Long-term baseflow estimation and environmental flow assessment in a mining-impacted catchment in Central Germany

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10 Abbildungen und 8 Tabellen

Abstract

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The local water regime of the small-scale Geisel catchment in Central Germany is vastly impacted by strong lignite-mining activities. Missing knowledge about hydrological regimes and low-flow discharges in this impacted region prevented integrated environmental flow assessments. As a consequence, targeted environmental flows of the lower Geisel usually cannot be achieved. To close this knowledge gap, we present a novel approach for an integrated environmental flow assessment in non-natural catchments using long-term baseflow rates, seen as an approach to environmental flows, and simple hydrological methods. Since baseflow rates cannot be estimated accurately in non-natural catchments, we combine 14 different hydrograph separation methods, statistical regionalization, and numerical catchment descriptors. The long-term baseflow equals 0.28 m³/s from 1981 to 2017 (75.4% of total discharge), and in the post-mining era since 2011, the mean baseflow equals 0.115m³/s (77.2% of total discharge). The combination of hydrograph separation with hydrological regionalization and numerical catchment descriptors reveals new opportunities for describing discharge components in non-natural catchments. Determined environmental flows are similar as achieved by other hydrological methods and can be linked to different intensities of anthropogenic impacts. The environmental flow assessment reveals required additional water amounts of 0.0608 m³/s during summer and 0.0874m³/s during winter for achieving quasi-natural flow regime conditions. The approaches enable long-term low-flow analyses and environmental flow assessments in mining impacted catchments.

Key words: post-mining water balance; environmental flows; hydrograph separation; hydrological regionalization; baseflow index; flow-duration-curve shifting method; Tennant method; 7Q10 method; low-flow hydrology; water recourses management

1 Introduction

Mining-impacted hydrological systems are usually characterized by non-natural processes of runoff accumulation through a disturbance of geological and hydrogeological structures and discontinuous mine dewatering, which lead to decreasing baseflow rates, groundwater lowering or mounding and increasing surface runoff volumes (LECLAIR et al. 2015, LIANG et al. 2019). Restoring quasi-natural hydrologic conditions in mining-impacted catchments and an integrated environmental flow assessment (EFA) typically require the definition of environmental flow requirements (EFR), which is primarily intended to ensure ecological functions (i.e. a habitat for fish and other organisms) of a streamflow (THARME 2003). Three groups of EFA models are known: Hydrological methods, hydraulic models, and biological response models (ACREMAN 2016). It is well known that EFR based on baseflow integration offer a higher level of detail (SHARMA & DUTTA 2020).

The overall objective of this study is to analyze and evaluate baseflow and EFR in the strongly mining-impacted Geisel catchment in Central Germany. In total, about 1.4 Gt of lignite were mined until June 30, 1993 (WIRTH et al. 2008). The recultivation plan targeted the EFR at 0.2 m³/s from October to February and 0.25 m³/s from March to September, respectively (REGIERUNGSPRÄSIDIUM HALLE (SAALE) 2003). However, the EFR were determined neglecting validated low-flow rates, anthropogenic impacts on the hydrological regime and future management perspectives (LANDESBETRIEB FÜR HOCHWASSERSCHUTZ UND WASSERWIRTSCHAFT SACHSEN-ANHALT 2012, LAUSITZER UND MITTELDEUTSCHE BERGBAU-VERWALTUNGSGESELLSCHAFT MBH 2018), and cannot be achieved under current hydrological conditions (REGIERUNGSPRÄSIDIUM HALLE (SAALE) 2003, WIRTH et al. 2008).

Under disturbed hydrological conditions or in non-natural or ungauged catchment, the integration of baseflow rates into EFR determination lacks knowledge about natural hydrological regime conditions. Baseflow is defined as the slowest responding and longest lasting discharge component, which cannot be associated with single precipitation events (HEWLETT & HIBBERT 1967). It generally sustains a streamflow between high flow events when surface runoff and interflow are diminished (DUNCAN 2019). For a numerical description, a conceptual relationship between a non-observable (i.e. conceptual) phenomenon, the baseflow, with a measurable phenomenon, the total discharge, must be developed. These relationships are usually disturbed in non-natural systems (THEODOROPOULOS et al. 2019).

Hence, we present a novel hydrological regionalization approach based on determining statistical relationships between estimated baseflow rates, physical catchment descriptors, and different stages of anthropogenic impacts, in order to derive validated baseflow rates (Fig. A1). These long-term baseflow values are used as minimum EFA considering different (and mining-impacted) hydrological processes.

We hypothesize that (i) validated baseflow rates in mining-impacted catchments can be estimated using a simple hydrological regionalization approach and physical catchment descriptors, (ii) this approach reveals typical hydrological conditions in different time periods dependent on the intensity of anthropogenic impacts, (iii) baseflow rates are an essential information for an integrated EFA in mining-impacted catchments, and (iv) a profound calculation of EFR in mining-impacted catchments is possible using regionalized baseflow rates and simple hydrological EFA models.

2 Materials and Methods

2.1 Study area and hydrological situation

The studied catchments are located in the dry region of Central Germany. All catchments are located in the southeastern foothills of the Harz Mountains and show comparable physical characteristics. Our main study site is the mining-impacted Geisel catchment with the gauge Frankleben (Fig. 1a). Flowing from west to east, River Geisel later joins River Saale. Annual precipitation amounts range from 495 to 550 mm/a on a long-term average with a gradient in SW-NE direction, which indicate dry conditions compared to other German regions. Monthly precipitation amounts range from 25 mm in February to 68mm in July. Air temperature ranges from 0.7 °C in January to 18.9 °C in July. In this study we used daily discharge data (period 1981 to 2017) measured at the gauge Frankleben and six other gauges (Table 1, Fig. 2).

Table 1 Investigated catchments. Missing data: Laucha – Jan 1981 to Oct 1997; Jan 2009 to Mar 2009; 2017. Rohne – Jun 1997 to Sep 1997; Jan 2015 to Feb 2015; Jan 2017 to Dec 2017. Salza – May 1990 to Dec 1993. Schlenze – Dec 2016 to Dec 2017. MQ = mean discharge; NQ = lowest discharge measured; HQ = highest discharge measures.

Tab. 1 Untersuchte Einzugsgebiete. Fehlende Daten: Laucha – Jan 1981 to Okt 1997; Jan 2009 to Mär 2009; 2017. Rohne – Jun 1997 to Sep 1997; Jan 2015 to Feb 2015; Jan 2017 to Dez 2017. Salza – May 1990 to Dez 1993. Schlenze – Dez 2016 to Dez 2017. MQ = mittlerer Abfluss; NQ = niedrigster gemessener Abfluss; HQ = höchster gemessener Abfluss.

Catchment (Einzugsgebiet)	Gauge (Pegelmessstelle)	Area (Fläche) [km²]	MQ (mittlerer Abfluss) [m³/s]	NQ (niedrigster Abfluss) [m³/s]	HQ (höchster Abfluss) [m³/s]
Geisel	Frankleben	208	0.371	0.036	4.95
Böse Sieben	Unterrißdorf	104	0.14	0.006	8.9
Laucha	Schkopau	119	0.107	0.004	1.4
Rohne	Allstedt	129.5	0.24	0.01	3.47
Salza	Zappendorf	547	0.987	0.14	7.56
Schlenze	Friedeburg	110	0.17	0.01	13.3
Weida	Stedten	173	0.298	0.053	21.2

Hydrological conditions in the Geisel catchment have been disturbed during four periods of different anthropogenic impacts: i) mining activity until June 30, 1993 (mean discharge equals 0.63 m³/s); ii) inactive period until June 29, 2003 (mean discharge equals 0.325 m³/s); iii) refilling period until April 29, 2011 (mean discharge equals 0.242 m³/s); and iv) recent period (mean discharge equals 0.149 m³/s). In the 1980s, several mine operations led to a high temporal streamflow variability of River Geisel. River channel relocations to create new opencast mining areas, catchment area modifications, morphological adaptions, subsequent groundwater lowering, and mine dewatering caused a disturbance of all significant water balance parameters and a delayed deployment of runoff-forming components to River Geisel (SCHROETER 1991). After closing the mine in 1993, recultivation plans were developed for improving the strongly impacted hydrological situation. Since June 30, 2003, the abandoned open pit was refilled with about 50 m³/d additional water from River Saale (SCHULTZE et al. 2010) in order to create Lake Geiseltal. Since April 30, 2011, the lower Geisel is regulated by a drainage structure, primarily aiming the EFR supply. We assume that influences on a catchment scale disturb the hydrograph. Hydrological trends should not be able to be explained by changing precipitation or potential evapotranspiration in this case. Although a negative discharge trend is visible (cp. discharge rates in different time periods explained above, and Fig. 2), the climatic conditions do not show any significant change (Fig. 1d) and are therefore not responsible for hydrological trends.

2.2 Applied hydrograph separation algorithms

A commonly used approach for baseflow estimation are hydrograph separation methods. These conceptual relationships analyze the flow´s time delay caused by different velocities (NATHAN & MCMAHON 1990, CARTWRIGHT et al. 2014). The slowest discharge component (i.e. baseflow) is assigned to the lower, slowly varying part of the hydrograph. The upper, rapidly varying part is considered as the signal of surface runoff. Furthermore, they are based on the assumption that different flow velocities are mainly caused by a gradual emptying of subsurface water storages under drought conditions (ARNOLD et al. 2000, SMAKHTIN 2001a) and that discharge then consists exclusively of slow subsurface flows. Fourteen different hydrograph separation methods were used to estimate baseflow rates, which can be divided into three different groups (cp. Table A1 for parameterization): *Graphical methods* – Fixed Interval, Sliding Interval (PETTYJOHN & HENNING 1979, SLOTO &CROUSE 1996), Local Minimum (GUSTARD et al. 1992); *Statistical methods* – Monthly low-flow (MoNQ)-method (WUNDT 1958), Mean monthly low-flow (MoMNQ) -method (KILLE 1970), six month mean low-flow (6-MoMNQ)-method (BAVARIAN STATE OFFICE FOR WATER MANAGEMENT 1996); *Recursive digital filter methods* – SWAT BFLOW (LYNE & HOLLICK 1979, ARNOLD et al. 2000), Chapman filter (CHAPMAN 1991); One-parameter filter (CHAPMAN & MAXWELL 1996), Two-parameter filter (CHAPMAN & MAXWELL 1996, DUKI et al. 2017), IHACRES filter (JAKEMAN et al. 1992, RUTLEDGE 1998), Eckhardt filter (ECKHARDT 2005, ECKHARDT 2008), EWMA filter (TULARAM & ILAHEE 2008), Furey-Gupta filter (FUREY & GUPTA 2001).

2.3 Hydrological regionalization

In order to estimate validated baseflow rates for ungauged or non-natural catchments, hydrological regionalization methods represent appropriate procedures (HE et al. 2011, REDDYVARAPRASAD et al. 2020). Three different approaches are known (HEŘMANOVSKÝ & PECH 2013), (i) the approach of spatial proximity (OUDIN et al. 2010), (ii) linear regression (WAGENER & WHEATER 2006), and (iii) the approach of physical similarity and comparability (PARAJKA et al. 2005). In this study, hydrological regionalization is carried out using six other catchments in Central Germany (cp. Table 1) and physical catchment descriptors, which describe a facet of a catchment in a single number (MILLS et al. 2014). For each catchment, 64 different physical catchment descriptors were determined (Table A2), based on

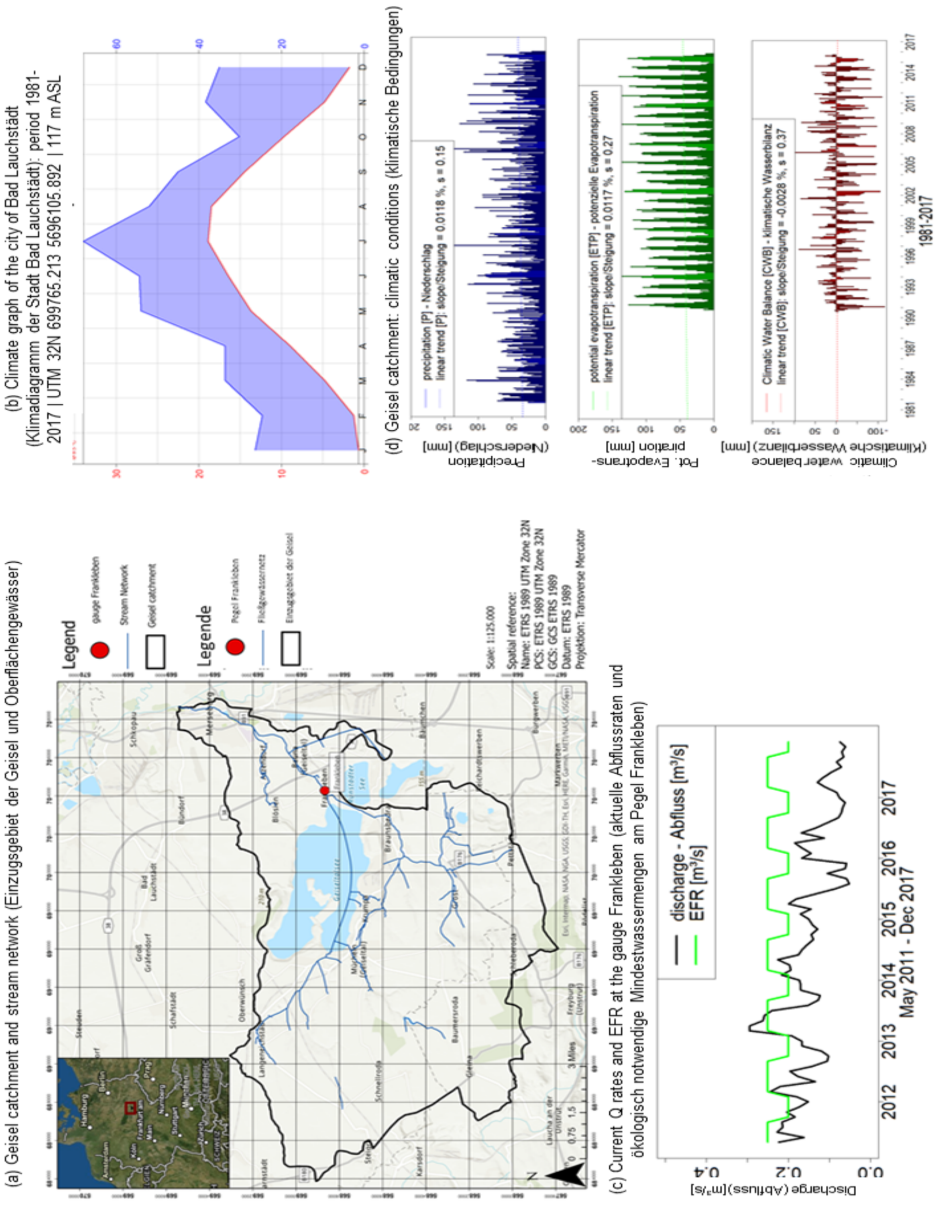


Fig. 1 (a) Geisel catchment and stream network; (b) climate graph for the climate station in the city of Bad Lauchstädt, Saxony-Anhalt, Germany; (c) current hydrological conditions at the gauge Frankleben and EFR determined in the recultivation plan for the post-mining era; (d) Different hydro-climatic parameters in the Geisel catchment of the investigated time period (1981 to 2017) to clarify that changes in Q are not due to climatic changes. Meteorological data are provided by the German Meteorological Service (DWD). Potential evapotranspiration data is only available since January 1991. Climatic water balance (CWB) is calculated as the difference between precipitation and potential evapotranspiration.

Abb. 1 (a) Geisel-Einzugsgebiet und Fließgewässernetz; (b) Klimadiagramm für die Klimastation in der Stadt Bad Lauchstädt, Sachsen-Anhalt, Deutschland; (c) aktuelle hydrologische Verhältnisse am Pegel Frankleben und ökologisch notwendige Mindestwassermengen, die im Rekultivierungsplan für die Bergbaufolgelandschaft ermittelt wurden; (d) verschiedene hydroklimatische Parameter im Geisel-Einzugsgebiet des untersuchten Zeitraums (1981 bis 2017), um zu verdeutlichen, dass die Abflussänderungen nicht auf klimatische Veränderungen zurückzuführen sind. Die meteorologischen Daten werden vom Deutschen Wetterdienst (DWD) bereitgestellt. Daten zur potentiellen Evapotranspiration sind erst seit Januar 1991 verfügbar. Die klimatische Wasserbilanz (CWB) wird als Differenz zwischen Niederschlag und potentieller Evapotranspiration berechnet.

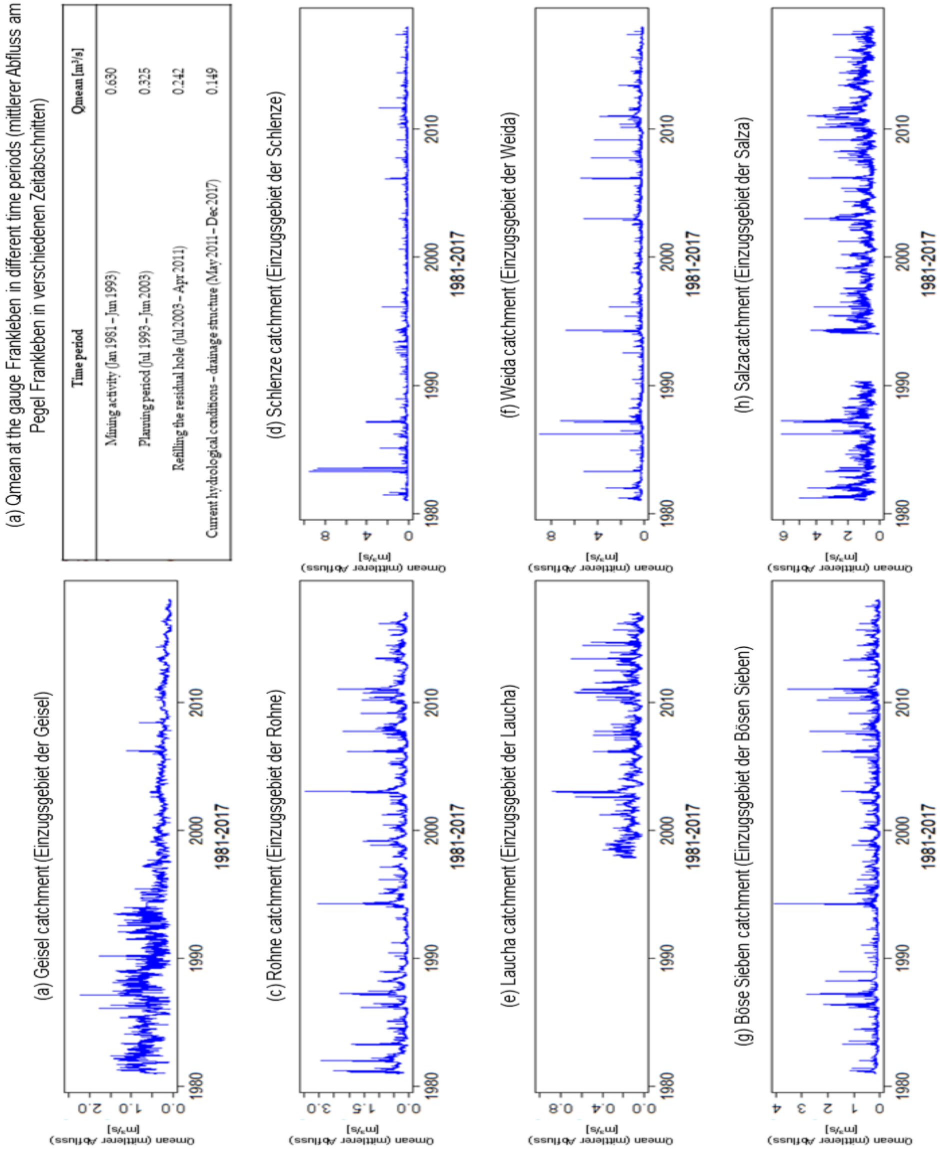
different theoretical approaches (GRAVELIUS 1914, HORTON 1932, MILLER 1953, WUNDT 1953, SCHUMM 1956, STODDART 1965, BOSCH 1978, BEVEN & KIRKBY 1979, GRIFFITH 1982, NATHAN & MCMAHON 1990, ARNOLD et al. 1995, DOWLING et al. 1998, HUGGETT & CHEESMAN 2002). We used single linear regression models with physical catchment descriptors as independent variables and baseflow indices (INSTITUTE OF HYDROLOGY 1980) as dependent variables instead of absolute baseflow rates. In each regression, the estimated monthly baseflow indices of the time period Jan 1981 to Dec 2017 at the gauge Frankleben and the other six catchments were related to a specific physical catchment descriptor. Overall, 28,416 single regression models were calculated. Nash-Sutcliffe-Efficiency (NASH & SUTCLIFFE 1970) was calculated for each residual. Each analysis was subjected to a case-by-case review.

2.4 Environmental flow assessment

Three different steps are applied to define minimum, basic, and optimum EFR of the lower Geisel and to delineate adaption strategies based on different management scenarios.

Firstly, seasonal minimum, basic, and optimum EFR are calculated based on measured discharge rates of a specific time period and mean seasonal regionalized baseflow indices. For minimum EFR, discharge rates of the time period from May 2011 to Dec 2017 (current hydrological conditions) are used. For basic EFR, discharge rates of the time period from Jul 2003 to Apr 2011 (refilling of the abandoned open pit) are used. For optimum EFR, discharge rates of the time period from Jul 1993 to Jun 2003 (planning period – nearly natural conditions) are used. Basic and optimum EFR are interpreted as discharge rates sufficient to meet ecological needs even during long droughtsand required to address a profound recultivation strategy and the restoration of quasi-natural hydrological conditions as they consider different intensities of anthropogenic impacts.

Secondly, basic and optimum EFR are calculated using the low-flow index or 7Q10 method (THARME 2003) and the discharge-based Tennant or Montana (TM) method (TENNANT 1976). The 7Q10 method is a commonly used approach for determining long-term EFR. Based on daily discharge rates, the method calculates a low-flow index, which is interpreted as the 7-day low-flow discharge within in 10-year return period. This low-flow discharge rate is considered as basic EFR for the respective year (THARME 2003). The TM method considers discharge as a “composite manifestation of the size of the drainage area, geomorphology, climate, vegetation, and land use” (TENNANT 1976). Changes in this relationship are based on fixed percentages of the annual discharge, linking the rate of change in hydraulic parameters at flows with habitat (TENNANT 1976).



(a) Qmean at the gauge Frankleben in different time periods (mittlerer Abfluss am Pegel Frankleben in verschiedenen Zeitabschnitten)

Time period	Qmean [m³/s]
Mining activity (Jan 1981 – Jun 1993)	0.630
Planning period (Jul 1993 – Jun 2003)	0.325
Refilling the residual hole (Jul 2003 – Apr 2011)	0.242
Current hydrological conditions – drainage structure (May 2011 – Dec 2017)	0.149

Fig. 2 Daily Q_{mean} rates at all investigated gauges ((a), (c)-(h)), and (b) Q_{mean} rates at the gauge Frankleben for four different time periods with different intensities of anthropogenic impacts.

Abb. 2 Tägliche Abflussmittelwerte an allen untersuchten Pegeln ((a), (c)-(h)) und (b) Abflussmittelwerte am Pegel Frankleben für vier verschiedene Zeiträume mit unterschiedlichen Intensitäten anthropogener Einflüsse.

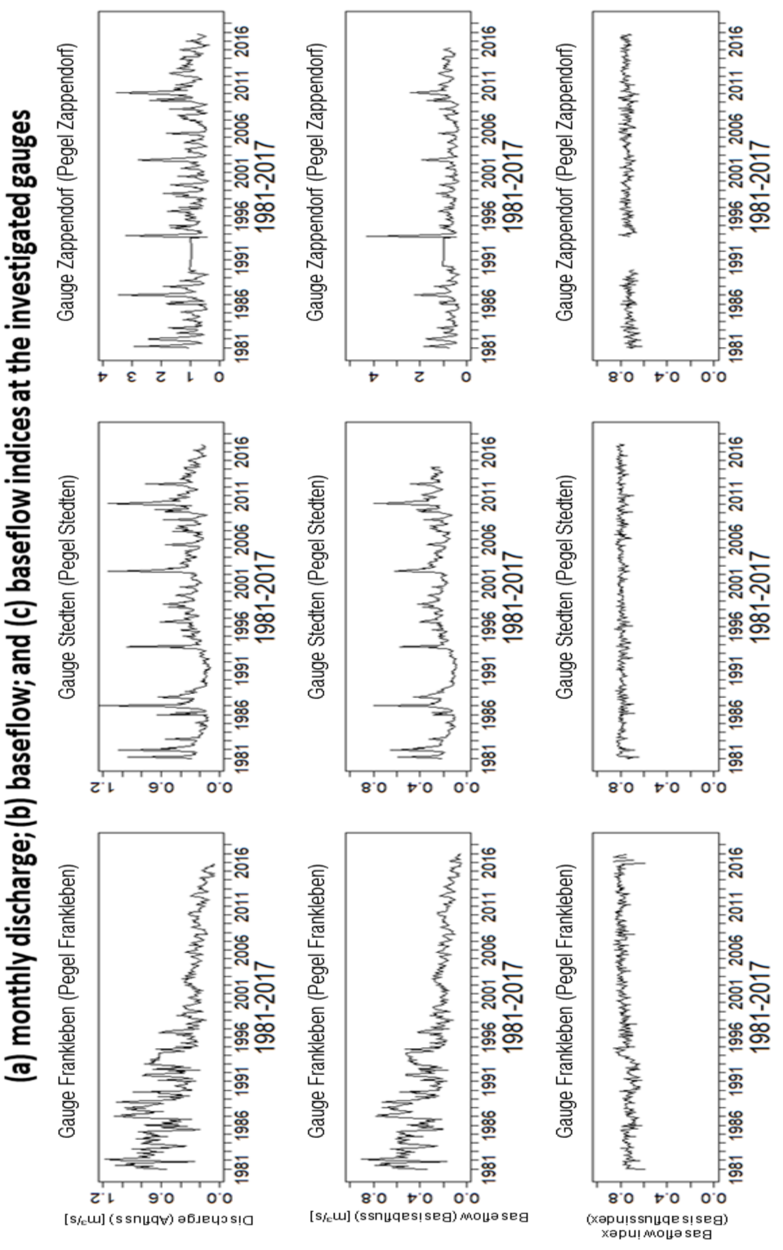


Fig. 3 (a) Monthly Q_{mean}, (b) estimated monthly Q_B rates, and (c) BFI at the gauges Frankleben, Stedten, and Zappendorf.

Abb. 3 (a) Monatliche Abflussmittelwerte, (b) geschätzte monatliche Basisabflussraten und (c) Basisabflussindices an den Pegeln Frankleben, Stedten und Zappendorf.

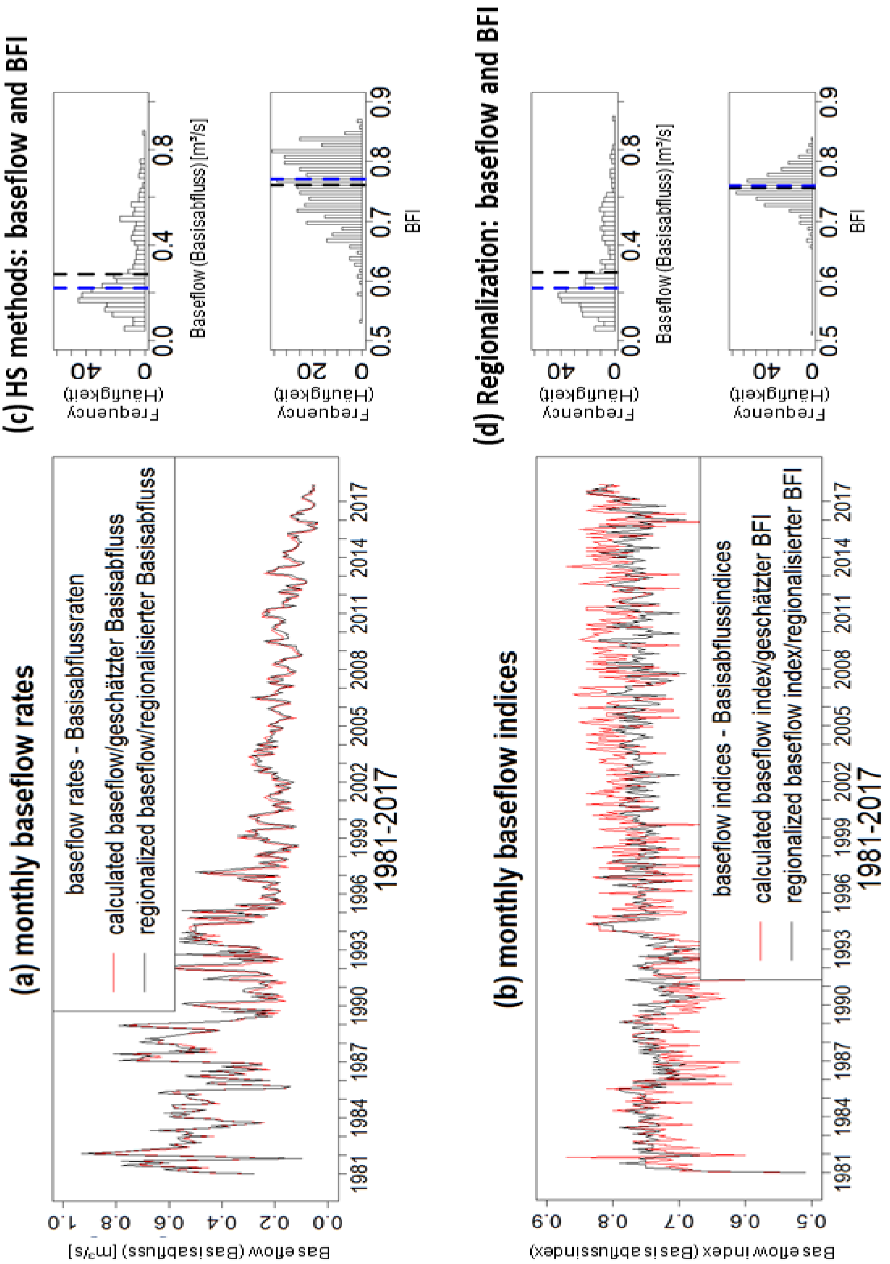


Fig. 4 (a) Monthly Q_{Bmean} and (b) BFI values of the time period 1981 to 2017 at the gauge Frankleben. (c) Distribution and statistical parameters of monthly Q_{Bmean} and BFI (HS). (d) Distribution and statistical parameters of monthly Q_{Bmean} and BFI (HR).

Abb. 4 (a) Mittlere monatliche Basisabfluss- und (b) Basisabflussindex-Werte des Zeitraums 1981 bis 2017 am Pegel Frankleben. (c) Verteilung und statistische Parameter des mittleren monatlichen Basisabflusses und Basisabflussindex (Ganglinienseparation). (d) Verteilung und statistische Parameter des mittleren monatlichen Basisabflusses und Basisabflussindex (hydrologische Regionalisierung).

3 Results

3.1 Calculated and regionalized baseflow rates at the gauge Frankleben

Due to anthropogenic impacts in the Geisel catchment, the estimated baseflow hydrograph at the gauge Frankleben shows specific characteristics, which are clarified by a comparison with two other quasi-natural catchments (Fig. 3, Fig. A2. The contained data can be queried from the author.). This “reference scenario” (i.e. typical baseflow conditions of quasi-natural catchments in Central Germany) is characterized by a strong seasonality. Additionally, perennial events with an above-average discharge are characteristic, resulting from strong precipitation events during spring and snowmelt in the Harz Mountains.

Unfortunately, the estimated baseflow rates at the gauge Frankleben are not comparable to this reference scenario. Neither are extended droughts evident, nor are the hydrographs characterized by perennial runoff events. Rather, the hydrological conditions are characterized by a strongly varying amplitude, especially in the early phase of the investigated time series (mining activity). The fluctuations decrease over time, dependent on the type and intensity of the influence on the hydrological regime. Theyindicate a delayed water supply and control of discharge rates by mine dewatering. The estimated baseflow indices show a slgihtly positive trend at all gauges (Fig. 3c). At the gauge Frankleben, this trend is more pronounced due the strong negative trends in baseflow and discharge. Additionally, a seasonality in baseflow indices is visible, due to their strong dependency on summer drought and precipitation events. It thusseems to be a suitable parameter for further analyses, since it is independent of external factors, but still sensitive to seasonal characteristics. The baseflow index indicates a normalization of baseflow to discharge and thus enables a comparability between different catchments.

The regionalized baseflow rates show only minor differences to the results of hydrograph separation (Fig. 4a). The success of hydrological regionalization is particularly evident from the baseflow indices (Fig. 4b) and the derived statistics (Fig. 4d). Although both hydrographs show a clear right skew, the frequency of baseflow events is reduced by hydrological regionalization. Baseflow rates are thus smoothed and less influenced by extreme events. A similar gradient was estimated at other gauges and can thus be interpreted as close to reality as it may be associated with changes in external conditions (e.g. climate or land use change; cp. Fig. 1d). Nevertheless, seasonal fluctuations could be maintained within hydrological regionalization. The most important result, however, is that these fluctuations have been reduced significantly in their extent. The baseflow index determined byhydrograph separation shows a flat distribution (Fig. 4c). However, the median and the mean value are already close together. The baseflow index distribution could be adjusted to an almost normal distribution, the median and mean value are almost identical (Fig. 4d). Hydrological regionalization has resulted in an adjusted average baseflow index in the entire investigated time period of 0.756. This corresponds to an average baseflow at the gauge Frankleben of 0.28 m³/s. A comparison of the hydrographs in different periods reveals the effect of different impacts on the estimated and regionalized baseflow rates (Fig. 5, Table

A4).

In the first period, typical lignite mining activities (especially mine dewatering) result in lower baseflow rates and baseflow indices. Furthermore, the delayed water supply explains the strong amplitude of all hydrographs and the slightly delayed occurrence of baseflow events. Hydrological regionalization leads to an adjustment of the baseflow indices but with the typical fluctuations maintained. In the second period, no major impacts on the hydrological situation in the Geisel catchment are known, so the hydrographs should show nearly natural courses. Nevertheless, the estimated fluctuations of baseflow indicescontradict the natural conditions found at other gauges in Central Germany. Small fluctuations should exist, reflecting the seasonal fluctuations of baseflow and thus the baseflow indices. Hydrological regionalization resulted in a significant reduction of the baseflow index amplitude. In the third period, the main impacts concerned the recultivation of the opencast pit holes. Nevertheless, the refilling of the abandoned open pit with water from River Saale (about 50 m^3/d) may have had an impact on the hydrological conditions of the lower Geisel. For example, the extraneous water supply may have triggered high flow events downstream. Additionally, subsurface fractures resulting from mining activities could have led to deeper infiltration losses in the newly formed Lake Geiseltal, which in turn would enhance the slow discharge signal (i.e. low-flow discharge) at the gauge Frankleben. The slightly stronger baseflow index amplitude compared to the previous period could be explained by these factors in addition to the known seasonal variations. In the fourth period, hydrographs should not show any fluctuations than those caused by seasonal discharge variations specified as EFR in the recultivation plan (cp. Fig. 1c). Nevertheless, the baseflow index shows fluctuations, resulting from the inherent normalization of discharge and baseflow events and a subsequent emphasis of external factors as strongprecipitation events, snowmelt, longer droughts, and possible infiltration losses at the bottom of Lake Geiseltal.

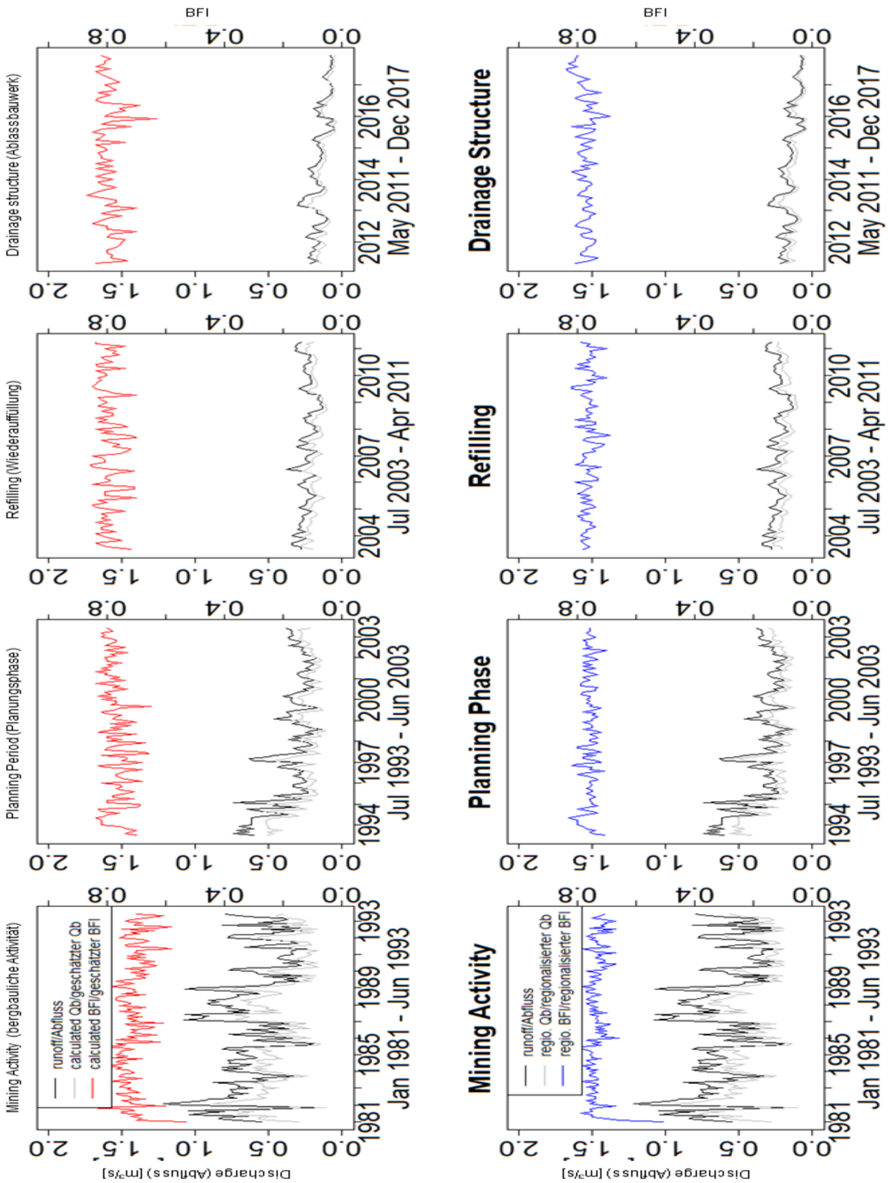


Fig. 5 Q_B characteristics at the gauge Frankleben divided into certain time periods of different anthropogenic impacts in the Geisel catchment. (a) Results of HS algorithms. (b) Results of HR.

Abb. 5 Basisabflussganglinien am Pegel Frankleben, unterteilt in bestimmte Zeiträume verschiedener anthropogener Einflüsse im Einzugsgebiet der Geisel. (a) Ergebnisse der Ganglinienseparationsverfahren. (b) Ergebnisse der hydrologischen Regionalisierung.

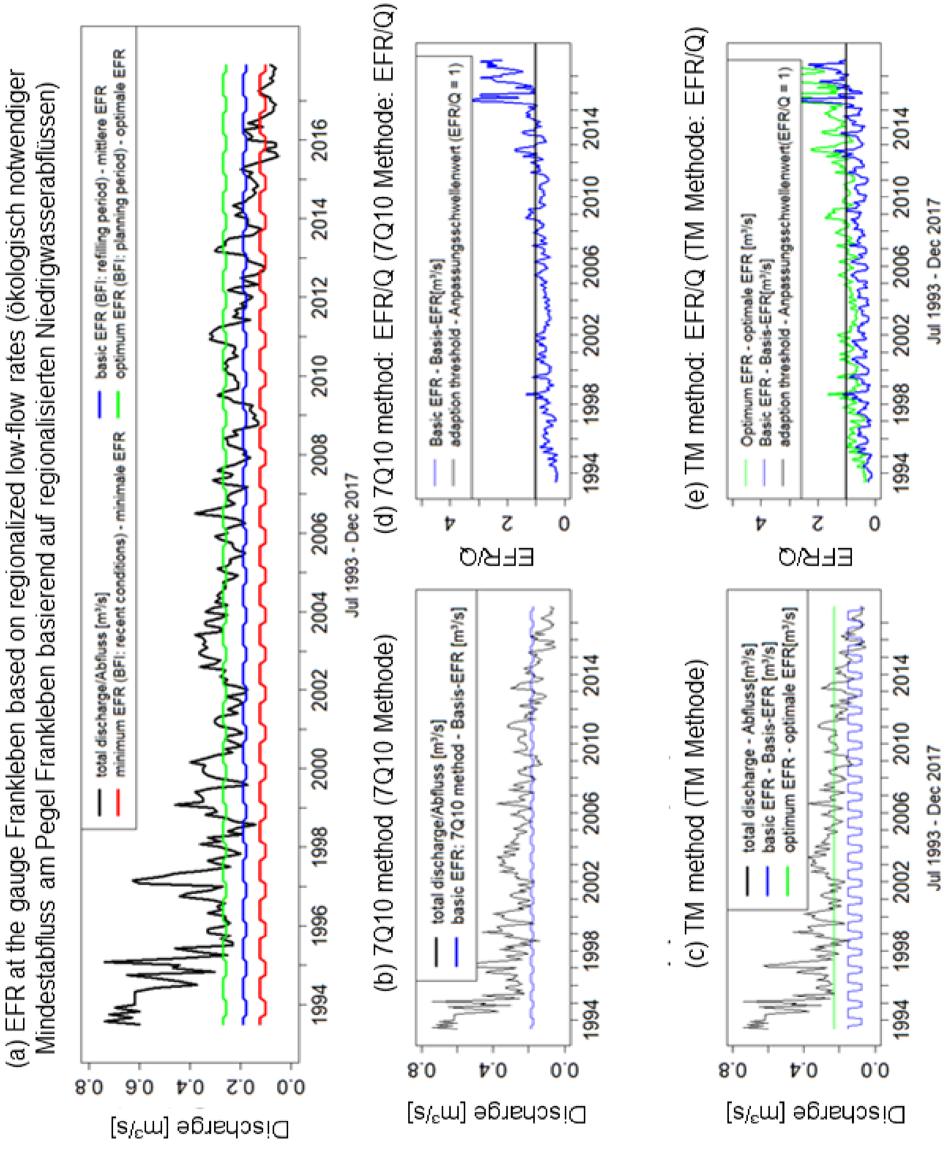


Fig. 6 Monthly EFR for the time period Jul 1993 to Dec 2017 (post-mining era) at the gauge Frankleben calculated by (a) regionalized BFI values; (b) 7Q10 method; and (c) TM based on long-term Q_{mean} (MAM) and (d) to (e) the respective exceedances (EFR/Q) calculated for each method.

Abb. 6 Monatliche ökologisch notwendige Mindestwassermengen für den Zeitraum Jul 1993 bis Dez 2017 (Nachbergbauzeit) am Pegel Frankleben, berechnet nach (a) regionalisierten Basisabflussindices, (b) der 7Q10-Methode und (c) der TM-Methode auf Basis des langjährigen mittleren Abflusses (MAM), sowie (d) bis (e) die jeweiligen Überschreitungen (EFR/Q), berechnet für jede Methode.

3.2 Environmental flow assessment

Four different methods were applied for an integrated EFA in the post-mining impacted Geisel catchment (Fig. 6. The contained data can be queried from the author.). The minimum EFR based on mean baseflow indices are regularly achieved under current hydrological conditions. Due to the applied method and the strong recession of discharge rates at the gauge Frankleben in the considered time period, basic and optimum EFR are only achievable under severe adaptions in the hydrological system (Fig. 6a). The 7Q10 basic EFR are similar to the basic EFR based on mean baseflow indices, the TM basic EFR are slightly lower (Fig. 6, Table 2). Nevertheless, seasonal fluctuations are calculated, which are due to seasonal discharge fluctuations. However, the winter EFR are below the minimum EFR based on mean baseflow indices, so TM basic EFR are not used for further considerations. The TM optimum EFR of 0.2286 m³/s are lower than the optimum EFR based on mean baseflow indices but are also unattainable under current hydrological conditions. These EFR required for optimal aquatic life habitats, in conjunction with the EFR determined in the recultivation plan for the Geisel catchment, indicate the need for adaption strategies. These needs are confirmed by the calculation of exceedance rates (EFR/Q) of determined EFR over the actual mean monthly discharge (Fig. 6d and 6e). Due to a strong increase of the number of months in which the threshold EFR/discharge> 1is exceeded – for both basic and optimum EFR – and the discharge rates required for maintaining habitats were reached exceptionally in recent years, different environmental management classes were tested using the flow duration curve shifting method. A clear convergence of individual environmental management classes toward lower EFR is calculated (Fig. 7). The monthly regionalized baseflow rates are located between scenario A (natural conditions) and B (slightly modified conditions). Interpreting baseflow as minimum EFR thus indicates that current hydrological conditions would not require severe strong adjustments to meet natural hydrological conditions. Variations are evident between (a) the calculated EFR and the regionalized baseflow rates and (b) the calculated EFR according to scenario A and B. While the baseflow rates at the beginning of the investigated time period are well below the EFR of scenario A, both hydrographs converge toward current hydrological conditions. Contrarily, the baseflow rates are initially at a fairly similar level to the EFR of scenario B but are significantly lower towards the end of the investigated time period. These long-term variations indicate the inclusion of decayed impacts on the hydrological regime in the EFR calculation. Although mining activities had ended before Jul 1993, anthropogenic impacts on the hydrological regime are still present, e.g. post-mining recultivation strategies, the refilling of the abandoned open pit and discharge regulation of the lower Geisel since May 2011.

Nevertheless, an EFR calculation does not aim at a general hydrological analysis. Rather, it intends to highlight catchment and landscape specific features of the hydrological regime, which are used for EFR determination. These characteristics are sufficiently illustrated by the calculated EFR. Furthermore, a comparison with long-term regionalized baseflow rates indicates that typical catchment characteristics are considered during hydrological regionalization. Current hydrological conditions (May 2011 to Dec 2017) serve as a guideline for designing adaption strategies. Furthermore, previous (i.e. quasi-natural) hydrological conditions need to be integrated in order to justify the designed adaption strategies. The hydrological regime´s quasi-natural conditions in the Geisel catchment were considered (a) by the inherent approach of the flow duration curve shifting method considering six different environmental management classes, and (b) by the analysis of the time series from Jul 1993 to Dec 2017. Accordingly, the current discharge rates are almost equal to scenario C EFR during summer (moderately modified conditions, mean discharge in summer = 0.1626 m³/s, $EFR_{C,\ summer}$ = 0.1623 m³/s), and almost equal to scenario D EFR during winter (largely modified conditions, mean discharge in winter = 0.1315 m³/s, $EFR_{D,\ winter}$ = 0.1309 m³/s, cp. Table 2), respectively.

Table 2 Mean seasonal EFR calculated with four methods for the post-mining era (Jul 1993 to Dec 2017) in the Geisel catchment.

Tab. 2 Mittlere saisonale Mengen des ökologisch notwendigen Mindestabflusses im Geisel-Einzugsgebiet, berechnet mit vier Methoden für den nachbergbauliche Zeitabschnitt (Jul 1993 to Dez 2017).

Method	**Calculated EFR**	**EFR values – Summer (March to September) [m³/s]**	**EFR values – Winter (October to February) [m³/s]**
BFI_{mean} method	Minimum EFR	0.123	0.099
	Basic EFR	0.188	0.178
	Optimum EFR	0.269	0.256
7Q10 method	Basic EFR	0.1896	0.1752
TM method	Basic EFR	0.1524	0.0762
	Optimum EFR	0.2286	0.2286
FDCS method	Scenario A (natural)	0.2238	0.2194
	Scenario B (slightly modified)	0.1903	0.1828
	Scenario C (moderately modified)	0.1623	0.1546
	Scenario D (largely modified)	0.1367	0.1309
	Scenario E (seriously modified)	0.1129	0.1107
	Scenario F (critically modified)	0.0915	0.0917

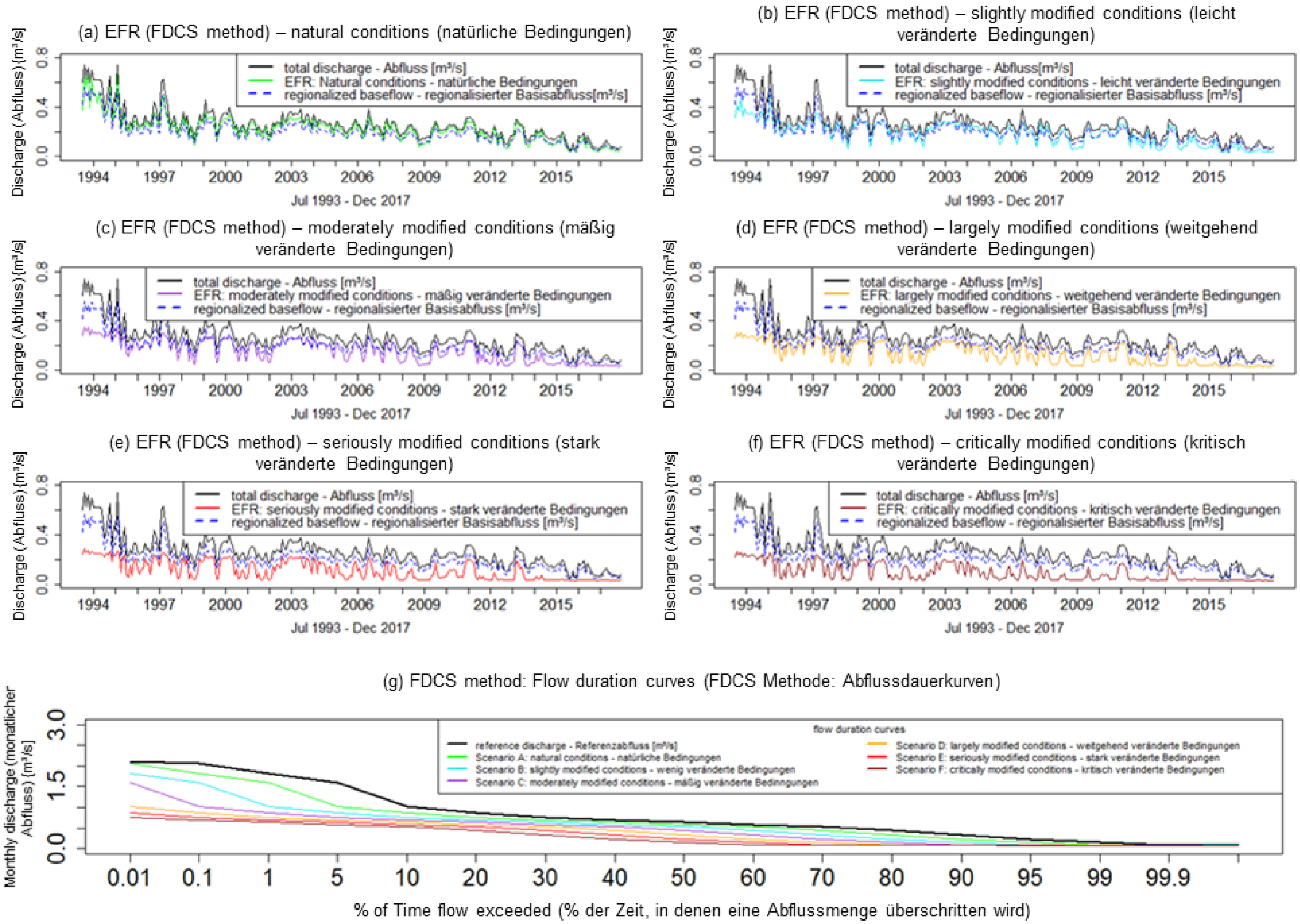

(a) EFR (FDCS method) – natural conditions (natürliche Bedingungen)
total discharge - Abfluss [m³/s]
EFR: Natural conditions - natürliche Bedingungen
regionalized baseflow - regionalisierter Basisabfluss[m³/s]
(b) EFR (FDCS method) – slightly modified conditions (leicht veränderte Bedingungen)
total discharge - Abfluss[m³/s]
EFR: slightly modified conditions - leicht veränderte Bedingungen
regionalized baseflow - regionalisierter Basisabfluss [m³/s]
(c) EFR (FDCS method) – moderately modified conditions (mäßig veränderte Bedingungen)
total discharge - Abfluss [m³/s]
EFR: moderately modified conditions - mäßig veränderte Bedingungen
regionalized baseflow - regionalisierter Basisabfluss [m³/s]
(d) EFR (FDCS method) – largely modified conditions (weitgehend veränderte Bedingungen)
total discharge - Abfluss [m³/s]
EFR: largely modified conditions - weitgehend veränderte Bedingungen
regionalized baseflow - regionalisierter Basisabfluss [m³/s]
(e) EFR (FDCS method) – seriously modified conditions (stark veränderte Bedingungen)
total discharge - Abfluss [m³/s]
EFR: seriously modified conditions - stark veränderte Bedingungen
regionalized baseflow - regionalisierter Basisabfluss [m³/s]
(f) EFR (FDCS method) – critically modified conditions (kritisch veränderte Bedingungen)
total discharge - Abfluss [m³/s]
EFR: critically modified conditions - kritisch veränderte Bedingungen
regionalized baseflow - regionalisierter Basisabfluss [m³/s]
Discharge (Abfluss) [m³/s]
0.0
0.4
0.8
1994
1997
2000
2003
2006
2009
2012
2015
Jul 1993 - Dec 2017
(g) FDCS method: Flow duration curves (FDCS Methode: Abflussdauerkurven)
flow duration curves
reference discharge - Referenzabfluss [m³/s]
Scenario A: natural conditions - natürliche Bedingungen
Scenario B: slightly modified conditions - wenig veränderte Bedingungen
Scenario C: moderately modified conditions - mäßig veränderte Bedingungen
Scenario D: largely modified conditions - weitgehend veränderte Bedingungen
Scenario E: seriously modified conditions - stark veränderte Bedingungen
Scenario F: critically modified conditions - kritisch veränderte Bedingungen
Monthly discharge (monatlicher Abfluss) [m³/s]
0.0
1.5
3.0
0.01
0.1
1
5
10
20
30
40
50
60
70
80
90
95
99
99.9
% of Time flow exceeded (% der Zeit, in denen eine Abflussmenge überschritten wird)

Fig. 7 Monthly EFR (FDCS method) for the time period from Jul 1993 to Dec 2017 (post-mining era) at the gauge Frankleben calculated by the FDCS method. (a) Natural conditions (84.1 % of Q_{mean}); (b) slightly modified conditions (71.0 % of Q_{mean}); (c) moderately modified conditions (60.3 % of Q_{mean}); (d) largely modified conditions (50.9 % of Q_{mean}); (e) seriously modified conditions (42.4 % of Q_{mean}); (f) critically modified conditions (34.7 % of Q_{mean}). (g) FDC for different EMC.

Abb. 7 Monatliche ökologisch notwendige Mindestwassermengen (FDCS-Methode) für den Zeitraum von Jul 1993 bis Dez 2017 (Nachbergbauzeit) am Pegel Frankleben, berechnet nach der FDCS-Methode. (a) Natürliche Bedingungen (84,1% des mittleren Abflusses); (b) leicht veränderte Bedingungen (71,0% des mittleren Abflusses); (c) mäßig veränderte Bedingungen (60,3% des mittleren Abflusses); (d) weitgehend veränderte Bedingungen (50,9% des mittleren Abflusses); (e) stark veränderte Bedingungen (42,4% des mittleren Abflusses); (f) kritisch veränderte Bedingungen (34,7% des mittleren Abflusses). (g) FDC für verschiedene EMC.

Comparing calculated flow duration curves at the gauge Frankleben (Fig. 7g, and Table A5 for flow duration curve data) with flow duration curves at quasi-natural gauges in Central Germany (The data can be queried from the author) supports the consideration of including catchment characteristics into EFR calculation. The flow duration curves at the gauge Frankleben are clearly flatter. Events with above-average discharge occur with a probability of max. 10%. At other gauges, these thresholds are already at 0.1% (Stedten), 0.01% (Unterrißdorf), and 1% (Zappendorf), respectively. The deviations at the gauge Frankleben are due to the disturbed hydrological conditions and discharge regulation compared to natural hydrological conditions in Central Germany (i.e. a strong dependence on discharge events and the occurrence of perennial flood events). Additionally, the mid-range flow duration curves of different environmental management classes (% time flow exceeded between 30% and 90%) at the gauge Frankleben are widely spaced compared to other gauges. These flow duration curve parts at the gauge Frankleben are due to smoothed discharge rates as a consequence of controlling the runoff volume of the lower Geisel under current hydrological conditions. With a probability of 0.01%, a mean monthly discharge of 2.2 m³/s is exceeded (cp. Fig. 7g). Those exceedings are significantly higher at other gauges, partly due to a larger drainage area and thus naturally higher discharge volumes (e.g. gauge Zappendorf). Natural hydrological conditions (event dependence) lead to higher discharge rates at the beginning of the flow duration curve (cp. Fig. A3).

4 Discussion

4.1 Design of hydrograph separation and application in non-natural catchments

Although critically discussed, hydrograph separation algorithms belong to the most frequently used methods in applied hydrology. The most critical issue concerns the assumption of a twofold separation (i.e. the location of an “artificial border”) of flows in hydrological systems where there are likely multiple water stores (Cartwright et al. 2014, Duncan 2019). The applied methods differ in their properties and characteristics as well as in their physical justification (Tallaksen 1995, Duncan 2019). The interpretation of the slower component is implemented through a different parameterization level (Pelletier & Andréassian 2020).

Unfortunately, external factors (e.g. hydrogeological structures (Wang et al. 2020), a varying groundwater level (TANG et al. 2015), long P events, or snowmelt (VON FREYBERG et al. 2018), which may affect the flow variability, are generally disregarded during hydrograph separation. Thus, the "not-too-delayed" part of the hydrograph may be incorrectly assigned to certain discharge components. Some autoregressive models try to implement a higher physical foundation of the filter parameters by including catchment characteristics (FUREY & GUPTA 2001, ECKHARDT 2005). First attempts postulate an integrated approach based on Horton´s infiltration capacity curve and a numerical solution of the Boussinesq equation (LIN et al. 2007), or a combination of an exponential master recession curve with the classical Lyne and Hollick recursive digital filter (CARLOTTO & CHAFFE 2019). Other approaches focus on connecting hydrograph separation with retention properties (WITTENBERG & SIVAPALAN 1999). Recursive digital filters already consider these retention characteristics of subsurface filter areas with the recursive design of the algorithms (ECKHARDT 2005, ECKHARDT 2008). Nevertheless, the subjective calculation of this retention based on a few parameters seems to be obvious as it is the essential prerequisite for the separation.

Generally, undisturbed discharge rates are required for every hydrograph separation, which are usually not available in anthropogenically impacted catchments. Many algorithms assume that the hydrological system responds in a relatively natural way to rainfall, runoff, and groundwater flows (TALLAKSEN 1995, ECKHARDT 2005). Multiple factors of anthropogenic impacts, streamflow regulations, and their impacts on hydrological data are generally disregarded (DUNCAN 2019, PELLETIER & ANDRÉASSIAN 2020). Approaches based on hydrological signatures (SU et al. 2016), (geochemical) tracer-based separation methods (PENNA & VAN MEERVELD 2019), or artificial neural networks (TAORMINA et al. 2015) may be possible solutions. Although the time lag of different flow components is measurable (KIRCHNER 2019), e.g. by tracer experiments, these methods still disregard past anthropogenic disturbances and therefore do not contribute to a better understanding of natural hydrological processes in mining-impacted catchments (JUNG & LEE 2020). Rather, algorithms must be developed that use natural catchment characteristics (e.g. pedological, geological information, or areal precipitation amounts) and their strong heterogeneity and consider anthropogenic impacts to attempt a flow component estimation in non-natural catchments. The non-suitability of hydrograph separation for non-natural catchments has been demonstrated by using the example of the strongly mining-impacted Geisel catchment in Central Germany. It is evident that anthropogenic impacts on the hydrological regime (i.e. the hydrograph) also show up on the baseflow hydrograph due to (a) the conceptual design of hydrograph separation methods, (b) the usage of measured (disturbed) discharge rates as the most important input parameter, and (c) the disregard of specific catchment characteristics.

4.2 Baseflow index and hydrological regionalization

Consequently, questions arise on (a) how to enable a comprehensive analysis of diverse (non-natural and quasi-natural) catchment with similar external characteristics, and (b) how to estimate validated baseflow rates for anthropogenically impacted catchments. We proposed a new simple hydrological regionalization approach based on mean monthly baseflow indices, 64 physical catchment descriptors and single linear regression models.

The baseflow index as a universally applied parameter for normalizing baseflow and discharge rates (SMAKHTIN 2001b) generally enables a comparability between different catchments (CARILLO et al.

2011). The suitability of baseflow indices for hydrological regionalization has been proven by multiple applications (ZHANG et al. 2020). Monthly baseflow indices were used, since daily values strongly scattered over a large interval. The interval, in which baseflow indices are scattering, must become increasingly smaller as soon as monthly or annual values are calculated, since averaging can be interpreted as a form of low-pass filtering (ECKHARDT 2005). Analyzing monthly baseflow indices is most suitable due to smoothing (i.e. low-pass filtering) and mitigation of event-based baseflow rates while maintaining typical seasonal characteristics and fluctuations.

Since different baseflow indicesare estimated with each hydrograph separation algorithm, it is unclear, which or how many hydrograph separation methods need to be applied in order to enable a valid estimation of baseflow even in natural catchments (DUNCAN 2019, PELLETIER & ANDRÉASSIAN 2020). This problem cannot be solved conclusively, since each method estimates baseflow rates based on a different interpretation of the separated discharge component (GUSTARD et al. 1992, ECKHARDT 2008). A validation, especially of longer time periods, e.g. with tracer methods, is usually not possible. Nevertheless, the baseflow indices at the gauge Frankleben indicate how strong external influences affect the variability of baseflow rates, irrespective of whether strong conceptual algorithms or physically-based models are used. In this study, the estimated baseflow indices of all applied hydrograph separation methods were averaged. The mean baseflow index is interpreted as a valid estimation of low-flow conditions. The fact that the average and the median are nearly equal (Fig. 4c) justifies this decision. Nevertheless, the mean baseflow index may disguise variations between different estimations, which are considered as effects of an inherent conceptualization of hydrograph separation methods. For example, the local minimum method with a moderate block size or the Eckhardt-filter with a high maximum baseflow index conceives that the stream may be baseflow dominated every few days or weeks between the high flow events (SLOTO & CROUSE 1996, ECKHARDT 2008). Contrarily, the chemical mass balance method (MILLER et al. 2015), a larger block size in the sliding interval method (STOELZLE et al. 2020), or a smaller maximum baseflow index conceives that the stream is rarely dominated by baseflow. In those cases, both baseflow and the frequency of "baseflow-dominated periods" are different. We assume that averaging the results of different methodological hydrograph separation approaches “averages” their differences, especially regarding the physical justification, and thus enables an acceptable estimation of baseflow rates.

For hydrological regionalization, all three known approaches were considered in this study: Proximity is ensured by using nearby catchments with similar conditions; hydrological regionalization itself is carried out with single linear regression models; physical comparability is achieved by applying physical catchment descriptors as independent variables. Although it is frequently suggested in numerous studies (ABDULLA & LETTENMAIER 1997, ZHANG et al. 2018b), we refused using multiple regression analyses, since our tests lead to questionable results. Nash-Sutcliffe-Efficiency was exceptionally low and fluctuated in a small range. The respective baseflow indices would therefore be predicted with similar accuracy by all physical catchment descriptors. Due to the inherent variability of different physical catchment descriptors, such small variations are unusual. Similar results were published elsewhere (SEFTON & HOWARTH 1998), suggesting principal component analyses and stepwise regression for deriving statistical relationships and using multiple regressions only for finishing hydrological regionalization, when all criteria for a good relationship are considered. Furthermore, small fluctuations in Nash-Sutcliffe-efficiency are due to interrelationships between individual model parameters, explained by the similarity of individual physical catchment descriptors (OUDIN et al. 2010). We assume that the influence of different physical catchment descriptors on the baseflow rates fluctuates more than calculated with multiple linear regression models. Hydrological regionalization applied to the gauge Frankleben resulted in a reduction of the baseflow amplitude. Furthermore, the regionalized baseflow index remains nearly constant during different time periods. The strong increase of baseflow indices estimated by hydrograph separation methods was not detected at other quasi-natural gauges. This gradient was reduced by hydrological regionalization and thus adapted to more typical conditions in quasi-natural catchments in Central Germany. A slightly positive slope of the baseflow index is plausible due to climatic changes and the observed decrease in total discharge. Other hydrological regionalization approaches use e.g. artificial neural networks (HEUVELMANS et al. 2006, SHU & OUARDA 2008), transfer functions (GÖTZINGER & BÁRDOSSY 2007), or procedures based on scaling relationships (CROKE et al. 2004). More precise results could be obtained by complex methods, but the proposed approach illustrate that simple methods provide reliable results on temporally higher scales. Further research in hydrological regionalization, e.g. case studies in heterogeneous catchments, is required to find a balance between complexity, simplicity in use, and accuracy of results.

4.3 Environmental flow assessment

An integrated EFA for River Geisel is carried out based on the regionalized mean baseflow index. Minimum, basic, and optimum EFR were calculated based on mean discharge at the gauge Frankleben of a specific time period and the seasonal regionalized mean baseflow index. We assume an equation of baseflow and EFR due to the basic definition of baseflow as low-flow discharge (GUSTARD et al. 1992, SMAKHTIN 2001b) and the definition of EFR as that discharge rate, which has to remain in a streamflow even in long drought periods (THARME 2003, DAI et al. 2010, ACREMAN 2016). Furthermore, relating mean baseflow indices with mean discharge rates of different time periods enables considering different anthropogenic impacts in the Geisel catchment. Mean baseflow indices were used instead of the directly estimated baseflow rates. Due to the normalizing character of the baseflow index natural low-flow conditions should emerge (INSTITUTE OF HYDROLOGY 1980), which are required for an integrated EFA (PASTOR et al. 2014, ARTHINGTON et al. 2018). The EFA was carried out on a seasonal scale following the EFR determined in the recultivation plan for the lower Geisel (REGIERUNGSPRÄSIDIUM HALLE (SAALE) 2003). A seasonal EFR determination is common practice (ARTHINGTON et al. 2006), due to hydrological variability shaping the biophysical streamflow attributes and functioning (KENNARD et al. 2010). Furthermore, higher $\text{EFR}_{\text{Summer}}$ are appropriate (ABDULLAH & JAIN 2020) due to higher environmental risks during summer (POFF et al. 2010, LATU et al. 2014).

Minimum EFR were defined as seasonal low-flow rates of the time period from May 2011 to Dec 2017 (current hydrological conditions). Basic EFR were defined as seasonal low-flow rates of the time period from Jul 2003 to Apr 2011. In this period, discharge amounts were slightly higher. Since basic EFR are generally interpreted as discharge rates required to ensure nearly optimal habitat conditions (TENNANT 1976, THARME 2003), the consideration of slightly higher discharge rates for EFR determination seems suitable. Optimum EFR were defined as seasonal low-flow rates of the time period from Jul 1993 to Jun 2003, where no major anthropogenic impacts on the hydrological regime are known. Therefore, we assume nearly natural hydrological conditions, which are required for optimum EFR determination (THARME 2003, HE et al. 2020). Since our proposed baseflow index based method includes specific catchment characteristics (i.e. anthropogenic impacts), the results are only valid for this catchment.

For validation and the delineation of adaption strategies for the lower Geisel, three widely tested hydrological EFA models were applied: the 7Q10 method (THARME 2003), the TM method (TENNANT 1976), and the flow duration curve shifting method (SMAKHTIN & ANPUTHAS 2006). These three EFA methods have been critically discussed recently (SHARMA & DUTTA 2020), concluding that they are not suitable for highly variable hydrological regimes, since variable flow is a major factor in maintaining ecological streamflow functions (POFF et al. 1997). In hydrological regimes, where an EFA based on two flow-periods (e.g. high flow dominated during winter, and low-flow dominated during summer) is sufficient, and no intra-seasonal flow variability occurs, EFR calculated with simple hydrological methods seem suitable (ACREMAN 2016, THEODOROPOULOS et al. 2019, SHARMA & DUTTA 2020). Furthermore, the applicability of simple hydrological EFA methods to characteristic seasonal flow regimes have been proven (ABDI & YASI 2015, KARIMI et al. 2021). However, their valid application to non-natural or regulated rivers is still discussed (RICHTER 2010, LIU et al. 2011), due to the inherent consideration of natural flow regimes, especially in the TM and flow duration curve shifting methods. Possible solutions deal with (a) incorporating thermal regimes (OLDEN & NAIMAN 2010), (b) calculating flow event variabilities (STEWARDSON & GIPPEL 2003, ZHANG et al. 2012), (c) using complex models (e.g. diffusivity models (BOUFFARD & BOEGMAN 2013), 2D habitat models (THEODOROPOULOS et al. 2018), or multiscale modelling (ALCAZAR & PALAU 2010)), or (d) disregarding special flow regime conditions and thus considering measured streamflow data only (LIU et al. 2011). Our results have shown that index-based methods (7Q10 and TM method) require more natural flow regimes and minor intra-seasonal flow variabilities. A strong decrease in discharge rates over the investigated time period (as found at the gauge Frankleben) may lead to too high EFR for current hydrological conditions. Otherwise, the flow duration curve shifting method calculates acceptable results for the impacted Geisel catchment. Analyzing the determined flow duration curves reveals differences to quasi-natural catchments and enables interpreting flow duration curve characteristics as consequences of anthropogenic disturbances on local water regime.

4.4 Uncertainties and reliability

The presented methodology for estimating baseflow rates and determining EFR is liable to an inherent uncertainty. This mainly concerns the application of conceptual hydrograph separation algorithms for a physically-based phenomenon, i.e. the estimation of baseflow rates. Moreover, hydrograph separation algorithms are not suitable for non-natural catchments. Nevertheless, we used hydrograph separation methods for baseflow estimation in a strongly mining-impacted catchment. Thus, a large uncertainty must be assumed in the estimated baseflow rates, especially regarding the further use for EFA methods. But a holistic uncertainty analysis of the estimated long-term baseflow rates in the Geisel catchment is largely impossible since non-disturbed total discharge rates would be required. An option would be the verification of estimated baseflow rates using tracer measurements. However, these are expensive and time consuming and thus unsuitable for long-term analyses, which in turn are required for an integrated EFA. Furthermore, as long as an accurate description of spatially distributed properties of hydrogeological conditions, and under consideration of local heterogeneities, is not possible, a physically-based analyse of specific discharge components and the processes of runoff generation and formation remains an ideal.

Nevertheless, the application of hydrological regionalization methods using several physical catchment descriptors and the applied methods for determining environmental flow rates allow some drawbacks on the validity of the estimated baseflow rates. First, hydrological regionalization led to a normalization of the estimated baseflow rates and indices at the gauge Frankleben. Similar results were obtained from other, quasi-natural catchments in Central Germany. Second, the similarity between the EFR determined with different, both conceptual statistical methods and more complex hydrological procedures, shows that the proposed approach may provide reliable results even in disturbed catchments. These drawbacks were confirmed by comparative analyses with other, non-disturbed catchments.

Table 3 Mean seasonal additional Q rates required to achieve specific EFR at the gauge Frankleben calculated based on regionalized BFI values, by the 7Q10 method, the TM method, and the FDCS method. The additional Q rates are based on mean seasonal Q rates ($Q_{meanSummer}$ = 0.163 m³/s; $Q_{meanWinter}$ = 0.132 m³/s) for the time period from May 2011 to Dec 2017 (current hydrological conditions).

Tab. 3 Mittlere saisonale Mengen des zusätzlich erforderlichen Abflusses, welche zur Erreichung und Sicherstellung spezifischer ökologisch notwendiger Mindestwassermengen am Pegel Frankleben erforderlich sind. Die Berechnungen basieren auf regionalisierten Basisabflussindices und wurden mit der 7Q10-Methode, der TM-Methode und der FDCS-Methode durchgeführt. Die zusätzlich erforderlichen Abflussmengen basieren auf mittleren saisonalen Abflussmengen ($Q_{meanSommer}$ = 0,163 m³/s; $Q_{meanWinter}$ = 0,132 m³/s) des Zeitabschnitts von Mai 2011 bis Dez 2017 (aktuelle hydrologische Bedingungen).

Method	**Calculated EFR**	**Additional Q rates – Summer (March to September) [m³/s]**	**Additional Q rates – Winter (October to February) [m³/s]**
BFI_{mean} method	Minimum EFR	-0.04	-0.033
	Basic EFR	0.025	0.046
	Optimum EFR	0.106	0.124
7Q10 method	Basic EFR	0.0266	0.0432
TM method	Basic EFR	-0.0106	-0.0558
	Optimum EFR	0.0656	0.0966
FDCS method	Scenario A (natural)	0.0608	0.0874
	Scenario B (slightly modified)	0.0273	0.0508
	Scenario C (moderately modified)	-0.0007	0.0226
	Scenario D (largely modified)	-0.0263	-0.0011
	Scenario E (seriously modified)	-0.0501	-0.0213
	Scenario F (critically modified)	-0.0715	-0.0403

4.5 Water management adaption strategies for the Geisel catchment

Based on the various EFR, we derived required additional discharge amounts to improve the current hydrological situation of the lower Geisel, and to provide the required flow rates to ensure ecological stream functions. These considerations are based on mean seasonal discharge rates at the gauge

Frankleben (mean discharge in summer equals 0.1626 m^3/s; mean discharge in winter equals 0.1315 m^3/s). The differences to the respective calculated EFR show flow quantities required under current hydrological conditions. Through the inherent consideration of past time periods into EFR calculation, quasi-natural hydrological conditions are regarded. The minimum EFR based on baseflow indices are attained during summer as well as during winter (Table 3). The basic EFR based on baseflow indices as well as the optimum EFR need additional water supply to be attained. The results of the flow duration curve shifting method enable possibilities for defining an additional discharge amount required to achieve a specific environmental management class. Additional water supplies of 0.0608 m^3/s during summer and 0.0874 m^3/s during winter, respectively, are required to achieve optimal hydrological conditions in the lower Geisel (Table 3).

5 Conclusions

In this study, we investigated the estimation of low-flow rates for an anthropogenic impacted catchment in Central Germany, their use for an integrated EFA, and the delineation of adaption strategies for improving hydrological conditions in a post-mining flow regime. The conceptual design of most hydrograph separation algorithms prevents the estimation of validated baseflow rates for non-natural catchments. This calls for new adapted 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.

By combining 14 different hydrograph separation methods with a simple hydrological regionalization approach based on single linear regression analyses and 64 physical catchment descriptors, validated long-term baseflow rates were estimated for the lower Geisel. We have shown that the baseflow hydrograph strongly correlates to the total discharge hydrograph and therefore to any hydrological impact. In the case of the Geisel catchment, the calculated baseflow rates do not correspond to "quasi-natural" baseflow conditions found in similar catchments. Using a simple hydrological regionalization approach, questionable baseflow rates could be adjusted, as long as mining-independent catchment characteristics are used. However, an in-depth analysis of differences and similarities between different hydrograph separation procedures has not been carried out since natural influences on baseflow formation are unknown for our study site due to various external impacts on the hydrological regime. Therefore, we recommend a comprehensive statistical analysis of the differences in estimated baseflow rates, especially since (a) every hydrograph separation method has its own advantages and disadvantages in theoretical approach and definition of the lowest flow component, and (b) there might be strong differences in application to differently characterized catchments. Nevertheless, the proposed regionalization approach might be an appropriate alternative to complex, physically-based hydrological models, since acceptable Nash-Sutcliffe-efficiency values were calculated for estimating baseflow rates via hydrological regionalization. From 1981 to 2017, the mean baseflow equals 0.28 m^3/s with a discharge equal to 0.371 m^3/s (75.4%). In the post-mining era since 2011, discharge rates of River Geisel are significantly lower than the long-term averages. The mean baseflow equals 0.115 m^3/s with a discharge equal to 0.149 m^3/s. (77.2%).

Thus, the first long-term baseflow rates have been estimated 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 discharge quantities (e. g. by external flooding) are necessary. The first step to a broad water management analysis in the Geisel catchment was carried out by proposing a new EFA approach based on regionalized baseflow indices. This approach resulted in promising EFR, when compared to classical EFA methods. Especially, strong similarities between determined EFR, the results of the flow duration curve shifting method and different intensities of anthropogenic impacts (and following different environmental management classes) in the Geisel catchment were revealed. Analyzing EFR determined with the 7Q10 method, the TM method and the flow duration curve shifting method enabled the calculation of additional water supplies to the lower Geisel in order to meet minimum, basic, and optimum EFR, or to attain a specific management scenario. Additional discharge amounts of 0.0608 m^3/s during summer and 0.0874 m^3/s during winter were calculated from management scenario A (natural conditions). In-depth adjustments of the hydrological regime are required to ensure long-term optimal environmental flow rates. The question on how to provide additional water amounts has not been discussed, since far more than hydrological and ecological aspects (e.g. financial, water management, and tourism needs) need to be considered for a holistic recultivation of the Geisel catchment. Nevertheless, the proposed methods enable long-term low-flow analyses and integrated environmental flow assessments in anthropogenically impacted catchments, although different physical catchment characteristics are present.

The proposed methods and the results of this study may be transferred to other non-natural or data-scarce hydrological systems, considering the discussed inherent uncertainties. The overall aim of this study – to present easy-to-use and reliable methods of an integrated EFA based on baseflow rates in non-natural catchments – was achieved using a variety of approaches. Fundamental validity of the methods can only be enabled by long-term application and verification in other catchments.

6 Zusammenfassung

WENZEL, J. L., SCHMIDT, G., USMAN, M., CONRAD, C., VOLK, M.: Langfristige Abschätzung des Basisabflusses und Bewertung des ökologisch notwendigen Mindestabflusses in einem bergbaulich beeinflussten Einzugsgebiet in Mitteldeutschland. - Hercynia N. F. 54/2 (2021): 103 – 143.

Durch jahrhundertelange bergbauliche Aktivität im natürlichen Einzugsgebiet der Geisel in Mitteldeutschland sind das lokale und regionale Wasserregime sowie die hydrologischen Verhältnisse stark beeinträchtigt. Eine ganzheitliche ökologische Bewertung der hydrologischen Verhältnisse im Einzugsgebiet sowie insbesondere im Bereich der unteren Geisel wird durch fehlende Kenntnisse über Niedrigwasserverhältnisse erschwert. Daraus folgt, dass die angestrebten ökologisch notwendigen Mindestwassermengen der unteren Geisel in der Regel nicht erreicht werden können. Als hydrologisch basierten Ansatz zur Verbesserung der Niedrigwassersituation sowie zur integrierten Analyse ökologisch notwendiger Mindestwassermengen in anthropogen beeinflussten Einzugsgebieten und Regionen mit geringer Datenverfügbarkeit, stellen wir eine neuartige Methode vor, die langfristige Basisabflussraten als Grundlage für ökologisch notwendige Mindestwassermengen ansieht und einfache hydrologische Methoden zur integrierten Bewertung verwendet. Da Basisabflussraten aufgrund der

Nutzung konzeptioneller hydrologischer Methoden zur Beschreibung physikalisch-basierter Prozesse in anthropogen beeinflussten und nicht-natürlichen hydrologischen Systemen nicht genau geschätzt werden können, werden 14 verschiedene Methoden zur abflussganglinien- und signaturbasierten Separation des Basis- vom Gesamtabfluss, Methoden der statistischen Regionalisierung sowie numerische Einzugsgebietsdeskriptoren verwendet.

Der mittlere langfristige Basisabfluss der Geisel beträgt im Zeitraum von 1981 bis 2017 0,28 m³/s (75,4% des Gesamtabflusses) und in der Zeit nach der bergbaulichen Beeinflussung seit 2011 etwa 0,115 m³/s (77,2% des Gesamtabflusses). Die Kombination von Methoden zur Ganglinienseparation mit Ansätzen zur hydrologischen Regionalisierung und numerischen Einzugsgebietsdeskriptoren zeigt neue Möglichkeiten zur Beschreibung von Abflusskomponenten in nicht-natürlichen Einzugsgebieten. Die ermittelten ökologisch notwendigen Mindestwassermengen sind vergleichbar mit denen anderer hydrologischer Methoden und können mit unterschiedlichen Intensitäten anthropogener Einflüsse in Verbindung gebracht werden.

Die ökologische Abflussbewertung ergibt zusätzlich erforderliche Wassermengen in der unteren Geisel von 0,0608 m³/s in Sommermonaten und 0,0874 m³/s in Wintermonaten zur Gewährleistung eines naturnahen Abflussregimes. Die Ansätze ermöglichen langfristige Niedrigwasseranalysen und ökologische Abflussbewertungen in bergbaulich beeinflussten Einzugsgebieten.

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Appendix

Fig. A1 Overview of study site characteristics, workflow, applied hydrological analyses and most important results: (1) different intensities of mining impacts cause different delay of slow discharge components. (2) low-flow rates may an important parameter for an integrated environmental flow assessment.

Abb. A1 Überblick über hydrologische Eigenschaften des Geisel-Einzugsgebiets, den Arbeitsablauf, die angewandten hydrologischen Analysen und die wichtigsten Ergebnisse: (1) Eine unterschiedliche Intensität der anthropogenen Beeinflussung verursacht eine unterschiedliche Verzögerung der langsamen Abflusskomponenten. (2) Niedrigwasserabflussraten sind ein essentieller Parameter für eine integrierte ökologische Abflussbewertung.

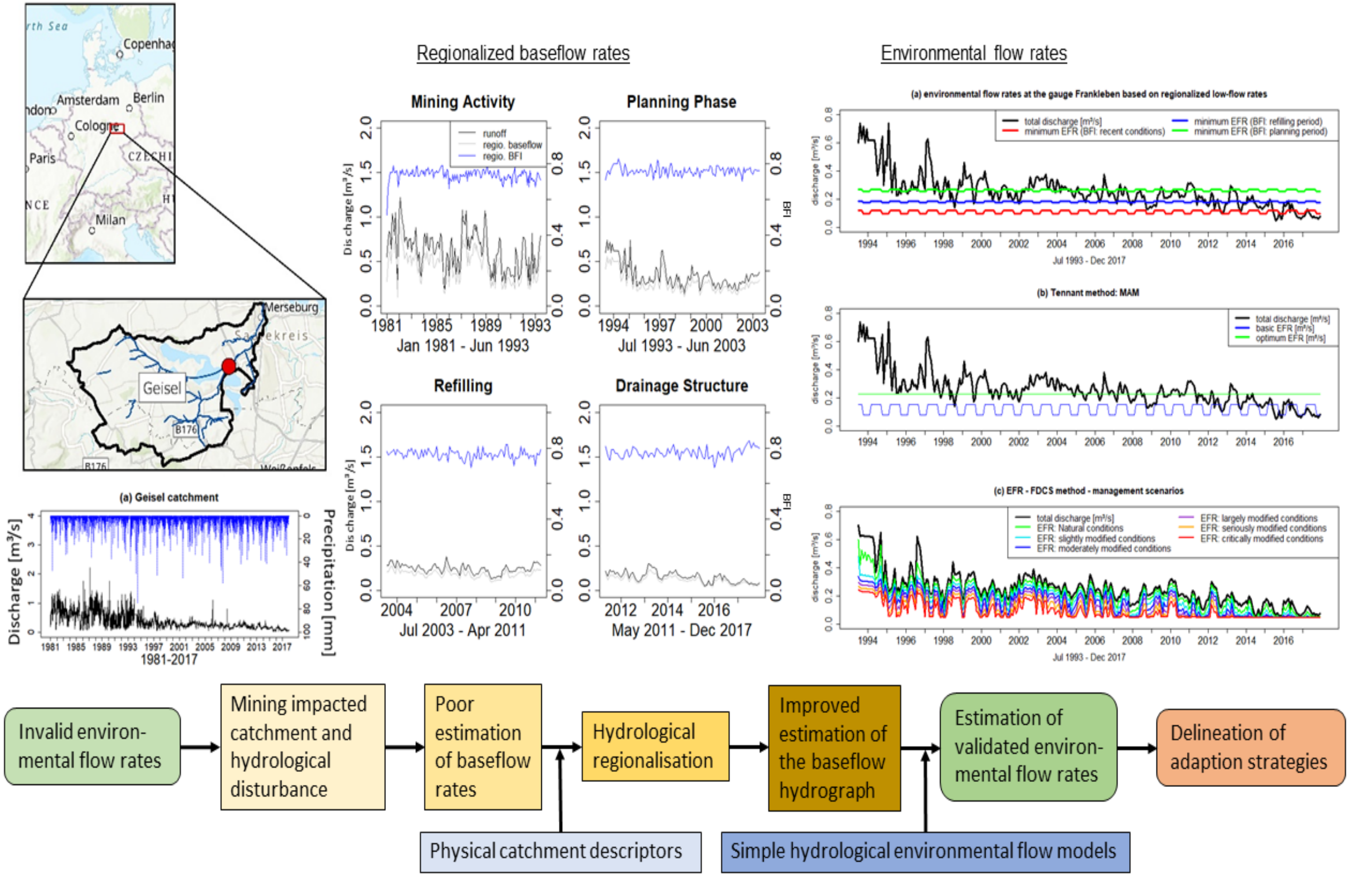
Regionalized baseflow rates
Environmental flow rates
North Sea
Copenhagen
Amsterdam
Berlin
London
Cologne
Paris
CZECHIA
FRANCE
Milan
Merseburg
Geisel
B176
(a) Geisel catchment
Discharge [m³/s]
Precipitation [mm]
1981-2017
Mining Activity
Planning Phase
Refilling
Drainage Structure
runoff
regio. baseflow
regio. BFI
Dis charge [m³/s]
BFI
Jan 1981 - Jun 1993
Jul 1993 - Jun 2003
Jul 2003 - Apr 2011
May 2011 - Dec 2017
(a) environmental flow rates at the gauge Frankleben based on regionalized low-flow rates
total discharge [m³/s]
minimum EFR (BFI: recent conditions)
minimum EFR (BFI: refilling period)
minimum EFR (BFI: planning period)
discharge [m³/s]
Jul 1993 - Dec 2017
(b) Tennant method: MAM
total discharge [m³/s]
basic EFR [m³/s]
optimum EFR [m³/s]
(c) EFR - FDCS method - management scenarios
total discharge [m³/s]
EFR: Natural conditions
EFR: slightly modified conditions
EFR: moderately modified conditions
EFR: largely modified conditions
EFR: seriously modified conditions
EFR: critically modified conditions
Invalid environ-mental flow rates
Mining impacted catchment and hydrological disturbance
Poor estimation of baseflow rates
Hydrological regionalisation
Improved estimation of the baseflow hydrograph
Estimation of validated environ-mental flow rates
Delineation of adaption strategies
Physical catchment descriptors
Simple hydrological environmental flow models

Table A1[123] Applied hydrograph separation methods, equation and parameterization, and conceptual interpretation of the delayed discharge components.

Tab. A1[123] Angewandte Ganglinienseparationsverfahren, Gleichungen und Parametrisierung sowie konzeptionelle Interpretation der verzögerten Abflusskomponenten.

Method	Equation / Approach	Parameterization	Delayedcomponent
FI	LM assigns Q_{MIN} in I = 2N to all days in I.	N = 0.827 x $A^{0.2}$; I = 5(Pettyjohn & Henning 1979; Sloto & Crouse 1996)	$Q_B + Q_I$
SI	SI finds Q_{MIN} in I = 0.5 x (2N – 1) days before and after the day being considered and assigns it to that day (Sloto & Crouse 1996)	N = 0.827 x $A^{0.2}$; I = 2 (Pettyjohn & Henning 1979; Sloto & Crouse 1996)	$Q_B + Q_I$
LM	LM checks each day if there is Q_{MIN} in I = 0.5 x (2N – 1) days before and after the day being considered. All LM are connected by linear interpolation	N = 0.827 x $A^{0.2}$; I = 2 (Pettyjohn & Henning 1979; Gustard et al. 1992; Sloto & Crouse 1996)	$Q_B + Q_I$
MoNQ	Q_B = MoNQ	MoNQ = monthly low-flow discharge(Wundt 1958)	$Q_B + Q_I$
MoMNQ	Q_B = MoMNQ	MoNQ = (long-term) mean monthly low-flow discharge(Kille 1970)	Q_B
6-MoMNQ	Q_B = 6-MoMNQ	6-MoMNQ = lowest mean value of the monthly averages of six continuous months(Bavarian State Office for Water Management 1996)	Q_B
BF	$Q_B(i) = \beta \text{ x } Q_B(i-1) + [(1 - \beta) / 2] \text{ x } (Q(i) - Q(i-1))$	β = 0.9; 0.925; 0.95(Nathan & McMahon 1990)	$Q_B + Q_I$
CA	$Q_B(i) = \beta \text{ x } Q_B(i-1) + [(1 - \beta) / 2] \text{ x } (Q_S(i) - Q_S(i-1))$	β = 0.9; 0.925; 0.95(Nathan & McMahon 1990; Chapman 1991)	Q_B
OP	$Q_B(i) = [k / (2 - k)] \text{ x } Q_B(i-1) + [(1 - k) / (2 - k] \text{ x } Q(i)$	k = 0.987(Chapman & Maxwell 1996)	Q_B
TP	$Q_B(i) = [k / (2 - C)] \text{ x } Q_B(i-1) + [C / (1 + C)] \text{ x } Q(i)$	k = 0.987; C = 0.195(Boughton 1993; Chapman & Maxwell 1996; Duki et al. 2017)	Q_B
IH	$Q_B(i) = [k / (2 - C)] \text{ x } Q_B(i-1) + [C / (1 + C)] \text{ x } Q(i) + \alpha \text{ x } Q(i-1)$	k = 0.987; C = 0.195; α = 0.001(Jakeman & Hornberger 1993; Rutledge 1998; Duki et al. 2017)	Q_B
ECK	$Q_B(i) = [(1 - B) \text{ x } K_B \text{ x } Q_B(i-1) + (1 - K_B) * B * Q(i)] / [1 - K_B * B]$	B = BFI_{max} = 0.8; K_B = 0.925 (Eckhardt 2005; Eckhardt 2008; Collischonn & Fan 2013)	Q_B
EWMA	$Q_B(i) = \alpha \text{ x } Q_D(i) + (1 - \alpha) \text{ x } Q_B(i-1)$	$0.003 <= \alpha <= 0.008$(Tularam & Ilahee 2008; Duki et al. 2017)	$Q_B + Q_I$
FG	$Q_B(i) = (1 - {}_x dt) \text{ x } Q_B(i-1) + {}_x dt(C_3 / C_1) \text{ x } [N(i-d_N-1) - Q(i-d_N-1)]$	$Q(i) = Q_B(i) + Q_S(i)$ $Q_B(i) = (1 - {}_x dt) \text{ x } Q_B(i-1) + {}_x dt(GWN(i-1))$	$Q_B + Q_I$

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[1] Statistical methods estimate baseflow on a monthly time scale.

[2] The parameterization is catchment specific and only valid for the Geisel catchment.

[3] Discharge components: Q = total discharge; Q_B = baseflow; Q_S = surface runoff; Q_I = interflow

	$Q_S(i) = C_1 \text{ x } N(i)$; $GWN(i+d_N) = C_3 \text{ x } N(i)$ $C_1 = 0.135$; $C_3 = 0.0691$; $N = 2.4$(FUREY & GUPTA 2001)

Table A2 Overview of the used physical catchment descriptors, each theoretical approach, and the results for each investigated catchment. Following groups of physical catchment descriptors were used: Land use and vegetation, mean discharge data, meteorological parameters, soil and geology, form indices, relief derivations, and recession parameters.

Tab. A2 Überblick über die verwendeten physikalischen Einzugsgebietsdeskriptoren, jeden theoretischen Ansatz und die Ergebnisse für jedes untersuchte Einzugsgebiet. Die folgenden Gruppen von physikalischen Einzugsgebietsdeskriptoren wurden verwendet: Landnutzung und Vegetation, mittlere Abflussdaten, meteorologische Parameter, Boden und Geologie, Formindizes, Reliefableitungen und Rezessionsparameter.

Theoretical approach		Frankleben	Allstedt	Friedeburg	Schkopau	Stedten	Unterrißdorf	Zappendorf
CORINE LandCover 2012. Intersect and extraktion in a local GIS		12.7	5.54	6.72	9.76	9.1	24.24	11.68
		5.86	14.86	0.93	1.91	14.03	19.58	8.78
		78.21	72.83	90.6	68.18	76.84	65.18	75.91
		6.04	2.19	2.76	2.43	3.65	7.31	4.19
		9.27	0	0	0	0.84	3.14	1.12
		5.86	14.7	0.93	1.91	12.88	17.99	8.05
		3.91	0.89	0.39	1.43	2.68	1.98	2.42
		0	0.16	0	0	1.15	1.59	0.73
German Weather Service. Intersect and extraktion in a local GIS		85.23	87.03	86.41	84.1	86.52	87.51	86.39
		308.28	307.91	308.04	308.33	308.03	307.86	308.02
		223.05	220.88	221.63	224.23	221.51	220.35	221.63
Gauge information and time series		31.109	41.532	31.166	22.286	48872	36.408	36.646
Hydrological yearbook	Lowest runoff ever measured	0	0.01	0.01	0.004	0.053	0.006	0.05
	Lowest runoff of the time series	0.036	0.01	0.01	0.004	0.053	0.006	0.14
	Average low flow volume	0.105	0.1	0.078	0.026	0.156	0.038	0.343
	Mean discharge	0.371	0.24	0.17	0.107	0.298	0.140	0.987
	Average high flow volume	1.17	0.54	4.45	0.751	5.22	3.42	3.8
	Highest runoff of the time series	4.95	3.47	13.3	1.4	21.2	8.9	7.56
	Highest runoff ever measured	8.6	3.47	20.3	1.4	21.2	8.9	7.56
	Lowest groundwater recharge of the time series	0.505	0.67	0.712	0.218	0.902	0.365	0.627
	Average groundwater recharge	1.855	2.01	1.55	0.897	1.724	1.379	1.80
	HIghest groundwater recharge of the time series	5.63	7.38	40.6	6.3	30.2	32.9	6.95
	Ratio of maximum to minimum discharge	0.007273	0.002882	0.000752	0.002857	0.0025	0.000674	0.018519
	Ratio of average low flow and high flow runoff	0.089744	0.185185	0.017529	0.034621	0.029885	0.111111	0.090263
German Weather Service. Intersect and extraktion in a local GIS		511.15	553.04	527.67	486.86	532.13	556.29	531.38
		615.51	595.49	607.11	621.83	604.16	596.04	606.26
		-104.36	-42.45	-79.44	-134.97	-72.03	-39.75	-74.88
		10.643	10.368	10.6	10.929	10.448	10.313	10.504
		67.432	66.974	66.284	66.947	67.068	66.721	66.829
		1633.64	1590.13	1609.96	1646.69	1604.54	1598.85	1610.76
		54.77	53.18	54.43	55.08	53.67	54.04	54.09
		222.98	216.78	218.07	225.11	218.77	216.8	219.14
		101.48	102.19	101.62	100.99	101.88	102.04	101.76
		60.29	62.32	60.92	59	61.49	62.35	61.24
Geological map (1:200.000)		83.96	53.67	78.86	59.56	57.11	87.54	59.59
German federal working group on water		208	129.5	110	119	173	104	547.0
		24.8	16.3	15.9	19.4	25.1	26.1	35.6
		93.1	56.3	55.1	54.1	93.6	71	145.4
Ci = p^2 / A [Dowling et al. 1998]		41.6712	24.4764	27.6001	24.595	50.6414	48.4712	386.493
Circ = ?(? x A) / P [Miller 1953]		0.3014	0.5131	0.4551	0.5107	0.248	0.2591	0.3250
Circ = 4A / P^2 [Griffith 1982]		0.096	0.1634	0.1449	0.1626	0.079	0.0825	0.1035
C = (4A x ?) / P^2 [Huggett & Cheesman 2002]		0.0058	0.0159	0.0165	0.0172	0.0057	0.01	0.0024
Comness = [?(?) x A] / P [Bosch 1978]		3.9589	4.0759	3.5376	3.8978	3.2752	2.5956	66.663
Ei = (? x a^2 x 0.5) / A [Stoddart 1965]		4.6424	3.2211	3.6083	4.9654	5.7174	10.2837	36.376
E = [?(A / P)] / a [Schumm 1956]		0.0603	0.093	0.0889	0.0764	0.0542	0.0464	0.0545
BasinE = a / [?(A / ?)] [Huggett & Cheesman 2002]		3.0471	2.5382	2.6864	3.1513	3.3815	4.5351	26.972
Comp = $?^2$ / (4A x ?) [Huggett & Cheesman 2002]		3.3178	1.9488	2.1975	1.9582	4.032	3.8592	30.772
Digital Elevation Model (5 m * 5 m)		158.41	203.16	172.41	135.25	190.97	203.77	179.84
		3.98	5.59	6.74	3.02	5.66	8.45	6.17
		0.56	0.74	0.89	0.43	0.77	1.13	0.83
German federal working group on water		84.75	100.99	61.22	41.8	106.79	122.39	311.27
Digital Elevation Model (5 m * 5 m)		81.12	121.4	67.67	80.78	76.07	77.34	29.62
		247.82	322.14	349.19	220.03	299.88	368.7	368.70
H = ELEVmax - ELEVmin [Huggett & Cheesman 2002]		166.7	200.74	281.52	139.25	223.81	291.36	339.08
Rho = H / P [Huggett & Cheesman 2002]		0.0018	0.0036	0.0051	0.0026	0.0024	0.0041	0.0023
Rh = H / L [Huggett & Cheesman 2002]		1.97	1.99	4.6	3.33	2.1	2.38	1.09
Dd = L / A [Gravelius 1914, Horton 1932, Huggett & Cheesman 2002]		0.41	0.78	0.56	0.35	0.62	1.18	0.57
S = H x Dd [Huggett & Cheesman 2002]		67.92	156.55	156.68	48.91	138.15	342.88	192.95
HypsInt = (ELEVmean - ELEVmin) / (ELEVmax - ELEVmin) [Huggett & Cheesman 2002]		0.46	0.41	0.37	0.39	0.51	0.43	0.44
TWI = ln(A / tanSl) [Beven & Kirkby 1979]		6.59	7.01	3.92	5.95	3.7	5.05	6.71
Kb = -ln(1 / TC) [Arnold et al. 1995]		4.69	4.93	4.97	4.85	4.91	5.06	4.64
TC = M / O [Nathan & McMahon 1990]		108.43	138.61	143.46	128.08	135.63	157.62	103.61
AFF = 100Q / P [Wundt 1953]		72.64	43.41	32.23	21.99	56.03	25.2	186.08

Table A3 Environmental management classes of the flow duration curve shifting method at the gauge Frankleben, respective management conditions, and applied percentages of natural mean annual discharge.

Tab. A3 Ökologische Bewirtschaftungsklassen der “flow duration curve shiftingMethode” am Pegel Frankleben, entsprechende Bewirtschaftungsbedingungen und angewandte Prozentsätze des natürlichen mittleren Jahresabflusses.

Scenario	**EMC**	**Management conditions**	**% of natural annual Q_{mean}**
A	Natural	pristine conditions or minor modifications	84.1
B	Slightly modified	largely intact biodiversity and habitats despite water resources development and/or basin modifications	71
C	Moderately modified	disturbed habitats and biota dynamics; ecosystem functions still intact; sensitive species are lost and/or reduced in extent; alien species present	60.3
D	Largely modified	large changes in natural habitat, biota and basic ecosystem functions have occurred; clearly lower than expected species richness	50.9
E	Seriously modified	habitat diversity and availability have declined; a strikingly lower than expected species richness; only tolerant species remain	42.4
F	Critically modified	modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota	34.7

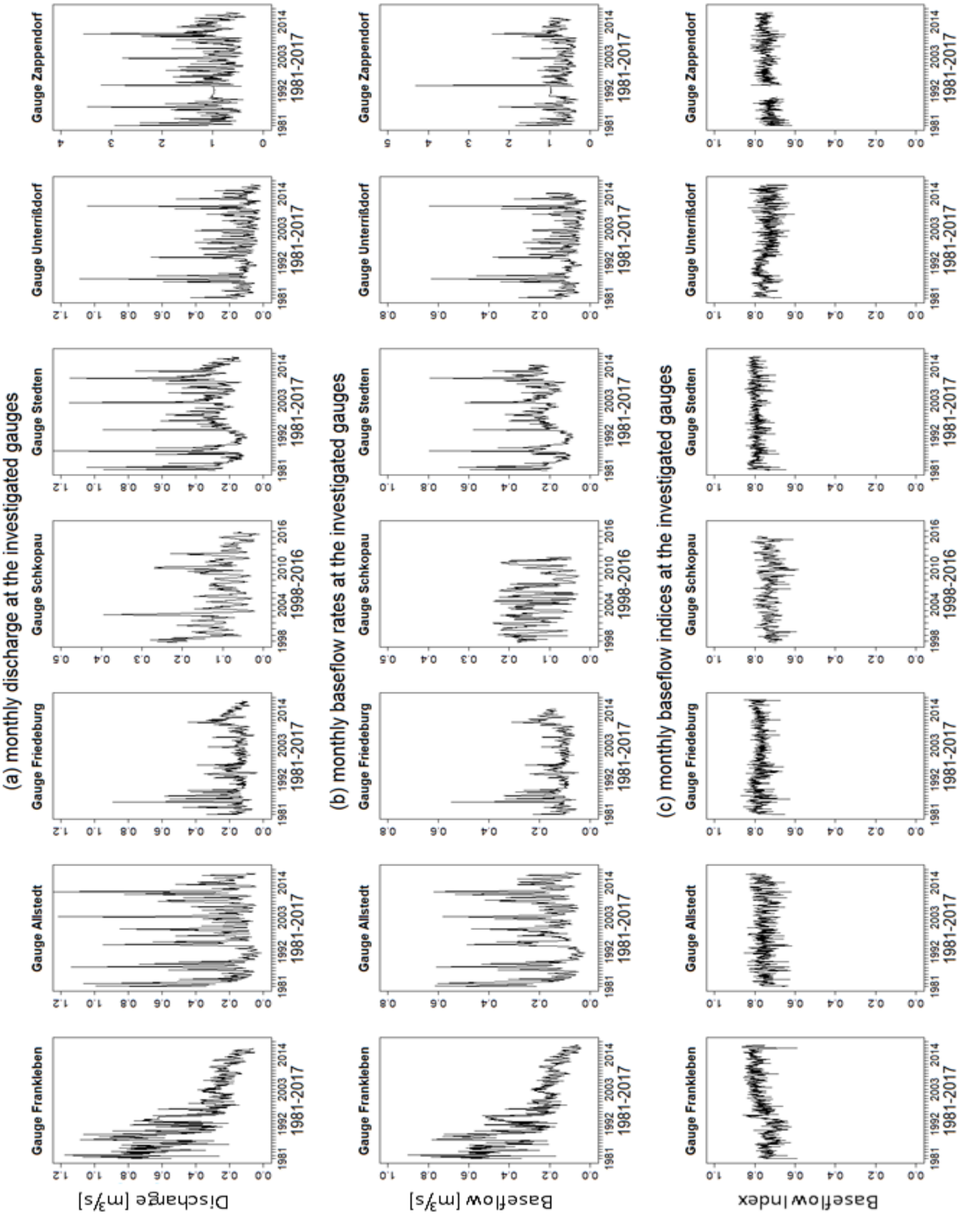

Fig. A2 (a) Mean monthly discharge, (b) estimated monthly baseflow rates, and (c) calculated monthly baseflow indices at all investigated gauges.

Abb. A2 (a) Mittlerer monatlicher Abfluss, (b) geschätzte monatliche Basisabflussraten und (c) berechnete monatliche Basisabflussindizes an allen untersuchten Pegeln.

Table A4 Measured discharge rates [m³/s], regionalized baseflow rates [m³/s], and regionalized baseflow indices at the gauge Frankleben for individual time periods with different intensities of anthropogenic impacts.

Tab. A4 Gemessene Abflussmengen [m³/s], regionalisierte Basisabflussmengen [m³/s] und regionalisierte Basisabflussindizes am Pegel Frankleben für einzelne Zeiträume mit unterschiedlicher Intensität der anthropogenen Einflüsse.

Time period	**Anthropogenic impacts**	**Measured Q_{mean} [m³/s]**	**Regionalized Q_{Bmean} [m³/s]**	**Regionalized BFI**
Jan 1981 – Jun 1993	Mining activity (e.g. dewatering, streamflow relocation)	0.63	0.463	0.74
Jul 1993 – Jun 2003	Planning period (no stronger impacts known)	0.325	0.246	0.76
Jul 2003 – Apr 2011	Refilling of abandoned open pit	0.242	0.185	0.76
May 2011 – Dec 2017	Current hydrological conditions (Q regulation with drainage structure)	0.149	0.115	0.78

Table A5 Flow duration curve data for six different environmental management classes calculated with the flow duration curve shifting method at the gauge Frankleben.

Tab. A5 Daten der Abflussdauerkurve für sechs verschiedene Ökologische Bewirtschaftungsklassen, berechnet mit der Methode der “flow duration curve shiftingMethode” am Pegel Frankleben.

%	Reference Scenario	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
0.01	2.101	2.068	1.817	1.607	1.018	0.857	0.75
0.1	2.068	1.817	1.607	1.018	0.857	0.75	0.696
1	1.817	1.607	1.018	0.857	0.75	0.696	0.643
5	1.607	1.018	0.857	0.75	0.696	0.643	0.589
10	1.018	0.857	0.75	0.696	0.643	0.589	0.532
20	0.857	0.75	0.696	0.643	0.589	0.532	0.441
30	0.75	0.696	0.643	0.589	0.532	0.441	0.338
40	0.696	0.643	0.589	0.532	0.441	0.338	0.214
50	0.643	0.589	0.532	0.441	0.338	0.214	0.156
60	0.589	0.532	0.441	0.338	0.214	0.156	0.101
70	0.532	0.441	0.338	0.214	0.156	0.101	0.0948
80	0.441	0.338	0.214	0.156	0.101	0.0948	0.0887
90	0.338	0.214	0.156	0.101	0.0948	0.0887	0.0829
95	0.214	0.156	0.101	0.0948	0.0887	0.0829	0.0776
99	0.156	0.101	0.0948	0.0887	0.0829	0.0776	0.0726
99.9	0.101	0.0948	0.0887	0.0829	0.0776	0.0726	0.0679
99.99	0.0948	0.0887	0.0829	0.0776	0.0726	0.0679	0.0635

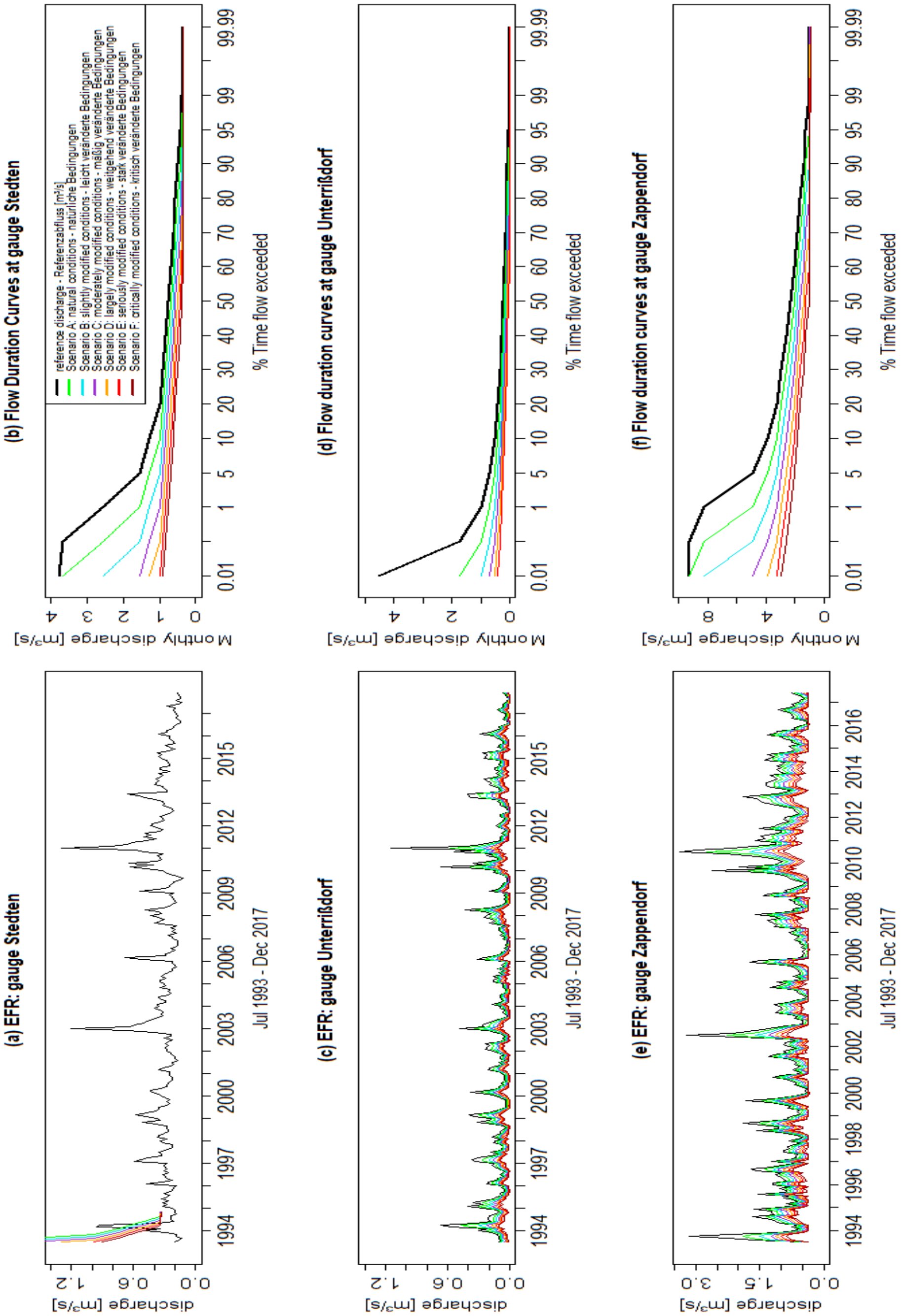
(a) EFR: gauge Stedten
discharge [m³/s]
0.0
0.6
1.2
1994
1997
2000
2003
2006
2009
2012
2015
Jul 1993 - Dec 2017
(b) Flow Duration Curves at gauge Stedten
Monthly discharge [m³/s]
0
1
2
3
4
0.01
1
5
10
20
30
40
50
60
70
80
90
95
99
99.99
% Time flow exceeded
reference discharge - Referenzabfluss [m³/s]
Scenario A: natural conditions - natürliche Bedingungen
Scenario B: slightly modified conditions - leicht veränderte Bedingungen
Scenario C: moderately modified conditions - mäßig veränderte Bedingungen
Scenario D: largely modified conditions - weitgehend veränderte Bedingungen
Scenario E: seriously modified conditions - stark veränderte Bedingungen
Scenario F: critically modified conditions - kritisch veränderte Bedingungen
(c) EFR: gauge Unterrißdorf
discharge [m³/s]
0.0
0.6
1.2
1994
1997
2000
2003
2006
2009
2012
2015
Jul 1993 - Dec 2017
(d) Flow duration curves at gauge Unterrißdorf
Monthly discharge [m³/s]
0
2
4
0.01
1
5
10
20
30
40
50
60
70
80
90
95
99
99.99
% Time flow exceeded
(e) EFR: gauge Zappendorf
discharge [m³/s]
0.0
1.5
3.0
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Jul 1993 - Dec 2017
(f) Flow duration curves at gauge Zappendorf
Monthly discharge [m³/s]
0
4
8
0.01
1
5
10
20
30
40
50
60
70
80
90
95
99
99.99
% Time flow exceeded

Fig. A3 EFR calculated with the flow duration curve shifting method for three quasi-natural gauges in Central Germany (Stedten, Unterrißdorf, and Zappendorf) and the respective flow duration curves. Percentages of mean annual discharge: gauge Stedten: scenario A = 85.9%, scenario B = 76.0%, scenario C = 68.3%, scenario D = 62.1%, scenario E = 56.8%, scenario F = 52.2%; gauge Unterrißdorf: scenario A = 72.9%, scenario B = 55.9%, scenario C = 43.6%, scenario D = 34.1%, scenario E = 26.4%, scenario F = 20.2%; gauge Zappendorf: scenario A = 85.1%, scenario B = 74.4%, scenario C = 65.9%, scenario D = 59.0%, scenario E = 53.2%, scenario F = 48.5%.

Abb. A3 Mit der “flow duration curve shiftingMethode”berechnete ökologisch notwendige Mindestwassermengen für drei naturnahe Pegel in Mitteldeutschland (Stedten, Unterrißdorf und Zappendorf) und die jeweiligen Abflussdauerkurven. Prozentsätze des mittleren jährlichen Abflusses: Pegel Stedten: Szenario A = 85,9%, Szenario B = 76,0%, Szenario C = 68,3%, Szenario D = 62,1%, Szenario E = 56,8%, Szenario F = 52,2%; Pegel Unterrißdorf: Szenario A = 72,9%, Szenario B = 55,9%, Szenario C = 43,6%, Szenario D = 34,1%, Szenario E = 26,4%, Szenario F = 20,2%; Pegel Zappendorf: Szenario A = 85,1%, Szenario B = 74,4%, Szenario C = 65,9%, Szenario D = 59,0%, Szenario E = 53,2%, Szenario F = 48,5%.

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