baseflow, originating from groundwater aquifers [8–9], or other delayed sources [1, 7, 10], seeps into the groundwater and contributes to streamflow. It can also be categorized as shallow baseflow (from upper subsurface layers) and deep baseflow (from deeper sources). Deep baseflow provides consistent streamflow even during prolonged droughts. Total flow combines baseflow and direct runoff, with baseflow index (BFI) quantifying the groundwater's contribution. Hydrograph separation distinguishes surface flow from baseflow.

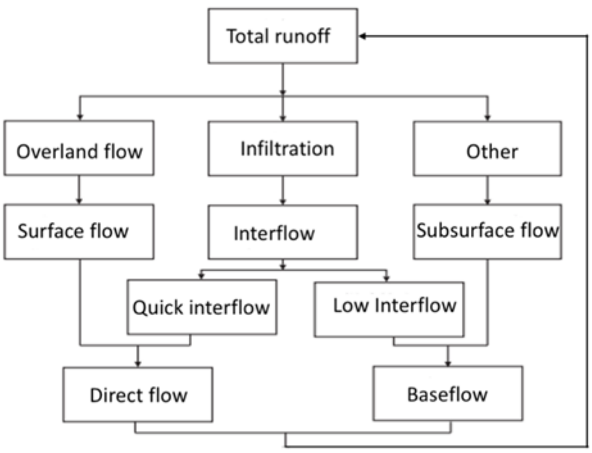

Figure 1. The flow components [11].

Baseflow is the average flow during the driest periods over recent years, as estimated in hydrological forecasts. Baseflow helps prevent excessively prolonged water drawdown if it constitutes a significant proportion of the total flow. Typically, baseflow is truncated at a certain threshold level, and subsequent predictions and convergence are added back to the baseflow.

In the field of applied hydrology, the overall flow in rivers and streams is typically divided into two primary components. Surface flow refers to the runoff that occurs directly over the land surface during rainfall events. It includes water flowing over impermeable surfaces, such as roads, rooftops, and paved areas. Baseflow represents the sustained contribution of groundwater to streamflow. It is the portion of flow that persists even during dry periods when direct precipitation is minimal. Groundwater flow and subsurface flow (such as flow through soil layers) contribute to baseflow. However, these components cannot be entirely separated due to their interconnected nature. Groundwater flow and subsurface flow are not explicitly distinguished because they cannot be entirely separated.

Therefore, applied hydrologists differentiate between surface flow and baseflow, categorizing precipitation into direct runoff, infiltration, and other losses. Baseflow is generated, and the infiltration process replenishes soil water storage until saturation occurs. Any remaining infiltrated water eventually contributes to baseflow.

The process of streamflow formation is complex, involving interactions between surface water, subsurface flow, and groundwater. Hydrologists use various methods to study and quantify these components. Currently, the concept of baseflow in hydrograph separation primarily includes both subsurface flow and deep baseflow. This deep baseflow results from delayed contributions, such as lateral groundwater flow or other sources.

Concise summary of the characteristic features of baseflow based on research papers [9, 12, 13] as follow:

1. Before a runoff event begins, low flow primarily consists of baseflow.
2. Following the rising limb, the baseflow persists for some time.
3. Baseflow reaches its peak after the total runoff reaches peak as the sub-surface storage and routing effect.
4. Baseflow recession typically follow an exponential decay function.
5. The baseflow rejoin the total flow as quickflow ceases.

3. Materials and methods

An analytical synthesis of forty-three scholarly inquiries dedicated to the formulation or application of baseflow separation was conducted. The term “baseflow” encompasses a spectrum of baseflow reseach.

3.1. Search procedure

To conduct a comprehensive search for literature on baseflow separation, the following strategies were used:

1. Terms and their combinations can be used: “Baseflow separation”; “Hydrograph separation”; “hydrograph analysis”; “Groundwater-surface water interaction”; “Streamflow components”; “Hydrological modeling and baseflow”; “Aquifer recharge estimation”. Boolean operators like “AND” and “OR” can be used to combine these terms for more refined searches, such as “baseflow separation AND hydrological modeling” or “groundwater-surface water interaction OR aquifer recharge”. These criteria and search terms will help ensure that the review is thorough, up-to-date, and relevant to the field of hydrology, particularly concerning the baseflow separation methods.
2. The selected data sources: Web of Science, Scopus, and Google Scholar combine rigor, breadth, and accessibility, ensuring a comprehensive review of baseflow separation methods. Researchers can confidently rely on these platforms to inform their investigations and advance hydrological science.

3. Beyond traditional databases, exploring institutional repositories, government reports, and technical bulletins can yield valuable insights. These sources often contain unpublished data and practical applications.

4. Studies published within a period from 1980 until now, to ensure the review captures the traditional as well as recent advancements in baseflow separation methods. Peer-reviewed articles, conference proceedings, and scientific reports to ensure the credibility and scientific validity of the information. Preference for articles published in journals with a high impact factor or a specific focus on hydrology and water resources. Studies that specifically address baseflow separation methods, including theoretical development, empirical studies, and application-based research. Papers that contribute to understanding the mechanisms of baseflow, its quantification, and the impact of different separation techniques on hydrological modeling.

3.2. Selection of studies and analytical criteria

Researchers initiate the selection process by systematically reviewing the titles and abstracts of relevant articles retrieved from databases. Articles that align with the study's focus on baseflow separation methods are retained for further evaluation.

The research conducted a thorough analysis by carefully selecting a subset of studies that significantly differed from others due to their unique characteristics, methodologies, or findings. Specifically, we focused on studies that proposed or employed techniques for baseline separation. This refined set consists of 26 chosen studies. In Section 4, we explore these 26 studies in detail.

4. Baseflow separation methods

Baseline separation methods encompass various techniques, categorizing these methods helps organize the diverse approaches, making it easier for researchers to understand and apply them, allow practitioners to quickly identify relevant techniques based on specific research goals or analytical requirements.

Efforts to distinguish baseflow from streamflow continuously over time can be grouped into four main approaches: (1) graphical, (2) tracer-based, (3) process-based approach, and (4) digital filter. Except for geochemical data, most of these methods rely solely on streamflow data. They are not universally applicable under all streamflow conditions and typically involve only a few parameters with well-defined physical interpretations.

4.1. Graphical Method

This hydrological approach involves graphically segmenting streamflow data to distinguish baseflow characteristics based on hydrological and geological features of different catchments. It assumes that between consecutive and distinct rainfall events, baseflow in a basin is equivalent to streamflow. In other words, during non-rainfall periods, the streamflow consists primarily of baseflow. To estimate baseflow under these conditions, a set of graphical extrapolation rules is applied to streamflow data. The hydrographs (Figure 2) before applying the separation method were compared with the after one. Or the tracer-based method has been used to verify the applied methods. It primarily includes the following techniques:

Straight line Method: This method connects flow with straight lines. Hydrologists use characteristic inflection points to segment baseflow, especially suitable for delineating baseflow and estimating groundwater resources in closed mountainous catchments. The segmentation is based on monthly average flow values, with a minimum flow threshold serving as the reference point. Below this threshold, the flow represents annual baseflow. In this approach, a diagonal line connects the flood peak and the inflection point of the recession limb in the daily streamflow hydrograph (Figure 3). The portion below this line corresponds to baseflow. The vadose zone conditions play a crucial role: When the vadose zone is thick and intense rainfall occurs within a short period, preventing groundwater recharge, baseflow can be segmented using a horizontal line on the flow recession curve. Conversely, when the vadose zone is thin, and groundwater recharge increases after rain, an oblique line can be used to separate baseflow.

For long-term baseflow segmentation, hydrologists often choose representative years from streamflow records. They create average daily flow duration curves for each year and use maximum monthly flows during the dry season (typically over a 3-month period). The small value used as a reference for segmenting the base flow is determined through the cross-sectional method. This method involves identifying the peak discharge point and the inflection point (also known as the branching point) along the river. The process connects these two points with a straight line. For high-flow seasons and multi-stage flood events, it is necessary to divide the river into segments below the diagonal line, representing the base flow during the flood season, which supplements the flow during the dry season. In general, the peak elevation of the flood peak is more distinct and easier to determine, while the inflection point of the recession segment requires using a pre-established comprehensive low-flow point for assessment. The comprehensive recession curve is constructed by extracting and plotting a set of recession curves that exclude the influence of rainfall on the river flow. These curves are horizontally shifted to align the tails of each recession segment. The outer envelope of this set of recession curves represents the comprehensive recession curve.

The construction of a comprehensive recession curve is a complex task, and manual drawing calculations are time-consuming and inefficient. To improve computational speed and meet the accuracy requirements for planning and engineering design, many scholars turn to computer-based methods.

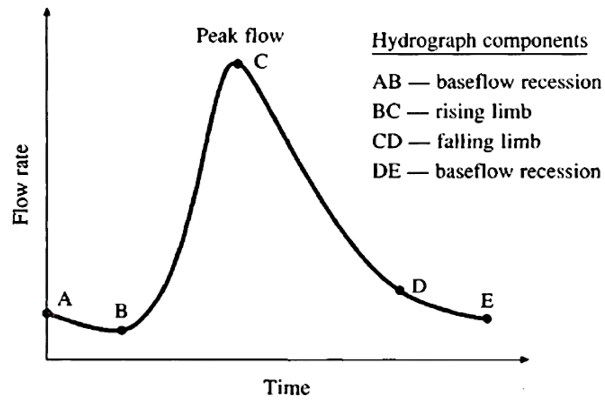

Figure 2. Components of discharge hydrograph [11].

Fixed based method: During a flood, the river has extra water, and this can seep into the ground, adding more water to the groundwater. After the flood, as the floodwater goes down, the baseflow also goes down because there is less water coming from the groundwater. Even after the flood, the groundwater can continue to feed the river, which increases the baseflow again. The inflection point is a spot in this process where things change direction - like when the base flow starts to increase after the flood. Where this point is located depends on how the river and the groundwater affect each other (Figure 3). The method described uses a time interval, called N, to measure how long it takes for the river to go from full flood back to normal [11].

Tracing the flow: Starting from when the floodwater has gone down, looking back in time to find where the water level started dropping quickly.

Connecting points: draw a line from this point back to a point on the graph that's N time units before the peak of the flood.

$$N = A^{0.2} \tag{1}$$

where A represents the catchment area; N denotes the direct runoff time. The typical time interval falls within the range of 3 to 11 days.

Variable Slope Method: Starting from the beginning of the surface flow, we extend the flow path forward as described above. Conversely, from the end point of the surface flow, we extend the base flow path backward until it intersects a vertical line passing through the inflection point on the downstream water branch. Finally, we connect these intersection points with straight segments (Figure 3).

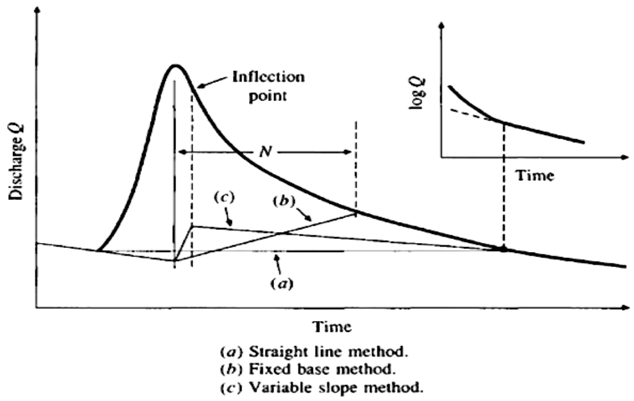

Figure 3. The diagram depicts the baseflow separation methods [11].

The graphical methods, exemplified by the work of the Institute of Hydrology [14] and Sloto and Crouse [15], use specific criteria to distinguish baseflow from surface runoff based on streamflow hydrograph analysis. By visually identifying recession limbs and inflection points, graphical methods provide insights into baseflow behavior. However, different graphical rules can lead to significantly different baseflow estimates using the same streamflow data. Some rules produce linearly increasing baseflow estimates during individual rainfall events, regardless of variations in rainfall and streamflow. However, these estimates may not be physically realistic. While the graphical approach is based on some physical reasoning, it is not always well-founded physically. One limitation is that it can become problematic when two or more rainfall events overlap [16]. Consequently, it is not particularly useful for baseflow separation over long periods of time.

4.2. Process-based approach

This method is also known as analytical approach, which based on fundamental rules governing the formation of subsurface flow. This approach solves equation related to storage, discharge, and water balance equations for underground reservoirs. It uses models to estimate plant water use, soil absorption capacity, and water penetration into underground layers. The approach characterizes each component of a river's base flow by its rate of change, origin, and the volume of water infiltrating from the ground. Mathematical models, such as the Sherman Unit Hydrograph and Horton Infiltration Equation, are employed to separate base flow from total streamflow. The Sherman Unit Hydrograph is instrumental in determining the flow process from rainfall-runoff to base flow, while the Horton Infiltration Equation is used to solve for base flow [17]. The widespread application of technologies (e.g., Remote Sensing, Geographic Information Systems), along with distributed hydrological models (e.g., SHE, SWAT, and TOPMODEL), provides effective methods for segmenting base flow within hydrological processes [18]. Birtles [19] represents the amount of water that infiltrates the ground surface and contributes to groundwater recharge. It includes rainfall, snowmelt, and other forms of precipitation that percolate into the soil. Birtles expressed groundwater recharge as a function of surface infiltration, curve-fitting parameters, groundwater recharge rate. This approach incorporated the subsurface processes to estimate groundwater recharge and provide valuable insights into the baseflow dynamics. The analytical approach in hydrology, while robust, the accuracy of hydrological models is heavily dependent on the availability and quality of data. In many cases, there might be a lack of spatial-temporal data, which can limit the effectiveness of the models. The baseflow index (BFI) and visual inspection are used to compare different methods.

4.2. Isotopic hydrograph segmentation method

This approach involves separating streamflow into surface runoff and baseflow using various tracers. The consistency of the separated baseflow was evaluated with isotope-tracer data [20–24]. Regarding isotopic hydrograph segmentation, there are currently three internationally recognized approaches:

1) Time-Based Separation: Divides the flow into event water and pre-event water, also referred to as “new water” and “old water”. Event water typically originates from rainfall, while pre-event water is stored prior to precipitation.

2) Mechanism-Based Separation: Classifies flow into Hortonian overland flow, variable-source slope flow, saturation-excess flow, interflow, and baseflow. These mechanisms account for changes in source conditions or varying slopes.

3) Geographical Separation: Based on spatial locations before water enters a stream, considering whether it is stored in the vadose zone or saturated zone. However, studies often do not explore the spatiotemporal distribution of isotopic abundance, and the flow pathway is divided into surface runoff and subsurface flow.

In reality, the isotopic composition of environmental water is influenced by factors such as precipitation amount, temperature, topography, and other conditions, with a wide range of variability. Additionally, the ^{18}O isotopic signature in groundwater flow within a catchment exhibits significant variations during rainfall events, particularly in arid conditions. Although the spatial and temporal variations are small, neglecting the time-dependent changes in isotopic composition of precipitation would lead to serious errors in hydrograph segmentation. Researchers [25, 26] have utilized isotopes (including ^{18}O) in precipitation and river flow to delineate hydrological processes. They propose that the influence of subsurface flow cannot be overlooked in the flow pathway. Notably, the dominant input for observed dissolved aluminum concentrations can be attributed to subsurface flow [27–28].

The study [29] employed monitoring devices from three water sources to segment stormflow, revealing that the flow in the vadose zone significantly contributes to the stormflow component within the catchment.

Gonzales et al. [30] meticulously evaluated various baseflow estimation techniques within a lowland region in the Netherlands. Their investigation encompassed both tracer-based and non-tracer-based methods, shedding light on the intricate dynamics of groundwater-surface water interactions. The tracer approach revealed responsiveness of groundwater to rainfall events in the study area. During flood events, surface water predominantly contributed to the measured discharge. The rating curve method utilizes empirical relationships between streamflow and water stage (discharge rating curves). It provides reliable estimates of baseflow. Eckhardt’s [2] approach employs digital filters to separate baseflow from total streamflow. It also yielded robust baseflow values. In summary, their comprehensive analysis underscores the importance of both tracer-based insights and sophisticated estimation techniques in understanding baseflow dynamics. However, these approaches are always labor-intensive, require extensive data and sampling, and cannot be applied to past events due to the absence of necessary chemical data [30]. Chemical reactions during the mixing of components, tracer measurements, and elevation effects on the isotopic composition introduce uncertainties in tracer-based methods. These uncertainties can lead to less reliable baseflow estimation results.

4.3. Digital Filter Approach

To simplify the process of separation baseflow, various time series analysis methods have been proposed. These methods primarily include the digital filtering method, smooth minimal method, and time step method. The baseflow process line obtained using digital filter methods was compared with that obtained using isotope-tracer data to evaluate the performance of the applied method.

4.3.1. Master recession curves (MRC)

The MRC method is a valuable tool for baseflow separation. It involves analyzing recession curves, which provide insights into hydrogeological processes related to groundwater inflow and outflow. To construct the MRC, individual recession curves are alighned horizontally and cumulatively superimposed until the MRC includes most of the tail ends of recession curves. Researchers directly check the master recession curve to understand recession characteristics [32].

$$B_t = B_0 k^t \tag{2}$$

$$B_t = \left(B_0 - c\right)k^t + c \tag{3}$$

The exponential form (Equation (2)) is commonly used to fit the master recession. It provides a versatile way to model various streamflow behaviors. Equation (1) is an alternative form, but it has limitations in capturing the full range of streamflow variations.

The exponential form allows for a more flexible representation of baseflow dynamics. When fitting the master recession, it is preferable to use an extensive historical streamflow dataset rather than single events. Baseflow is a slow-moving process, and analyzing long-term data provides a more accurate representation of its behavior. To fit the master recession, hydrologists often perform initiating the analysis from the most current data points. This approach ensures that the most up-to-date information is considered when estimating baseflow. Hydrologists often visually fit the master recession curve to the streamflow data. This involves adjusting the parameters (such as (k) and (c)) until the fitted curve aligns well with the observed streamflow recession.

Duncan [32] demonstrate an effective method for baseflow separation, enhances our understanding of baseflow dynamics by accounting for variations across different sites. Typically, low flow preceding a hydrological event primarily consists of baseflow. The peak value occurs after the peak of total runoff. As quickflow (surface runoff) ceases, baseflow rejoins the total hydrograph. The baseflow recession follows an exponential function. During the rising limb (when discharge is increasing), modeled baseflow doesnot continue to decrease. Typically, one might expect all components of flow to increase as overall flow increases. However, it’s essential to note that baseflow separation methods may not consistently preserve this feature.

The MRC approach comprises a single backward pass through the observed total flow data to fit an exponential master baseflow recession curve to smooth the connection between segments of the master recession. An additional constraint pro-hibiting negative quickflow, implied but not always stated in previous descriptions, must be strictly observed for correct operation of the smoothing algorithms.

4.3.2. Nathan and McMahon’s digital filtering method

The digital filtering technique was first applied for baseflow segmentation in 1990 [11]. Over recent years, this method has become the most widely used approach for baseflow segmentation worldwide. Its popularity stems from its ability to capture the rapid response of direct runoff processes in river basins. By combining characteristics of high-frequency signals (representing surface flow) and low-frequency signals (representing baseflow), the method effectively dissects the flow regime [2, 31]:

1. Separate the flow process into: direct flow and baseflow using digital filters.

2. The baseflow division equation [3] is as follows:

- Surface flow at time step i:

$$Q_d\left(i\right) = \alpha Q_d\left(i-1\right) + \frac{1+\alpha}{2}\left[Q\left(i\right) - Q\left(i-1\right)\right] \tag{4}$$

- Baseflow at time step i:

$$Q_b\left(i\right) = Q\left(i\right) - Q_d\left(i\right) \tag{5}$$

where $Q_d(i)$; $Q_d(i\text{-}1)$ represent the filtered surface flow at time steps i and i-1; Q(i); Q(i-1) correspond to the total flow at time steps i and i-1; $Q_b(i)$ represents the baseflow.

The filter coefficient α is typically recommended to be 0.925 for daily discharge has been recommended [9, 11].

4.3.3. Chapman's modified equations for baseflow separation

Chapman [18] introduced modifications to Equation 12 as follows:

1. Direct Flow Component (Q_d):

$$Q_d(i) = \frac{3\alpha - 1}{3 - \alpha} Q_d(i-1) + \frac{2}{3-\alpha}\left[Q(i) - \alpha Q(i-1)\right] \quad (6)$$

2. Baseflow Component (Q_b):

Chapman and Maxwell [18] suggest that during a specific time interval, the baseflow can be expressed as weighted average of the surface flow at the current and the previous time step:

$$Q_b(i) = kQ_b(i-1) + (1-k)Q_d(i) \quad (7)$$

where k represents the recession coefficient, typically set to 0.95. $Q(i) = Q_b(i) + Q_d(i)$, we can eliminate $Q_d(i)$

$$Q_b(i) = \frac{k}{2-k} Q_b(i-1) + \frac{1-k}{2-k} Q(i) \quad (8)$$

3. Practical Application:

Researchers have compared various baseflow estimation techniques and found that Chapman and Maxwell's proposed approach could be optimal in certain contexts [33]. The baseflow coefficients obtained using this method exhibit minor variability, and their Baseflow Index (BFI) remains relatively stable, within the range of 0.4 to 0.5. In practice, Equations 3 and 4 are commonly used as filtering equations:

$$q_t = \beta q_{t-1} + \frac{1}{2}(Q_t - Q_{t-1}) \quad (9)$$

$$b_t = Q_t - q_t \quad (10)$$

where q_t and q_{t-1} represent the filtered surface flow at t and t-1; Q denotes the total flow; β is the filter parameter affecting baseflow attenuation. Empirical studies suggest that a value around 0.9 yields baseflow estimates that closely align with actual observations. In other words, this value helps us capture the real behavior of groundwater contributions to streamflow. Typically, values of 0.9, 0.925, and 0.95 are used for baseflow separation, with the most suitable parameters determined based on specific watershed characteristics. Factors like geology, vegetation, and climate influence the optimal value.

Arnold and Allen [34] conducted a rigorous study across six representative river basins in the western and eastern United States. They verified a method (likely the one using β) and found that this method consistently produced similar results when applied multiple times, easy operation, few parameters which simplify the process, and fast implementation.

Mau and Winter [35] compared the results of the method (likely involving β) with a graphic segmentation approach. The results showed good agreement between the two methods, reinforcing the reliability of the method using β.

4.3.4. Eckhardt Filter method

Eckhardt [2] proposed the Eckhardt filter method, and its equation is as follows:

$$b_1 = \frac{(1 - BFI_{max})\alpha b_{t-1} + (1-\alpha) BFI_{max} Q_t}{1 - \alpha BFI_{max}} \quad (11)$$

where α represents the water retention constant, which can be determined through analysis of recession flow; BFI_{max} represents the maximum proportion of streamflow that comes from baseflow. Eckhardt [2] applied this method to study 65 randomly selected river basins in the United States. They suggested that the BFI_{max} values for perennial rivers are 0.8, rivers have flow variations throughout the year (for seasonal rivers), the BFI_{max} value is 0.5, and the perennial rivers flow through hard rock formations, the BFImax value for these rivers is 0.25.

The Eckhardt filter method is a powerful tool for baseflow separation. It operates by adjusting the Baseflow Index (BFI) values. When compared to alternative methods, the Eckhardt filter exhibits gradual changes in BFI, resulting in a smoother baseflow hydrograph. Under typical hydrological conditions, this filtering technique yields a more stable representation of baseflow. However, intriguingly, certain regions specifically semi-arid and humid areas deviate from this norm, especially where low-flow coefficients are small and intense rainfall occurs over short periods, river basins exhibit sharp and uneven hydrographs. These conditions are primarily due to excessive infiltration during high-flow periods and lower groundwater flow coefficients.

Xie et al. [36] conducted a study on 1,815 river basins across the United States to measure the baseflow. They used nine different methods that involve visual analysis and five that use computer algorithms to estimate these values. They applied a strict rule where only the water flow observed during dry periods was considered true baseflow. After analyzing the data, they determined that the method developed by Eckhardt was the most effective for predicting baseflow throughout the mainland United States, based on their extensive testing across all the river basins.

4.3.5. Minimum smoothing method

This method divides an entire continuous streamflow sequence into non-overlapping blocks with a fixed width of 5 days. Within each block, the minimum value is determined, using a specified threshold. The rule involves identifying the minimum values to form inflection points and connecting these inflection points to obtain the baseflow hydrograph. This method is straightforward, easy to implement, and has been applied in various countries and regions.

Sun et al. [37] separated the baseflow from the total streamflow in the upper part of the Yitong River. This technique aims to estimate the maximum baseflow index (BFI_{max}) accurately. The SMT aligns well with isotope-tracer data and exhibits stability and reliability in the Second Songhua River. Compared to other methods, it is believed that the smooth minimum method provides the smallest baseflow index values. However, there are certain challenges when applying this method for baseflow segmentation:

The lower envelope of the total streamflow, including some multi-segmented streamflow paths, is related to basin precipitation. The smooth minimum method includes partially unrecessed groundwater flow from previous floods, leading to increased groundwater flow and inconsistency with actual conditions. The baseflow hydrograph, defined as a smooth curve without inflection points, may not fully reflect the catchment's flow dynamics.

4.3.6. The time-step method

It also known as the HYSEP method, is a computer program used for streamflow segmentation. It incorporates three different segmentation techniques: the fixed interval (FI), the sliding interval (SI), and the local minimum (LM) [16]. All three methods utilize empirical formulas to calculate direct runoff time: $N = A^{0.2}$

where A represents the catchment area; N denotes the direct runoff time. The typical time interval falls within the range of 3 to 11 days. The nearest odd number to 2N is chosen as the time interval, and baseflow calculations are performed based on this interval.

1. Fixed Interval (FI):

For the time frame being studied, the smallest amount of water that was recorded flowing in the river each day is used to represent the baseflow.

The endpoint of this calculation is then used as the starting point for the next iteration.

2. Sliding Interval (SI):

For a given day, looking at a time range that extends (2N-1)/2 days before and after that day. Within this time frame, we calculate the minimum flow rate. This minimum value is then used for analysis or comparison within the selected interval.

This value represents the minimum flow contributed by groundwater, baseflow, and a similar approach is used to calculate baseflow for the subsequent day.

3. Local Minimum (LM):

First, calculate the center within adjacent time steps.

The baseflow value at the center point, as well as the baseflow within the time range outside the center point, are determined using linear interpolation.

The method for calculating baseflow at the center point in the time step is as follows:

Choose the time interval of (2N-1)/2 days before and after a minimum value day.

Assign this value as the baseflow for that day.

Then use the endpoint of this calculation as the starting point for the next iteration to compute baseflow at the center point of the subsequent time step.

Partington et al. [38] explored four ways to estimate baseflow. They considered methods like HYSEP [16], PART [39], BFLOW [32], and Hydro-GeoSphere (HGS) [40], HGS [40] ombined with a hydraulic mixing-cell approach, provided synthetic baseflow values for a V-shaped catchment. Li et al. [41] ested various recursive digital filters using synthetic data from HGS. The Lyne and Hollick filter performed well, closely matching HGS synthetic baseflow across diverse catchment conditions. Optimal filter parameters varied based on the specific hydrological context [2, 11, 17, 18, 42]. Su et al. [43] investigated the Eckhardt filter method. After calibrating it using hydrological signatures, the filter showed improved performance.

Table 1. Baseflow separation methods.

Gourped approaches	Advantages	Disadvantages
Graphical approaches	Based on physical reasoning	Problematic when multiple rainfall events overlap Not useful for baseflow separation over long periods.
Process-based	Based on fundamental rules governing subsurface flow Provide valuable insights into baseflow dynamics	Heavily dependent on the availability and quality of data Complexity involved
Tracer-based	Shed light on intricate groundwater-surface water interactions. Revealed groundwater responsiveness to rainfall events Provides reliable baseflow estimates	Labor-intensive, require extensive data and sampling Cannot be applied to past events due to the absence of necessary chemical data Uncertaintíe due to tracer measurements, and isotopic composition
Digital Filter	Yielded robust baseflow values	Lack a physical basis for application frequency and direction Limited by arbitrary constraints to prevent exceeding total streamflow or becoming negative. Focus on low-frequency streamflow, which is usually associated with baseflow. This might also contain quick surface runoff, especially after heavy rains

4. Conclusion

The study offers a in-depth perspective on baseflow separation methods, providing insights that are both practical and scientifically significant (Table 1). When comparing different methods for estimating baseflow from streamflow data, it's clear that only a few methods are grounded in physical science, particularly during periods when the streamflow is decreasing. Some methods estimate baseflow during rain events in a way that changes with the amount of rain, which seems logical but isn't based on physical principles. These methods can be very subjective, especially when rain events overlap.

The tracer-based technique provides an objective understanding of flow behavior and has gained recognition for its ability to study flow mechanisms, model moisture movement in soil, analyze water source components within a river basin, and monitor flow pathways.

Filter methods are more reliable in these cases and seem more rigorous than graphical methods. However, they too lack a physical basis for their application frequency and direction. They are also limited by arbitrary constraints to prevent baseflow estimates from exceeding total streamflow or becoming negative. Ideally, filters should work without these limits. Filters are designed to separate the steady baseflow from the total streamflow (Figure 1). These filters focus on the low-frequency part of the streamflow, which changes slowly and is usually associated with baseflow. However, some experts argue that this slow-changing part might also contain quick surface runoff, especially after heavy rains. This means that the filters might not be perfectly accurate.

The process-based approach improve this by using physical principles to estimate baseflow during both dry periods and when it's raining. Process-based method is more complex because it uses many different factors and an iterative process, which means it repeats steps to get closer to the correct estimate. But this complexity can also make it harder to get consistent results, especially when the streamflow changes rapidly, and the accuracy of hydrological models is heavily dependent on the availability and quality of data.

Various baseflow segmentation methods are known to produce divergent outcomes, primarily due to the inherent challenges in directly observing the flow process associated with each technique. Among various baseflow separation approaches, digital filter methods have gained popularity due to their simplicity and effectiveness, use numerical algorithms to partition streamflow into its constituent components. However, selecting appropriate filter parameters is crucial for accurate results.

To enhance the robustness of baseflow analysis, it is advantageous to combine different segmentation methods. This can be achieved by integrating the strengths of individual techniques to compensate for their respective limitations. For instance, one could apply a digital filter method to obtain a preliminary separation of baseflow and then refine the results using a more physically-based approach, such as recession curve analysis. This hybrid strategy leverages the simplicity and computational efficiency of digital filters while incorporating the detailed insights provided by physical methods, especially during varying flow regimes. The combined approach not only ensures consistency across different flow conditions but also tailors the analysis to the unique hydrological characteristics of the study area.

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