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Conceptual approach for a holistic low-flow risk analysis

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Abstract

Low-flow events, characterized by a significant water deficiency in river systems, have profound impacts on various water users and river ecology. Recent low-flow events in Europe have had severe economic and ecological consequences such as disruptions to hydropower production, irrigation bans, constraints on navigation and complete river drying. These events highlight the urgent need for effective low-flow risk management and demand a holistic risk analysis as a basis. The existing approaches to low-flow analysis often focus on hydrological aspects, utilizing indices such as the *Standardized Runoff Index* (SRI) or *Low-flow Index*. However, these indices lack information regarding consequences and impacts. Other approaches consider parts of a risk approach but often focus on special aspects, such as the economy; in general, no holistic assessment is made. This study introduces a conceptual approach to a holistic low-flow risk analysis. The approach provides a continuous long-term simulation to capture the special long-term behaviour of low-flow events and therefore avoids the complex definition of scenarios. In this conceptual approach, the low-flow risk is analysed using a combination of various analyses that cover all aspects from occurrence to consequences. Meteorological analysis is used to generate synthetic long-term weather data time series, which are transformed into runoff time series in hydrological analysis. Based on these results, hydrodynamic analysis quantifies the water levels, water temperatures, and flow velocities along the river. The consequences are analysed in terms of socio-economic and ecological consequences. The results represent a long-term series of damage values. Finally, the damage values are summed in the risk analysis and divided by the number of years considered in the analysis. For testing and demonstration purposes, the presented conceptual risk approach is partly applied to a proof-of-concept at the Selke catchment, a small river catchment in Germany. Finally, the results are presented, evaluated, and discussed.

KEYWORDS
consequences, drought risk, low-flow, low-flow modelling, low-flow risk, risk analysis, risk management, low-flow risk analysis

1 | INTRODUCTION

Low flow is a natural phenomenon that often occurs as a result of prolonged drought events. Hydrological drought or so-called blue-water drought is defined by Sayers (2016) as an 'unusual and significant deficiency in the water stored in freshwater lakes, rivers, aquifers and wetlands'. The present study primarily focuses on low-flow in perennial rivers, located in temperate climate zones. In Europe, low-flow events in recent years have highlighted the eminent consequences of low-flow for various water users and river ecology. Energy production has often been hindered by low flow in various ways, including reduced production from hydroelectric power plants due to low discharges in rivers and low reservoir levels, particularly during the years 2015, 2018 and 2022. Furthermore, there have been frequent restrictions on the withdrawal of cooling water, which limited or completely halted electricity generation in nuclear or fossil power plants, such as Chooz, Fessenheim or Golfech (European Commission et al., 2020; European Commission & Joint Research Centre, Toreti, Bavera, 2022; Internationale Kommission zum Schutz des Rheins, 2020). The condition of the drinking water supply in some regions of the Netherlands, France, and the Czech Republic, as well as other European areas, was critical and had to be supported by tankers (European Commission & Joint Research Centre, 2022; van Lanen et al., 2016). During the low-flow periods in 2018 and 2019, significant disruptions occurred in European waterways (European Commission et al., 2018; European Commission et al., 2019). Due to the high level of shipping traffic, the Rhine is particularly vulnerable and experienced damage amounting to 2.7 billion euros in 2018 as a result of disruption to shipping alone (Streng et al., 2020). Consequent limitations on shipping have led to disrupted supply chains, which in turn result in reduced production capacities at plants. According to BASF alone, the company experienced losses of over 250 million euros due to low-flow-related impacts in 2018 (BASF, 2019). Between 2015 and 2019, many small rivers in Europe dried up completely. Rivers that still had sufficient water often had to deal with a severe deterioration of water quality. In addition to the higher concentration of pollutants, increased algal growth and high water temperatures are the result of extremely low flow. Due to the prevalence of low-flow conditions in numerous areas, fish die-offs occurred, which could, at the very least, be partly attributed to the impact of these events. A noteworthy instance was the significant fish die-off that occurred in the Oder River in 2022, which was attributed to saltwater injections but compounded by a low-flow event (Schulte et al., 2022).

The massive consequences of recent events for the environment and society show the urgent need for effective low-flow risk management. In water management, risk-based approaches are already extensively used in flood risk management. However, they are rarely used in low-flow risk management. In the field of drought risk management, there are several approaches that consider low-flow as part of an overarching drought event but not explicitly as the main issue. Drought risk management considers drought with all its consequences, such as the loss of agricultural yields, forest fires, or restriction of navigation. There is no specific consideration for the low flows in rivers. In low-flow risk management, on the other hand, only the river and the consequences resulting from the low flow are examined in detail.

The basis of low-flow risk management is a low-flow risk analysis, which combines the probability of occurrence and the consequences that occur. The presented work highlights an approach for an effective low-flow risk analysis where pure hydrological risks are transformed into economic and societal risks. In detail, the following research questions will be addressed: (i) is the use of long-term series for low-flow risk analysis expedient, (ii) what could a holistic approach for low-flow risk analysis look like and (iii) is the proposed holistic approach suitable for modelling low-flow risk.

In this paper, we conduct a comprehensive review of existing literature to identify strategies for managing low-flow risks and monitoring. The risk approach is based on continuous long-term modelling to adequately capture the consequences of low-flow events. The complex definition of scenarios is avoided. Furthermore, the significance of adopting a comprehensive approach that incorporates various analyses is shown. Hence, several analyses are combined: meteorological, hydrological, and hydrodynamic analysis. The impacts of low flow, which are analysed for socio-economic and ecological consequences, are also considered. Finally, the low-flow risk is calculated as the loss sums per consequence category (e.g. €, points) over years divided by the number of simulated years. To demonstrate the interdependence of the different analyses and the practical feasibility of the proposed method a proof-of-concept is implemented using a hypothetical example.

The following passage presents a summary of the low-flow analyses that have been reported in previous literature. From a hydrological perspective, statistical variables are often used to characterize low-flow events. One of the most frequently used parameters for the statistical description of low-flow is the 95-percentile discharge at a gauge station during a hydrological year. This represents the discharge, which is exceeded on 95% of the days. An additional statistical value is the mean annual minima, which is used as the average of the low discharges of a defined time period. The duration of the days varies, with the most frequent durations being 1, 7, 10, 30, and 90 days (Manual on low-flow estimation and prediction, 2008). In Germany for example, the MNQ, which is defined as the average low-flow, and the NNQ, the lowest discharge ever measured, are also used for low-flow characterization (LAWA, 2017). Also, indices are widely used to classify the severity of low-flow events. The *Standardized Precipitation Index* (SPI) (McKee et al., 1995) and *Standardized Precipitation Evapotranspiration Index* (SPEI) (Vicente-Serrano et al., 2010) indices, developed for drought, form the basis of the *SRI* established by Shukla and Wood (2008) which uses runoff data instead of precipitation data. The runoff deficit is then used to determine the SRI using different distribution functions, for instance, the 2-parameter log normal or gamma distribution. An index developed specifically for low-flow events is the *Low-flow Index* (Cammalleri et al., 2016). It classifies low flows into four drought classes (mild, moderate, severe, and extreme) based on a statistical analysis of the discharge data. The index was developed for operational drought monitoring at the European Drought Observatory. Although a characterization and hydrological classification of a low-flow event is possible with the above-mentioned hydrological variables and indices, they do not provide any information about the potential consequences or risks associated with such events.

The general definition of risk is the product of the probability of occurrence of an event and its consequences (DIN EN ISO 12100:2011-03, 2010). This definition includes hazard, exposure, and vulnerability. Hasan et al. (2022) presented a risk-based assessment approach specifically for hydrological drought. The presented framework is based on various indices. Daily streamflow data were characterized and used to calculate the *Hydrological Drought Hazard Index* (HDHI). *The Hydrological Drought Vulnerability Index* (HDVI) is based on social and economic data. The *Hydrological Drought Risk Index* (HDRI) was calculated by multiplying the two aforementioned indices. However, this approach does not consider ecological consequences and, therefore, cannot be considered holistic. Mens et al. (2022) conducted a hydrological drought risk assessment using a long-term series in the Netherlands. They applied the National Water Model (NWM), which consists of different sub-models, to quantify socio-economic impacts based on simulated discharges. Risk is calculated in €/year and is the basis for reliable long-term risk management. A monetary evaluation is used to assess the measures and in particular, the implementation time. The model focuses strongly on economic impact. Owing to the different sub-models, NWM is also extremely computationally intensive (Mens et al., 2021). The ecological impacts are assessed in conjunction with other consequences, such as the consequences of low flow on infrastructure or stability of embankments. All considered consequences are quantified solely by a shadow price, which represents the marginal value of an additional cubic metre of water for agricultural use during a period of low flow. Our approach takes into account the full range of consequences associated with low flow, including both socio-economic and ecological impacts. Physically based models are grounded in the laws of nature, whereas data-driven models rely solely on historical data, which may not accurately capture the complexity of real-world systems. Implementing measures to mitigate the impacts of low-flow events or consider the effects of climate change is simpler in physically based models because they can be modified to reflect changes in the underlying physical processes.

2 | MATERIALS AND METHODS

In the context of this paper, low-flow pertains to the uncommon and substantial scarcity of water found in perennial freshwater rivers. The following chapter provides a comprehensive description of the holistic low-flow risk approach, with a particular emphasis on the employment of long-term series and the suggested analyses implemented within the framework.

2.1 | Scenario-based versus long-term series approach

In the field of flood management, scenario-based approaches are often applied. Therefore, extreme values are extracted from statistical analyses of long-term data and used as a basis for the scenario definition. A clear distinction of flood events is comparatively simple due to (i) the relatively short duration of flood events from a few days to a few weeks, and (ii) negligible links from one (hydrological but also in terms of consequences) to previous flood events. However, for low-flow risk modelling, the definition of scenarios is considerably more complex due to their long-term development and a pronounced dependency on previous conditions. Through a multi-year consideration, hydrological correlations, such as the emptying of the groundwater reservoir or the water stored in reservoirs, can be accounted for. Also, the effects on ecology require a long-term perspective. By considering fish as an indicator of ecological consequences resulting from low flows, this becomes evident. For example, long-term low-flow events can damage fish populations in addition to the short-term damage that occurs, whereas in a subsequent wet year, populations recover quickly and no long-term damage occurs (Bond et al., 2008).

Therefore, a long-term simulation approach is proposed for the low-flow risk analysis. In the field of flood risk analysis, a long-term approach is applied by Falter et al. (2016). The fundamental model concept of this approach is adapted for low-flow modelling. With the help of long-term series of several hundred years, for example, it is feasible to model extreme events, for instance with a probability of occurrence of one time in 100 years since these are statistically reproduced in the time series. In order to produce extreme low-flow events, a weather time series is transformed into low-flow events through the use of hydrological and hydrodynamic modelling. Using a statistical evaluation of existing weather time series, extreme value statistics are created. The statistical distribution serves as a basis for the generation of the long-term series and is reproduced in those. The synthetic long-term weather time series applied in the modelling is derived from a statistical analysis of a selected reference period. The reference period describes the time period that serves as the basis for the generation of extreme value statistics for the generation of time series. Depending on the user's requirements, it is possible to use different time periods, provided that sufficient data are available for the respective period. This reference condition can be, for instance, the status quo or the future state of the climate in 30 years (including climate change). However, to adequately consider future changes such as climate change, it is necessary to apply these changes in time series generation. Therefore, it is necessary to adjust the extreme value statistics based on the selected climate change scenario. The aim of the time series is to accurately represent extreme events in the reference period. Within the synthetic-generated time series, no changes in climate or socio-economic changes take place.

2.2 | Holistic low-flow risk approach based on long-term series

The aim of the holistic approach is to cover all relevant aspects of a low-flow event, including hydrological and hydrodynamic effects as well as consequences. Additionally, all aspects, such as drivers, consequences, and their interactions, should be considered in the analysis.

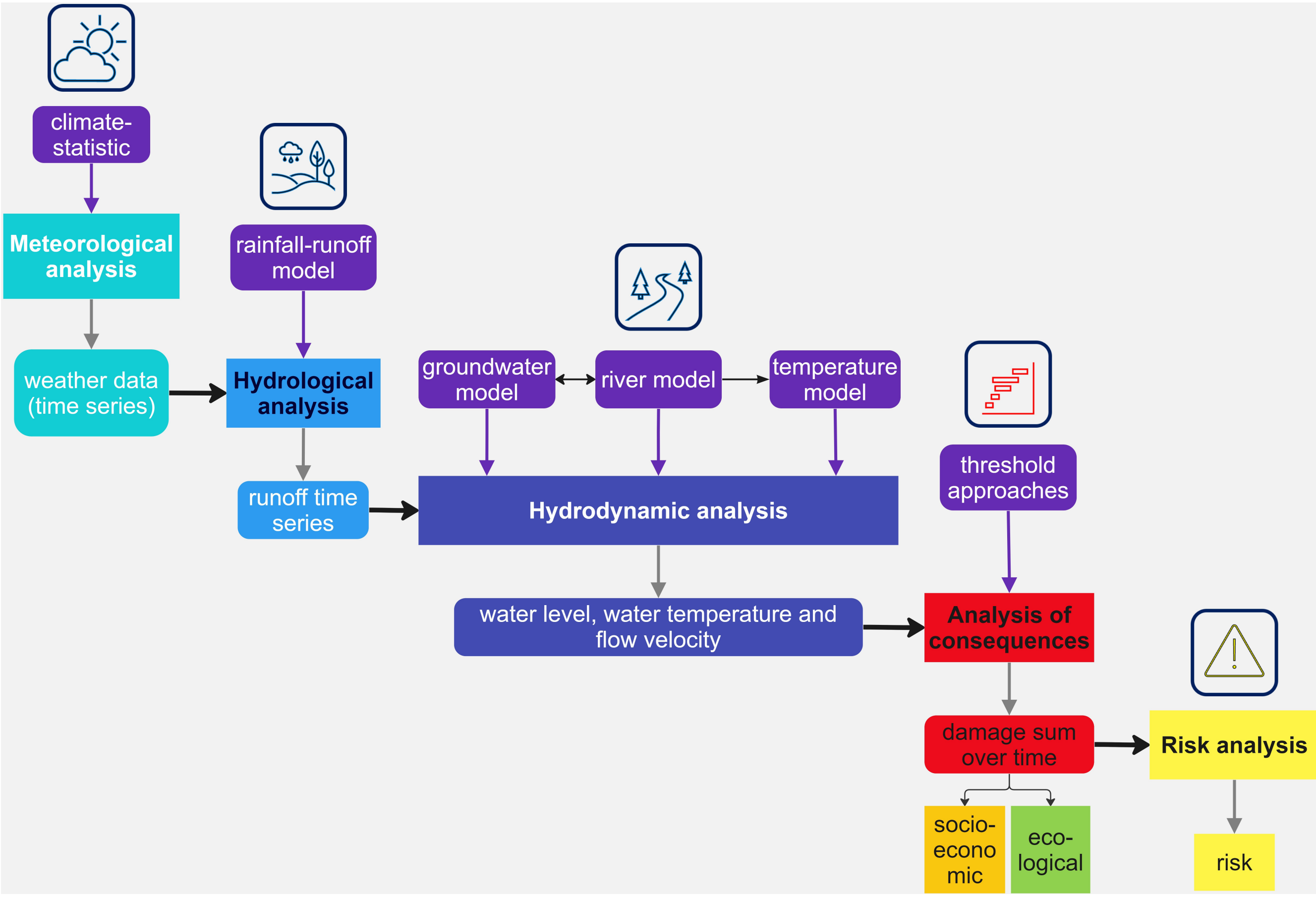

FIGURE 1 Overview of the modules applied in the holistic low-flow risk analysis.

To achieve this, this approach is subdivided into several analyses that are optimized for a low-flow risk approach.

Figure 1 provides an overview of the applied modules and their interfaces. In the following sections, individual analyses of the holistic risk approach and its interfaces are conceptually described. Please note that the following list is not exhaustive and may be subject to change. Due to this, a comprehensive description of each analysis is not provided.

2.2.1 | Meteorological analysis

In the first step, a meteorological analysis is performed. In this analysis, a statistical assessment of climate for a selected reference period (e.g. from 1990 to 2020) is conducted. This results in extreme value statistics for the climate variables in the reference period. Empirical formulas and statistical analyses are used to record the interrelationships and correlations between the various parameters. Again, extreme value statistics are used to generate a synthetic time series of weather data. The synthetically generated data must correspond to the extreme value statistics of the selected period. A stochastic weather generator can be used for this purpose.

2.2.2 | Hydrological analysis

In the hydrological analysis, the synthetic long-term weather data from the meteorological analysis are used as input parameters. Further input data, such as land use and topography, are considered and long-term runoff time series are produced. A rainfall-runoff model can be applied in this context. Anthropogenic influences, such as discharges from sewage treatment plants, industrial operations, or even withdrawals from the river, must be recorded separately and transformed into additional time series.

2.2.3 | Hydrodynamic analysis

In the hydrodynamic analysis, the long-term runoff time series from the hydrological analysis is transformed into hydrodynamic values, such as water level, water temperature, and flow velocity. Three submodels were used. The core of hydrodynamic analysis is a 1D river model that models the water levels and flow velocities along the river. A 1D river model seems suitable for this purpose due to the almost static behaviour of low-flow events; local and convective acceleration can be neglected. In addition to hydrological data, further input data relating to the river, such as cross-section geometry and friction coefficients, are considered in the model.

For adequate consideration of the exchange with the near-surface groundwater in the form of ex- and infiltration, a groundwater model is part of the hydrodynamic analysis. The 2D groundwater model calculates the groundwater levels in the immediate vicinity of the river and is bidirectionally coupled to the river model. In this way, exchange processes between the river and groundwater, which become especially relevant during low-flow times, are modelled more realistically.

Water temperature, which is an important parameter for the analysis of low-flow consequences, could be computed using a 1D temperature model. After completing the computational run of the 1D river model, the hydrodynamic results are transferred to the temperature model. The coupling is unidirectional. Weather data from the meteorological analysis, such as global radiation or air temperature and anthropogenic discharges with temperature influence, are further input parameters to the temperature model. Finally, hydrodynamic analysis provides a time series of water levels, water temperatures, and flow velocities along the river.

2.2.4 | Analysis of consequences

Due to the holistic claim, the analysis of consequences involves various categories of consequences. In addition to the socio-economic consequences, which quantify the consequences for various water users, the ecological consequences are also considered. Essentially, the analysis is based on a long-term series from the hydrodynamic analysis.

In principle, the analysis of socio-economic consequences is quantified based on threshold approaches. The analysis can be further subdivided into different sectors of water users; consequently, threshold approaches are defined differently for different sectors of water users. Folkens et al. (2023) summarized the sectors of water users socio-economically affected by low-flow events. These sectors include inland navigation, tourism and recreation, water suppliers and households, and energy and industry.

Ecological consequences are subdivided into consequences for fish populations and macro zoobenthos. Threshold approaches are also used in this case. These are based on indices that describe the fish abundance. Changes in the fish abundance are reflected in the changes in the indices. The consideration of the consequences for macro zoobenthos is analogous to that of fish and can also be carried out with the help of indices. Approaches for this are still under development. A final monetary evaluation of ecological consequences is debatable, as described by Bartkowski et al. (2015), but not mandatory.

The results of the analysis of consequences are time series for different categories of consequence i. Finally, the time series of the respective category of consequence i are summed over n simulated years j to obtain the total damage value K_i:

$$K_i = \sum_{j=0}^{n} K_{i,j} \tag{1}$$

The total damage value K_i obtained from the analysis of consequences can be expressed in monetary (e.g. €) or non-monetary units (e.g. score points).

2.2.5 | Risk analysis

Finally, the risk analysis combines the consequences with probabilities. Due to the long-term series approach, the total damage value K_i per category of consequence is divided by the number of simulated years n:

$$R_i = \frac{K_i}{n} \tag{2}$$

It results in the risk R_i per category of consequence i. Units are, corresponding to the category of consequences, monetary (e.g. €/a) or non-monetary (e.g. score points/a). In this case, a direct monetary trade-off between the categories is not possible. However, multicriteria approaches are able to evaluate these kinds of problems.

2.3 | Proof-of-concept

The main purpose of the following proof-of-concept is to test and evaluate the functionality of the proposed approach for low-flow risk analysis. Practical aspects to be investigated are the required resources of the approach, such as the calculation time and data requirements. These are the key aspects to ensure the application of the approach in low-flow risk management. The focus of this proof-of-concept is on the hydrodynamic analysis (the 1D river modelling and the temperature model), the analysis of consequences, and the risk analysis. To validate the results of the hydrodynamic analysis, the generation of synthetic long-term series is omitted and a long-term series from historical data is used instead. This allows a comparison between the modelled and measured data (at least for the hydrodynamic part) and serves to verify the applied hydrodynamic models. To demonstrate the general functioning of the analysis of consequences, fictitious, but realistic generic data are applied. This has the advantage that the functioning of the approach is demonstrated in general and is thus independent of the catchment area. A comprehensive analysis of all categories of consequences that have been mentioned previously would go beyond the scope of this study.

2.3.1 | Study area

The river Selke is a tributary of the river Bode, which is part of the Elbe catchment in Germany (see Figure 2). The Selke drains an area of

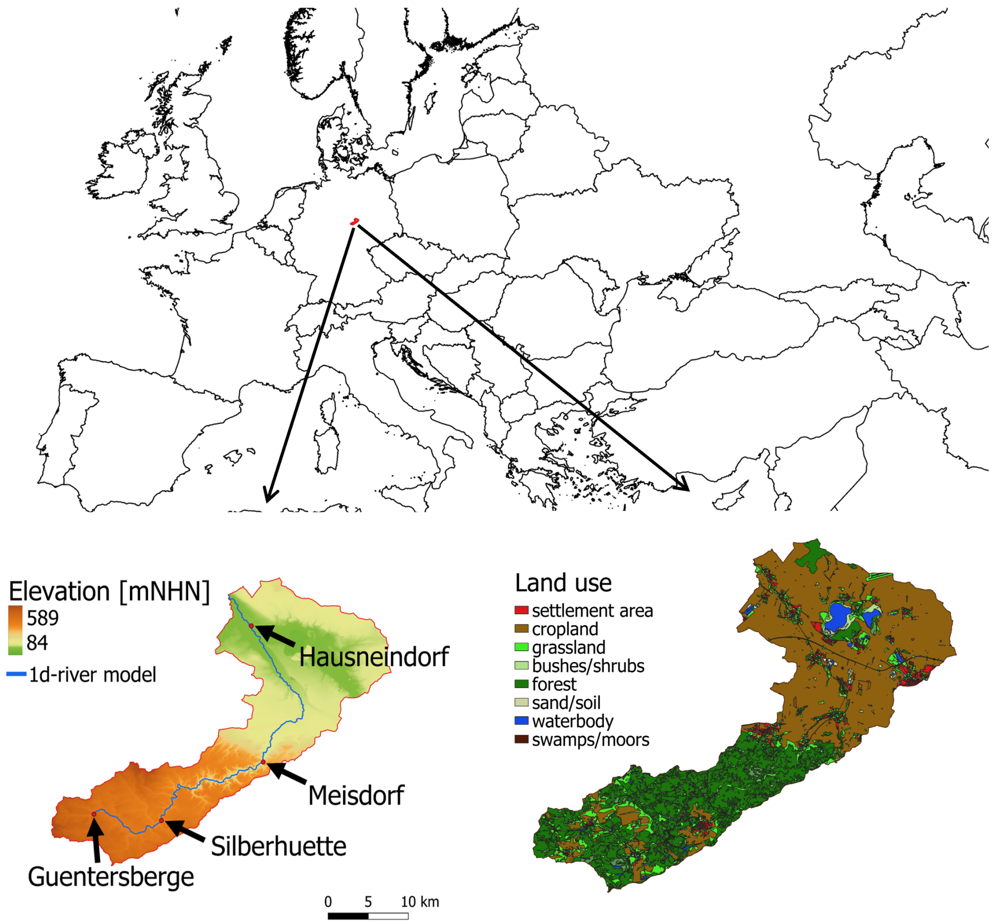

FIGURE 2 Location (top), elevation (bottom left) and land use (bottom right) of the Selke.

approximately 470 km^2 in the southeastern part of the Harz Mountains region at a length of approximately 64 km. The catchment of the river Selke is characterized in its upstream and upper midstream areas by steep topography with geodetic heights ranging from 150 to 589 m NHN (German height system based on the Amsterdam Ordnance Datum) and predominantly forestry use. In the lower midstream and downstream areas, the river Selke flows through an agricultural lowland area with heights of approximately 83–150 m NHN. Due to the heterogeneous catchment, precipitation and temperature vary along the course of the river. The Selke catchment has a moderate climate, with an average precipitation of 660 mm/a and an annual average temperature of approximately 10°C. Four gauges are placed in the catchment area. The Guentersberge gauge is located at the outlet of Muehlenteich reservoir in the village of Guentersberge and covers a catchment area of 26 km^2. The Silberhuette gauge covers a catchment area of 105 km^2 and is located in the upstream part of the river Selke. The Meisdorf gauging station is located in the midstream area of the river Selke at river km 29.4 and has an upstream catchment area of 189 km^2. The Hausneindorf gauging station is located in the downstream section shortly above the mouth into the Bode at river km 5.5 and covers a catchment area of 456 km^2, which means that it covers almost the entire catchment area of the river. An overview of the catchment area is shown in Figure 2.

The Selke is characterized by large discharge dynamics. The mean discharge ranges between 1.07 m^3/s (Silberhuette), 1.50 m^3/s (Meisdorf), and 1.69 m^3/s (Hausneindorf). While discharge values of less than 0.150 m^3/s occur weekly at the Silberhuette gauge during low-flow, the discharge can be up to 60 m^3/s at the Hausneindorf gauge during extreme floods. The Selke has been the focus of extensive scientific research due to its specific characteristics. Along with hydrological and geological aspects, the ecohydrological implications of the drought years have also been thoroughly examined (see e.g. Sinha et al., 2016; Winter et al., 2023; Yang et al., 2023). In past decades (1990–2020), the Selke had to cope with low-flow events on a regular basis. In 2006, the lowest discharge of the time period occurred at the Silberhuette gauge with respective 0.07 m^3/s. As expected, the extreme events of 2018, 2019, and 2020 are also mirrored in the discharge data of the river Selke, especially at the Silberhuette (0.076 m^3/s) and Meisdorf (0.087 m^3/s) gauges. A new low-flow record was measured at the Hausneindorf gauge on 26 August 2019, with a discharge of approximately 0.013 m^3/s. In 2019 and 2020, the minimum discharge of the Kiliansteich reservoir was temporarily increased from 5 to 50 l/s to support discharge within the river Selke (Richter, 2020). In 2019, a fish die-off occurred in the lower reaches near Gatersleben, which can mainly be attributed to a low-flow event (mz.de, 2019).

2.3.2 | Model set-up

The proof-of-concept is carried out for the period 1990–2020 (inclusive), which serves as a substitute for the generation of long-term series based on weather data. The hydrodynamic analysis is conducted using the hydrodynamic HYD module of the free LoFloDes software package (LoFloDes, 2023). This software package, which is currently under development, will contain modelling approaches for a low-flow risk analysis. The 1D river model is established using surveyed cross sections of the Selke River, which are provided by the Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt. The Selke River is represented by 1247 cross sections, with a distance between the cross sections of approximately 50 m. The model starts at the Guentersberge gauge and covers in total approx. 61.5 km of the river, which ends at the river mouth. The output time step is chosen as hourly values, as these are decisive when assessing the ecological consequences. The measured discharge values between 1990 and 2020 at the gauge stations Silberhuette, Meisdorf, and Hausneindorf are used to derive the boundary conditions of the 1D river model. Based on the measured discharges of the tributaries, a discharge ratio is assessed. The measured discharge at each gauging station is distributed to two upstream tributaries by the predetermined discharge ratio. If there is a remaining discharge volume, it is added through diffusive inputs. The groundwater model, which considers near-surface groundwater, is not applied because it is still under development and is not mandatory to show the functionality of the risk approach. The applied temperature model is also part of the HYD module of LoFloDes. It models a pure 1D convective temperature transport in the river based on a 1D flow velocity (from hydrodynamic analysis); diffusive temperature transport is neglected. The model considers the heat fluxes of the most relevant processes such as evaporation, solar radiation, and riverbed exchange. Those sources and sinks are represented by a combination of different equations from the existing temperature models (Boyd & Kasper, 2003; Gallice et al., 2016; Westhoff et al., 2007, 2011). Weather data, required as boundary conditions for the temperature model, are extracted from the data of the weather stations Harzgerode, Brocken, Halle-Kröllwitz, Wernigerode, Aschersleben-Mehringen, and Quedlinburg of the German Weather Service (DWD). The water temperatures of the tributaries are implemented in the model using an annual hydrograph of water temperature based on single measurements.

The analysis of the consequences is carried out as an example based on fictitious consequences. In the proof-of-concept, hydropower generation is used as a representative sector of the socio-economic consequences of K_{hydro}. A hydropower plant is dimensioned based on its average annual yield (€/a). This reference yield is determined according to the long-term hydrological data from the gauging stations. Using the equations from Giesecke et al. (2014), the actual annual yield is calculated based on the results of the hydrodynamic analysis. The equation for P (kW) contains some constants, such as the density of the water ρ_w (kg/m^3) and the gravitational constant g (m/s^2), and varying parameters, such as the discharge Q (m^3/s), the head h_f (m), and the energy conversion efficiency of the hydropower plant η_{tot} (–), which vary depending on utilization.

TABLE 1 Simple index system for the analysis of ecological consequences.

Index-score (–)	*h* (m)	*v* (m^2/s)	*T* (K)	*d* (h)
0	>0.3	>1	≥291.15	<50
1	≥0.3	≥1	≥291.15	≥50
2	0.1–0.3	0.5–1	>293.15	10–50
3	0.1–0.3	0.5–1	>293.15	≥50
4	<0.1	<0.5	>295.15	10–50
5	<0.1	<0.5	>295.15	≥50

$$P = \eta_{tot} \times \frac{\rho_w \times g}{10^3} \times Q \times h_f \tag{3}$$

By applying formula (3), the power is calculated on an hourly basis, which represents the energy generated in 1 h. The annual amount of energy is multiplied by a price of 0.4 €/kWh to calculate the annual yield. The profits or losses are derived from the difference between the actual yield per year and the reference yield.

For the analysis of ecological consequences, K_{eco}, a simple index system with index scores ranging from 0 (no influence) to 5 (large negative influence) is applied. It should be noted that any exceedance of the index-score of 0 is regarded as stress or damage to ecology. This system is mainly based on expert knowledge. The index-score is mainly influenced by the hydrodynamic (water depth h, flow velocity v, and duration d) and temperature T values. Table 1 summarizes the threshold values. We hypothesized that insufficient water levels and slow flow rates would create stress for both fish and macrozobenthos, particularly when coupled with high water temperatures. The particular threshold values employed by the authors are open to debate. The primary objective of this paper is to evaluate the low-flow risk, and thus, the examination of ecological consequences is secondary in nature.

In this study, the consequences are spatially analysed at three gauge stations Silberhuette, Meisdorf, and Hausneindorf, assuming that there is one hydropower plant per gauge and each gauge is representative of the ecological consequences in this river section. To determine the consequences for the three hydropower plants, the annual yield per plant is calculated based on Equation (3). The ecological consequences are assessed by computing the index-score based on the information presented in Table 1. In the risk analysis, the annual profit/losses of hydropower are summed over 31 years and over the three gauges (K_{hydro}). Similarly, the ecological indices of each modelled year are summed over all gauges (K_{eco}). The respective sums are divided by the number of calculated years n, resulting in a low-flow risk R_i for the catchment.

3 | RESULTS

The computation time for the 1D river model, temperature model, and analysis of the consequences amounts to a total of approximately

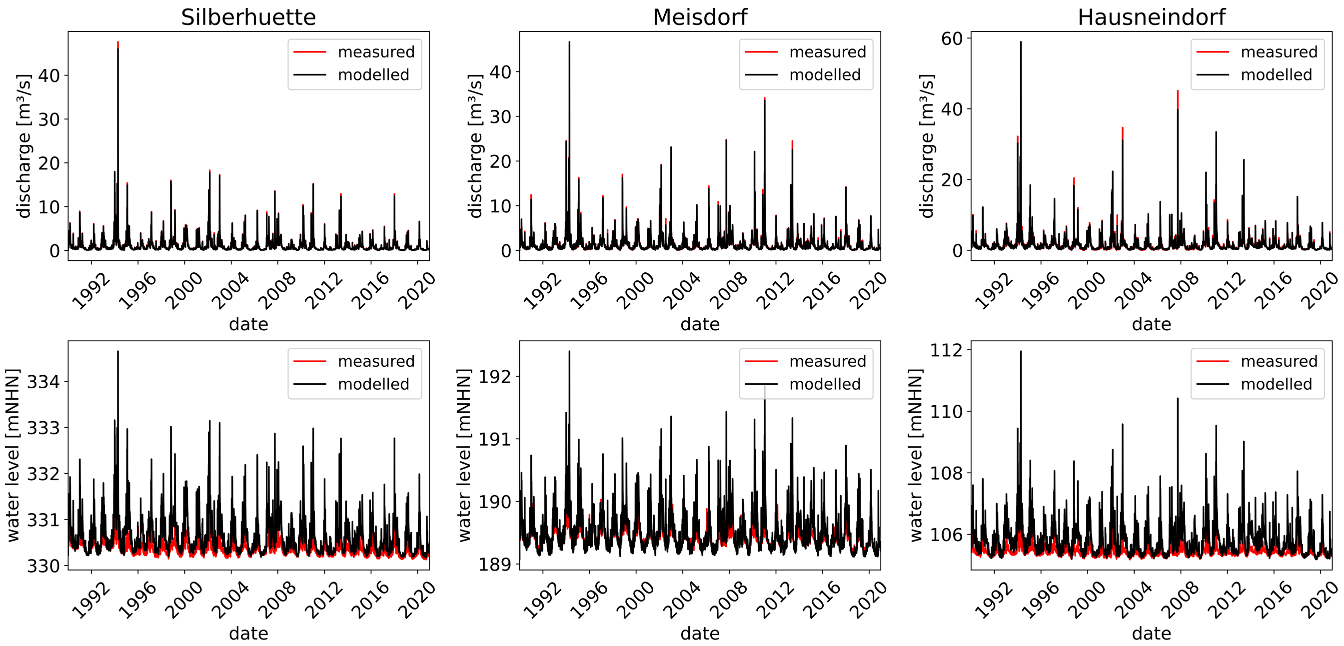

FIGURE 3 Measured values and modelled results of the hydrodynamic analysis (1990–2020) discharges (top) and water levels (down) at the river Selke for the three gauges.

573 min, that is, less than 10 h. This results in an average calculation time per modelled year of approx. 18.5 mins.

The amount of data is an interesting issue when modelling a long-term series. The result files were output on an hourly basis, with a data requirement of 0.185 gigabytes per modelled year. The amount of data is manageable and offers considerable potential for optimization.

Figure 3 shows the measured (red) and modelled (black) discharges (top) and water levels (bottom) for the three gauging stations Silberhuette, Meisdorf and Hausneindorf on the river Selke. Focussing on the discharge, the shape of the modelled curve corresponds to the shape of the measured curve. Only the discharge peaks during flooding are not fully represented in the model. This has just a negligible effect on low-flow periods. Overall, the results of the 1D river model (discharges and water levels) show good agreement for periods of low flow for the three gauges along the Selke. The model quality is further evaluated using quality coefficients. For the discharge in the river, the Nash–Sutcliffe model efficiency coefficient (NSE with an optimum of 1) (Moriasi et al., 2007; Schaake et al., 1977) over all values is 0.97 (Silberhuette), 0.99 (Meisdorf), and 0.96 (Hausneindorf) and the root mean square error (RMSE) is 0.25 m^3/s (Silberhuette), 0.20 m^3/s (Meisdorf), and 0.44 m^3/s (Hausneindorf). This demonstrates a good model quality. Although the modelled water levels follow the shape of the measured water levels, they often exceed or fall below them. The deviation increases significantly for medium and high discharges. For low-flow phases, the modelled water levels show good agreement with the measured values. The RMSE for water levels resulting from discharge events below the mean minimum discharge (MNQ) is 0.09 m in Silberhuette, 0.06 m in Meisdorf and 0.12 m in Hausneindorf. These values indicate a very good model quality focussing on low-flow events. However, when all discharge events (including high discharges) are considered, the RMSE increases significantly, which indicates a decrease in the model quality. This results in RMSE of 0.36 m in Silberhuette, 0.19 m in Meisdorf and 0.50 m in Hausneindorf.

The results of the temperature modelling are shown in Figure 4. The water temperature of the Selke reaches 275 K (2°C) in winter and peaks between 295 K (22°C) and 300 K (27°C) in summer. The modelled temperatures largely correspond to the measured temperatures. The daily, seasonal, and annual variation in water temperature is well represented by the model. However, in winter, there is a permanent overestimation of the water temperature by the model. In addition, the extreme temperature peaks that occur in the measured values can only be partly reproduced. A further model quality evaluation is performed using the RMSE value. At the Silberhuette gauge, an RMSE of 1.84 K occurs, which is primarily due to the overestimation of water temperatures in the winter period and the overestimation of peak temperatures. The situation at the Meisdorf gauge is similar, but the RMSE is 2.70 K due to a higher overestimation. No measured temperatures are available for the Hausneindorf gauge within the calculation period. According to previous studies (for example, Caissie et al., 2007; Laanaya et al., 2017) a RMSE ≤2 K is generally considered as a good fit for water temperature modelling. Thus, the results at the Silberhuette gauge are good, but the Meisdorf gauge shows only sufficient results for water temperature modelling.

The results of the analysis of consequences are shown in Figure 5. The top graph shows the socio-economic consequences, defined as the deviation from the reference yield, for each hydropower plant in each year. Profits (positive values) and losses (negative values) are shown. The ecological consequences, which are analysed

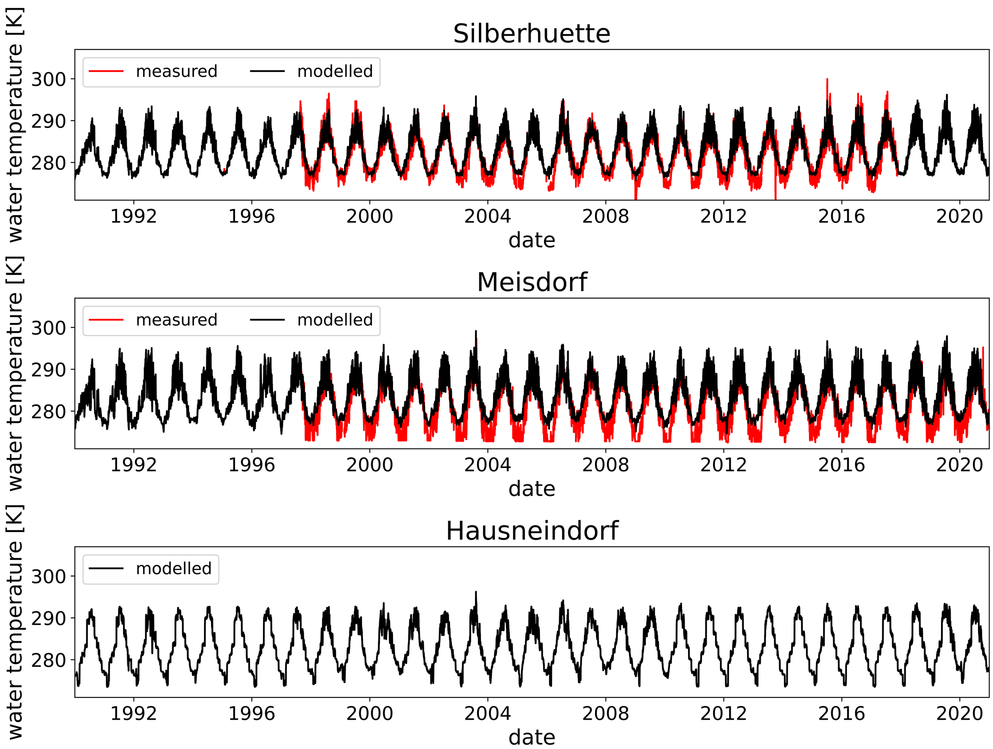

FIGURE 4 Measured values and modelled results of the temperature model (1990–2020) at the river Selke for the three gauges.

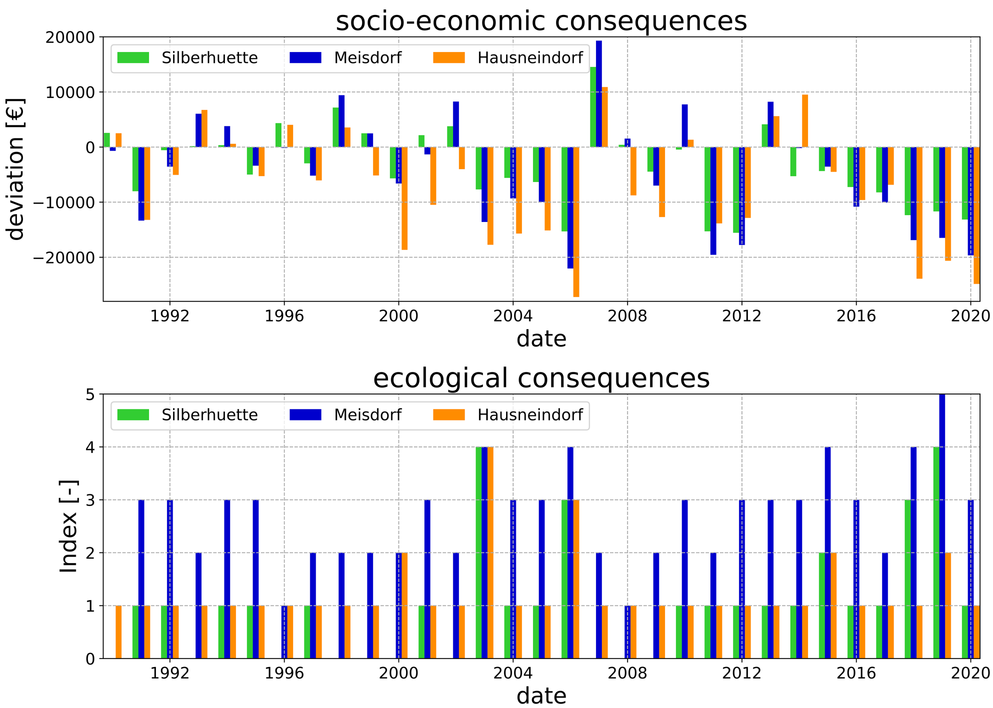

FIGURE 5 Results from the analysis of consequences based on fictitious consequences for the river Selke (1990–2020): socio-economic consequences (top); ecological consequences (down).

using an index-score, are shown in the diagram at the bottom. The heights of the bars indicate the (negative) impact on the ecosystem. The low-flow years 2006, 2015, and 2018–2020 can be clearly identified for both the socio-economic and the ecological consequences. Analysing the results of the socio-economic consequences, a total deficit of €113 190 results at the Silberhuette hydropower plant, with the highest losses of more than €15 000 per year occurring in 2006, 2011, and 2012, followed by the dry years of 2018, 2019 and 2020. The highest surplus was achieved in 2007 at €14 536. At the Meisdorf gauging station, the total deficit for the time period from 1990 to 2020 was €144 391, with the highest losses of more than €19 500 in 2006 and 2020. In 2007, the highest surplus was achieved with €19 297. At the Hausneindorf hydropower plant, the total damage amounted to €237 432, with the highest losses of more than €23 800 in 2006, 2020, and 2018. The highest surplus was recorded in 2007 at €10 882.

The ecological consequences are expressed by an index-score between 0 (no influence) and 5 (large negative influence). For the Silberhuette River section, the peak of negative ecological consequences occurred in 2003 and 2018 with an index-score of 4, closely followed by the years 2006 and 2019 with a value of 3. The sum of all values at the Silberhuette River section was 32. In the river section Meisdorf, the sum is significantly higher (82). In 2019, the poorest (from an ecological point of view) index-score of 5 was even reached. A poor index-score of 4 is reached in 2003, 2006, 2015, and 2018. At the Hausneindorf River section, the index-score of 4 is only reached in the dry year 2003. The consequences at the Hausneindorf River section show different behaviour than those of the other two river sections. At the Hausneindorf River section, the value 0 is never reached, whereas values above 1 are only reached in 5 years. Due to the accumulation of runoff along the river, very low water depths and flow velocities, which are used to assess the index-score, occurred less frequently in the downstream section. Simultaneously, a decrease in the longitudinal gradient results in a reduction in the overall flow velocity, which in turn results in a permanent index-score of 1. In addition, high water temperatures were rarely observed at the Hausneindorf gauge; hence, a temperature-related index-score rarely occurred.

The calculated total socio-economic risk (sector hydropower) is −15 968 €/year for the Selke catchment; the total ecological risk in the catchment is 1.65 index-score/year. Thus, it is obvious that low flow causes damage to water users (socio-economic) and ecosystems.

Analysing the spatial distribution of low-flow risk in the catchment, the socio-economic risk for the hydropower plant Silberhuette is 3651 €/year, for hydropower plant Meisdorf 4658 €/year, and for hydropower plant Hausneindorf it is 7659 €/year. Strong regional differences in ecological risk are stated by the model. While the risk in the Silberhuette and Hausneindorf River sections is quite moderate at 1.03 and 1.26 index-score/year respectively, the Meisdorf River section is the most severely affected, with a risk of 2.65 index-score /year.

4 | DISCUSSION

This novel method has not yet been subject to any comparative studies, and as a result, the incorporation of specialist literature is restricted to a minimal extent. One practical aspect of a risk-modelling approach based on long-term series is runtime. The high computational time requirement is a significant disadvantage of the long-term series approach. Mens et al. (2021) stated that the computation time for a 100-year time series is more than two months for their model. The model applied in this work has a reasonable calculation time of 18.5 min per modelled year. For the modelling of a 100-year time series, this would result in a runtime of approximately 31 h, which proves the feasibility of the approach in terms of run time. However, the addition of a 2D groundwater model, representing the proximity of the river, will significantly increase runtime. Additional optimization of the calculation time can be achieved by simplifying the used models. For instance, calculating just one groundwater layer in the groundwater model promises considerable time savings. It must be stated that a long-term series contains several years in which no low-flow events occur and which have no influence on low-flow events. However, when applying the long-term series approach, these years are completely calculated and cost valuable computational time. In contrast, in a scenario-based risk approach, only the relevant scenarios are calculated. Hence, the computation time is drastically reduced. Therefore, an approach would be conceivable that only uses modelling when low-flow conditions are present and does not include the times without these. Parallelization of computing operations and distribution across several CPU/GPU cores can save a considerable amount of time.

The amount of data generated is manageable at 0.185 GB/year, although there is still potential for optimization. Data requirements can play a role in large models in combination with long-term modelling.

The results of the 1D river model show good agreement, particularly for the low-flow phases. It must be stated that the influence of groundwater plays a decisive role in the Selke River during low-flow events. Mader et al. (2018) found in their study that the river Selke exfiltrates into the groundwater and that there is a reduction in discharge in the watercourse itself. In the wells investigated in the vicinity of the river Selke, the calculated proportion of river water from the Selke was 93%. This process is not yet represented by the model but will be implemented and tested at a later stage.

To evaluate the uncertainties associated with the hydrodynamic and temperature models utilized, the period from 1990 to 2020 was chosen, as it encompasses a timeframe during which water level, discharge, and temperature measurements are plentiful. To assess the outcomes, the root mean square error (RMSE) was employed, providing a clear indication of the level of uncertainty. As the hydrological data that was measured served as the boundary conditions, it is only influenced by the inaccuracy of the measured values, and not by the uncertainty of a model. The deviations in the water levels – especially for high discharge events – can be explained by particularly rough friction coefficients. The model was calibrated using the friction coefficients for low-flow events. In low-flow phases, the coarse bed material in the Selke causes strong frictional forces, which explains the required rough friction coefficients. By increasing the discharge/water levels, the frictional forces are reduced. The application of dynamic friction coefficients, which is not part of the applied hydrodynamic model, could significantly reduce the water level deviation for high discharge events. However, due to the strong focus on low-flow events, the inaccuracy of higher discharge phases is acceptable.

All gauges show excessively high temperatures during winter. A conducted sensitivity analysis showed that this was mainly attributed to the assumption of a constant riverbed temperature throughout the year. At the Silberhuette gauge, the temperature curve was close to reality. At the Meisdorf gauge, the temperature model shows a significant deviation with an RMSE of 2.70 K. The reason for the high deviations is presumably the missing temperature inflow from the tributaries. In the temperature modelling of the Selke, the temperature inflows from the tributaries are quite important as they usually have lower temperatures than the Selke itself. Thus, they exhibit a cooling effect. In the area between the Silberhuette and Meisdorf gauges, only two smaller tributaries could be identified for which information is available. Because of a lack of information, other cooling tributaries are not included in the model, resulting in an overestimation of the temperature at the Meisdorf gauge. However, the deviation of the temperature at the Meisdorf gauge has no significant impact on the test of the practicability of the risk approach in general.

The relationship between the modelled consequences and actual low-flow events in the Selke River has been thoroughly examined and the findings suggest a plausible connection. However, it should be noted that the data available are limited, making it challenging to provide a definitive validation of the modelled consequences.

The definition of consequences caused by low-flow appears complex because (potential) losses occur even in years with sufficient discharge. Due to the discharge dynamics of natural rivers the maximum possible yield cannot be achieved every day. By summing up all the considered years, it is possible to compare the modelled yield of the hydropower plant with the design yield: if the sum of all yields is negative, we consider a loss since the temporary losses and profits in some years have already been considered in dimensioning. In this context, the long-term approach appears highly suitable for modelling low flows and especially the consequences of low flows. The problem of defining damage resulting from low-flow events is similar to other socio-economic consequences, such as shipping or withdrawal restrictions.

The results of the ecological consequences also show good correlation with historic low-flow events. In addition, the water temperature, which can rise significantly as a result of heat periods, has a considerable influence on ecology. The increased index-score at the Meisdorf gauge is due to the high water temperatures. At the Hausneindorf gauge, the permanent index-score of 1 is due to the naturally higher water temperatures accumulating along the course of the river. The suitability of the simple rating system presented for the analysis of ecological consequences must be further analysed and improved, if necessary.

A significant concern associated with the consequences of low-flow is the lack of monitoring mechanisms. Unlike floods, the repercussions of low-flow are intricate and can span an extended duration. In numerous instances, there is no centralized data repository, rendering it practically impossible to assess the identified consequences. Therefore, the examination of consequences is often characterized by a significant degree of uncertainty. It is essential to record the consequences of future events in order to obtain comparable data for subsequent research.

The reliability of the proposed low-flow risk approach is heavily reliant on the reliability of the individual analyses within the complete model chain. Any uncertainties within these analyses are further spread through the model chain and have the potential to impact the overall risk analysis. Experiences from flood risk analysis show, that the analysis of consequences, which is based less on physical principles, introduces major uncertainties to the holistic analysis. This is also a finding of Mens et al. (2022). It is crucial to delve deeper into this aspect in future research. However, when testing this new risk analysis approach, the accuracy of the results has second priority, as the interaction of the different analyses and demonstrating the functionality of the approach are the main objectives.

5 | CONCLUSIONS

The consequences of low-flow events that have occurred along various rivers in Europe in recent years emphasize the necessity of low-flow risk management. The basis for risk management is a low-flow risk analysis. Current approaches are usually based on statistical or index-based analyses. In this study, we have presented a new holistic modelling approach for analysing low-flow risk based on a long-term-series. This seems to be more suitable for modelling the long-term characteristics of low-flow events. The complex scenario definition is avoided.

The risk approach was tested using a proof-of-concept modelling the river Selke between 1990 and 2020. A chain of models was applied, starting from hydrological runoff time series to hydrodynamic analysis and analysis of consequences. The 1D river model results showed good agreement for low-flow periods, with some deviations explained by the influence of groundwater and friction coefficients. Despite some limitations related to the absence of temperature boundary information, the temperature model also seems to be adequate to demonstrate the functioning of the risk approach. Although the analysis of the consequences is based on fictitious consequences, both socio-economic and ecological consequences correlate well with known low-flow events in recent years. The calculated risk of −15 968 €/year for socio-economic consequences and 1.65 index-score/year for ecological consequences emphasizes the damage that low-flow events can cause to both water users and ecosystems.

Within low-flow risk management, the risk analysis has multiple purposes. Analysing the low-flow risk for the status quo of the catchment helps to identify existing problems related to socio-economic water users or ecological aspects. The risk analysis and the generated information also support the pre-design of mitigation measures. The reduction of low-flow risk in the catchment due to the implementation of a measure provides a powerful quantitative value to evaluate the performance of a measure. Finally, a risk analysis supports the evaluation and interpretation of future system states, which are mainly shaped by climate or socio-economic changes. In both cases (measure implementation and future system states), a second risk analysis (compared to the status quo) is required.

Overall, this study confirms the applicability of the proposed low-flow risk-modelling approach.

The presented approach can be utilized in other catchments situated within moderate climate zones. More extensive application and evaluation of the method are desirable to identify any shortcomings and enhance its effectiveness.

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CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest for the authors or co-authors.

DATA AVAILABILITY STATEMENT

The data used in this study, with the exception of the measured water temperatures, are accessible and can be requested from the author if required. Similarly, the software (LOFLODES: https://github.com/dabachma/LoFloDes) and Python scripts used are also available.

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