



Analysis of drought conditions and their impacts in a headwater stream in the Central European lower mountain ranges

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Received: 12 April 2021 / Accepted: 16 April 2022
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Abstract

Headwaters represent a significant fraction of the global stream length and are important for streamflow quality and quantity. Since climate change is predicted to affect runoff generation processes fundamentally, it is essential to understand potential consequences for the water availability in headwater catchments. The Lehstenbach catchment, located in the Fichtel Mountains (Germany), represents many headwater catchments in the lower mountain ranges in Central Europe. This study's primary objective is to predict and analyze potential shifts in the catchment's water balance, estimate periods of hydrological drought conditions, and their characteristics. For this purpose, we used an integrated process-based hydrological model to represent surface/groundwater interactions and runoff generation mechanisms for the Lehstenbach catchment until 2100, using a Regional Climate Model Ensemble. The simulations indicate decreased water availability in summer and autumn, mainly due to increased evapotranspiration rates. The Minimum Environmental Flow (MEF), a quantitative measure of aquatic species' exposition to abnormally low streamflow conditions, implies an increase of low flow conditions towards 2100. A first estimate indicates a possible increase of hydrological drought duration and intensity in the future. These findings suggest severe impacts on ecosystem health and services, such as decreasing water availability, leading to consequences like forest and wetland degradation and declining biodiversity. These findings can be used to implement suitable mitigation strategies to reduce climate change effects on the headwater ecosystems, such as water shortage for irrigation and drinking water supply and loss of flora and fauna.

Keywords Central European headwater · Climate change · Drought · Minimum environmental flow

Introduction

Headwaters account for 89% of the global stream length (Downing et al., 2012; Allen et al., 2018) and are integral to every river continuum. They are characterized by complex ecosystems that provide many functions and services, such as sediment and pollutant control, water cooling, water purification, nutrient enrichment of water for downstream fauna and flora, and erosion slowing (Kaplan et al., 2008).

However, headwaters without storage reserves (i.e., lakes or snowpacks) are also prone to suffer the consequences of climate change more drastically (Bennett et al., 2012) due to their perennial dependence on precipitation. Hence, they are more sensitive to warmer air temperatures, altered precipitation regimes, and land-use change, potentially leading to decreased water availability than rivers and streams with higher discharge and larger and more diverse catchment areas. Riparian wetlands are often part of headwaters and act as water retention areas during flooding, and storage and release areas during drought conditions (Fossey and Rousseau, 2016; Hokanson et al., 2020). Besides rainfall inputs, riparian wetlands can also receive water directly from the local aquifer (Dwire et al., 2018), making them vulnerable to water table fluctuations. As water saturated areas, wetland ecosystems depend on permanent water availability, and their ability to function decreases in dry periods.

Stream discharge is a crucial component of ecosystem functionality. It is the basis for runoff in downstream

Communicated by Arpita Mondal.

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reaches, often serving as drinking water and irrigation supply, habitats for many aquatic species, and water sources for many terrestrial species (Gomi et al., 2002). Extended low flow periods (weeks to months), i.e., hydrological drought, threaten these sensitive ecosystems through high water temperatures and low water availability. Prolonged low flow conditions can accelerate nutrient transformation and increase oxygen depletion, endangering species in the entire river ecosystem (Freeman et al., 2007). Water availability in rivers and streams is usually directly correlated to high temperatures and evapotranspiration rates (Teuling et al., 2013).

The IPCC (2014) predict an increase in frequency and duration of extreme climatic events until 2100. In general, floods have been investigated intensively for a long time due to their sudden and powerful destructive nature. While van Loon (2013) states that drought events only recently received growing attention, Spinoni et al. (2018) stress that past drought events were analyzed extensively. However, they point out that possible future drought conditions did not receive much attention yet. They also state that there is still no consensus whether Europe might experience more frequent and more prolonged drought conditions in the future. Huang et al. (2015) investigated the potential consequences of an increased likelihood of flooding and drought events for Central Europe. Zerbisch et al. (2005) highlighted an increasing flood probability in general and overall decreasing water availability in rivers and streams during summer. Pfeifer et al. (2015) confirmed the decreasing water availability with a predicted reduction of snowfall and increased precipitation events during the winter months and a possible decrease of precipitation during summers.

Bernsteinová et al. (2015) and Beudert et al. (2018) investigated the effects of climate change on two headwater catchments located in Central Europe from 1978 to 2013. They found evidence that mainly temperature increase (i.e., increased evapotranspiration) is responsible for runoff decreases. Also, Poschlod et al. (2020) investigated different types of headwater catchments in Central Europe and found that flow regimes shift in many of them. Considering rain-driven catchments only, they found a clear trend towards increasing runoff rates in winter and decreasing runoff rates in summer and autumn (May to Oct) in the next 80 years. To the author's knowledge, there are no studies targeting drought characteristics in Central European headwater catchments with a large proportion of riparian wetlands. However, these headwaters are common in the lower and middle mountain ranges of Central Europe, and prolonged drought events endanger their hydrological and ecological functionality. They play an essential role in providing ecosystem services and functionality, including streamflow and sediment control and vital habitats for many organisms.

To investigate how water availability in the future might develop for these catchments, scientists often use modeling

chains consisting of different models and methods. Global Climate Models (GCM) predict the general climate for regions worldwide with varying grid size resolution, depending on the GCM. For example, the two GCMs used in this study have grid sizes of 80 km (Haarsma et al., 2020) or 200 km (Mauritsen et al., 2019). Since the grid-cell areas of the GCMs (i.e., 6400 or 40,000 km²) are often much more extensive than typical headwater catchment areas (i.e., usually below 10 km² (Hill et al., 2014)), there have been methods developed to downscale these projections to a much higher resolution of about 5 km × 5 km grids. Regional Climate Models (RCM) are applied to incorporate regional climate patterns. Downscaling methods are implemented and reviewed in Teutschbein and Seibert (2012) and Teutschbein et al. (2011).

Since this is an ongoing area of research and insights are still developing, many studies investigating future climate change effects on headwater catchments often lack sophisticated methodical combinations introducing unnecessary high biases. Teutschbein and Seibert (2010) state in their review that only one-third of their analyzed studies use an RCM ensemble, i.e., a multi-member model approach. The choice of the ensemble members plays an important role. For example, Poschlod et al. (2020) use an ensemble; but they only analyze the RCP 8.5 (highest emissions) scenario. Bürger et al. (2007) only uses the A2 scenario to simulate future streamflow in Spain. Since all scenarios must be viewed as equally probable (i.e., we cannot foresee future developments), this selection introduces a considerable bias. Sometimes, there are no specifications on the bias correction methods used, leading to the assumption that none have been applied. Fortunately, recently, the number of studies applying downscaled, bias-corrected GCM-RCM ensembles is increasing (e.g., Su et al., 2017; Givati et al., 2019; Rodrigues et al., 2020), providing more reliable and understandable results. The choice of the hydrological model applied is also essential. Goderniaux et al. (2009) and Faticchi et al. (2016) state that process-based models can predict potential changes caused by climate change better than conceptual or statistical models. They are adaptive to new patterns and depend less on static environmental variables (e.g., in process-based models, evapotranspiration rates are calculated based on soil moisture instead of fixed parameters).

With this study, we want to contribute to this ongoing research topic by investigating the potential effects of climate change on water balances of headwater systems and the evolution of drought events, including their frequency, intensity, and duration in the Central European lower mountain ranges. Our study will focus on investigating and predicting the likelihood of hydrological drought conditions, because of humanly induced climate change, for a small headwater (Lehstenbach catchment) located in South-East Germany. The Lehstenbach catchment was the object of

various environmental studies over the last 30 years (Lüers et al., 2017). This catchment represents many catchments in Central Europe with a larger fraction of riparian wetlands, no water-course constructions, and regular logging. We use a climate change ensemble with 19 members of three different climate projections from two global climate models. By implementing the process-based model, HydroGeoSphere (Aquanty Inc., 2015), we can not only calculate the water balance explicitly both on the surface and in the subsurface, but we can also simulate water movement in the saturated and unsaturated zone and surface/groundwater interactions. We can account for different runoff generation mechanisms. We want to identify how a shift in water balance will impact the future water availability in the Lehstenbach catchment, focusing on drought conditions. Will stream discharge rates decline in the future and thus provide less available water for the ecosystem? Will water availability for flora and fauna

be sufficient in the future? Are drought conditions increasing, and if so, what are the potential consequences for the ecosystem?

Data and methods

Study site

The Lehstenbach catchment (4.2 km²; 695–877 m a.s.l., Fig. 1), located in the Fichtel Mountains (SE Germany), has been studied extensively since 1986 (Heindl et al., 1995). The catchments' climate is classified as humid continental (Peters and Gerchau, 1995), with an average annual air temperature of 6.5 °C and an average total precipitation rate of 1038 mm (Lüers et al., 2017). Preliminary climate data (1970–2000) published in Gerstberger et al. (2004) showed

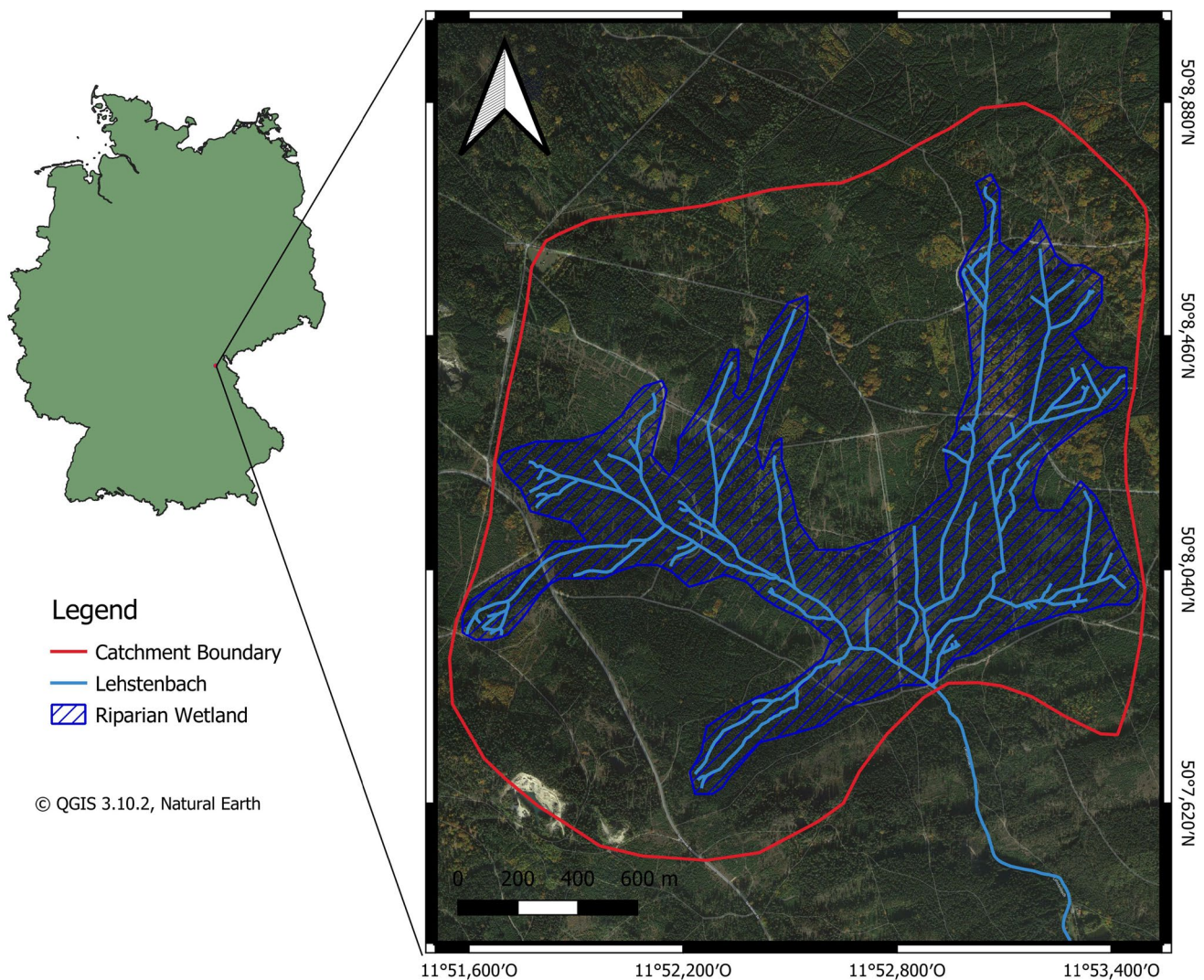


Fig. 1 Map of the Lehstenbach catchment, with catchment boundaries, stream, and wetland areas

an average annual temperature of 5.3 °C and annual precipitation of 1156 mm, indicating a shift towards dryer and warmer conditions. A clear seasonality is apparent with a minimum average temperature of -2.6 °C in January and 16.0 °C in July. Precipitation is distributed equally over the whole year, with 26% in winter, 21% in spring, 29% in summer, and 25% in winter of the total annual precipitation.

During the 1990s, a large-scale research project investigated the catchment concerning acid rain and ecosystem functionality in detail. Lüers et al. (2017) published their results in the context of past climate changes. They found shifting conditions from an entirely humid climate to the appearance of at least one dry season and hot instead of warm summers. Additionally, they found a past continuous temperature increase of 0.4 K every 10 years and a regime shift towards alternating prolonged dry and intensive rain phases from spring to autumn.

Due to ore mining since the eleventh century and peat digging, the forest has been anthropologically altered, including periods of deforestation and reforestation and dug peat areas (Heindl et al., 1995). Norway Spruce (*Picea abies* (L.) KARST.) covers the catchments' slopes with some individual beech (*Fagus sylvatica*), white fir (*Abies alba*), and maple (*Acer pseudoplatanus*) stands (Gerstberger et al., 2004). About 30% of the catchment's area is classified as riparian wetlands (Partington et al., 2013) containing species such as *Dicranum scoparium*, *Brachythecium curvifolium*, *Plagiothecium undulatum*, and *Polytrichum formosum* (Gerstberger et al., 2004). The riparian areas are mainly

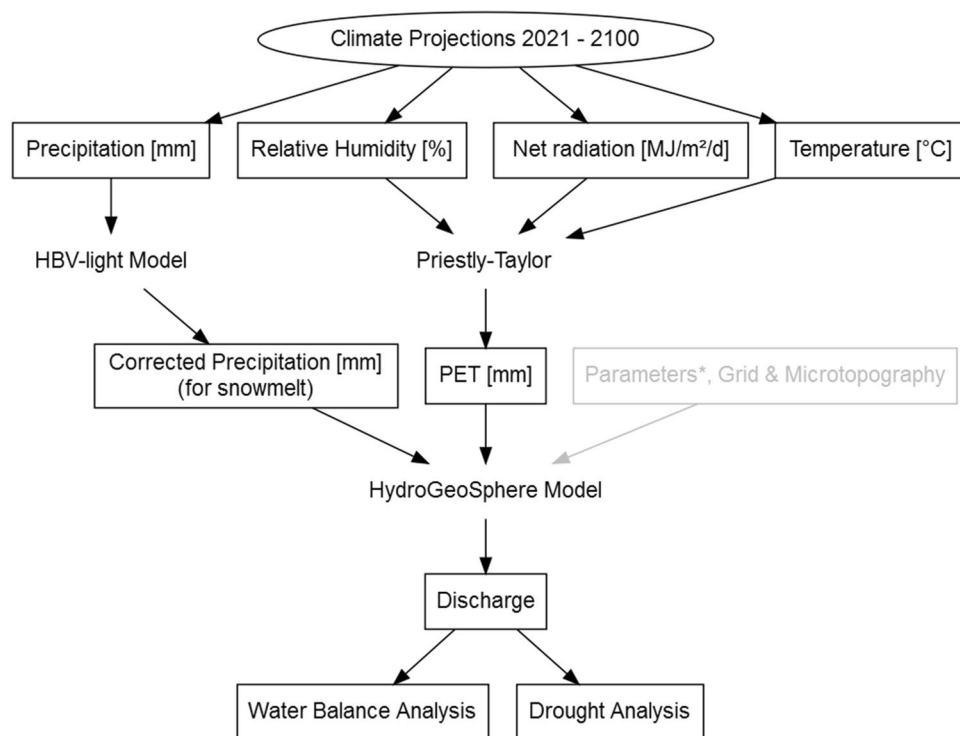
characterized by groundwater-fed, peaty mires with some isolated peat bog structures. These areas are located along the stream, can harbor great biological diversity, maintain bank stability, and reduce flood and drought peaks.

The aquifer consists of regolith, a porous and highly permeable material produced by the weathering of granite. The average thickness of the regolith aquifer in the catchment is about 20–30 m and overlies a Variscian granite bedrock. The base flow originates from this aquifer. Detailed information about the catchment's geology and the groundwater aquifers can be found in Partington et al. (2013). The stream's discharge is mainly generated in the dissolved-organic carbon-rich wetland areas (Strohmeier, et al., 2013), which are close to the catchment's outlet (Partington, et al., 2013). Frei et al. (2010) found overland flow due to micro-topographical structures (i.e., hollows and hummocks) dominating the discharge during rainstorms. Once the depressions are filled, water starts to drain in channels to the stream. Otherwise, rainwater infiltrated the subsurface. Further details on discharge generation processes can be found in the Supplementary Material.

Hydrological modeling

To simulate the future catchment's water balance, we used the fully integrated surface–subsurface hydrological model HydroGeoSphere (Therrien et al. 2010) coupled with climate projections, as shown in Fig. 2. The model was already calibrated and validated for the Lehstenbach catchment by

Fig. 2 The flow chart depicts how climate projection time series were prepared for hydrological model input. Precipitation data were corrected for snowmelt, and potential evapotranspiration (PET) was calculated after Priestly-Taylor. Discharge was calculated with the processed-based hydrological model HydroGeoSphere, which was already established for the catchment. Parameter determination and calibration (*for soil, vegetation, and transport), grid details, and microtopography are gray since they were not part of this study



Partington et al. (2013), based on a previous study on micro-topography of the Lehstenbach wetland by Frei et al. (2010). We applied the logarithmic Nash–Sutcliffe Efficiency (NSE) to assess calibration and validation performance to account for systematic over- and underprediction, the coefficient of determination r^2 , and the Percent Bias (PBIAS). The catchment’s topography is represented by a Digital Elevation Model (DEM) with a spatial resolution of 5×5 m. Daily input time series include precipitation and potential evapotranspiration. The meteorological data for calibration and validation was provided from the Waldstein climate station. Further details are shown in the Supplementary Material.

Climate change scenarios

We analyzed three Representative Concentration Pathways (RCP): 2.6, 4.5, and 8.5, named after their net radiative forcing in 2100 (Van Vuuren et al., 2011). The RCPs are “representative” for a range of scenarios with similar assumptions. However, as Van Vuuren et al. (2011) stress, that there is no probability of occurrence attached, meaning each RCP must be treated equally probable. We examined seven combinations of Global and Regional Circulation Models (GCM and RCM, respectively) for RCP 8.5, six combinations for RCP 4.5, and six for RCP 2.6 (see Table 1 for further details).

In detail, the projections are based on two different GCMs. The EC-EARTH is a joint European global climate model (Hazeleger et al., 2010). The MPI-ESM is a global climate model developed by the Max-Planck Institute in Germany (Mauritsen et al., 2012). The Bavarian State Office for Environment provided the data and averaged it over 60 grid cells with an area size of 1500 km². Results of the data evaluation are presented in the Supplementary Material and demonstrate a good agreement between climate projections and past measurements. Although a new climate model generation is now available, climate projections applied in this study are based on Coupled Model Intercomparison Phase 5 (CMIP5) generation models. The hydrological simulations started in 2019, when downscaled and bias-corrected CMIP6 projections were not available for Bavaria yet. Discharge was simulated for every climate projection individually, summing up to 19 model runs. We performed equal-weighting averaging to calculate the ensemble mean, where each ensemble member receives one vote.

As input for the HydroGeoSphere model, we used simulated climate time series that reach 2100. The Bavarian State Office for Environment pre-processed this data. Scenarios were provided already selected, downscaled, bias-corrected, and averaged over a suitable grid cell number. The selection process included an analysis of suitability for Bavaria.

Table 1 Overview of the average annual temperature [T, °C] and the total annual precipitation [P, mm] for all climate change scenarios, including their Global Climate Model (GCM) and Regional Climate Model (RCM) combination with Abbreviation (Abbr.). The last col-

umn (Δ 2021–2100) provides the difference of the average air temperature and precipitation between the near (2021–2050) and the far (2071–2100) future

	Model			1994–2018		2021–2050		2071–2100		Δ 2021–2100	
	GCM	RCM	Abbr	T [°C]	P [mm]	T [°C]	P [mm]	T [°C]	P [mm]	T [°C]	P [mm]
RCP 8.5	EC-Earth	KNMI-RACMO22E r1	EC-KNMI1	7.2	896	7.8	973	10.1	921	+2.3	−52
	EC-Earth	KNMI-RACMO22E r12	EC-KNMI12	7.1	917	8.2	981	10.7	993	+2.5	+12
	EC-Earth	CLMcom-CCLM4-8–17	EC-CLMcom	7.3	952	8.1	1024	10.4	1034	+2.3	+10
	EC-Earth	SMHI-RCA4	EC-SMHI	7.2	977	7.9	974	10.2	1040	+2.3	+66
	MPI	CLMcom-CCLM4-8–17	M-CLMcom	6.9	947	7.3	974	9.5	991	+2.3	+17
	MPI	SMHI-RCA4	M-SMHI	7.0	915	7.5	935	10.1	1035	+2.6	+100
	MPI	UHOH-WRF361H	M-UHOH	7.0	947	7.4	912	9.5	895	+2.1	−17
RCP 4.5	EC-Earth	KNMI-RACMO22E r1	EC-KNMI1	7.2	933	7.7	932	8.6	981	+0.9	+49
	EC-Earth	KNMI-RACMO22E r12	EC-KNMI12	7.2	938	8.0	954	9.0	1015	+1.0	+61
	EC-Earth	CLMcom-CCLM4-8–17	EC-CLMcom	7.2	972	8.0	998	9.0	1034	+1.0	+36
	EC-Earth	SMHI-RCA4	EC-SMHI	7.1	975	8.1	940	8.9	971	+0.8	+31
	MPI	CLMcom-CCLM4-8–17	M-CLMcom	6.9	940	7.4	980	8.1	985	+0.7	+5
	MPI	SMHI-RCA4	M-SMHI	7.0	925	7.6	964	8.5	989	+0.9	+25
RCP 2.6	EC-Earth	KNMI-RACMO22E r12	EC-KNMI12	7.2	1009	7.7	986	7.9	1020	+0.2	+34
	EC-Earth	CLMcom-CCLM4-8–17	EC-CLMcom	7.2	992	7.5	945	7.7	973	+0.2	+28
	EC-Earth	SMHI-RCA4	EC-SMHI	7.2	996	7.8	942	8.0	958	+0.2	+16
	MPI	CLMcom-CCLM4-8–17	M-CLMcom	6.6	930	7.5	1023	7.4	971	−0.1	−52
	MPI	SMHI-RCA4	M-SMHI	6.7	898	7.9	1010	7.7	966	−0.2	−44
	MPI	UHOH-WRF361H	M-UHOH	6.8	924	7.7	947	7.8	884	−0.2	−63

In detail, a reference data set (1970–2000) was created for Bavaria based on observed data, which was corrected for elevation and interpolated with inverse distance weighting. Several bias indicators (e.g., annual mean, monthly mean, seasonal, and spatial deviation) were chosen to compare the reference data set and the climate projections. Plausibility was tested in two steps: (1) all climate projections were excluded from institutions, for example, the German Meteorological Society, already excluded from the German climate ensemble. Moreover, (2) the projections are tested for their reliability to provide realistic daily climate values. Further details can be found in the climate change projection documentation of the Bavarian State Office for Environment (2020). The original data set was selected from the EuroCORDEX (2020) and ReKliEs-DE (2020) projects.

Downscaling is done to overcome the too coarse scaling of Regional Climate Models, increasing the resolution from 12.5 to 5 km. In that way, one can account for natural climatic variability on a local scale, as Marke (2008) states. A remapping method based on regression analysis to account for the local topography was implemented. For bias correction, quantile delta mapping after Mpelasoka and Chiew (2009), Teutschbein and Seibert (2012), and Cannon et al. (2015) was applied, which Willkofer et al. (2018) found to be the best method at this time. It aims at fitting the simulated time series distribution function to the observed one by keeping the relative changes of the climate variables. By including a larger number of grid cells (in our case, 60), we could minimize uncertainties stemming from single time series by averaging these.

Drought indices

To analyze drought events, we applied the Standardized Streamflow Index (SSI) (Modarres, 2007), as recommended by the World Meteorological Society (Svoboda and Fuchs, 2016). Discharge time series were utilized as input. Further details can be found in the Supplementary Material.

To make any assumptions about the impact of a drought on the ecosystem, we applied a threshold-based method to identify the frequency and duration of critical streamflow rates. As a threshold, we used the reference Minimum Environmental Flow (MEF) for small rainfall-rich streams in the lower mountain ranges (Bavarian State Office for Environment, 2017, p.53), which is 0.25 mm d^{-1} for the Lehstenbach catchment. The MEF was calculated based on ecological data, which is much more reliable than other standard methods, such as Q95 or Tennant, as Nikghalb et al. (2016) stated. The MEF is an important indicator of ecosystem health. The value was calculated as a guiding value for different stream types in Bavaria to keep or improve fluvial ecosystem health according to the Water Framework Directive of the European Union, as described in Bavarian

State Office for Environment (2020). It is based on minimum water availability for macrozoobenthos as well as fishes. These taxonomic groups are susceptible to low discharge values due to less available dissolved oxygen (i.e., higher water temperatures) and its consequences.

Results

Model performance

The process-based model was calibrated (11/2000–10/2001) and validated (11/2001–10/2006) with daily time steps. These relatively short periods for calibration and validation are typical for integrated hydrological models, as demonstrated by De Schepper et al. (2017), Glaser et al. (2016), and Cornelissen et al. (2013). Due to the high computational demand, the model takes up to 7 days to calculate the output for a single year (i.e., calibration period). Hence, a manual calibration was necessary. The comparably long validation period was applied to demonstrate reliable calibration results. This approach is common for HydroGeoSphere models, as the studies cited above demonstrate. To evaluate climate change impact, model results are satisfactory. The log NSE are 0.67 and 0.64 and the r^2 values are 0.74 and 0.69, for calibration and validation, respectively. The Percentage Bias (PBIAS) is 8.9% and 11.6% for calibration and validation, respectively. HydroGeoSphere simulated discharge very well for base flow conditions, as seen in Fig. 3. The simulation proved challenging when high flow conditions were encountered since peak discharges were often systematically underestimated.

Impacts of climate change on discharge in the Lehstenbach catchment

The water balance of a catchment represents the balance of precipitation, actual evapotranspiration, discharge, and storage change. These components can aid in understanding shifting hydrological conditions. In further analysis, the average water balance components change between the near future (2021–2050) and the far future (2071–2100) were compared. Precipitation (P) is the sole water input in the studied catchment. The results are depicted in Table 2.

The ensemble mean annual P is projected by the models used in this study to increase by 22 mm between the near and far future (Fig. 4A). While the applied projections for RCP 4.5 show the largest increase with 35 mm a^{-1} , for RCP2.6, they show a decline of precipitation of 11 mm a^{-1} . In general, 84% of all simulations showed increasing annual P rates. Snow is considered as solid precipitation, occurring when the air temperature drops below a certain temperature threshold. HBV-light simulates snow as snow

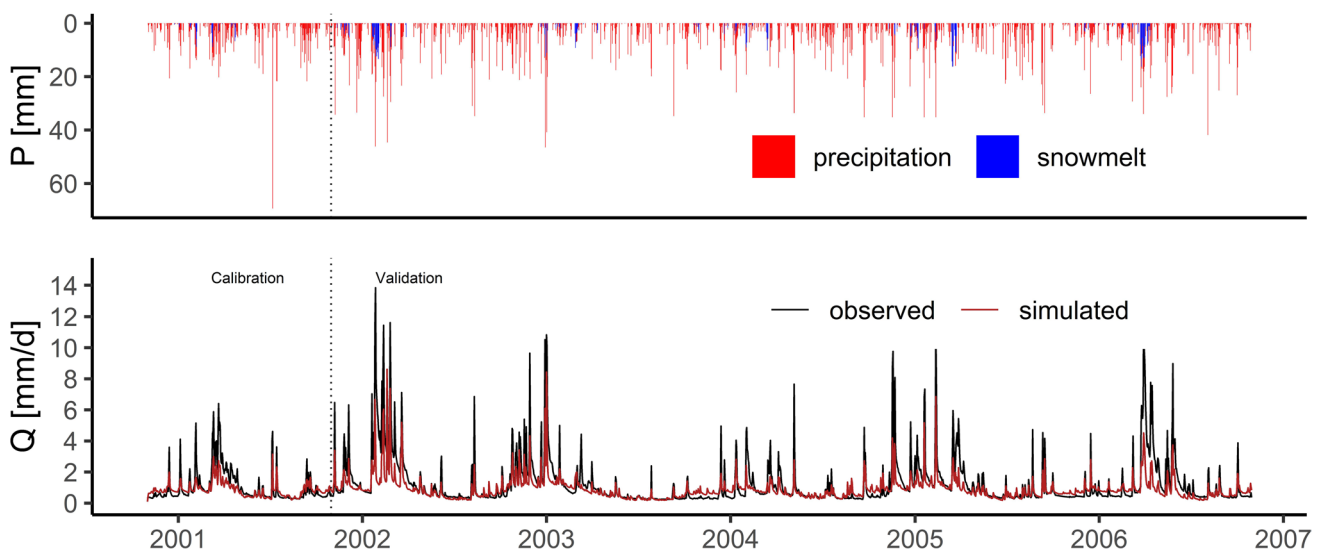


Fig. 3 Calibration and validation of the Lehstenbach catchment model from 11/2000 to 10/2006. Evaluation metrics show satisfactory results for log NSE, r^2 , and PBIAS

Table 2 Overview of the water balance components. Values are depicted as change between near (2021–2050) and far (2071–2100) future. Precipitation (P), Snow Water Equivalent (SWE), Actual Evapotranspiration (AET), and Discharge (Q) are compared using average annual values. The annual and seasonal values are provided for the catchment’s water balance (P-AET) and the difference in storage (ΔS)

Δ far, near future [mm/year]	Ensemble mean	RCP2.6	RCP4.5	RCP8.5
P	+22	-11	+35	+20
SWE	-10	-3	-5	-20
AET	+26	+1	+17	+61
Q	-1	± 0	+13	-27
P-AET	-18	-11	+18	-42
Winter	+8	-11	+16	+20
Spring	+10	± 0	+17	+12
Summer	-27	-1	-14	-65
Autumn	-9	2	-2	-9
ΔS	± 0	± 0	+1	-1
Winter	+1	-1	+1	+4
Spring	+1	± 0	+1	+1
Summer	-3	± 0	-2	-6
Autumn	+1	+1	± 0	+1

water equivalent (SWE). Between the near and far future, a reduction of the annual SWE of 10 mm is observed in the simulations. The most considerable reduction of SWE has been simulated for the RCP 8.5 projections with 20 mm a^{-1} .

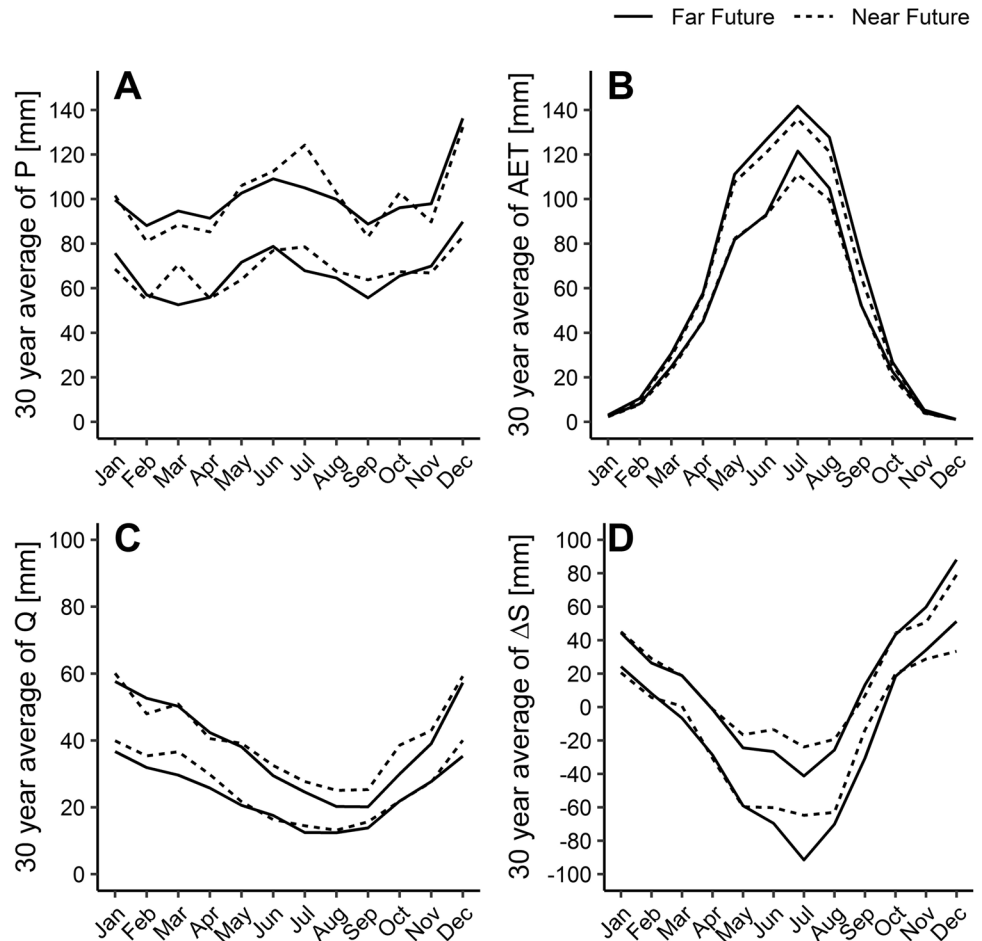
Actual evapotranspiration (AET) was estimated as a function of potential evapotranspiration, soil moisture, and vegetation parameters. Overall, 74% of all climate change

simulations show an increase in AET. AET strongly correlates to the temperature increase caused by the varying radiative forcings (i.e., more substantial increase with RCP 8.5 and smaller increase with RCP 2.6). The ensemble mean depicts an increase of the mean annual AET of 26 mm (Fig. 4 B).

Comparing P and AET’s change, we would expect discharge (Q) to show declining rates. However, there is no clear trend visible in the data, quickly recognized when looking at the ratio of simulations showing increasing (58%) and decreasing (42%) Q rates. For RCP 8.5, the average annual Q is dropping by 27 mm, which was expected since AET is increasing three times as much as P. Regarding RCP 4.5, the average yearly Q increases by 13 mm. This is consistent with the increase of P compared to AET with a factor of two. For RCP 2.6, the average annual Q is neither increasing nor decreasing, which is also plausible when we view the decreasing P rates in the context of slightly increasing AET rates. The ensemble mean Q change depicts a decrease of 1 mm.

While the annual Q shows no clear trends towards the end of the century, a seasonal change is easily detectable (Fig. 4C). When comparing the mean daily Q across months, one can see a widening of the envelope containing all simulations during winter and a narrowing during summer until the end of the century. The simulations imply that during the winter months, Q rates might become more variable but remain constant on a high level. Contrary, during the summer months, Q rates might decline more sharply in the far future (2071–2100) with less variability and remain, especially from June to October, below the level seen in the near future (2021–2050).

Fig. 4 Visual summary of water balance components averaged over 30 years for near (2021–2050) and far future (2071–2100). The components are depicted as ranges (minimum to maximum) of all climate change projections, where the dotted lines show the near future range, and the solid lines the far future range. **A** averaged total monthly Precipitation (P) in [mm month⁻¹], **B** averaged total monthly Actual Evapotranspiration (AET) in [mm month⁻¹], **C** averaged total monthly Discharge (Q) in [mm month⁻¹], and **D** averaged total monthly Storage deficit (ΔS) in [mm month⁻¹]. Envelopes contain all climate change projections



This behavior is consistent with the results shown in Table 2. For RCP 8.5 and RCP 4.5, simulation results point to the same trends. During winter and spring, water availability is high and even increases towards the end of the century. In contrast, in summer and autumn, water availability is much lower and decreases further. In winter and spring, P rates are increasing much more than AET rates, and vice versa for summer and autumn. RCP 2.6 members behave differently with decreasing water availability in winter, spring, and summer and increasing autumn availability. This could be due to decreasing precipitation rates in winter and spring.

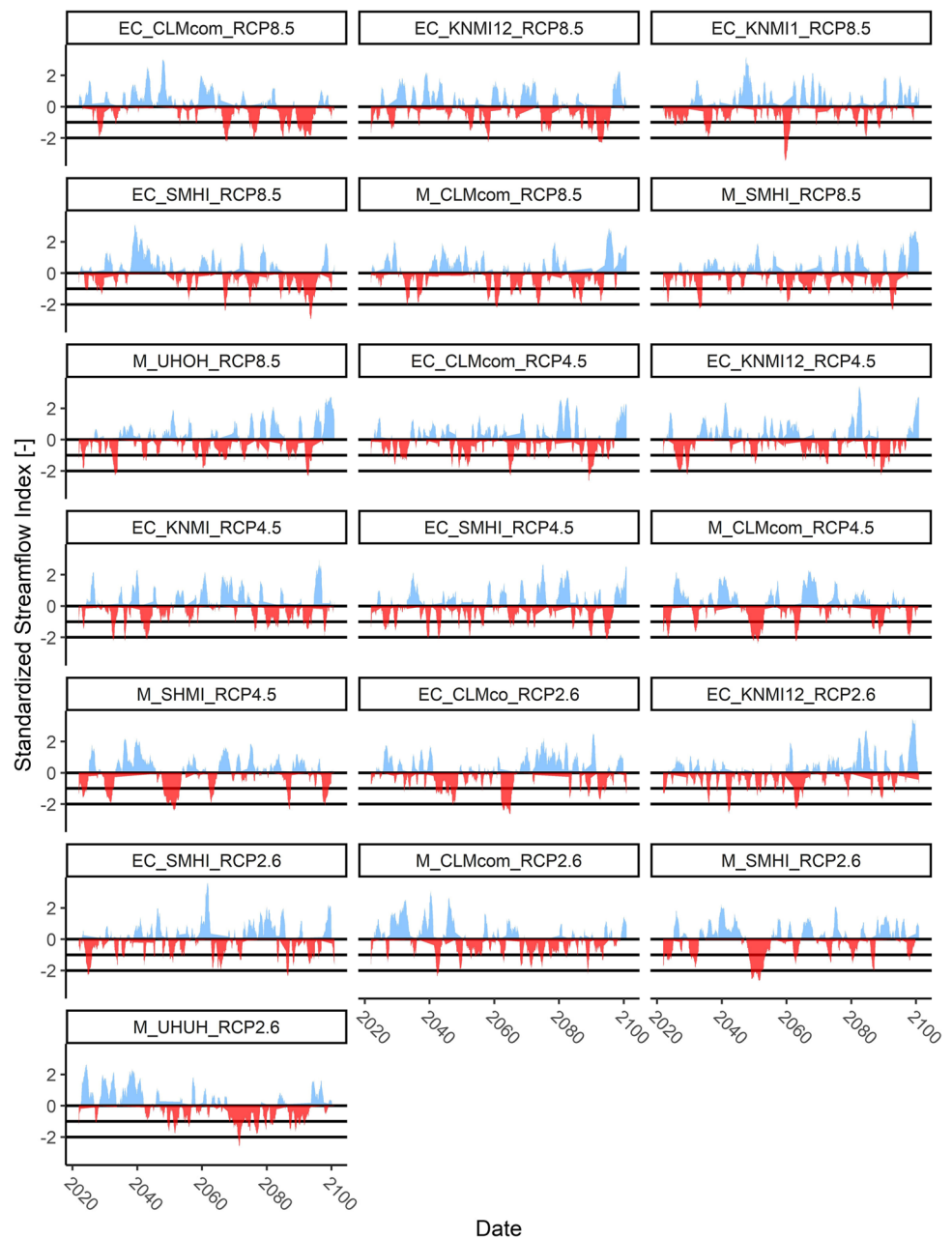
Water can be stored in the soil and groundwater in a catchment. Long-term storage (ΔS) changes can provide a more in-depth insight into a catchment's water balance. Considering storage changes between the near (2021–2050) and far (2071–2100) future (Fig. 4D), continuous decreasing water storages of 0.2 mm a^{-1} can be seen in general. However, this result is mainly due to the RCP 8.5 simulations, which show average decreasing water storage of 1.0 mm a^{-1} , while RCP 4.5 show average increasing storage of 0.7 mm a^{-1} and RCP 2.6 a stable storage. Seasonal changes indicate increasing water storage towards the end of the century in winter, spring, and autumn for RCP 8.5, with a large storage

loss in summer. While RCP 4.5 showed the same patterns, absolute values are much lower, leading to a positive storage balance. RCP 2.6 showed minimal changes with decreasing winter storage and increasing storage components in the remaining seasons.

The Standardized Streamflow Index (SSI) is a popular method to detect drought events in a time series and aids in determining drought characteristics. This knowledge can help in understanding possible impacts on a watershed's ecosystem. The index returns a dimensionless value ranking a month after its dryness (see the “Drought indices” section for further explanation). The analysis (Fig. 5, further details in the Supplementary Material) is performed for each month separately to disregard annual and seasonal patterns. When the SSI drops below -1 , drought conditions start in the catchment and continue until the SSI rises above zero. The ensembles mean number of drought events averages to 1.3 events per decade in the next 80 years.

Compared to regular and wet months, the proportion of drought months averages to 31.0%, which means that one-third of all months can be defined as “dry.” The ensembles average drought duration accumulates to 28 months, i.e., 3.5 months per decade. Drought intensity was analyzed by

Fig. 5 Standardized Streamflow Index for all 19 simulations. Wet and dry conditions are marked by colors (blue and red, respectively). Black horizontal lines indicate index value 0 (drought ends), -1 (drought begins) and -2 (extreme drought begins)



evaluating events when the SSI falls below -2, indicating extreme drought conditions. The duration of such extreme events averages to 34 months, with a frequency of one occurrence every 40 years.

We compared these findings to the SSI from a past 30-year period (1987–2016). The index is comparing the deviation from the average streamflow, which presents the opportunity to compare past and future streamflow properties. We can identify an increase in duration (+11 months) and a decrease in frequency (-0.6 events) compared to the future simulations’ ensemble mean. However, extreme events show an increase in average duration (+15 months) and a stable frequency with 0.4 events per decade.

Comparing drought characteristics between the near and far future allows us to evaluate the change of future drought properties. For RCP 8.5, we see both a general increase in drought duration and frequency, and extreme drought duration and frequency for the far future. However, for RCP 4.5, we observe a decrease in drought duration and an increase in drought frequency, in general. For extreme events, we see no change in duration and a reduction in frequency. RCP 2.6 shows decreasing drought duration and frequency in general, but the increasing duration of extreme drought events and no change in frequency. Averaging these different behaviors to an ensemble mean, we find a general increase in duration and frequency for

both drought intensities and extreme drought events for the far future.

A threshold-based approach was applied to analyze the possible impacts low-flow conditions have on the ecosystem. The Minimum Environmental Flow (MEF) is an essential indicator for ecosystem health. It describes the minimum discharge needed to provide water with tolerable temperature and oxygen content for organisms. In the past 30 years (1987–2016), the discharge was below MEF for 7 days per year on average. These low discharge values appeared in 27% of the observed years. Considering the whole future ensemble, both duration, and frequency of discharge below MEF increase towards the end of the twenty-first century. However, the RCPs show very variable results. While RCP 8.5 shows the largest increase of duration and frequency comparing near and far future, it also displays the lowest values for the near future. RCP 2.6 shows the lowest duration and frequency in the far future, while RCP 4.5 has the largest duration and frequency in both the near and far future.

Discussion

The hydrological model was calibrated and validated successfully with both NSE and r^2 values > 0.5 and PBIAS $< 25\%$ (Moriassi et al., 2007). Both visual inspection and PBIAS indicate a slight underestimation of the simulated values, mainly observed on simulated peak discharges. Underestimation could be due to limitations concerning the model setup (Partington et al., 2013). The soil was separated into two types for simulation: forest soil (Regolith) and wetland soil (peat) with a spatial homogeneous parameterization. However, spatial heterogeneity is likely, especially in the riparian wetland, and a more complex soil type distribution could lead to faster water movement through the subsurface (including preferential flow). Precipitation (P) and Evapotranspiration (ET) are spatially uniformly distributed over the entire catchment, and the temporal resolution of the hydrological model required daily input. Since the catchment is small and precipitation is moving in scales of minutes to hours, peaks might have been missed. This, combined with the simplified soil types, could lead to deviations in peak discharges. However, the presented study focuses on drought conditions, i.e., low flow conditions where the presented model showed a good performance based on the calibration and validation data set.

Vegetation parameters used to calculate Actual Evapotranspiration (AET) were assumed to be steady over the simulation period. However, it is very likely, that the vegetation composition, especially tree species, will change in the next 80 years. Possible reasons include changing climate conditions, i.e., drought events, bark beetle infestation in spruce stands, and evolving forest management goals promoting

mixed forests. Unfortunately, including vegetation scenarios would have exceeded our limits.

The process-based model was run with each ensemble member separately, and results were averaged for the RCPs and the entire ensemble, respectively. Each member received one vote. Ensemble weighting has been discussed quite controversially in the literature (e.g., Christensen et al., 2010; Weigel et al., 2010; Chen et al., 2017; Knutti et al., 2017; Lorenz et al., 2018). There are two challenges: (1) the ensemble members are usually chosen randomly out of a much larger population, and they are likely nonuniformly distributed. Hence, it is essential to use as many simulations as are available for the catchment. In that way, it is more likely to compensate unknown but possible outlier ensemble members. Moreover, (2) the ensemble members might have a varying performance introducing biases into the ensemble. However, weighting methods require many information, e.g., each member's skill, error, and noise, and often this information is not available (Weigel et al., 2010). Hence, Weigel et al. (2010) stated that equal weighting is the safest method. Chen et al. (2017) investigated ensemble weighting in detail and found only minor differences between various weighting methods and state that equal weighting (i.e., each member receives one vote) is appropriate.

Our results indicated that climate change impacts discharge conditions in the Lehstenbach catchment, with mainly decreasing water availability in summer and autumn but increasing water availability in winter and spring. Future water availability strongly depends on the RCP we take into consideration. While RCP 8.5 shows less water availability with reduced annual discharge due to very high summer evapotranspiration rates, RCP 4.5 indicates the opposite with more annual discharge and increased water availability mainly due to a much lower evapotranspiration increase. Between these two scenarios, RCP 2.6 indicates only minimal changes. Generally, summer water availability is declining in all RCP projections. Decreasing precipitation rates are accompanied by increasing evapotranspiration rates, which contribute both to intensifying summer dryness.

The RCP projections encompass the literature's scenarios, but they should not be viewed as absolute bounds of how climate might evolve (Van Vuuren et al., 2011). The projection RCP 8.5 is often regarded as a "business-as-usual" scenario (e.g., Wells et al., 2017; van der Zande et al., 2020). However, there are several reasons against this assessment. The majority of scenarios (i.e., 68%) fit the RCP 4.5 projection, whereas only about 21% fit the RCP 8.5 projection, developed as a worst-case scenario (Van Vuuren et al., 2011; Hausfather and Peters, 2020). These worst-case scenarios also include a severe overestimation of future coal consumption, as Hausfather and Peters (2020) further state. They also stress that, although we are currently moving on the pathway of RCP 8.5, current policies will probably cause us to jump

to the RCP 4.5 pathway, reaching global warming of about 3 °C until 2100. Nevertheless, climate feedback, such as tipping points, is not fully understood (Lenton et al., 2019). This is why we did not disregard RCP 8.5 and treated all projections as equally probable.

Decreasing water availability potentially impacts the entire catchment's ecosystem. As seen in RCP 8.5 and RCP 2.6, a continuously decreasing annual water availability causes severe impacts. In all climate projections, we see a (strongly) declining water availability during the summer months. In combination with the higher air temperatures, this leads to an increase in stream water temperature, shown in the global study by van Vliet et al. (2013). They stress the negative impact of elevated water temperatures on water and habitat quality and water quantity for drinking water production. Also, Karvonen et al. (2010) demonstrated increased water temperatures in summer, causing health risks to freshwater species due to higher transmission rates of certain diseases. Mitigation strategies include increased canopy cover, as suggested by Johnson and Almlöf (2016), to cool stream water.

Discharge is the integrated signal of a catchment's water availability. With declining discharge rates, both forests and riparian wetlands suffer from low water tables and declining soil water volume, especially during the summer months. When riparian wetlands fall dry, peat begins to decompose, releasing large amounts of CO₂ into the atmosphere. This would also lead to a potential vegetation change (not included in this study).

Nevertheless, Rabbel et al. (2018) demonstrate that water shortage leads to a much slower growth rate for spruce trees, which are the dominant tree species in the catchment. Also, infestation with pest species (e.g., bark beetle) is much more likely when spruce become weakened because of water stress (de Groot and Ogris, 2019; Jakoby et al., 2019). In connection to climate change, Jakoby et al. (2019) also found an "increasing number of generations" and an early spring swarming to be causes for higher infestation rates. This is additionally increasing the possibility of severe mass-infestation. Riparian wetlands are essential for regulating peak and low flows in small catchments. They might lose parts of their functionality due to prolonged dry spells combined with higher temperatures caused by climate change (Fossey and Rousseau, 2016). The mosses, e.g., *Sphagnum* spec., as dominant plant community in wetlands, store significant amounts of carbon (Moore and Waddington, 2015) and are adapted to specific soil water levels (Hölzer, 2013). Hence, Fossey and Rousseau (2016) stress the conservation of these areas to mitigate more unstable discharge regimes.

In this context, it is also necessary to view anthropogenic impacts in the catchment. Although the streambed is natural, some tributaries are not. Due to wood logging and peat digging, drainage channels have been implemented in the past

(Heindl et al., 1995). Additionally, during a site inspection, we found modern harvesting machines to leave deep trails in the soil, especially in the riparian wetland, creating new drainage channels. These channels, both created in the past and now, are often under 1 m wide and randomly distributed in the catchment, causing the water to drain much faster. Hence, the water has less time to infiltrate into the upper soil zones and leaves the catchment altogether much faster. Mitigation strategies would include closing these drainage channels and adapting logging methods by moving parallel to the hill slope, creating deep trails that keep the water in the landscape, and even increase infiltration time compared to a natural hillslope aiding in slowing down the drying of the landscape.

The Minimum Environmental Flow (MEF) was used to define a threshold indicating when habitat requirements for species groups, e.g., fish and macro-invertebrates become unmet. The simulation ensemble shows that both the frequency and duration of such events increases. Periods when discharge is below MEF, threaten the composition of the freshwater community and affect the flow regime. Streams might get disrupted by very low discharge values, leading to the stream system's possible temporal disconnection (Ward et al., 2020). The probability of such events increases due to decreasing water availability in summer. This may prevent species from migrating to suitable habitats. Especially during these low flows, dissolved oxygen levels are falling, and water temperature spikes. For intermittent streams, Majdi et al. (2020) state that the meiofauna community could recover after drying out of the streambed quickly. However, species communities unadapted to such dry events might face trouble to regain vitality fast. This might lead to a shift in the species composition of the streams community. One way to mitigate these effects would be to promote wetland health since it releases water much slower and helps maintain higher low flow discharge (Arthington, 2012).

Our analysis provides a first estimate that the catchment might experience increasing drought duration and intensity in the future, compared to the past 30 years in the Lehstenbach catchment. Recently, drought events received increasing attention in the literature due to abnormally long dry periods (Van Lanen et al., 2016) in 2015, higher frequencies with drought events repeating in 2018 and 2019, and very severe intensities (Boergens et al., 2020). Brunner and Tallaksen (2019) found European catchments that are rain-driven and experience less snowfall in winter to be more at risk for droughts lasting longer than one year in the future.

The severity of a drought event has a direct effect on the ecosystem's ability to rebound. Boergens et al. (2020) state that the summer droughts in 2018 and 2019 in Northern Europe each have severe negative water anomalies that cannot be replenished within 1 year. Prolonged droughts events are likely to cause the aquatic community to experience

extended stress. A decreasing frequency, however, will likely give the community time to recover. This might happen either via avoidance and active emigration to more favorable habitats followed by successive re-colonization from non-impacted river reaches or by the endurance of unfavorable drought conditions in refuges (Lytle and Poff, 2004; Hershkovitz and Gasith, 2013). The existence of refuges, such as cold-water refuges and refuge-microhabitats in the aquatic ecotone as well as the presence of intact riparian wetlands, regulating the hydrologic environment of streams, and providing shading, are essential factors mediating and reducing the impacts of these climate change scenarios for aquatic communities and are expected to reduce the severity of climate change disturbances.

Summary and conclusions

The Lehstenbach is a catchment in the Fichtel Mountains that is exemplary for many catchments in the lower mountain ranges in Central Europe. The results obtained in this study can thus be seen as representative for headwater catchments of a similar size, land cover, vegetation, and soil composition (i.e., forested catchment with riparian wetland). Based on our simulations, we identified a shift in the water balance and a first indication of increasing drought duration, intensity, and frequency, due to climate change. The most relevant results include (1) a shift towards drier summers in all climate projections (RCP 8.5, 4.5, and 2.6), (2) decreasing (RCP 8.5, 2.6) or increasing (RCP 4.5) annual water availability, and (3) discharge falling below the Minimum Environmental Flow more often and for more extended periods towards the far future (2070–2100).

The simulated developments will possibly have severe implications for the aquatic and semi-terrestrial community and the entire catchment's ecosystem. Decreasing discharge, especially in combination with high air temperatures during the summer, might cause a wide range of impacts, such as decreasing dissolved oxygen availability, increasing nutrient cycling, and higher transmission rates of diseases. The surrounding forest and wetland will also suffer from low water tables during summer and possible severe drought events by reducing their ecosystem services, such as tree growth, water retentions, and CO₂ storage. Their vitality might also decline to provoke shifting habitat conditions.

For all considered habitat types, i.e., forest, riparian wetland, and the stream itself, suitable mitigation strategies include increasing water flow pathways and storage in the catchment. Thus, artificial drainage should be avoided, the streambed should become and stay shaded by a canopy, and the riparian wetland's health should be promoted. It is of particular interest to support research on these and other suitable mitigation strategies for small headwater

catchments in Central Europe to keep these habitats and species communities as vital and abundant as possible. By protecting these sensitive ecosystems, we might be able to weaken at least some effects of climate change, including multiyear hydrological drought events, shortage of irrigation and drinking water supply, flooding, water pollution, and loss of flora and fauna.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10113-022-01926-y>.

Acknowledgements This work was supported by the Bavarian State Ministry of Science and the Arts in the Bavarian Climate Research Network (bayklif). We thank the Bavarian State Office for Environment for providing the climate change scenarios (original dataset obtained from Euro-Cordex and ReKliEs-DE) and the Department of Micrometeorology (University Bayreuth) for the climate data from the Waldstein climate station.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors declare no competing interests.

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