Baseflow estimation for a mining-impacted catchment using hydrograph separation and hydrological regionalisation

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Abstract

The development and application of automated baseflow separation algorithms for describing individual discharge components still cover a major part of modern hydrology. A key problem is the applicability of baseflow separation methods in ungauged or anthropogenically impacted catchments due to their complex conceptuali-ty. With increasing anthropogenic impact, the dependence of calculated baseflow rates on measured total runoff also increases. In this study, we suggest statistical approaches for testing the suitability of different hydrograph separation algorithms. For our main study site, the mining-impacted Geisel catchment in the Central Ger-many, we calculated a mean baseflow rate of 0.28 m^3/s for the period from 1981 to 2017. First, 14 different algorithms (graphical and statistical methods, digital-filter-approaches, and one physically based algorithm) were tested in seven catchments. The calculated baseflow rates for the Geisel catchment showed questionable curves, in particular a high amplitude. Thus, similarities between measured dis-charge and calculated baseflow were demonstrated (quasi-parallelism), which were quantified with correlation analyses on different time scales. Following this, a pro-found analysis of the baseflow index (BFI) was carried out. Finally, we applied a sta-tistical regionalisation approach to derive validated baseflow information for the Geisel catchment using the calculated baseflow indices and numerical catchment descriptors. As a result, the questionable baseflow hydrographs of the Geisel could be corrected. This promising method enables improved estimations of environmental flow components, improved analyses of the hydrological processes to foster the un-derstanding of anthropogenic impacts, and provides essential information for water management in the Geisel catchment. Furthermore, characteristic properties of long-term BFI values were revealed, which can be used to develop new physically based hydrograph separation procedures by including spatially distributed physical catchment descriptors.

Short Information

This paper deals with the applicability of hydrograph separation procedures to anthopogenically influenced catchments. With the analysis of baseflow rates and baseflow indices, differences and similarities between several algorithms can be identified. Using the new term of quasi-parallelism, statements in particular regarding to the optimal time scale and to the specifics of the hydrological situation in a mining influenced catchment in Central Germany can be derived. To calculate validated baseflow rates for this catchment, a statistical regionalisation approach using physical catchment descriptors was chosen.

Title

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A case study from Central Germany

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Abstract

The development and application of automated baseflow separation algorithms for describing individual discharge components still cover a major part of modern hydrology. A key problem is the applicability of baseflow separation methods in ungauged or anthropogenically impacted catchments due to their complex conceptuality. With increasing anthropogenic impact, the dependence of calculated baseflow rates on measured total runoff also increases. In this study, we suggest statistical approaches for testing the suitability of different hydrograph separation algorithms. For our main study site, the mining-impacted Geisel catchment in the Central Germany, we calculated a mean baseflow rate of 0.28 m^3/s for the period from 1981 to 2017. First, 14 different algorithms (graphical and statistical methods, digital-filter-approaches, and one physically based algorithm) were tested in seven catchments. The calculated baseflow rates for the Geisel catchment showed questionable curves, in particular a high amplitude. Thus, similarities between measured discharge and calculated baseflow were demonstrated (quasi-parallelism), which were quantified with correlation analyses on different time scales. Following this, a profound analysis of the baseflow index (BFI) was carried out. Finally, we applied a statistical regionalisation approach to derive validated baseflow information for the Geisel catchment using the calculated baseflow indices and numerical catchment descriptors. As a result, the questionable baseflow hydrographs of the Geisel could be corrected. This promising method enables improved estimations of environmental flow components, improved analyses of the hydrological processes to foster the understanding of anthropogenic impacts, and provides essential information for water management in the Geisel catchment. Furthermore, characteristic properties of long-term BFI values were revealed, which can be used to develop new physically based hydrograph separation procedures by including spatially distributed physical catchment descriptors.

Keywords: **hydrograph separation, baseflow index, quasi-parallelism, statistical regionalisation, impacted catchment, physical catchment descriptors**

1 Introduction

Despite the various criticism of hydrograph separation (e.g. Beven, 2012; Hewlett & Hibbert, 1967) especially regarding the strong conceptiuality of several algorithms, the publication of new algorithms and results prove the continuous interest in calculating different runoff components (e.g. Miller, Johnson, Susong, & Wolock, 2015). There is no standard method for understanding all runoff generation processes in all aspects (Beven, 2012), but for estimating baseflow rates, hydrograph separation is best suited to distinguish between surface flow and baseflow (Tallaksen, 1995; Uhlenbrook, Frey, Leibundgut, & Maloszewski, 2002).

Nevertheless, it is still discussed, which hydrograph separation algorithm is best suitable to solve a specific problem and how information can be derived for anthropogenically influenced catchments. Thus, this study tests the suitability of hydrograph separation methods by using the example of the mining impacted Geisel catchment in Central Germany. Various hydrological adjustments were made due to the open-cast lignite mining activities, including several relocations of the natural stream of the river Geisel.

In such cases of strongly impacted flows, calculated baseflow hydrographs need to be critically checked. In our study, we derived validated baseflow rates for the Geisel catchment using common methods of hydrological regionalisation and numerical catchment descriptors. The specific objectives of this paper are to i) compare different groups of baseflow separation algorithms, their calculated results and pointing out essential differences and similarities, ii) analyse the differences in the results achieved in anthropogenically influenced catchments and iii) use other catchments and numerical catchment descriptors for calculating validated information on groundwater and runoff during droughts in such influenced catchments. We postulate that i) significant differences in hydrograph separation methods occur, which must be considered in further analysis, ii) statistically validated baseflow rates for mining-impacted catchments can be derived using hydrograph separation algorithms combined with hydrological regionalisation methods and iii) a higher parameterisation in hydrograph separation algorithms does not always lead to better results.

We present new, pragmatic methods for analysing baseflow rates and indices in hydrology and for water management that do not require complex, physical-based models to derive validated information on the hydrological situation in anthropogenically influenced catchments. Furthermore, with the proposed statistical analyses we want to remind that calculated baseflow rates and indices must always be associated with processes of runoff formation on the catchment scale.

2 Theory and methods

2.1 Study area and data used

The Geisel catchment is located in Central Germany in the South of the Federal State of Saxony-Anhalt and drains an area of approximately 208 km^2 (Figure 1A). Flowing from west to east, the river Geisel later joins the river Saale. Precipitation ranges from 495 to 550 mm/a on a long-term average with a gradient in the SW-NE direction (Figure 1C). Of particular importance for the development of the Geisel valley into a lignite deposit was the subrosion of the anhydrites in the middle Eocene that was triggered by tectonic movements (Lotsch, 1968). The subtropical climate in the Eocene and the widespread moors and forests encouraged intensive lignite formation. The resulting rich lignite beds have been mined since 1698 (Wirth, Eichner & Schroeter, 2008).

These opencast mining activities have affected huge areas of land, leaving behind entire new landscapes and considerable impacts on the landscape water balance. The runoff concentration of the River Geisel was delayed by mining dewatering, which led to considerable groundwater lowering. After finally closing the mining activity in the year 1993, the filling of the mined-out pit occurred between 2003 and 2011 and led to the generation of the post-mining lake Geiseltal. Since May 2011, the discharge volume at the gauge Frankleben is regulated by a drainage structure at Lake Geiseltal. The mining activities have influenced the entire water balance of the catchment, due to several changes of physical catchment properties such as the relief (and thus the processes of runoff concentration) and geo-hydraulic conditions. As a consequence, it is not possible to obtain any qualitative and statistically justified and validated information on various runoff components. Due to those mining impacts, the discharge rate was significantly higher in recent years. Today, the mean runoff is equal to 0.149 m^3/s (period 2011 to 2017). In the entire time series investigated (period 1981 to 2017), the mean runoff is equal to 0.371 m^3/s at gauge Frankleben, while the hydrograph is characterised by strong fluctuations.

By comparing the hydrograph at gauge Frankleben with the streamflow data of other (quasi-natural) catchment areas in southern Saxony-Anhalt the anthropogenic influence becomes obvious (Figure 2). For better understanding, daily precipitation amounts of the same time series from a representative weather station were added in Figure 2. It becomes clear that the strongly negative trend in total runoff volume at gauge Frankleben is due to anthropogenic influences and not to external factors, such as climatic changes.

This study uses the total daily runoff volume measured at seven gauges in Central Germany. Our main study site is the Geisel catchment as described above. The other six catchments were selected because of their spatial proximity to each other (Appendix 1) and the fact that long-term series of hydrological data are available for all gauges. The data (period 1981 to 2017 on a daily scale, Appendix 2) were provided by the State Agency for Flood Protection and Water Management of the Federal State of Saxony-Anhalt.

2.2 Baseflow and hydrograph separation principles

Baseflow is the portion of streamflow that is fed to surface streams by groundwater. Besides interflow and snow melt, it mainly sustains streams between precipitation events (Arnold, Muttiah & Allen, 2000). With an increasing trend for extreme events and a changing climate it is becoming more important to analyse the baseflow component of hydrological processes, due to the significant contribution of baseflow rates to dry weather or low flow runoffs (i. e. environmental flow) (Dai, Chu, Du, Stive & Hong, 2010; Hall, 1968; Wittenberg, 2003; Wundt, 1958).

Hydrograph separation is based on three principles (Hall, 1968; Nathan & McMahon, 1990). Firstly, the concentration of individual runoff components is caused by surface and underground flows with different velocities and different damping factors. Secondly, if no precipitation event has occurred for a longer time, the total runoff consists exclusively of the baseflow. If this period lasts longer, underground drainage becomes perceptible and total runoff is reduced. Various methods make use of this state by determining a master recession curve based on these decline period (Wittenberg, 1994, 1999; Wittenberg & Sivapalan, 1999). Thirdly, surface runoff (Q_D) generally flows faster than baseflow, but local heterogeneities in the subsurface can lead to an increased velocity of groundwater flow Q_B. Long precipitation events or snowmelt can distort the low-frequency signal at the gauge.

2.3 Applied hydrograph separation algorithms

For the baseflow calculation 14 hydrograph separation algorithms (Table 1) were applied, which can be divided into the following groups.

Graphical methods (Pettyjohn & Henning, 1979; Sloto & Crouse, 1996), published as a part of the USGS HYSEP program, using the hydrograph´s geometric properties. For this purpose, the upper, rapidly varying part is associated with Q_D, the lower, slowly varying part with Q_B. It is assumed, that Q_B between two runoff events corresponds to Q_D. Three methods for an automatic hydrograph separation were implemented: *Fixed Interval* ,*Sliding Interval* , and *Local Minimum* .

Statistical methods do not refer to single runoff events but to the analysis of complete time series. In this way, special conditions, such as spatially unevenly distributed precipitation or an above-average high groundwater table, should lose their significance for the long-term time series by the calculation of mean values, which reveals specific catchment characteristics. Wundt (1958) developed a procedure based on the assumption that monthly low flow discharges (MoNQ) represent Q_B. The classic Wundt method (*MoNQ-Method*) has been continuously developed over years, mainly due to the fact that there are Q_B calculated, which are too high for very humid periods (e.g. Kille, 1970; Schraeber & Szymszak, 1984). Kille (1970) argues that in months with high precipitation the MoNQ values contain a significant proportion of the interflow. The Kille method (*MoMNQ-Method*) was developed accordingly: As in Wundt (1958), the MoNQ values are first calculated and then arranged in ascending order. The values are then corrected by extending the quasi-linear low flow range. Those calculated monthly Q_B values are allocated to the corresponding months again. Another improvement of the Wundt method is proposed by BSW (1996) by determining the monthly MoNQ values and calculating the long-term monthly mean values for each month. Afterwards the lowest value of six consecutive months (*6-MoMNQ-Method*) is interpretated as Q_B for those six month.

Digital-filter algorithms are based on the assumption that separating the total runoff into Q_D and Q_B can also be systematically regarded as fast or slow runoff (Beven, 2012; Chapman, 1991, 1999; Eckhardt, 2005; Hollick & Lyne, 1979; Nathan & McMahon, 1990; Wittenberg, 1994) and on the equation first developed by Hollick and Lyne (1979):

$Q_B\ \ (i) = \beta * Q_B\,(i-1) + \frac{1-\beta}{2} * Q\,(i) + Q\,(i-1)(1),$

with Q_B as the calculated baseflow in $\frac{m^3}{s}$ (daily averages), Q as the total runoff in $\frac{m^3}{s}$ (daily averages), i as the day of the investigated time series, and β as a dimensionless filter parameter.

This original form is still a frequent component of hydrograph separations, e.g. in the *SWAT-BFLOW* application (Arnold, Allen, Muttiah & Bernhard, 1995; Arnold & Allen, 1999; Smakhtin, 2001). Chapman (1991) inserted in his *classic filter algorithm* a further filter parameter, since otherwise Q_B would remain constant as long as $Q_D = 0$. The "*One-parameter algorithm"* insertsQ_D as a variable and a second parameter, k, equals to a recession constant (Chapman & Maxwell, 1996). The "*Two-parameter algorithm* " inserts another parameter C, which is interpreted as a sum of catchment properties for a successful performance (Chapman, 1999). The *IHACRES algorithm* (Jakeman & Hornberger, 1993) is characterised by a third parameter α, which describes a general filter parameter that is determined as a function of the total discharge volume. Also the *Eckhard filter* algorithm was applied. It results from studies by Eckhardt (2005, 2008) and further development by Collischonn and Fan (2013). It is one of the most frequently used digital-filter algorithms today (e.g. Bosch, Arnold, Allen, Lim & Park, 2017; Li, Maier, Partington, Lambert & Simmons, 2014; Zhang, Zhang, Song & Cheng, 2017). The Eckhardt filter adds another parameter,BF$I_{\max}$ based on the assumption that the surface runoffQ_D generally occurs in a wide spectrum and that there is a risk of incorrect allocation of Q_B to Q_D (Eckhardt, 2008). It thus results automatically from the assumption that the aquifer is a linear reservoir and the baseflow result from low-pass filtering of the total runoff. The last Digital-filter-model applied is the *EWMA algorithm* (Tularam & Ilahee, 2008), which corresponds to the mathematical implementation of the graphical method exponential smoothing.

Physically-based-filter: Furey and Gupta (2001) proposed the physically-based filter algorithm tested in this study. Their approach is based on the continuity equation and physical functions forQ_B from a slope. The most important requirement for a successful hydrograph separation with the *Furey-Gupta algorithm* is the assumption that a catchment is considered to be the sum of several slopes (Furey & Gupta, 2001).

2.4 Baseflow Index and Quasi-parallelism

The results of testing different hydrograph separation methods are analysed by using the concept of the baseflow index (BFI, Institute of Hydrology, 1980). From several studies on the BFI (e.g. Bloomfield, Allen & Griffiths, 2009; Carillo et al., 2011; Chapman, 1999; Eckhardt, 2008; Smakthin, 2001) the question arises on how long a time series has to be to calculate a stable BFI. Daily BFI values are scattered over a great interval, which becomes increasingly smaller as soon as monthly or annual values are calculated. This can be explained by the seasonal effect on the total runoff volume, which should have a much greater influence on the BFI distribution than runoff volume variations between different years. Calculating the mean runoff values is a form of low-pass filtering. The suppression of the high-frequency runoff components increases with the duration of the averaging interval. Also, with an increasing averaging interval, the low-frequency runoff components – the baseflow – are emphasized. To announce this behavior, the concept of quasi-parallelism (Bottaro, Corbett, & Luchini, 2003; Partington et al., 2012; Singh, 1969; Wittenberg, 1994) is used and validated. Quasi-parallelism describes a statistical relationship between similarly measured runoff and baseflow time series and, as a consequence, the arrangement of individual hydrograph separation algorithms according to the absolute value of the calculated baseflow as a constant function over the entire period (Rojanschi, 2006).

2.5 Hydrological regionalisation

To calculate validated baseflow rates for ungauged or anthropogenically influenced catchments, methods of hydrological regionalisation represent appropriate procedures (e.g. Haberlandt, Klöcking, Krysanova, & Becker, 2001; He, Bárdossy, & Zehe, 2011; Reddyvaraprasad, Patnaik, & Biswal, 2020). Regionalisation in a hydrological context describes the derivation of hydrological information from other catchments. There are three groups of theoretical approaches (Heřmanovský & Pech, 2013), (i) the approach of spatial proximity (e.g. Oudin, Andréassian, Perrin, Michel, & Le Moine, 2008), (ii) linear regression (e.g. Wagener & Wheater, 2006), and (iii) approach of physical similarity and comparability (e.g. Parajka, Merz, & Blöschl, 2005; Young, 2006)

In this study, hydrological regionalisation is carried out using physical catchment descriptors (PCD). These are properties that describe a single facet of a catchment in a single number (Mills, Nicholson & Reed, 2014). In this study 64 different PCD and catchment properties were determined for each catchment. However, our selection was mainly based on investigations by Kokkonen, Jakeman, Young and Koivusalo (2003), Merz and Blöschl (2004) and Sefton and Howarth (1998) and focused on the sub-groups "land use and vegetation", "mean runoff data", "climate", "soil and geology", "form indices", "relief derivations" and "recession parameters" (Appendix 3).

The regionalisation was carried out on a monthly time scale. With the help of PCD, residuals of the BFI values at the gauge Frankleben were calculated, including the BFI at other gauges. Although it is frequently suggested in numerous studies (e.g. Abdulla & Lettenmaier, 1997a, 1997b; Haberlandt et al., 2001; Zhang, Chiew, Li, & Post, 2018), we refused the idea of using multiple regression analyses, since our tests lead to questionable results. Not only very low values at Frankleben gauge were calculated, but also, despite different regressors, theR^2-coefficients fluctuated only to a very small extent. To obtain more reliable results, we tested single linear regressions. The results of multiple regressions are due to interrelationships between individual model parameters and can be explained by the similarity of individual PCD (Oudin, Kay, Andréassian, & Perrin, 2010; Yadav, Wagener, & Gupta, 2007). Due to a higher range of R^2, it is necessary to calculate weighted arithmetic mean depending on the calculated R^2. We assume that the influence of different PCD on runoff formation, i.e. the baseflow rates, fluctuate more than calculated with multiple linear regression models. A higher range of R^2 thus seems to correspond more to realistic conditions. Similar performances of multiple regression models have been proven by Merz and Blöschl (2004). However, the main methodological uncertainty concerns directly the Geisel catchment itself. The refilling of the mined-out pit in the Geisel valley created an artificial lake with a surface of approximately 18.4 km^2, which represents an influencing factor for the local water balance due to higher evapotranspiration rates and the controlling of the discharge volume at Frankleben gauge. It is therefore questionable, in how far the lake acts as a source or a sink for the discharge volume at Frankleben gauge. Within the hydrological regionalisation the evapotranspiration of Lake Geiseltal, as well as other water balance parameters, can be disregarded since the BFI at all investigated gauges function as dependent variables.

3 Results

3.1 Statistical results and correlation analyses

Figure 3 shows the dispersion of calculated BFI values for eight different time scales at the gauge Stedten. The values were calculated by averaging all hydrograph separation results. A clear convergence along the time scale can be observed. Furthermore, the results presented in Figure 3 indicate that the seasonal effect on the hydrograph has significantly more influence on the BFI distribution than differences between different years.

The consequence is that the separation lines should be analysed on monthly or annual scales (Figure 4). It should be noted that the results are similar for all other investigated gauges except the gauge Frankleben. The hydrographs are not identical but show almost parallel progressions following the total runoff hydrograph curve.

If this quasi-parallelism were valid, this would lead to high correlation coefficients K between the individual results. Table 2 presents the average K-values for calculated baseflow rates of the seven investigated catchments on a daily (A), monthly (B), and annual (C) scale.

$K \geq 0.95$ is illustrated in dark grey and $0.90 \leq K < 0.95$in light grey. With mean K-values of 0.89 (daily), 0.95 (monthly), and 0.98 (annual) an almost identical dynamic of the separation hydrographs was proven. Baseflow rates calculated by statistical separation algorithms have not been included in correlation analyses for validation of quasi-parallelism, because they were calculated on a monthly scale. The standard deviations of the correlation values are 0.08 (daily), 0.06 (monthly), and 0.03 (annual), they are thus small enough to prove the findings (made on daily values) as fundamental characteristics of the separation process. Nevertheless there are significant differences between individual methods, in particular in the theoretical and methodological approach. The high K-values are resulting from temporal and spatial averaging. Otherwise, Figure 4 shows that there is a clear convergence concerning the relative level of an indivual algorithms below the hydrograph. The baseflow index BFI quantifies this level and becomes therefore a sufficient parameter to distinguish separation processes from each other.

3.2 Characteristics at Frankleben gauge

Due to the anthropogenic impacts in the Geisel catchment, it was expected that the baseflow hydrographs at the gauge Frankleben show specific characteristics. Also, due to the different parameterisation and different theoretical approaches, different baseflow rates and BFI are obtained for each method (cp. Figure 5A and Figure 5B).

The negative trend of the baseflow at the gauge Frankleben (Figure 5A) coincides with a negative trend of the total discharge volume. However, the relative distance of the mean baseflow below the hydrograph increases over time, apparent by a positive slope of the BFI. (Figure 5B). This slope could also be proven in all other (quasi-natural) catchments.

The most important characteristic of the baseflow hydrographs is the amplitude, which varies considerably over time. At the beginning of the investigated time series until the end of mining activity in 1993, the baseflow is characterised by a very high amplitude, which decreases over time, depending on the type and intensity of the influence on the hydrological conditions in the catchment. In contrast, the BFI (Figure 5B) – taking outliers into account – remains nearly constant. The interquartile distance is reduced from about 0.5 to about 0.3. Furthermore, the mentioned correlation coefficients K between the results of the applied hydrograph separation procedures are significantly lower at Frankleben gauge. We conclude that various statistical parameters, e.g. correlation coefficients, are strongly correlating with the amplitude of the mean baseflow rates. These amplitudes are also found in the total runoff hydrograph. As a result, hydrograph separation procedures are only limited suitable for application to impacted catchments, provided that the discharge hydrograph shows a disturbing course. Of course the results of the separation could be correct. However, according to its formation, baseflow is much less influenced by extreme events. A high amplitude in the baseflow hydrograph thus seems as an indicator for disregarding external, spatial factors responsible for the baseflow formation in the separation process. These factors may be able to smooth the baseflow hydrograph and thus shape it to more realistic conditions.

3.3 Hydrological Regionalisation

The proposed regionalisation approach allowed the adjustment of the calculated baseflow rates at the gauge Frankleben. The regionalised baseflow rates show only minor differences to the averaged hydrograph separation results (Figure 6A). The success of regionalisation is particularly evident from the BFI course (Figure 6B) and the derived statistics (Figure 7).

The small differences among the hydrographs depicted in Figure 6A occur only in periods with very low total discharge values (see also Figure 7). Although both hydrographs are normally distributed with a clear right skew, the frequency of baseflow events is reduced by regionalisation. The regionalised baseflow rates are thus smoothed in comparison with the baseflow rates calculated by hydrograph separation and are less influenced by extreme events. This is particularly clear from the calculated BFI values (Figure 6B). Also, the slope of the BFI has been reduced over time. This determined gradient can be interpreted as close to reality;

a slight increase of the monthly BFI values was also determined at other gauges and can be associated with changes in external boundary conditions over time (e.g. climate change). It should be noted, however, that in both charts the first monthly BFI (Jan. 1981 to Mar. 1981) is not usable due to the recursive nature of the individual hydrograph separation procedures. Nevertheless, the typical seasonal fluctuations could be maintained within the hydrological regionalisation. The most important result, however, is that these fluctuations have been reduced significantly in their extent. The regionalisation has resulted in an adjusted average BFI of 0.756. This corresponds to an average baseflow at the gauge Frankleben of 0.28 m^3/s.

The BFI determined by applying hydrograph separation methods shows a flat distribution (Figure 7). However, the median and the mean value are already relatively close together. The BFI range is about 0.3, the interquartile distance about 0.1. The outliers can be identified as the BFI values at the beginning of the time series. The BFI distribution could be adjusted to an almost normal distribution, the median and mean value are almost identical. Also, the range and interquartile distance could be reduced. This supports the consideration that the curves have been smoothed by regionalisation methods.

For the entire time series, a mean total discharge of 0.371 m^3/s was measured. With the hydrological regionalisation, a mean monthly baseflow of 0.28 m^3/s was calculated, which results in a BFI of 0.756. By hydrograph separation algorithms a mean baseflow of 0.274 m^3/s with a BFI of 0.729 was calculated. As shown in Figure 6, the baseflow rates now show a realistic course while maintaining typical seasonal fluctuations and a significant slope, which was calculated at all other gauges. A comparison of individual periods reveals various stages of anthropogenic impact at the gauge Frankleben and their effects on the calculated and regionalised baseflow rates (Figure 8). In the first period, the mean baseflow is equal to 0.463 m^3/s with a total runoff equal to 0.63 m^3/s ($BFI = 0.74$). In the second period, the mean baseflow is equal to 0.246 m^3/s with a total runoff equals to 0.325 m^3/s ($BFI = 0.76$). In the third period, the mean baseflow is equal to 0.185 m^3/s with a total runoff equals to 0.242 m^3/s ($BFI = 0.76$). In the fourth period (actual conditions), the averaged baseflow is equal to 0.115 m^3/s with a total runoff equals to 0.149 $m^3/$ s ($BFI = 0.78$), so the relative level of the baseflow hydrograph under the total runoff hydrograph arises with time, which has been proven at other gauges in this study.

4 Discussion

This study evaluates the applicability of hydrograph separation to mining-impacted catchments using the example of the Geisel catchment in Central Germany. We used the hydrological data of the gauge Frankleben, where baseflow rates were previously unknown. Moreover, methods of hydrological regionalisation were used to derive corrected baseflow rates based on data of adjacent catchments. The calculated baseflow rates could be used for further research, e.g. environmental flow studies, and serve for a better insight on regional water balances.

4.1 Evaluation of hydrograph separation procedures

Although critically discussed, hydrograph separation procedures belong to the most frequently used methods in applied hydrology. Since each method uses only the total runoff as input (apart from model parameters), the question of their suitability is arising. Smakthin (2001) noted that digital filter methods usually account for the total runoff volume in a more specific way than other algorithms and allow a more continuous basis. Su, Peterson, Costelloe, and Western (2016) also addressed this problem and proposed an approach based on hydrological signatures. Especially the recursiveness of several algorithms requires further analyses (Cartwright, Gilfedder, & Hofmann, 2014; Eckhardt, 2005), in particular as they do not consider the physical processes responsible for the baseflow generation (Li, Maier, Lambert, Simmons, & Partington, 2013). Apart from the applicability of methods for influenced catchments, the focus of comparing different algorithms is primarily on the absolute characteristics of baseflow rates about total discharge quantities, accounting for the influences of spatial and temporal scales. In this respect, the quasi-parallelism played a special role in our results. There are algorithms, which systematically calculate high BFI values (e.g. SWAT BFLOW, EWMA, Sliding and Fixed Interval), and algorithms, which calculate exceptionally low BFI values (e.g. Furey-Gupta, Wundt, Kille). In theory, it would be possible to use only two methods – one for the upper BFI limit and one for the lower limit. However, since all methods have both advantages and disadvantages in their approach, we decided to use the mean BFI value of all methods. This could be criticised, but the median and the mean of the regionalised BFI are almost equal justifies this decision (cp. Figure 7).

The appplicability of hydrograph separation procedures at the Geisel catchment needs to be further investigated, due to strong fluctuations of calculated baseflow rates. Also, a significantly higher amplitude of baseflow rates were calculated compared to other catchments, shown by correlation analyses on different time scales. The coefficients K at the gauge Frankleben are significantly lower than at other gauges, which leads to the conclusion that an averaged K correlates with the amplitude of the mean baseflow rates. Of interest is the BFI development over time and as a function of catchment characteristics. A strong correlation between area characteristics and the BFI development has been demonstrated. Analysing the quasi-parallelism solves this problem and enables the comparison of heterogeneous catchments.

However, a high amplitude in baseflow rates does usually not correspond to realistic conditions (Birtles, 1978; Latron & Gallart, 2007; Nathan & McMahon, 1990; Samuel, Coulibaly, & Metcalfe, 2012). Due to the results and the strong conceptuality of the methods (Beven, 2012; Tallaksen, 1995), we conclude that the usual hydrograph separation methods are only suitable for (quasi) natural catchments. Various alternatives, such as (geochemical) tracer experiments (e.g. Bicalho et al., 2019;;; Penna & van Meerveld, 2019; Wels, Cornett, & Lazerte, 1991), the use of artificial neural networks (Corzo & Solomantine, 2007; Taormina, Chau, & Sivakumar, 2015;) or the integration of physical concepts (Pelletier & Andréassian, 2020) have been proposed. It is clear that calculated baseflow rates only represent an approximation of real conditions. Consequently, we think a more precise parameterisation could provide more reliable results. With increasing parameterisation not only the computational effort but also possible interrelations between parameters increases (e. g. Carlotto & Chaffe, 2019; Stoelzle, Weiler, Stahl, Morhard, & Schuetz, 2015; Voutchkova, Miller, & Gerow, 2019). Also, two significant methodological problems arise: The first one concerns the recursiveness of several procedures. The recursiveness is comprehensible to capture the autocorrelation in hydrological data, and to consider the importance of subsurface filter areas, which leads to a retention of total discharge in relation to the baseflow rates determined from it (Eckhardt, 2005, 2008; Wittenberg, 1994). The subjective calculation of this retention represented by the recession of the hydrograph based on a few parameters seems to be obvious as it is the essential prerequisite for a successful hydrograph separation (Buttle, 2018; Eckhardt, 2005; Wittenberg, 1994). It would be possible, for example, to couple the baseflow separation with a calculation of the subsoil retention capacity, whereby in any case the most important catchment characteristics such as pedological, geological information, or areal precipitation and their strong heterogeneity must be included. A promising approach was proposed by Aksoy, Kurt, and Eris (2009). They suggested to couple the smoothing minima method according to Hisdal, Clausen, Gustard, Peters, and Tallaksen (2003) with a standard recursive digital filter method. Koskelo, Fisher, Utz, and Jordan (2012) proposed a physical-based algorithm including precipitation data into baseflow separation (SARR). The calculated BFI values are significantly higher than in other methods, due to an event-based calculation. The applicability of SARR to only small catchments is problematic, despite the stronger empirical basis, a high practicability, and the implemented event identification.

Secondly, problems exist with the fact that in some algorithms only the total runoff is used as input. Of course, the baseflow is highly dependent on the total discharge volume, as has been demonstrated by a variety of statistical analyses, but it can be assumed that the correlation between total discharge and baseflow is considered as too high. This has been shown by using our catchments that are in one of the driest regions of Germany, where runoff in streamflows often consists mainly of groundwater runoff ($\mathrm{BF}I_{\mathrm{mean}} \approx 0,74$) due to precipitation scarcity ($\mathrm{CW}B_{\mathrm{mean}} = -78.26mm/a$ for the period 1981 to 2017). A solution could again be the inclusion of further parameters such as precipitation.

4.2 Hydrological regionalisation

Without using a physically-based model, there are three basic approaches for hydrological regionalisation. In this study, all of them were applied: Proximity is ensured by using nearby catchments that show similar climatic conditions; the regionalisation itself is carried out with linear single regressions, and physical comparability is achieved by applying the concept of physical catchment descriptors as independent variables. The adjustment relates primarily to a reduction in amplitude, which was interpreted as an indicator of impacted baseflow hydrographs.

While the BFI calculated by hydrograph separation rises disproportionately in each period, the regionalised BFI remains relatively constant. There are no values with $BFI = 1$, due to the use of monthly averages for regionalisation. Nevertheless, differences in the intensity of the mining impacts over the entire time series at the gauge Frankleben become clear with significant differences in the calculated baseflow rates and BFI values. Both the total runoff and the calculated baseflow at the gauge Frankleben decrease strongly over the investigated time series. The relative level of the baseflow hydrograph under the total runoff hydrograph arises with time, but stronger than at all other investigated gauges. This gradient was reduced by hydrological regionalisation and thus adapted to typical conditions in catchment areas in Central Germany. A slightly positive slope of the BFI is plausible due to climatic changes and the observed decrease in total runoff.

There are many other approaches for hydrological regionalisation (Razavi & Coulibaly, 2013), such as artificial neural networks (Heuvelmans, Muys, & Feyen, 2006; Shu & Ouarda, 2008), transfer functions (Götzinger & Bárdossy, 2007) or procedures based on scaling relationships (Croke, Merritt, & Jakeman, 2004). We assume that more precise results could be obtained by more complex procedures, but one of our objectives was to illustrate simple approaches which provide reliable results on temporally higher scales. Further research in hydrological regionalisation, especially case studies in heterogeneous catchments, is required to find a balance between complexity, simplicity in use, and accuracy of results.

5 Conclusions

In this study, we investigated the calculation of baseflow rates for an anthropogenically impacted catchment in Central Germany. Due to the strong conceptual design of most hydrograph separation algorithms, validated baseflow rates for impacted catchments could not be derived. This calls for new optimized procedures with a stronger relation to processes of runoff formation and concentration. As long as no deterministic record of percolation rates and groundwater characteristics is available, a process-based baseflow separation algorithm is still far away. We proposed a method suitable for other mining-impacted catchments, provided that a sufficiently long time series of hydrological data is available. Our results suggest the use of the SWAT BFLOW algorithm due to the most validated results, theoretical background, and simplicity of application. However, other algorithms might be more appropriate in catchments with different biogeophysical conditions. We recommend a comprehensive analysis of the differences in calculated baseflow rates before the application of an algorithm.

We could show that a calculation of baseflow rates in a mining-impacted catchment could be solved using a simple regionalisation approach. We were able to calculate the first long-term baseflow for our study site. This information should be used for a holistic analysis of the hydrological processes to understand anthropogenic impacts, but it can also be used for land-use adaptation (impact on evapotranspiration, stream- and baseflow) to climate change. Moreover, our study provides essential information for an appropriate water management regulation in the Geisel catchment. The catchment shows a problematic landscape water balance (water stress), where various adjustments in the existing runoff quantities (e. g. by external flooding) are necessary.

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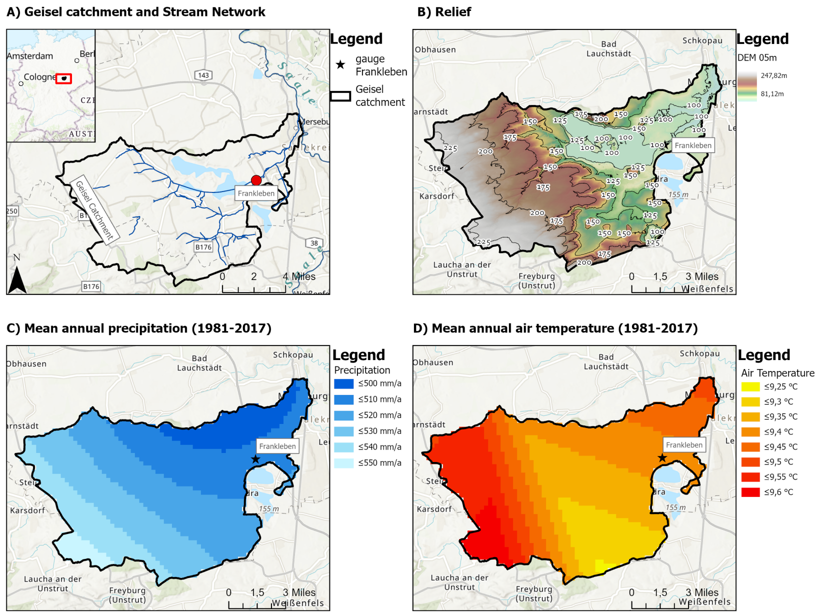
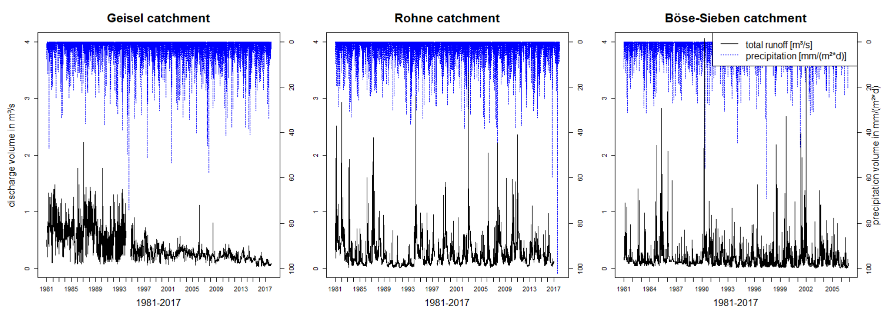
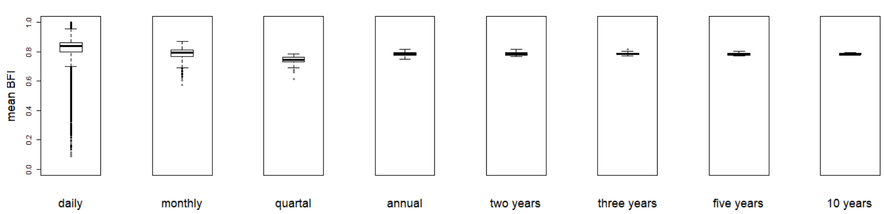
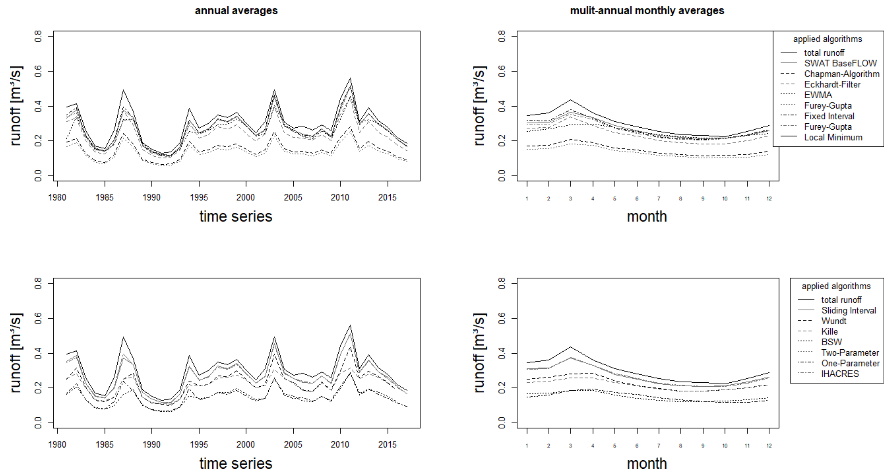
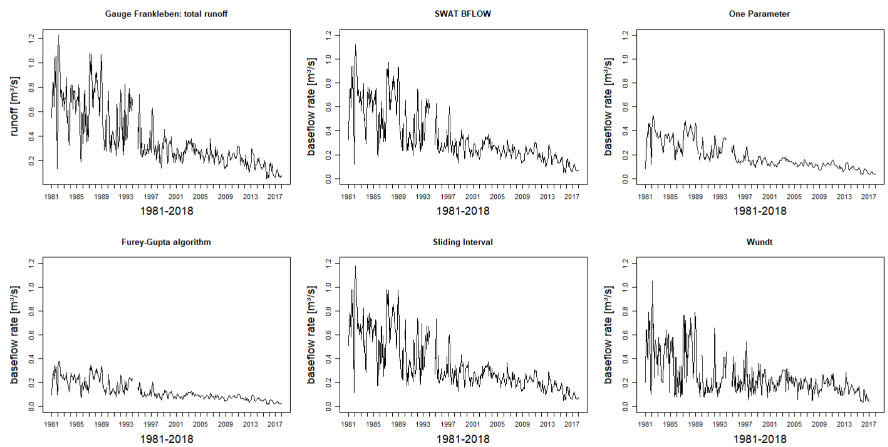
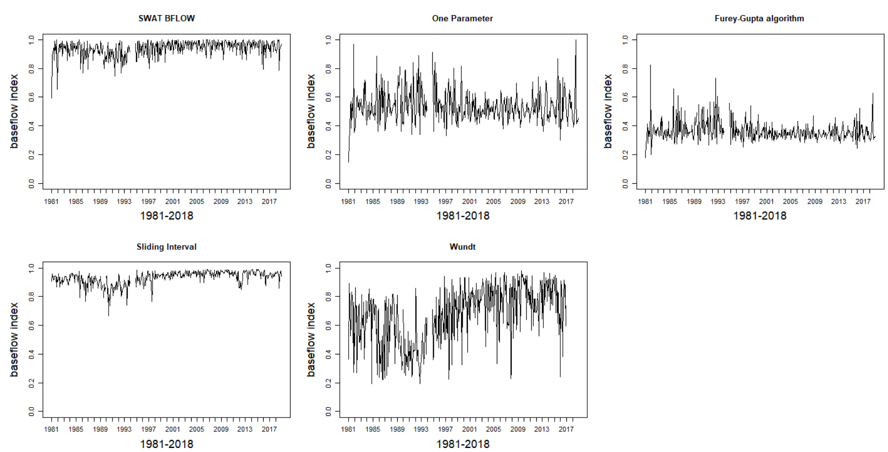

A) Geisel catchment and Stream Network
Legend
gauge Frankleben
Geisel catchment
Amsterdam
Cologne
Frankleben
Geisel Catchment
0 2 4 Miles
B) Relief
Legend
DEM 05m
Obhausen
Bad Lauchstädt
Schkopau
Karsdorf
Laucha an der Unstrut
Freyburg (Unstrut)
Weißenfels
0 1,5 3 Miles
C) Mean annual precipitation (1981-2017)
Legend
Precipitation
≤500 mm/a
≤510 mm/a
≤520 mm/a
≤530 mm/a
≤540 mm/a
≤550 mm/a
D) Mean annual air temperature (1981-2017)
Legend
Air Temperature
≤9,25 °C
≤9,3 °C
≤9,35 °C
≤9,4 °C
≤9,45 °C
≤9,5 °C
≤9,55 °C
≤9,6 °C

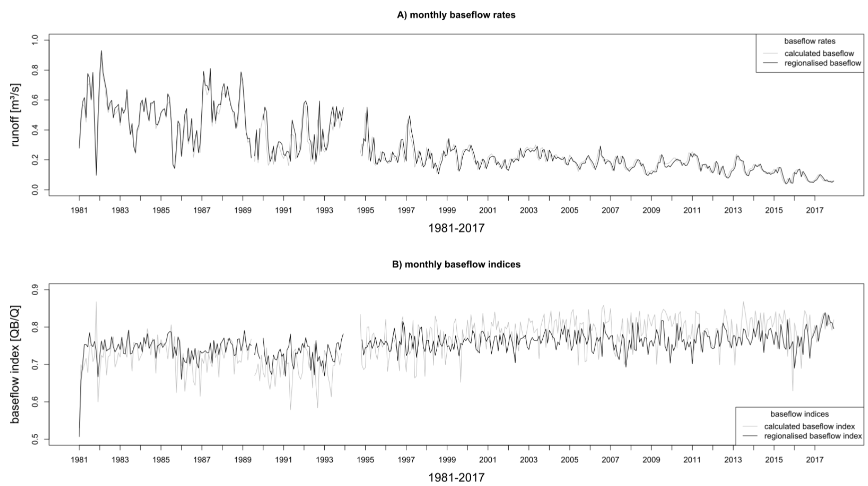

Geisel catchment
Rohne catchment
Böse-Sieben catchment
total runoff [m³/s]
precipitation [mm/(m²*d)]
discharge volume in m³/s
precipitation volume in mm/(m²*d)
1981-2017

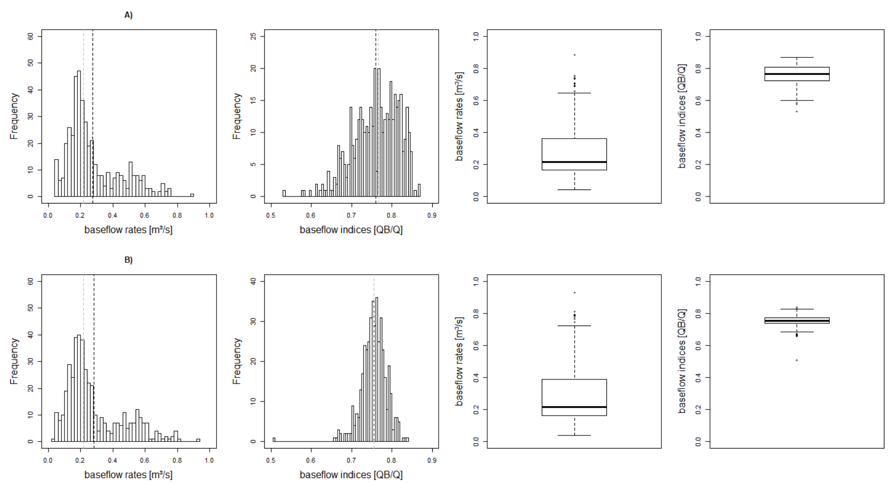

mean BFI
daily
monthly
quartal
annual
two years
three years
five years
10 years


annual averages
mulit-annual monthly averages
runoff [m³/s]
time series
month
applied algorithms
total runoff
SWAT BaseFLOW
Chapman-Algorithm
Eckhardt-Filter
EWMA
Furey-Gupta
Fixed Interval
Furey-Gupta
Local Minimum
applied algorithms
total runoff
Sliding Interval
Wundt
Kille
BSW
Two-Parameter
One-Parameter
IHACRES


Gauge Frankleben: total runoff
SWAT BFLOW
One Parameter
Furey-Gupta algorithm
Sliding Interval
Wundt
runoff [m³/s]
baseflow rate [m³/s]
1981-2018


SWAT BFLOW
One Parameter
Furey-Gupta algorithm
Sliding Interval
Wundt
baseflow index
1981-2018





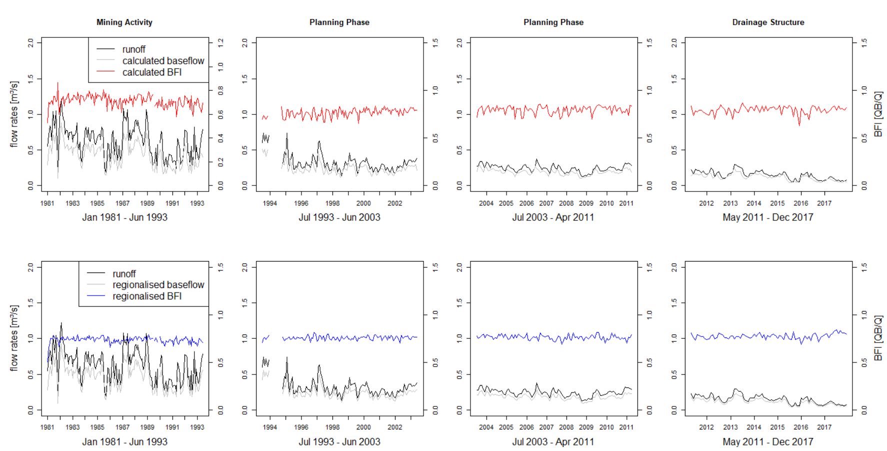


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Table 1.xlsx available at https://authorea.com/users/361173/articles/482692-baseflow-

estimation-for-a-mining-impacted-catchment-using-hydrograph-separation-and-hydrological-regionalisation

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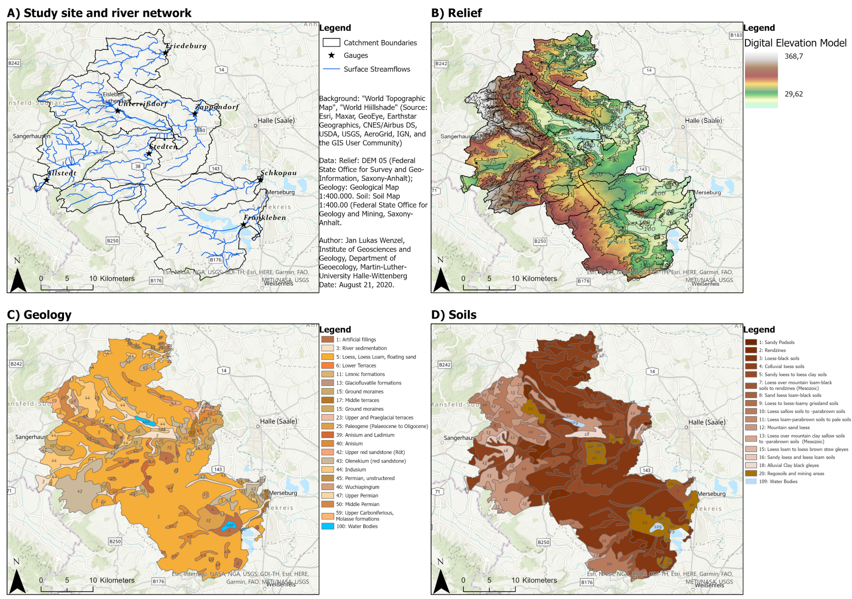
TABLE2.pdf available at https://authorea.com/users/361173/articles/482692-baseflow-estimation-for-a-mining-impacted-catchment-using-hydrograph-separation-and-hydrological-regionalisation



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APPENDIX2.pdf available at https://authorea.com/users/361173/articles/482692-baseflow-estimation-for-a-mining-impacted-catchment-using-hydrograph-separation-and-hydrological-regionalisation

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APPENDIX3.pdf available at https://authorea.com/users/361173/articles/482692-baseflow-estimation-for-a-mining-impacted-catchment-using-hydrograph-separation-and-hydrological-regionalisation