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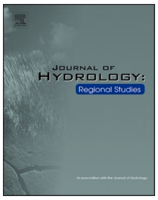

Attributing the effects of climate change and forest disturbance on runoff using distributed modeling and indicators of hydrological alteration in Central European montane basins

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ABSTRACT

Study region: Eight unregulated basins in the headwaters of five mid-latitude mountain ranges in Central Europe, including the Šumava Mts. (Vydra, Blanice), Krkonoše (Mumlava, Úpa), Orlické Mts. (Zdobnice), Jeseníky Mts. (Branná), and Beskydy Mts. (Čeladenka, Vsetínská Bečva).

Study focus: This study examines the impacts of climate warming and forest disturbances on hydrological alterations in montane headwater basins. Using the MIKE SHE distributed hydrological model, scenario-based simulations assessed changes in runoff seasonality, evapotranspiration, streamflow, and variability. Hydrological alteration indicators were applied to disentangle the contributions of these drivers and their interactions under varying environmental conditions.

New hydrological insights for the region: Climate warming is the primary driver of hydrological change, causing shifts in runoff seasonality, increased evapotranspiration, and reduced streamflow. Forest disturbances amplify these effects during dry conditions, intensifying runoff variability, increasing low-flow frequency, and modifying peak flows. Regional differences show greater sensitivity in steeper eastern basins due to limited snow accumulation and higher runoff variability. This study highlights the interconnected impacts of climate warming and forest disturbances, with warming driving systemic shifts and disturbances acting as amplifiers in extreme conditions. The findings provide a framework for disentangling the effects of climate and land-cover changes on hydrology, offering insights for managing sensitive montane ecosystems and water resources under changing environmental conditions.

1. Introduction

The global hydrological cycle is undergoing significant transformations driven by climate change and forest disturbances, leading to profound impacts on water resources and ecosystems. These changes are primarily attributed to rising temperatures, shifting precipitation patterns, and increased frequency and severity of extreme weather events (IPPC, 2023). Additionally, forest disturbances such as deforestation, wildfires, and insect outbreaks are altering streamflow regimes by modifying land cover, evapotranspiration rates, and soil moisture dynamics (Bonan, 2008; Piao et al., 2010). Mid-latitude montane basins are particularly vulnerable to the impacts of climate change and forest disturbances, serving as sensitive indicators of these environmental changes. The Central European region, the focus of this study, has experienced notable hydrological alterations in response to rising temperatures and shifts in

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precipitation patterns associated with climate change (Blahušiaková et al., 2020; Fischer et al., 2023).

Among the most significant hydrological impacts observed in the region are shifts in runoff seasonality and a decrease in mean annual runoff. These changes are driven by alterations in snowpack distribution and an increase in evapotranspiration due to rising mean annual temperatures (Langhammer and Bernsteinová, 2020; Stagl et al., 2014; Stahl et al., 2010). Furthermore, these montane regions are experiencing significant changes in intra-annual runoff variability. Hydrological droughts are occurring more frequently and with greater severity (Langhammer and Bernsteinová, 2020), adversely affecting forest health and acting as a potential trigger for tree diseases (Allen et al., 2010; Anderegg et al., 2013). In several regions of Central Europe, prolonged drought conditions have contributed to the overpopulation of bark beetles (Ips typhographus), leading to widespread tree mortality and the decay of extensive European spruce forest covers (Økland et al., 2016).

In addition to drought, other factors such as windfall events can trigger bark beetle infestations. For instance, the most extensive bark beetle infestation in the region occurred in the Šumava mountains as a consequence of windstorms that have been occurring since the mid-1980s (Hais et al., APR 15 2009). The initial bark beetle outbreak was initiated by a windstorm in November 1984, leaving more than 7 million m^3 of damaged timber. There was a substantial acceleration after the winter storm Kyrill in January 2007, which damaged more than 8 million m^3 of timber (Brázdil et al., 2018). The forest damage, occurring in Norway spruce monocultures, enabled a rapid and extensive outbreak of bark beetles, leading to the disturbance of 20–50 % of forest habitats in the catchments in the region (Su et al., 2017).

While the hydrological impacts of gradual forest disturbances, such as disease or insect infestations, may initially be less apparent, their effects on altering hydrological processes can be similar to those caused by rapid, short-term disturbances. Both types of disturbances have been documented to potentially increase the runoff coefficient due to reduced interception, transpiration, and decay of the forest canopy, as seen in several studies (Bladon et al., 2019; Kopáček et al., 2020; Stednick, 1996).

An example of such a process is observed in the Große Ohe basin (Bavarian Forest, Germany), where a bark beetle infestation during the dry period of 1995–1998 led to significant changes in hydrological processes. By 1998, approximately 30 % of the forest had decayed, resulting in a 12 % increase in the runoff coefficient (Zimmermann et al., 2000). However, the impact of forest disturbances on the runoff coefficient can vary depending on the timing and hydrological conditions. For instance, in the adjacent basin within the Czech part of the Bohemian Forest, the most intensive bark beetle infestation occurred in 2008 during a period of wet hydrological conditions, and the effect on the runoff coefficient between the pre- and post-impact periods was not significant (Beudert et al., 2018).

The application of process based distributed hydrological models offers a robust approach for simulating the impacts of climate change and forest disturbances on hydrological processes in complex mountainous terrain (Fatichi et al., 2012; Hrachowitz and Clark, 2017). In contrast to lumped conceptual models, distributed models explicitly represent the spatial heterogeneity of basin characteristics, including topography, soil properties, land cover, and climatic forcings. This enables a more realistic depiction of hydrological responses across the landscape (Zhu and Scott Mackay, 2001). Such an approach is particularly advantageous in mountainous regions, like the Große Ohe basin and the Czech part of the Bohemian Forest, which are characterized by high spatial variability in precipitation, temperature, and vegetation patterns.

However, the implementation of distributed models is data-intensive, requiring comprehensive spatial datasets on terrain characteristics, soil properties, land cover, and meteorological variables at high spatial resolutions (Orth et al., 2015). The availability and quality of such input data can be limiting factors, especially in remote or poorly gauged mountain basins (Viviroli et al., 2009). Moreover, the computational demands and parameterization complexities associated with distributed models present challenges, although advances in computational power and remote sensing data have facilitated their more widespread application in recent decades (Gao et al., 2014).

In this study, the MIKE-SHE model, based on the Système Hydrologique Européen (SHE) modeling system (Abbott et al., 1986), was chosen for its suitability in simulating hydrological processes in mid-latitude mountain basins. The model choice was driven by its complexity, reliability, and proven frequent use in modeling water-related environmental issues (Ma et al., 2016). The modeling system has been successfully used also in studies estimating the impact of forest cover change in Denmark (Sonnenborg et al., 2017). This model's distributed and physically-based structure allows for explicit consideration of spatial variations in topography, soils, vegetation, and meteorological inputs (Refsgaard et al., 2010). The MIKE-SHE model was chosen from several suitable options (e.g., SWAT, HydroGeosphere) based on its ability to implement raster time series in a fully distributed form, its comprehensive integration of main hydrological processes, its ready-to-use solution, and our previous experience with it (Bernsteinová et al., 2015; Langhammer and Bernsteinová, 2020) (Bernsteinová et al., 2015; Langhammer and Bernsteinová, 2020).

Its comprehensive representation of hydrological processes including precipitation distribution, interception, evapotranspiration, overland flow, channel flow, and groundwater dynamics enables accurate simulations in mountainous environments with heterogeneous landscapes and diverse hydrological regimes (Graham and Butts, 2005). A major advantage of complex physical process oriented models is their ability to design realistic modifications to the process, even though the overall performance is often lower than that obtained by training data-oriented models (Mendoza et al., 2015).

Statistical indicator sets have been developed to quantify and analyze hydrological changes in watersheds, providing essential tools to characterize flow regime alterations, identify trends, and attribute observed changes to potential drivers such as climate change and forest disturbances (Gao et al., 2009). The Indicators of Hydrologic Alteration (IHA) (Mathews and Richter, 2007), and Environmental Flow Components (EFCs) (Olden and Poff, 2003) are widely used metrics that capture various aspects of the streamflow regime, including flow magnitude, timing, duration, frequency, variability, and hydrological extremes. These indicator sets have been employed in numerous studies to analyze hydrological responses to climate and environmental changes across different geographical regions (Gunawardana et al., 2021; Habel et al., 2023; Langhammer and Bernsteinová, 2020; Principato and Viggiani, 2009). The EFC and IHA frameworks have been integrated into the comprehensive, open-source eflowcalc library in Python, which comprises 159 environmentally relevant indicators (T. Hallouin, 2021; Olden and Poff, 2003). This tool was utilized in this study to calculate indices that quantify alterations in the hydrological regimes across the study basins.

Despite the recognized impacts of climate change and forest disturbances on hydrological processes in mid-latitude montane basins, several key knowledge gaps remain. Current research has primarily focused on climate change as the dominant driver of hydrological alteration, but limited studies have quantified the role of forest disturbances in amplifying these changes (Stephens et al., 2021; Sun et al., 2019). A research gap remains in understanding the interaction of these two drivers of change, as well as how forest disturbances interact under wet and dry conditions, and how they affect specific hydrological parameters such as runoff variability and streamflow extremes (Goeking and Tarboton, 2020; Poff and Zimmerman, 2010). Addressing these gaps is crucial for more accurately predicting and managing the hydrological changes in regions affected by both climate change and forest disturbances.

We hypothesize that climate change and forest disturbances have separate but connected impacts on hydrology, affecting the size, timing, and frequency of streamflow changes. While climate change likely drives long-term, large-scale shifts, forest disturbances can intensify these effects, especially during extreme weather conditions. We expect that forest disturbances will have a stronger impact during prolonged droughts, worsening the effects of climate change. Local features like topography and land use are likely to influence how each area responds to forest disturbances, causing site-specific variations. By combining distributed hydrological modeling with hydrological indicators, we aim to disentangle the individual contributions of climate change and forest disturbances to observed changes in hydrological regime.

This study addresses these gaps by: (i) employing distributed hydrological modeling to simulate forest disturbance and climate change effects in montane catchments, (ii) identifying key hydrological regime changes using hydrological alteration indicators, and (iii) comparing the hydrological responses under contrasting wet and dry conditions.

2. Materials and methods

2.1. Study area

The study sites were selected from basins that have experienced an increase in air temperature and forest disturbances over the past two decades. These basins represent various mountain ranges and physiographic conditions. The eight basins are located within five different mountain ranges in the Czech Republic, a region in Central Europe affected by climate warming in recent decades (Hanel et al., 2012; Langhammer and Bernsteinová, 2020). Specifically, the basins include Vydra (VYD) and Blanice (BLA) in the Šumava Mountains; Mumlava (MUM) and Úpa (UPA) in the Krkonoše Mountains; Zdobnice (ZDO) and Branná (BRA) in the Orlické Mountains; Branná (BRA) in the Ore Mountains; and Čeladenka (CEL) and Vsetínská Bečva (VSB) in the Beskydy Mountains (Fig. 1).

All basins are located in the upstream areas of the border mountains of the Czech Republic (Fig. 1). The basins are of comparable size, ranging from 31 to 90 km^2, with an average basin elevation between 715 and 1125 m a.s.l. (Table 1). Previous analyses in these basins showed that their environment is largely undisturbed by human activities, with dominant forest cover, only sparse settlements concentrated in downstream valleys and no regulating structures altering the flow regime (Langhammer and Bernsteinová, 2020). The forests across these mountain ranges are primarily dominated by spruce monocultures (Picea abies), which are susceptible to bark beetle infestation, as demonstrated by the Vydra catchment in the Šumava Mountains (Hais et al., 2016).

The geological formation of the basins varies significantly between the western and eastern mountain ranges. The basins in the western mountain ranges (BLA, VYD, UPA, ZDO, BRA) are part of the Hercynian system, dominated by crystalline bedrock (Balatka et al., 2015). In contrast, the basins in the eastern mountain ranges (CEL, VSB) are associated with the Alpine-Himalayan system, where

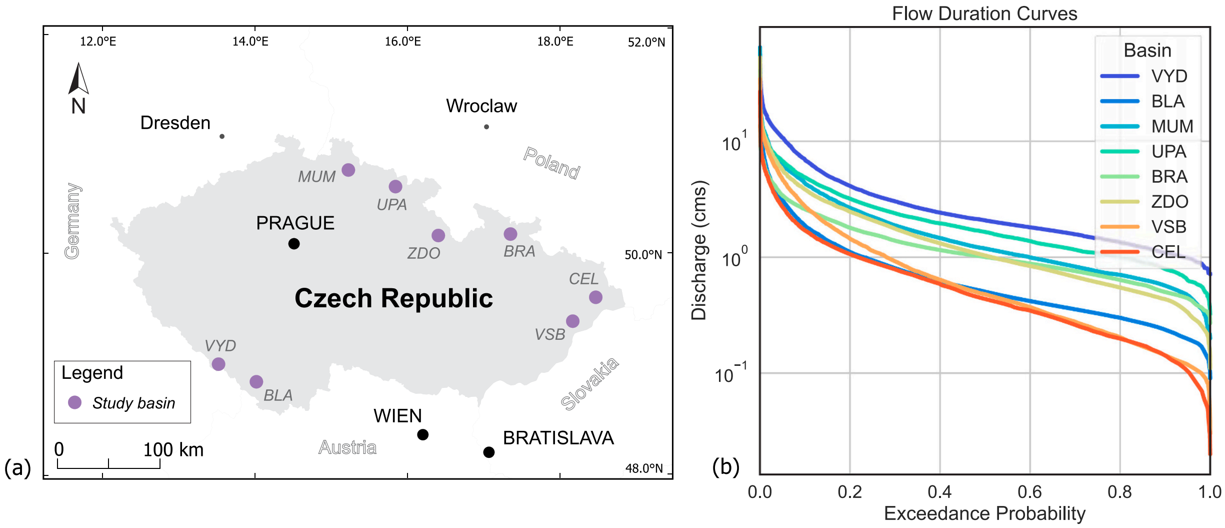

Fig. 1. Study basins. a) Location of study basins, b) flow duration curves of observed daily discharge values for period 1999–2020.

Table 1
Study basins physiography, geology and landuse. Data: CHMI, CGS, Corine landcover.

Code	Basin - Station	Area [sq. km]	Mean altitude	Mean slope	% Crystalline	% Sedimentary	% Forest	% Meadows	% Built-up
VYD	Vydra - Modrava	89.0	1125	12.0	90.1	9.9	91.4	3.8	4.4
BLA	Blanice - Blanicky mlyn	85.5	883	13.0	100.0	0.0	68.1	26.1	0.4
MUM	Mumlava - Harrachov Janov	51.3	986	24.0	95.6	4.4	83.7	6.8	9.4
UPA	Upa - Horni Marsov	82.0	1025	32.0	98.1	1.9	85.2	9.9	3.0
ZDO	Zdobnice - Slatina	84.2	715	20.0	94.6	5.4	64.9	24.5	1.7
BRA	Branna - Jindrichov	90.3	754	24.0	100.0	0.0	65.6	22.5	1.0
CEL	Celadenka - Celadna	31.0	805	36.0	0.0	100.0	79.4	4.4	1.5
VSB	Vsetinska Becva - Velke Karlovice	68.5	747	31.0	0.0	100.0	99.8	0.0	0.2

Mesozoic and Tertiary sedimentary rocks predominate (Table 1).

Located in mid-latitude mountain headwaters. the basins are characterized by humid and cold weather compared to the lowland regions, with mean annual temperatures ranging from 4.2 to 6.5 deg. C. and precipitation totals ranging from 1006 to 1378 mm. Mean annual runoff is low, ranging from 0.83 to 3.3 m.s-1. (Table 2).

From 2014, Central Europe experienced a four-year period of recurrent droughts, impacting water availability, groundwater levels, and ecosystems, particularly in montane regions (Ionita et al., 2017; Jaagus et al., 2022). These droughts affected surface water availability and groundwater levels, as well as ecosystems, highlighting the importance of studying the resilience and response of mountain hydrological systems to climate variability and change.

Differences in the physiography among the basins are reflected in their hydrological properties, as seen in flow duration curves (FDCs) based on daily observations (Fig. 1b). The VYD basin in the Šumava Mountains shows high flow variability, while western basins (BLA, MUM, UPA, ZDO, BRA) exhibit moderate variability with stable groundwater contributions. In contrast, the CEL and VSB basins in the eastern Beskydy Mountains show lower flows, indicating greater drought susceptibility.

These patterns have important implications for climate change resilience. Specifically, the VYD basin is vulnerable to flooding but resilient to low flows. The BLA and MUM basins exhibit balanced regimes but remain moderately sensitive to flow changes, while the CEL and VSB basins, with low discharges, are particularly vulnerable to water shortages during droughts.

2.2. *Applied methodology*

To achieve the objectives, we used a processing workflow that combined distributed hydrological modeling, analysis of indicators of hydrological change, and statistical analysis (Fig. 2), which allowed us to analyze the main aspects of change in the hydrological regime. The MIKE-SHE model (Graham and Butts, 2005) is employed to simulate a range of scenarios reflecting the effects of forest disturbance during both wet and dry periods under real climate conditions.

The eflowcalc library, providing set of 159 environmentally relevant streamflow indicators (T. Hallouin, 2021) was applied to assess the scope of hydrological responses resulting from scenario-based model simulations. The indicators of hydrological change are then used to quantitatively assess the impact of these scenarios on various aspects of the hydrological regime, including runoff balance, baseflow, runoff seasonality, and changes in the occurrence, magnitude, and frequency of extreme flows.

2.3. *Hydrological modeling*

The comprehensive distributed process-based hydrological model MIKE SHE (Graham and Butts, 2005; Refsgaard et al., 2010) was employed in this study. The model captures all significant hydrological processes, conceptualized at a scale appropriate to the problem definition and the available data. It uses a uniform database of distributed properties in an orthogonal grid format with a spatial resolution of 100 m. This spatial distribution was chosen as a balance between the number of calculation points (51,860) and the assumption of homogeneity within each grid cell.

Table 2
Study basins hydrometeorological properties in period 1980–2021. Data: CHMI.

Code	Basin - Station	Mean annual temperature [°C]	Annual precipitation [mm]	Annual runoff [mm]	Mean annual discharge [m3.s-1]
VYD	Vydra - Modrava	5.6	1378	325.6	0.88
BLA	Blanice - Blanicky mlyn	4.2	1188	1158.4	3.30
MUM	Mumlava - Harrachov Janov	4.6	1326	1218.5	1.98
UPA	Upa - Horni Marsov	4.3	1211	923.3	2.40
ZDO	Zdobnice - Slatina	6.5	1056	702.8	1.87
BRA	Branna - Jindrichov	5.9	1006	506.5	1.45
CEL	Celadenka - Celadna	6.2	1159	841.1	0.83
VSB	Vsetinska Becva - Velke Karlovice	6.3	1085	549.4	1.19

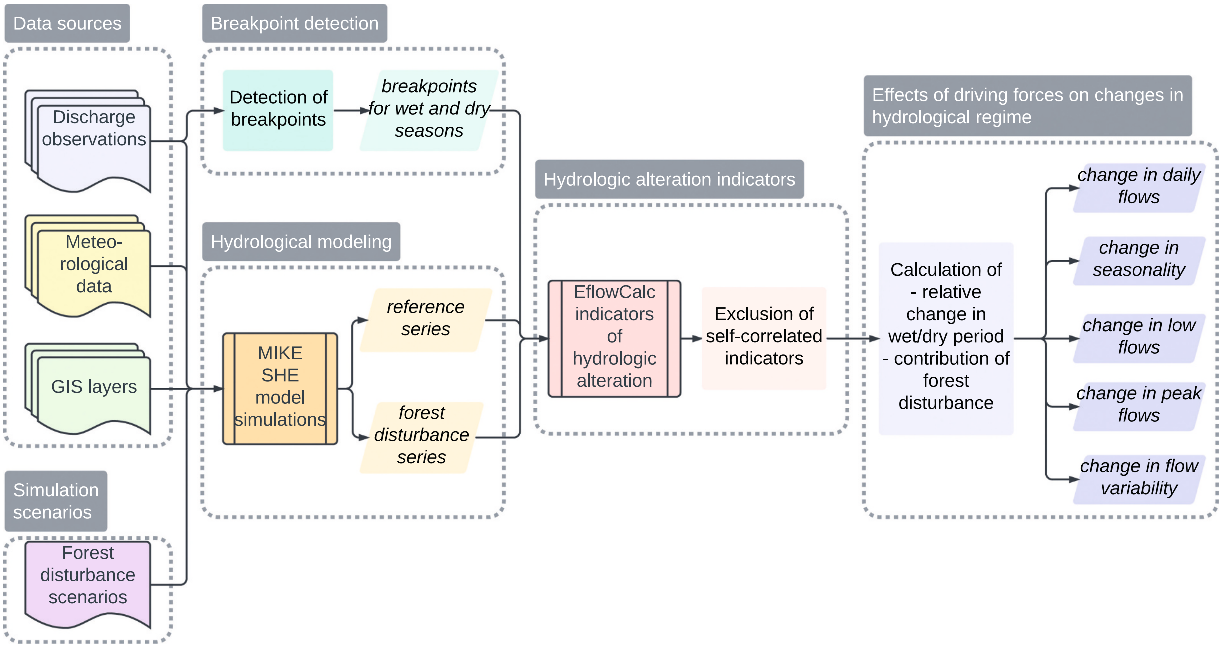

Fig. 2. Processing workflow.

2.3.1. Model setup and scenarios

The model used in this study includes a physically-based description of overland flow, coupled with a fully dynamic representation of streamflow. This integration allows for bidirectional interaction between the aquifer and stream, accounting for both baseflow and streambed leakage. Unsaturated zone processes are described using Richards' equation, based on the van Genuchten soil moisture model (van Genuchten, 1980), including macropore flow. Saturated zone flow is solved using Darcy's law in 3D. Subsurface runoff is described by a linearized concept of drainage from the saturated zone to a local recipient (river reach), where the subsurface level determines the thickness of the drained layer, and the time constant governs the runoff rate. The model includes a 3D description of the groundwater flow in the saturated zone that is coupled with the unsaturated zone. Due to the lack of detailed hydrogeological information the parameters of groundwater flow description were subjected to model calibration. Groundwater flow mainly occurs in the shallow weathered mantle in the form of fast response formed mainly by slope geomorphological characteristics and transmissivity coefficient and therefore we accepted this degree of simplification.

Actual evapotranspiration includes evaporation from canopy interception, surface ponded water, exposed soil, and plant transpiration from both unsaturated and saturated zones. Snow storage and melt are modeled using a simple degree-day approach. Hortonian flow is not anticipated in the region and is therefore excluded. Parameters with the highest uncertainty - saturated zone transmissivity, subsurface flow characteristics, and snowmelt parameters - were calibrated, while soil and vegetation parameters were fixed.

2.3.2. Data sources

The study is employing data from publicly available repositories. The hydrometeorological analysis was based on daily streamflow and meteorological observations at monitoring stations of the Czech Hydrometeorological Institute (CHMI) in eight study catchments (CHMI, 2019). To model the impacts of climate change and forest disturbances, a 20-year period from 1999 to 2019 was analyzed. During this time, hydrological patterns exhibited significant floods, prolonged droughts, and high-flow events. Notably, major floods occurred in 2002 and 2013, with additional peak flows of lower magnitude observed across different basins.

CORINE land cover database (EEA, 2023), digital elevation model DMR-5 (CUZK, 2016), the digital water management map (VUV, 2024), and soil type map (CGS, 2022) were used as primary GIS layers to describe of physiographic properties of basins in the model setup.

Time series data with a daily time step over the entire simulation period provide the model boundary conditions, including climate variables (precipitation, reference evapotranspiration, temperature) and non-stationary vegetation parameters (LAI, root depth, crop coefficient). Vegetation data were derived from satellite-based MODIS global 8-day products (Spies et al., 2015), retrieved and processed via the Google Earth Engine platform using its Python API, enabling automated raster data manipulation and geoprocessings (Wu, 2020).

For precipitation and temperature, raster time series with a 500-meter resolution were provided by the Czech Hydrometeorological Institute. Reference evapotranspiration (ETref) was calculated using the Oudin formula (Oudin et al., 2005) and validated against ETref values obtained via the simplified Penman-Monteith equation (Allen et al., 1998; Penman, 1963). While the Penman-Monteith method requires extensive climate data unavailable in the Czech Republic, Oudin's approach relies only on temperature time series, which are accessible daily for all stations. The data sources used for constructing, training, and validating the MIKE SHE model are listed in Table 3.

2.3.3. Model calibration and parameter sensitivity

Model parameters were divided into two main groups. Those that can be estimated based on site specific physical properties (mainly hydropedological and vegetation parameters) were fixed and conceptual parameters or unknown physical properties were subjected to sensitivity analysis and optimization. Less sensitive parameters were kept on their estimated value. Key parameters of the model performance were those describing saturated zone properties, namely saturated hydraulic conductivity and parameters of conceptualized hypodermic flow. The upper and lower parameter bounds were set for the hypodermic flow level to [-0.5;2.0], for flow time constant to [1.00E-07; 1.00E-05], and for saturated zone hydraulic conductivity to [5.00E-07; 1.00E-05]. Results of the sensitivity analysis are given in Fig. 3. It is obvious that the most sensitive parameter is the saturated zone hydraulic conductivity.

The primary objective of model calibration was to match simulated and observed discharges at the outlet profiles of each basin. The calibration period (2000–2010) was chosen for its climate and vegetation homogeneity, excluding the dry years of 2013–2015. The performance in the consequent period (2011–2016) was tested during the validation phase. Calibration focused on three tasks, each addressed sequentially but with equal importance. First, mean annual discharges were compared to ensure the overall water balance fit (Fig. 4). Second, an overall fit was achieved in the time series of monthly means (Table 4), evaluated separately for winter and summer flow regimes. Finally, daily discharge fits were assessed.

A comparison of simulated and observed data reveals that the model likely underestimates the number of days with snow cover, due to biases in winter precipitation records (Fig. 4, Table 4). Snow accumulation and melt are critical for mountain water balance, influencing spring and early summer runoff. Daily snow depth data from monitoring stations were used to calibrate the degree-day factor and threshold temperature for snowmelt, as snow water equivalent data were unavailable. Calibration criteria focused on fitting the number of days with snow cover during each snow season, optimizing based on root mean square error (RMSE) and Pearson correlation coefficient (r). The correlation assessed using Nash-Sutcliffe model efficiency coefficient (NSE) between observed and simulated snow cover days was strong (0.86 ± 0.09).

2.4. Simulation scenarios

The simulation scenarios were designed to reflect realistic environmental changes anticipated in mountainous watersheds in Central Europe. These changes were derived from clear patterns observed in streamflow time series over recent decades. The simulation period (1999–2019) includes the extreme flood event of August 2002 in the Elbe River basin (Brázdil et al., 2006), which significantly impacted the study catchments in the southwestern region (VYD, BLA, UPA). All catchments have experienced rising air temperatures, resulting in changes in runoff variability, with a consistent pattern of alternating wet and dry years emerging over the past decades.

2.4.1. Detection of wet and dry periods

To identify changepoints in the observed discharge time series, the multiple changepoint analysis method was applied using the PELT (Pruned Exact Linear Time) algorithm (Killick et al., 2012), as implemented in the Ruptures Python package (Truong et al., 2018). This analysis revealed two significant breakpoints in years 2006 and 2013 (Fig. 5).

The year 2006 marks the beginning of a five-year period of higher streamflow, while 2013 marks the start of an exceptionally dry and hot five-year period (Fig. 5). These changepoints correspond to the onset of distinct multi-year wet and dry periods.

A comparison of mean annual runoff values across the entire study period (1999–2019), the wet period (2006–2010), and the dry period (2013–2017) was conducted to define the model scenarios. During the wet period, all basins experienced increased runoff, with BLA and BRA showing the highest relative increases of + 36.46 % and + 37.07 %, respectively. In contrast, during the dry period, all basins experienced a decrease in runoff, with ZDO exhibiting the largest decline of −41.54 % (Table 5). These changes highlight the substantial impact of wet and dry periods on runoff, while consistent patterns persisted across the basins.

The Standardized Precipitation-Evapotranspiration Index (SPEI), calculated using a 24-month sliding window, was used to define wet and dry years.The Standardized Precipitation-Evapotranspiration Index (SPEI) measures climatic water balance by comparing the

Table 3
Main data sources used for MIKE SHE model setup.

Dataset	Features	Source
Model extent	Hydrologic divide	DIBAVOD, VÚV, 2020
Digital terrain model	Mean raster elevations	DMR5G, ČÚZK, 2016
River network	Detailed position flow concentration paths	DIBAVOD, VÚV, 2020
Soil map	Polygons of soil types with hydropedological conditions	ČGS, 2020
Geology	Map defining main structures of saturated zone, transmissivity discontinuities and springs	ČGS, 2020
Land Use	Polygons of land cover categories	CLC2018, EEA, 2020
Climate	Raster time series of spatially distributed daily precipitation and temperatures	CHMI, 2020
Leaf area idex (LAI)	Spatially distributed LAI from remote sensed data	MODIS, 2022
Discharges	Time series of observed discharges	CHMI, 2020

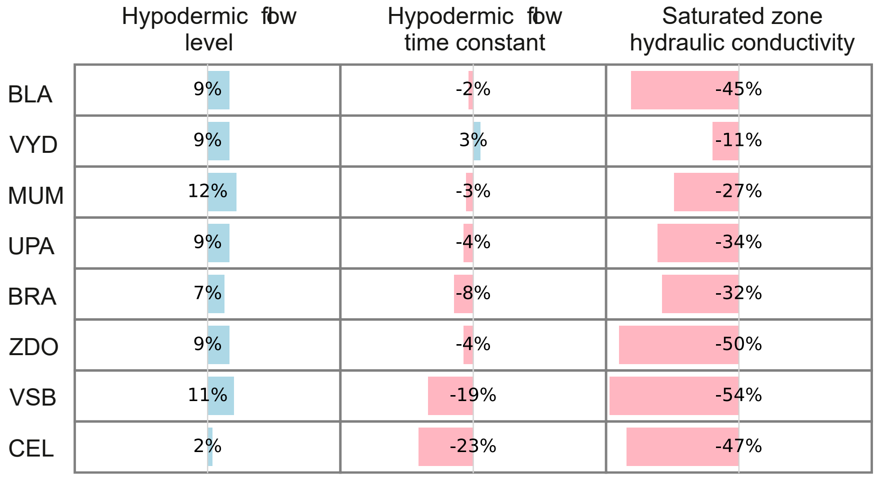

Fig. 3. Sensitivity analysis of key model parameters. Ratios represent the effect of 100 % change of parameter on mean discharge in a basin.

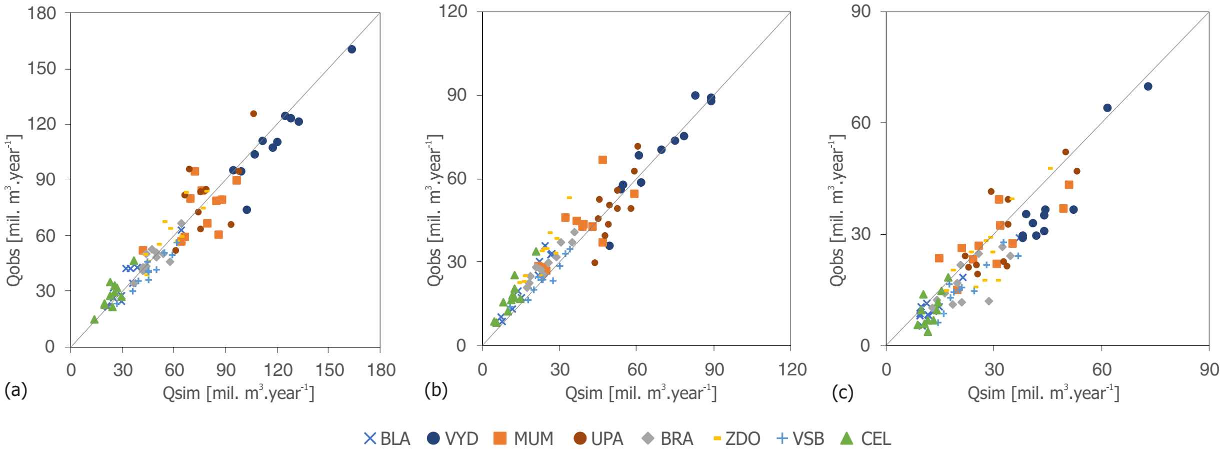

Fig. 4. Comparison of simulated and observed runoff in modeled basins. (a) Mean annual runoff, (b) mean runoff in summer season (IV-IX), and (c) in winter season (X-III).

Table 4
Performance metrics for observed vs simulated mean monthly discharges at basins.

	Calibration period (2000–2010)				Validation period (2011–2016)			
	Performance metrics				Performance metrics			
Basin	r	RMSE	NSE - winter	NSE - summer	r	RMSE	NSE - winter	NSE - summer
BLA	0.84	0.45	0.48	0.86	0.88	0.40	0.82	0.65
VYD	0.72	1.45	0.53	0.87	0.75	1.01	0.79	0.74
MUM	0.67	1.58	0.51	0.65	0.74	0.75	0.87	0.32
UPA	0.63	1.71	0.41	0.60	0.74	1.30	0.53	0.71
BRA	0.78	0.97	0.55	0.50	0.90	0.56	0.75	0.67
ZDO	0.61	1.34	0.49	0.72	0.61	1.22	0.51	0.50
CEL	0.63	0.59	0.50	0.76	0.71	0.53	0.78	0.55
VSB	0.56	0.72	0.43	0.72	0.57	0.72	0.59	0.51

difference between precipitation and potential evapotranspiration (PET) over a specified time period. It standardizes this balance to identify wet and dry conditions, with positive values indicating wetter-than-average conditions and negative values indicating drier-than-average conditions.

The SPEI extends beyond precipitation-based indices, incorporating potential evapotranspiration (PET) to provide a more comprehensive picture of water balance changes (Vicente-Serrano et al., 2010). A 24-month window was chosen to capture the

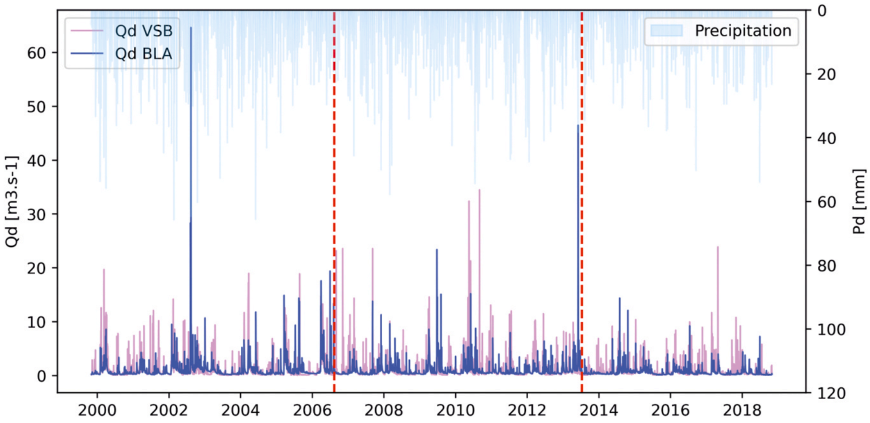

Fig. 5. Daily discharges in selected basins from 1999–2019, showing calculated breakpoints in 2006 and 2013, used to analyze changes in the hydrological regime (Data: CHMI).

Table 5
Mean annual runoff in the study basins for the entire study period and for the scenarios of the wet period (2006–10) and the dry period (2013–17).

Period	VYD (mm)	BLA (mm)	UPA (mm)	BRA (mm)	ZDO (mm)	VSB (mm)	CEL (mm)
1999–2019	3.13	0.96	2.05	1.16	1.30	1.29	1.65
Wet (2006–10)	3.66	1.31	2.09	1.59	1.34	1.55	1.99
Dry (2013–17)	2.52	0.71	1.50	0.80	0.76	1.04	1.34

significant and prolonged hydrological events, such as multi-year droughts, and to suppress the effect of short-term or seasonal variations in a longer time scale (Berhail and Katipoğlu, 2023).

Calculation of SPEI index with a 24-month sliding window confirmed the identification of the distinct wet (2006) and dry (2013) periods (Fig. 6). From the mid-1990s to the mid-2000s, most basins experienced significant wet periods. These wet periods tended to exhibit less synchronization across the basins compared to drought events, which suggests that wet conditions are influenced by a broader range of factors, particularly basin-specific physiographic properties and land cover characteristics. In contrast, drought events have been more synchronized, with an intense and widespread drought across all basins since 2013. Some basins, such as UPA and ZDO, even experienced earlier onset of dry conditions.

2.4.2. Forest disturbance scenarios

The impact of forest disturbance, the second major driver of change, was simulated based on the extent of bark beetle outbreaks and subsequent forest decay in the Czech and German parts of the Šumava region (Hais et al., 2016). The decay affected 20–30 % of the total area in complex watersheds, with core disturbance zones exceeding 50 % of the watershed area (Langhammer et al., 2015). Therefore, deforestation in 40 % of the watershed area was used as a reference scenario to simulate the effect of severe disturbance in a complex montane watershed. This scenario is realistic for Central European forests, where spruce monocultures are dominant across all catchments and thus vulnerable to bark beetle infestations.

A series of scenarios were constructed to illustrate the potential consequences of forest decay in areas covered by coniferous forests. These scenarios were applied to basins where no bark beetle disturbance had been recorded (all basins except VYD). The disturbance scenario assumed 40 % of coniferous trees affected, with the spatially distributed time series of vegetation parameters (namely LAI, Root depth and Kc) adjusted to show a sudden decline in one year, followed by a gradual 15-year regeneration process. Assuming that 40 % of the coniferous stands will decay, all values in vegetation parameter raster time series that belong to the coniferous forest land use class have been reduced to 40 %. During regeneration, vegetation parameters increased each year, reaching healthy forest values at the end of the period. The regeneration process was schematized as linear increase toward the pre-disturbance state.

In contrast, for the VYD catchment where disturbance has already taken place, it was necessary to prepare a reference set reflecting status prior disturbance. A realistic set of vegetation parameters was generated by replacing the years impacted by disturbance with those from a period of healthy forest. A comparable dataset for all basins was created by recalculating healthy forest parameters similarly for the undisturbed basins.

2.5. Indicators of hydrological alteration

Hydrologic regime changes were analyzed using a comprehensive set of hydrologic regime change indicators. The analysis utilized the eflowcalc package, a Python tool designed to calculate a wide range of streamflow characteristics (T. Hallouin, 2021). Eflowcalc derives a wide range of indicators of hydrologic alteration (Olden and Poff, 2003), including i.e. the sets of IHA and EFC indicators

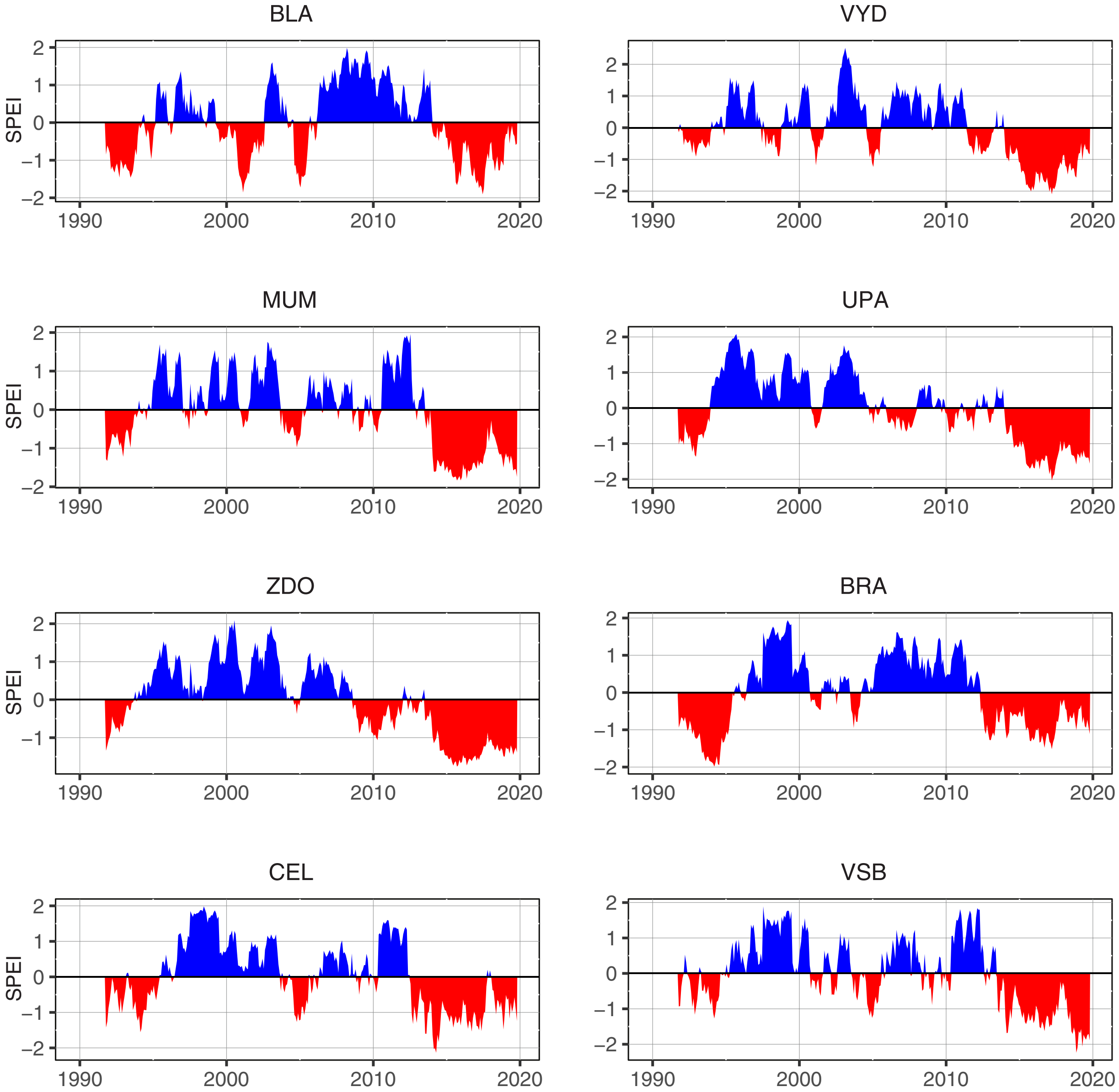

Fig. 6. SPEI drought indicator values, aggregated with a 24-month window based on daily discharge values.

(Habel et al., 2023). The included indicators allow assessing changes in flow magnitude and seasonality (90 indicators), flow duration (41 indicators), frequency of low and high flow events (13 indicators), flow rate (9 indicators), and 6 indicators of flow timing (T. Hallouin, 2021). The calculations were performed using Python with Numpy, Scipy, and Hydroeval libraries (Thibault Hallouin, 2021; Virtanen et al., 2020), while Matplotlib and Seaborn libraries were used for visualizing the results (Hunter, 2007).

Hydrological change indicators were calculated for all scenarios, comparing time series before and after the breakpoints. This included the reference scenario for the periods before and after the 2006 breakpoint, marking the transition to wet conditions, and the periods before and after the 2013 breakpoint, marking the shift to dry conditions. The same approach was applied to scenarios with forest disturbance.

Since many indicators in the dataset capture similar aspects of the flow regime using different methods, correlation analysis was conducted to remove redundant indicators. This resulted in a reduced set of 28 indicators across 5 groups, reflecting the most critical aspects of hydrological regime change for further analysis (Table 6).

For each indicator, relative rates of change were calculated to quantify the intensity of change between post- and pre-break values for each scenario (Eqs. 1–3).

$$\text{chgref} = (\text{pos\_ref} - \text{pre\_ref}) / \text{pre\_ref} * 100 \tag{1}$$

$$chgdis = (pos\_dis - pre\_dist) / pre\_dist * 100 \quad (2)$$

$$effdis = (pos\_dis - pos\_ref) / pos\_ref * 100 \quad (3)$$

Where:

chgref is the relative change in the reference time series between indicator values in the pre- and post-break periods, calculated for both wet and dry breaks,
pre_ref is the indicator value for the pre-break period, and *pos_ref* is the indicator value for the post-break period in the reference time series,
pos_dis is the indicator value for the post-break period in the series simulating forest disturbance,
chgdis is the relative change in the time series simulating the effect of forest disturbance, compared with the pre-break period for both wet and dry periods,
effdis represents the relative effect of disturbance on the overall change.

These indicators capture the relative intensity of change in either the reference or disturbed state for a breakpoint that separates the initial conditions from subsequent wet or dry periods.

3. Results

3.1. Changes in daily flows

The principal changes in daily flow patterns observed across the basins during both the dry period (2013) and the wet period (2006) include a decrease in mean daily streamflows and an increase in baseflow contributions (Fig. 7a). This general trend can be attributed to the gradual rise in air temperatures observed across all studied mountain ranges. The increase in temperature leads to more intense evapotranspiration and, in the absence of increased precipitation, results in lower daily streamflows and greater reliance on groundwater storage to maintain streamflow, thereby increasing baseflows. This decline in mean daily streamflow is accompanied by a decrease in maximum daily discharge values. These changes in the reference time series are more pronounced during the dry period compared to the pre-change period. Although the decline in maximum daily flows is evident, the differences between wet and dry conditions are less distinct. Additionally, most basins exhibit an increase in minimum daily flows, although some basins show only marginal increases. The rise in minimum flows is driven by more intense baseflow contributions, which compensate for the reduction in total discharge (Fig. 7a).

The effect of forest disturbance (Fig. 7b) is reflected in changes in flow intensity, although the overall direction of change remains consistent across all catchments. In most catchments, the simulated series following disturbance indicates a slight increase in mean daily flows compared to the reference series for the same period, covering both wet and dry seasons. However, the impact of forest disturbance on mean streamflow is significantly less pronounced compared to the broader changes driven by rising air temperatures and altered runoff seasonality. These differences can be further influenced by local physiographic and environmental factors, in addition to the effects of disturbance.

Regional differences between catchments are particularly evident in the intensity of the decrease in mean daily discharge. Catchments in the eastern mountain ranges of Jeseníky and Beskydy (BRA, CEL, VSB) show a smaller decrease than those in the western part of the area in Šumava (BLA, VYD) and Krkonoše (MUM, UPA, ZDO). A similar regional gradient is observed in the distribution of the values of the changes in baseflow. However, these differences are only noticeable during the wet season. During the dry season, especially when combined with the effect of disturbance, the regional differentiation is reduced.

3.2. Shifts in runoff seasonality

Some of the observed changes in seasonality exhibit general patterns, while others are specific to particular regions and catchments. The overall trend indicates an increase in runoff during winter and summer, accompanied by a decrease in runoff during spring and

Table 6
Selected indicators of hydrologic regime alterations.

Group of indicators	Number of indicators	Eflowcalc codes	Eflowcalc indicators
Characteristics of flow magnitude and balance	4	ma1, dl11, dh11, ml17	Qd mean, Qd min, Qd max, Base flow
Characteristics of flow seasonality	12	ma12 - ma23	Mean monthly flow (I-XII)
Characteristics of low-flow events	4	ml15, dl4, dl16, fl1	Qa min, 30 day minimum flow, Low-flow pulse duration, Low-flow pulse count
Characteristics of high-flow events	4	mh21, fh1, dh15, mh15	Mean flood volume, High-flow pulse count, High-flow pulse duration, Q1 value
Characteristics of flow variability	4	ma6, ra1, ra3, ta2	Q90 / Q10, Rise rate, Fall rate, Predictability

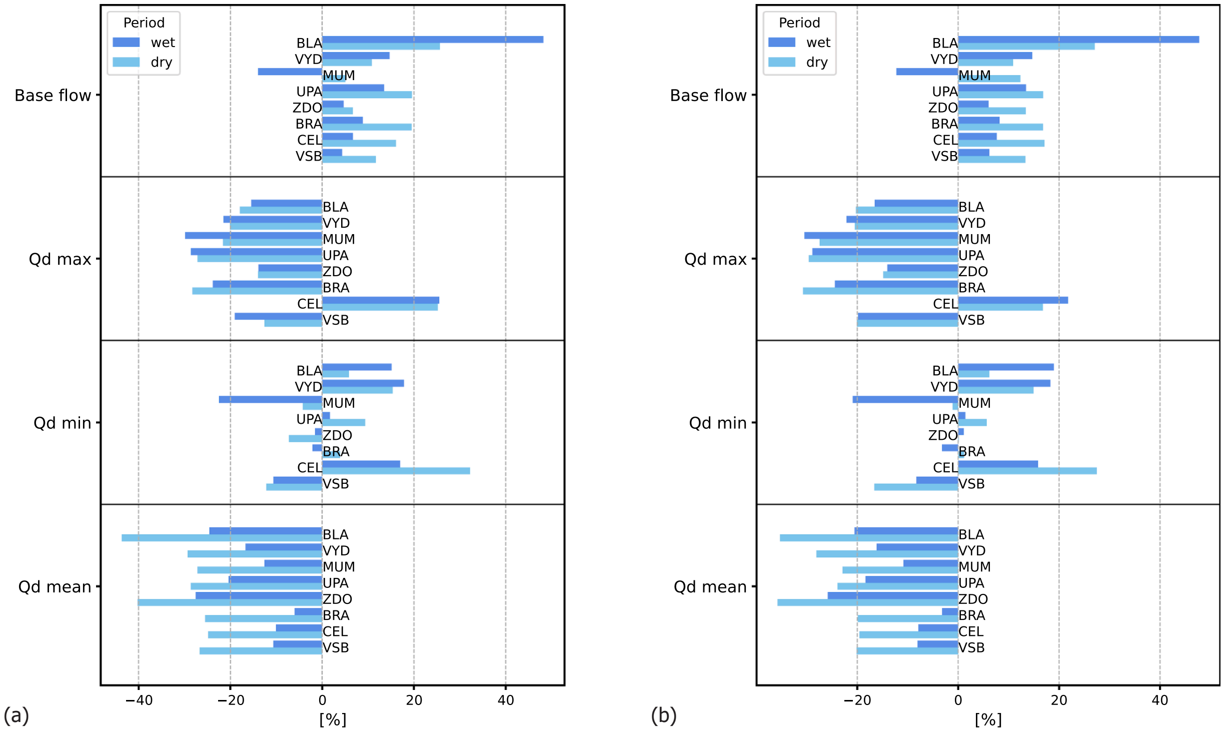

Fig. 7. Daily flows. Changes in time series with breakpoints separating the initial series and subsequent wet (2006) and dry (2013) periods. (a) Change in the reference conditions series, (b) change in the series simulating the effects of forest disturbance.

autumn. This pattern is consistently evident across all river basins.

Across the study catchments in all the mountain ranges studied, the results indicate that the dry period has a significant effect on the seasonal distribution of runoff, while the effect of forest disturbance alters the intensity of this change (Fig. 8). This effect is evident in the shifts in runoff seasonality comparing the initial reference period with periods after the breakpoint marking wet (post-2006) or dry (post-2013) conditions. Time series representing simulated scenarios during the reference period or periods of simulated forest

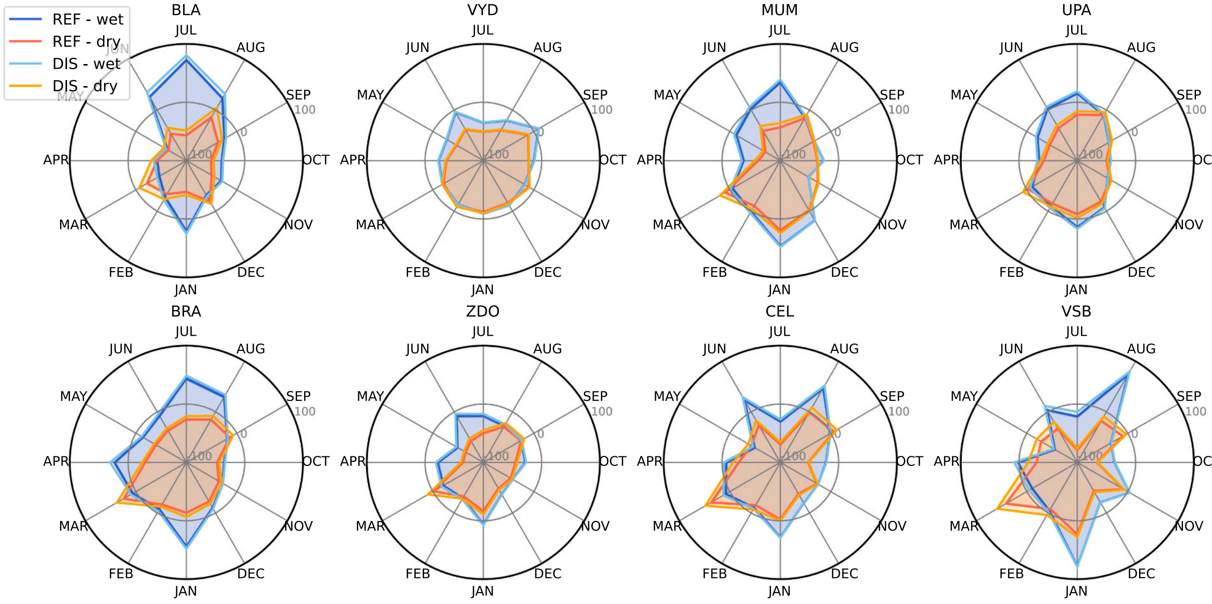

Fig. 8. Changes in mean monthly flows in scenarios reflecting changes during wet or dry conditions for reference status and for simulation of the forest disturbance.

disturbance show the same patterns of seasonal distribution after breakpoints marking wet and dry conditions in all basins, with variations in changes in intensity of change.

The results show that in all catchments there is a significant flattening of the seasonal distribution of runoff throughout the year. The warm and dry period is reflected in the basins by a decrease in average monthly streamflow in late spring and early summer, a period characterized by high flows for the mountain streams in the region. Another notable decrease in mean monthly streamflow occurs in early winter in January. Conversely, changes in seasonality in most watersheds show higher mean streamflow values in the early spring period, induced by earlier snowmelt.

The effect of forest disturbance shows an increase in mean monthly streamflow in most of the basins after the disturbance, maintaining the patterns of seasonal distribution (Fig. 8). The increase in streamflow is more pronounced during the dry season, particularly in the early spring.

3.3. Changes in low and peak flows

An overall increase in annual minimum flows is observed in the basins, with an apparent regional west-east gradient. The largest increases in minimum annual flows are observed in basins in the western mountain ranges (BLA, VYD, MUM, UPA), with a decreasing trend towards eastern basins (CEL, VSB), where changes are marginal (Fig. 9). The mean minimum annual flow generally increased in most basins during both wet and dry periods following forest disturbance, indicating a potential increase in baseflow. The increasing values of minimum annual flows are related to changes in the surface water and groundwater balance at the outlet. Groundwater provides a more stable source of water compared to surface runoff, and the increased contribution from the baseflow propagates to higher flow values during the minimum flow period and thus an increase in minimum annual flows. This is evidenced by a significant decrease in the variability of mean annual minimum flows in most basins (Fig. 9).

The results show substantial decrease of values of 30-day minimum flows during the simulated period, both for dry and wet conditions, as well as for the simulated forest disturbance. Aggravating of minimum flows in the period of rising air temperatures indicate higher vulnerability of montane basins by drought in the conditions of warming climate.

The frequency and duration of low flow events do not show uniform patterns. However, the montane basins tend to have shorter low-flow event durations during wet periods but longer durations during dry periods after disturbance. However, some basins (UPA and BRA) showed increased pulse durations in both wet and dry periods. The basins in the eastern regions (CEL, VSB) show some neutral trends with slight increases in the wet period but decreases in the dry period (Fig. 9a).

Forest disturbance generally resulted in more frequent low-flow events (mean annual number of low-flow pulses) in basins such as VYD, BRA, CEL, and VSB, but a decrease in the UPA basin. Variability in minimum monthly streamflow decreased after the disturbance

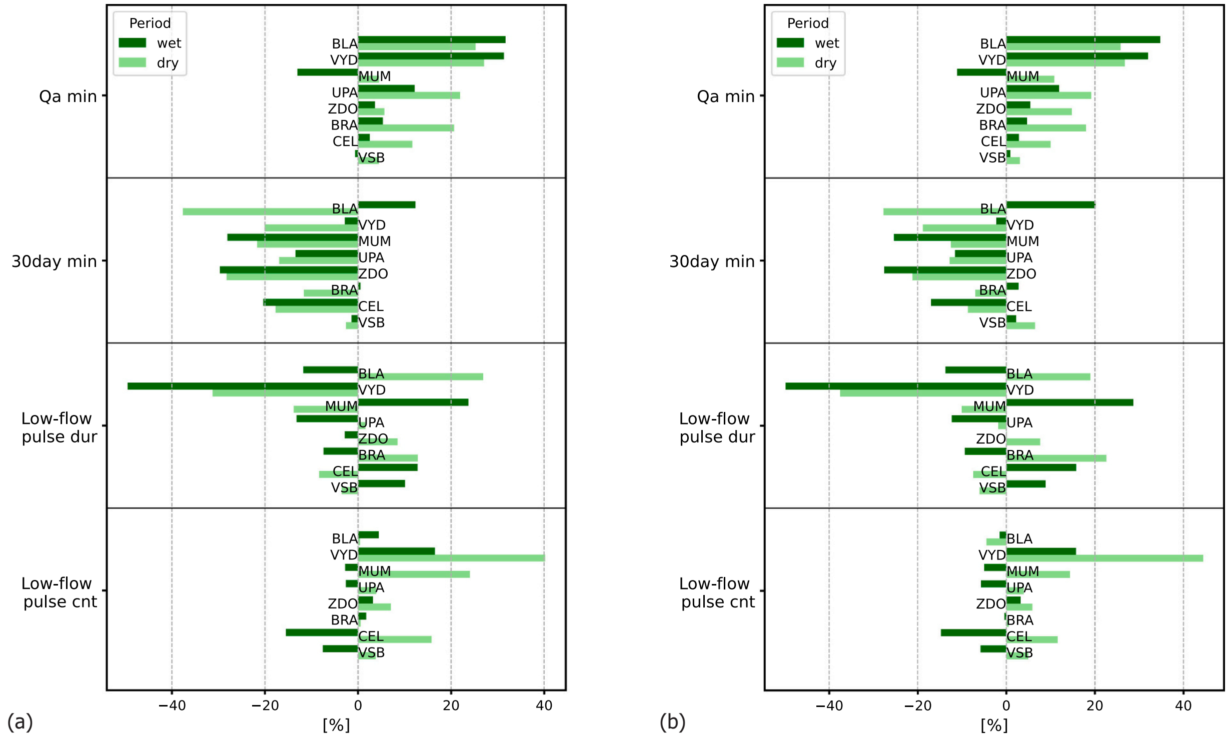

Fig. 9. Low-flows. Changes in time series with breakpoints separating the initial series and subsequent wet (2006) and dry (2013) periods. (a) Change in the reference conditions series, (b) change in the series simulating the effects of forest disturbance.

in most basins (VYD, UPA, ZDO, BRA), except for CEL and VSB, which initially increased during wet periods but decreased during dry periods (Fig. 9b).

In contrast to low flows, the indicators of changes in peak flows exhibit a more uniform response across montane basins. A general decrease is evident in indicators reflecting peak flow magnitudes, such as average flood volume and the flow corresponding to a one-year flood (Q1), during the period of rising air temperatures in both the reference series and the forest disturbance scenario. The average duration of high-flow pulses has also significantly decreased, with more intense but shorter pulses observed in most catchments, particularly during the dry season. Conversely, the number of high-flow pulses has increased, with a more pronounced rise during the dry period (Fig. 10a).

Regional differences between catchments in terms of changes to high and flood flows are not particularly pronounced. The response remains relatively homogeneous across individual parameters, though some variability is observed, reflecting differences in physical geography and runoff conditions.

The impact of simulated forest disturbance on peak flow parameters is generally limited for most variables, in both wet and dry periods. Among the changes detected following disturbance, only the increase in mean flood volume is significant, particularly during the dry period, but also noticeable during the wet period (Fig. 10b).

3.4. Changes in runoff variability

There is a general tendency for decreased intra-annual flow variability during the period of climate warming in the studied montane basins, a pattern that is even more pronounced under dry conditions. This is particularly evident in the decreasing ratio between the 90th and 10th percentiles, a measure of flow variability that quantifies the spread between high and low flows. Additionally, a decline is observed in the indicators of rise and fall rates, which reflect the flashiness of the river system and provide insights into how quickly a watershed responds to hydrological events (Fig. 11).

Flow predictability, recognized as a sensitive indicator of stream ecological status (Wałęga et al., 2022), also shows significant sensitivity to wetness conditions. During wet periods, predictability decreases, whereas in dry periods, it increases sharply. This rise in predictability corresponds to more stable flow conditions, which could have potentially negative impacts on stream biota diversity (Fig. 11). Both trends are further amplified by forest disturbance, although the overall direction of change remains consistent.

A regional differentiation is also apparent in the flow variability indicators, with western basins (VYD, BLA, UPA, ZDO) exhibiting a more pronounced decrease, while eastern basins (BRA, CEL, VSB) show no significant changes.

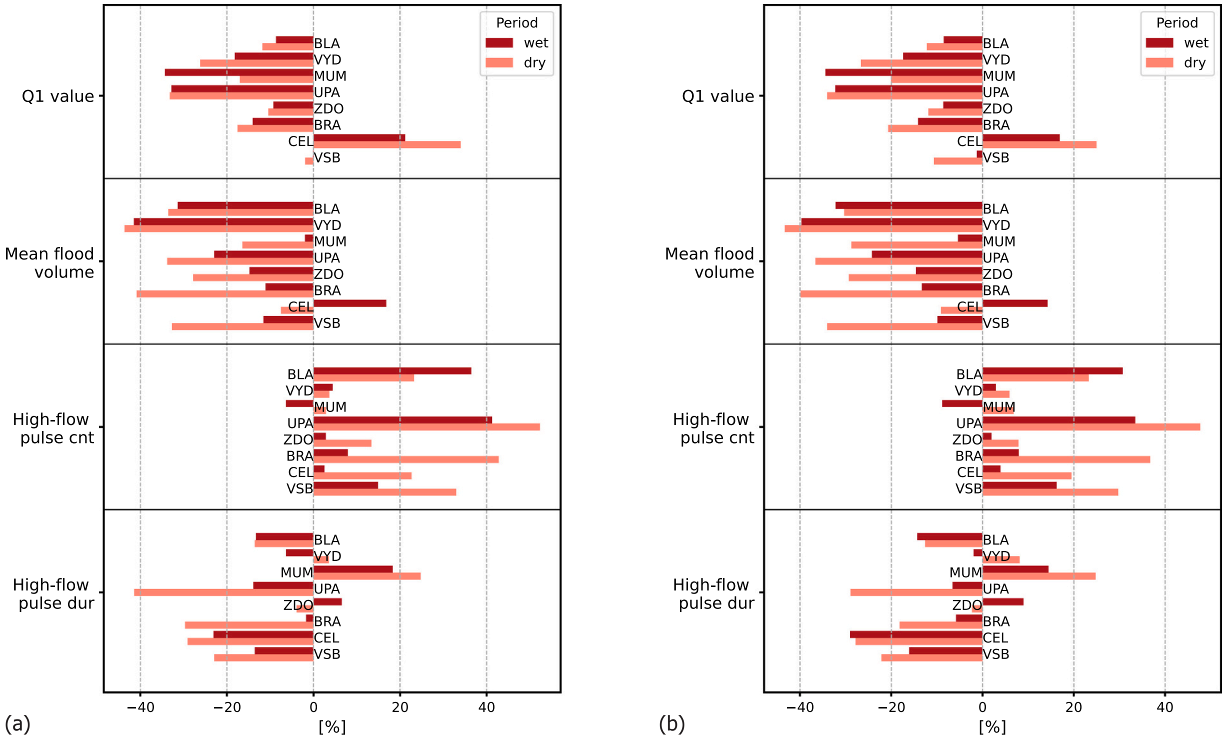

Fig. 10. High-flows. Changes in time series with breakpoints separating the initial series and subsequent wet (2006) and dry (2013) periods. (a) Change in the reference conditions series, (b) change in the series simulating the effects of forest disturbance.

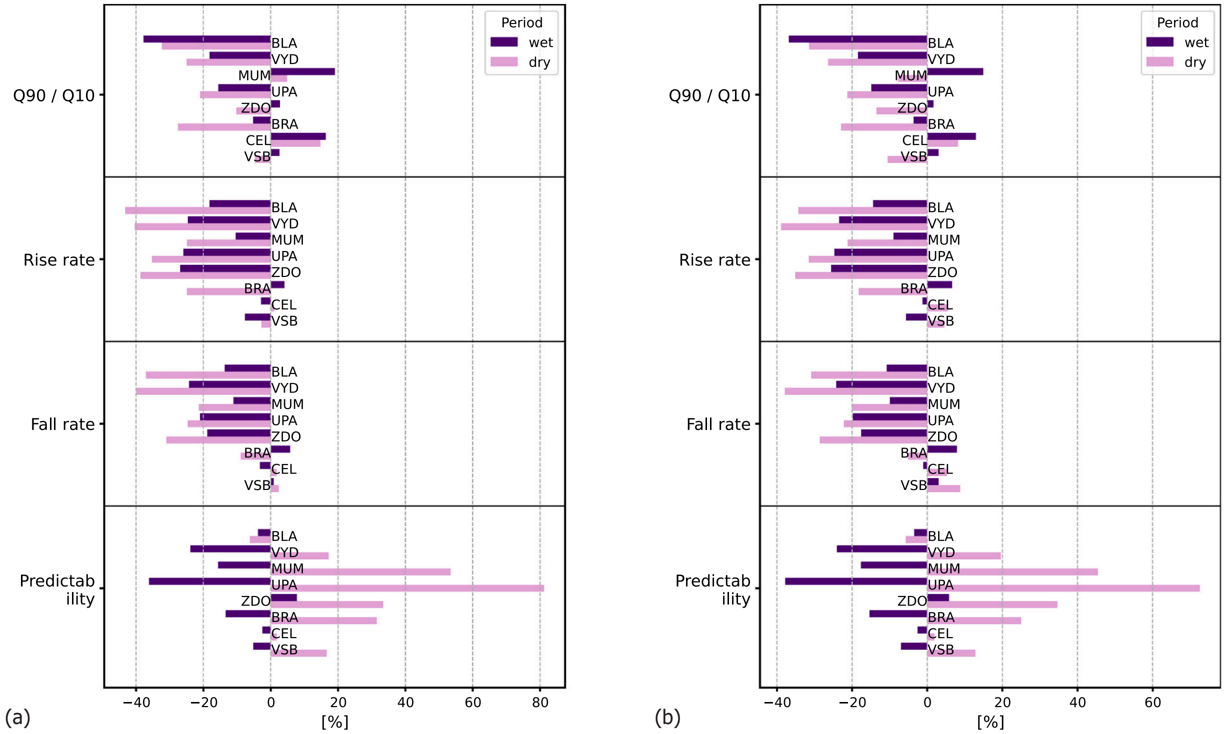

Fig. 11. Intra-annual variability of streamflow. Changes in time series with breakpoints separating the initial series and subsequent wet (2006) and dry (2013) periods. (a) Change in the reference conditions series, (b) change in the series simulating the effects of forest disturbance.

3.5. Contribution of forest disturbance to changes

Analysis of indicator of effect of forest disturbance (effdis, Eq. 3) for daily flows, shows that the largest impacts are observed in mean and maximum daily flows, particularly in dry periods, where the reduction of forest cover leads to increased runoff and slightly diminished peak flows. In all basins, forest disturbance contributes to an increase of mean daily flow, which can be linked to reduced evapotranspiration after disturbance. The rise of daily flows is further amplified in dry periods, while in some basins, due to local physiography, this effect can be significant.

Maximum daily flows are generally reduced across most basins due to disturbance, particularly under dry conditions. The effect is less pronounced under wet conditions, where most basins show relatively smaller reductions or slight increases. For minimum flows, there are generally small positive or negative changes. Most basins under wet conditions see little change or slight reductions in minimum flows (Fig. 12). This suggests that forest disturbances may reduce low flows in wet periods. Dry conditions appear to be less affected, with minor fluctuations mostly under ± 1 %.

The minor effect on baseflow in most basins suggests that forest disturbances may not greatly influence groundwater recharge processes in the short term, though notable increases are seen in a few cases under wet conditions (Fig. 12).

Forest disturbances tend to affect low-flow conditions, particularly by increasing minimum flows and reducing the frequency and duration of low-flow pulses, especially during dry periods. Most basins exhibit small increases in annual minimum flows, with more pronounced increases observed in UPA under dry conditions (+8.6 %) and VSB under wet conditions (+3.5 %). The most significant increases are seen in the minimum 30-day flow indicator, with a notable amplification under dry conditions. This response may reflect reduced evapotranspiration and suggests that forest disturbances can enhance the lowest annual flows in certain basins, potentially due to more intense groundwater recharge during low-flow periods. However, this effect varies across basins, with some regions experiencing more pronounced changes (Fig. 12).

The reduction in low-flow pulse duration and count in many basins (especially under dry conditions) suggests that forest disturbance may lead to fewer and shorter low-flow events, reflecting increased baseflow contributions in disturbed watersheds during dry periods.

Changes in low-flow indicators show that forest disturbance can temporarily improve water availability in streams during periods of minimum flow by reducing transpiration and increasing groundwater recharge. In the long term, however, this can lead to depletion of groundwater storage, which can exacerbate the severity of heat waves and droughts.

Forest disturbances appear to have a mostly limited effect on short-term changes in peak flows compared to the overall changes driven by rising air temperatures. Unlike indicators of mean or minimum flows, the response of peak flows is more sensitive to wet or dry conditions and varies significantly among basins, indicating the influence of basin properties.

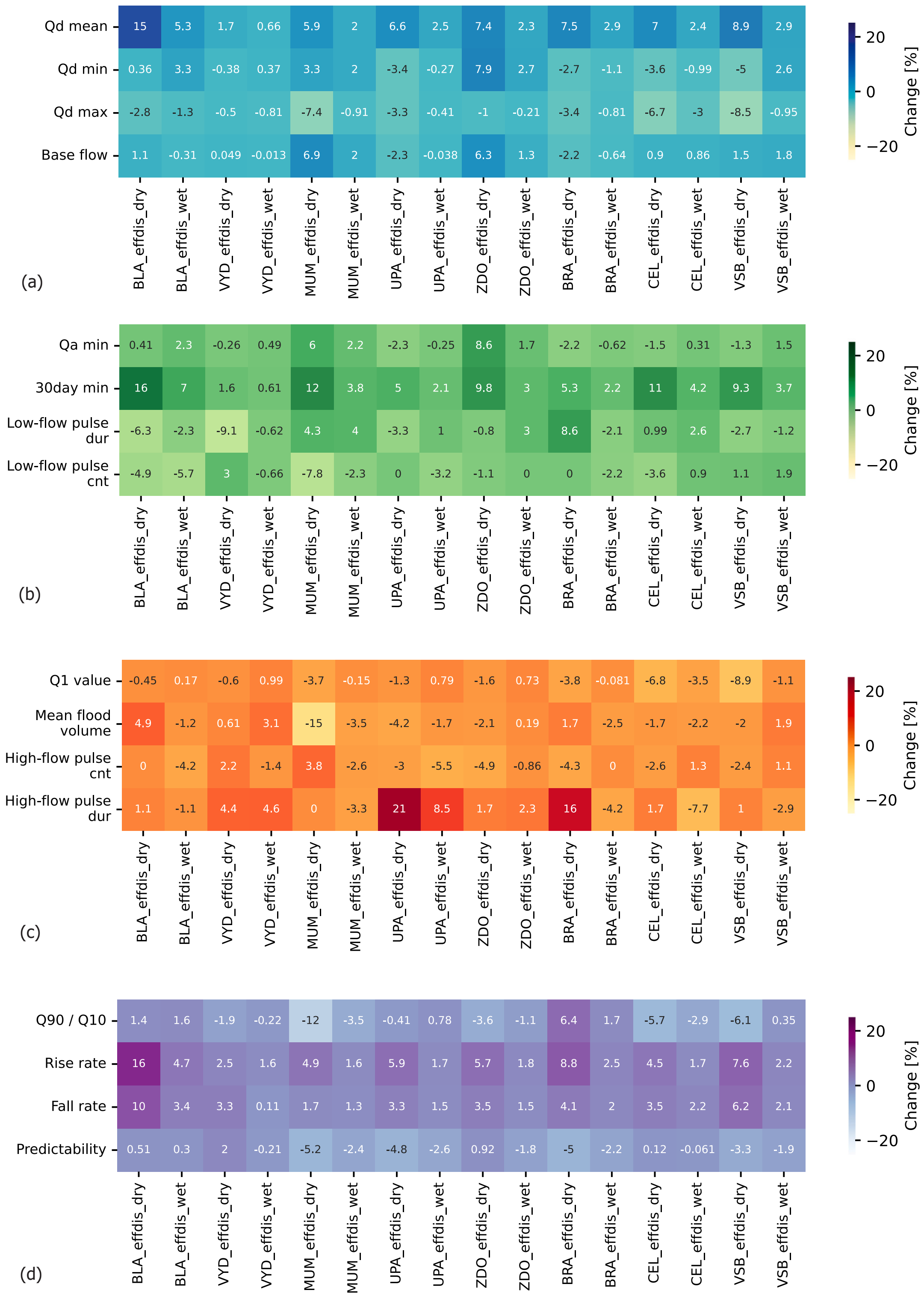

Fig. 12. Impact of forest disturbance on relative change in wet and dry period for indicators of a) mean flows, b) low flows, c) peak flows, d) flow variability.

As a measure of flood intensity, the Q1 value generally increases in most basins following forest disturbance under wet conditions but decreases under dry conditions. However, the overall effect in both scenarios remains very limited. Other indicators exhibit considerable variability among basins, suggesting that the impact of forest disturbance is sensitive to local physiographic conditions.

Specifically, changes in mean flood volume show a slight decrease in most basins, although some experience an increase. High variability is also evident in high-flow pulse count and duration. In certain basins (notably BLA and UPA), disturbances may increase the frequency or duration of high-flow events, while in others, the effect is negligible or negative. Compared to overall changes (Fig. 12), the impact of forest disturbance on peak flows is minimal across most indicators.

Forest disturbance tends to increase streamflow variability, with the most pronounced effects observed under dry conditions, particularly in terms of accelerating the flashiness of flows.

Flow variability (Q90/Q10) exhibits mixed responses across basins, with UPA and ZDO experiencing increased variability in dry and wet conditions, respectively, while other basins demonstrate reduced flow variability. The effects of disturbance on predictability are limited and variable, underscoring the influence of local physiographic characteristics.

A notable impact of forest disturbance is the significant increase in rise rates, particularly in dry conditions, with the most pronounced change observed in the BLA basin (16 %). A similar trend is observed in fall rates, with the effect again amplified under dry conditions. This suggests that disturbed forests contribute to more rapid changes in streamflow, affecting both the rising and falling limbs of the hydrograph.

4. Discussion

The hydrological regime of the studied catchments is influenced by both climate change and forest disturbance, manifesting in various ways. The observed changes align with findings from similar studies in other regions, where climate change is characterized by a gradual increase in air temperature, alongside periods of intense drought and wetness (Stagl et al., 2014). Higher temperatures lead to increased evaporation and transpiration, reducing overall water availability. These processes are consistent with other studies that show a reduction in streamflow due to increased evapotranspiration under warming conditions (López-Moreno et al., 2014; Wanders and Wada, 2015). Additionally, climate warming alters the seasonal distribution of snowpack, resulting in a shorter snow season and earlier snowmelt, which is supported by the work of (Barnett et al., 2005) and (Adam et al., 2009), who noted similar shifts in snowmelt timing in mountainous regions worldwide. In this study, the schematization of forest disturbance in the first year leads to a similar effect as could be observed by deforestation. Numerous studies examining afforestation and deforestation in paired catchments have documented proportional changes in runoff corresponding to the extent of the modified area (e.g., Sonnenborg et al., 2017). Our study builds on these findings, using observed datasets (Zimmermann et al., 2000; Beudert et al., 2018), and the directions and magnitudes of the modeled changes align with these empirical observations. Changes in vegetation cover primarily affect transpiration, both during the wet season, when sufficient soil moisture enables vegetation to influence evapotranspiration potential, and during the dry season, when transpiration is constrained by rooting depth. However, the representation of evapotranspiration in MIKE SHE is notably simplified. Future improvements could involve incorporating a more detailed calculation based on the radiation balance (Sonnenborg et al., 2017).

4.1. *Effects of climate warming on changes in hydrological regime*

The simulations reflect the effects of gradual air temperature rise, with breakpoints marking periods of intense drought or wetness. Consistent with findings by (Jenicek and Ledvinka, 2020), substantial shifts in runoff seasonality were observed across all basins, predominantly driven by rising air temperatures. The earlier snowmelt shifts the timing of peak flows, leading to a significant decrease in water availability during spring, a phenomenon also documented by (Stewart, 2009)in the western United States. Prolonged summer low flows, indicative of earlier onset and extension of low-flow periods, were similarly reported by (Stahl et al., 2010), who highlighted the increasing frequency of low-flow conditions under a warming climate.

A noticeable increase in minimum annual flow values following forest disturbance is apparent across the regions. This trend suggests that forest disturbance enhances baseflow contributions, leading to a higher proportion of low-flow conditions relative to overall flow volumes. This is consistent with findings from (Bearup et al., 2014), who reported substantial increases in baseflow following forest disturbance due to reduced evapotranspiration and interception.

The observed changes in low flows, which are closely related to the altered balance between surface water and groundwater at the outlet, suggest an increased reliance on groundwater following forest disturbance. However, with a warming climate, decreasing snowpack, and changing precipitation patterns, such a trend poses a risk of accelerated depletion of groundwater storage and a risk of more intense droughts.

The frequency and duration of low-flow periods indicate a general increase in the number of low-flow events post-disturbance. This pattern is consistent with the findings from other regions (Li et al., 2018), showing that forest removal tends to increase the frequency of low-flow periods, although their duration may vary depending on local conditions.

The variability in low-flow responses among basins highlights the complex interactions between forest disturbances and local hydrogeological conditions. This complexity underscores the importance of site-specific factors in understanding hydrological responses to forest changes, as noted by (Andréassian, 2004). Physiographic characteristics, such as topography, geology, soil properties, vegetation cover and status, are then playing a critical role in understanding local-specific hydrological responses to climatic and environmental changes (Merz and Blöschl, 2009).

A marked decrease in values of most indicators related to peak flows and flood events was observed during periods of rising air temperatures in both reference and disturbed scenarios. In studied basins, the mean annual maximum values of high flows decreased, with a notable breakpoint identified during the wet season in 2006 and an even more pronounced decrease during the dry season in 2013. The reduction in high-flow durations, aggravated by forest disturbances, suggests that these disturbances may compound the effects of climate change, diminishing catchments' ability to sustain high-flow events. This finding is in line with study by (Kundzewicz et al., 2008), which showed that climate change generally leads to a reduction in the magnitude of peak flows, particularly in regions where warming is coupled with decreased precipitation.

4.2. Effects of forest disturbance on peak and low flows

The influence of forest disturbance on hydrological indicators stems from alterations to canopy interception, evapotranspiration, and soil infiltration capacity. Disturbance reduces vegetative cover, leading to increased surface runoff, decreased groundwater recharge, and higher variability in flow regimes (Andréassian, 2004; Bladon et al., 2019). These mechanisms are particularly pronounced under dry conditions, where reduced transpiration exacerbates baseflow contributions but simultaneously heightens streamflow variability and low-flow event durations, reflecting the complex interplay between vegetation loss and catchment hydrological processes (Bearup et al., 2014; Teuling et al., 2019). Forest disturbances also appear to influence the frequency and magnitude of high flows, particularly for lower magnitude events. The decrease in the average duration of high flow pulses, observed in most catchments during dry seasons can significantly reduce the flood volumes, particularly in small, steep catchments. This trend is apparent in the reference series, with more pronounced changes observed during the dry season (2013), reflecting the compounding effects of climate change and forest disturbance.

The observed general decrease in intra-annual flow variability, particularly during dry conditions, aligns with findings from other studies that have documented similar trends under changing climate conditions. Increasing values of predictability and decreasing values of the ratio between the 90th and 10th percentiles of flow rates indicate a more stable and less variable hydrological regimes. These observations are consistent with the study (Schneider et al., 2012), who found that increased temperatures and altered precipitation patterns contribute to a reduction in flow variability across various European river basins.

In contrast to low flows, where the hydrological impacts of climate change and forest disturbances are relatively clear, the effects on high flows are associated with greater uncertainty (Blöschl et al., 2019; Hall et al., 2014). Numerous studies suggest an increase in flood risk intensity, with high variability over time and space. This variability is particularly pronounced in mid-latitude regions, where the expected impacts vary significantly depending on climatic and geographical characteristics. Observations since the 1980s in mountainous areas of Central Europe indicate an increase in the frequency of low-severity events and an overall decrease in runoff from flood situations.

In particular, during wet conditions, forest disturbance tends to increase runoff and peak flow events. The loss of forest cover reduces interception and evapotranspiration, leading to increased surface runoff. This finding aligns with observations in other studies, detecting increased discharges following large-scale forest disturbances (Kovačič et al., 2020; Li et al., 2018). Forest disturbances such as bark beetle outbreaks, windthrow, and forest management alterations, exacerbated by climate change, disrupt hydrological regimes, leading to elevated runoff and peak flows in affected areas (Hou and Wei, 2024). Such an effect is particularly pronounced during periods of heavy rainfall, as reduced canopy cover and altered soil structure result in increased peak flows, thereby heightening the risk of downstream flooding (Andréassian, 2004; Brown et al., 2005).

Additionally, forest disturbance during dry periods can lead to reduced streamflow and prolonged low flow conditions. The reduction in vegetation decreases transpiration but also reduces soil moisture and groundwater recharge, aggravating drought conditions and water scarcity during dry seasons (Teuling et al., 2019).

The main advantage of a credible physical process-oriented model is its realistic performance under modified model characteristics. Although vegetation recovery is assumed in the model to be a linear process of regeneration, the effect of disturbance on runoff is complex and besides the forest regeneration is reflecting the actual hydroclimatic conditions (Fig. 13).

In the first year after a disturbance, the runoff response is reduced due to catchment inertia. In the second year the effect is the strongest. This result is consistent with the findings of (Oda et al., 2018), where the maximum deviation of runoff after forest disturbance was estimated to be 1.4 years after the impact. The magnitude of the impact is influenced by annual wetness in most of the catchments and in both periods, but there are exceptions that demonstrate more complex causal conditions.

4.3. Regional differentiation of changes in hydrological regime

The selection of study areas located in the border mountain ranges of the Czech Republic allowed for insights into the regional differentiation of hydrological changes. Analysis of the distribution of changes revealed selective regional differentiation, with most identified trends, such as the effects of climate warming and forest disturbance, being of a general nature. However, in some aspects of hydrological changes, gradients between the western and eastern basins were apparent. For instance, the more intense effect of forest disturbance in the eastern basins (BRA, CEL, VSB), particularly in the change in mean streamflow and intra-annual variability, is consistent with regional studies that have documented similar east-west gradients in hydrological responses due to differences in physiography and climatic conditions (Barnett et al., 2005; Stahl et al., 2010). The different physiography of the mountain ranges, with the eastern mountains having steeper topography and limited zones for snow accumulation, results in greater sensitivity to changes in climate conditions and greater volatility in runoff. This finding is supported by (Adam et al., 2009; Kundzewicz et al., 2014), who highlighted the importance of physiographic characteristics in determining the hydrological response to climate change and land use alterations.

To understand the spatial pattern of disturbance-driven change, a Pearson correlation was evaluated between the intensity of change in the study catchments and their physical properties (Table 7). There is a strong correlation between climatic characteristics and runoff change in both wet and dry periods. A significant difference between wet and dry periods was found for the other catchment

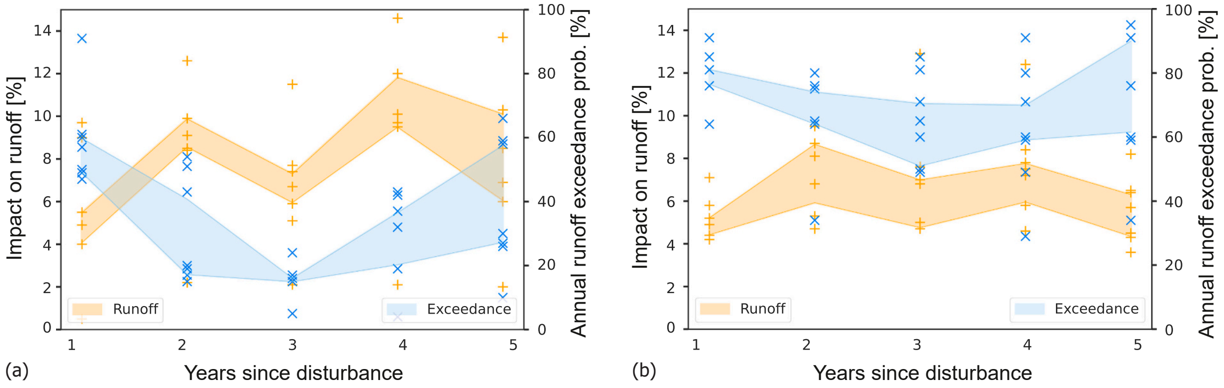

Fig. 13. Impact of forest disturbance on runoff in 5 consequent years and under (a) dry and (b) wet conditions. Orange area represents changes in runoff due to forest disturbance and blue area represents wetness conditions of the year represented as probability of annual discharge exceedance in the entire study period 1999–2019. Areas are delimited by 30 and 70 percentile of results aggregated from 8 basins and original values are appropriately marked by orange and blue points.

specific properties tested.

While the intensity of post-disturbance runoff change is driven by climate in the wet period, the role of catchment-specific physical properties is more evident in the dry period. During the wet period, when there is sufficient soil moisture to fulfill evapotranspiration potential, the change in runoff caused by forest disturbance is independent of the physical characteristics of the catchment. In contrast, during the dry season, evapotranspiration is more likely to be limited by water content, and the impact of disturbance is greater and more site specific. The intensity of the change in the dry period correlates with most of the physical properties tested, with the highest significance in the first year after the impact. Negative correlations were found for precipitation, altitude, proportion of waterlogged soils, specific runoff of the catchment and runoff coefficient of the reference condition (undisturbed). Positive feedbacks were found for temperature, slope and forest cover and negative feedbacks were found for wetness and waterlogged soils. In the wet period the pattern is similar but the relationship is weaker and insignificant (Table 7).

The hydrological impacts observed in the studied montane basins exhibit patterns consistent with other mountainous regions, although specific responses are strongly influenced by local physiographic conditions such as topography, soil characteristics, and elevation. This study underscores the importance of considering both climate change and land-use changes in future hydrological assessments, particularly in mountainous regions where these factors interact in complex ways. The findings emphasize the necessity of adaptive management strategies to mitigate the compounded effects of climate change and forest disturbance on water resources in these sensitive environments.

4.4. Potential uncertainties and their mitigation

Acknowledging the challenges and potential biases that might affect the interpretation of the findings is vital for a correct understanding of uncertainties of the modeling results. Various factors could introduce uncertainties and limitations into the study, such as the following (i) Model selection: The assumptions made in the hydrological model, such as the impact of physiography or vegetation changes should be able to capture the principal drivers of hydrological dynamics of basins to minimize the discrepancies between modeled and actual hydrological responses (Refsgaard et al., 2007). (ii) Data availability and quality: The accuracy of the hydrological models depends heavily on the quality and availability of input data. Incomplete or inaccurate data on precipitation, temperature, and streamflow can introduce biases into the model outputs (Beven, 2006; Sivapalan, 2009). (iii) Spatial and temporal scales: The study's findings are always specific to the spatial and temporal scales analyzed. Extrapolating the results to other regions or

Table 7
Pearson correlation of runoff deviation due to forest disturbance and catchment-specific physical properties (listed on the left) of all 8 studied basins in the first five years after impact.

	WET period (2006)				DRY period (2013)			
	1st year	2nd year	5th year	5-year mean	1st year	2nd year	5th year	5-year mean
Temperature	0.49	0.50	0.78	0.71	0.48	0.51	0.81	0.72
Rainfall	−0.61	−0.65	−0.78	−0.82	−0.54	−0.67	−0.84	−0.84
Reference runoff c.	−0.36	−0.44	−0.53	−0.54	−0.40	−0.66	−0.88	−0.80
Slope	−0.08	−0.28	−0.46	−0.29	0.68	−0.17	−0.13	0.11
Altitude	−0.03	−0.14	0.04	−0.14	−0.68	−0.33	−0.50	−0.58
Water logged soils	−0.12	−0.17	−0.11	−0.21	−0.72	−0.37	−0.59	−0.66
Forestation	0.19	−0.07	−0.45	−0.13	0.66	−0.03	−0.21	0.14
Specific runoff	−0.63	−0.61	−0.31	−0.62	−0.73	−0.78	−0.72	−0.91

time periods even in a homogeneous environment is related with uncertainties, as hydrological responses can vary significantly across different scales (Blöschl and Sivapalan, 1995). (iv) Physiographic variability: The physiographic properties of the catchments, such as topography, soil properties, and vegetation cover, play a critical role in hydrological responses, and their variability as well as their correct representation in the model has significant effect on complexity and uncertainty of the modeling process (Merz and Blöschl, 2009).

These potential limitations were considered in the design of the study. The selection of a fully distributed MIKE-SHE model was made with respect to coverage of the major layers of information affecting runoff generation in a mid-latitude, montane environment. Careful selection of study areas was then a second fundamental principle to minimize uncertainties. We aimed to select a smaller number of but representative catchments, covering the unaffected basins with a similar spatial scale and coherent and uninterrupted time series covering areas was a primary means to mitigate the typical uncertainties arising from modeling studies in heterogeneous regions.

The hydrological impacts observed in the studied montane basins exhibit patterns consistent with other mountainous regions, although specific responses are strongly influenced by local physiographic conditions such as topography, soil characteristics, and elevation. This study underscores the importance of considering both climate change and land-use changes in future hydrological assessments, particularly in mountainous regions where these factors interact in complex ways. The findings emphasize the necessity of adaptive management strategies to mitigate the compounded effects of climate change and forest disturbance on water resources in these sensitive environments.

5. Conclusions

This study investigates the combined effects of climate change and forest disturbance on the hydrological regime of mid-latitude mountain basins in Central Europe. The research methodology is based on a novel approach that integrates simulations using a distributed hydrological model MIKE SHE with the determination of indicators of hydrological change from the simulation results. Such an approach allowed to disentangle the individual and combined effects of climate and forest disturbances and to quantitatively assess their scope and intensity.

Our findings reveal that while climate change is the dominant driver, forest disturbances significantly amplify hydrological changes, particularly during extreme wet and dry conditions. Notably, the interaction between these factors results in shifts in runoff seasonality, enhanced variability, and altered baseflow contributions.

The impact of forest disturbance was found to differ significantly based on whether it occurred under wet or dry conditions. In wet conditions, forest disturbances in the studied catchments led to amplified runoff and peak flows, increased streamflow variability, altered soil infiltration, and reduced baseflow contributions. Under dry conditions, disturbances resulted in reduced streamflow, extended low-flow periods, changes in streamflow timing, and decreased groundwater recharge. While similar effects were observed in the reference time series, forest disturbances generally intensified these trends.

Climate warming primarily affects the hydrological cycle by increasing temperatures and altering precipitation patterns, leading to shifts in streamflow timing, greater variability, and overall reductions in water availability. Forest disturbances further exacerbate these changes by modifying vegetation cover and soil properties, which in turn increases runoff, peak flows, and alters infiltration rates. This dual impact highlights the need for integrated management approaches that consider both climatic and land-use factors in understanding hydrological changes.

Future research should focus on the long-term interactions between forest regeneration, hydrological processes, and climatic variability. Expanding the application of the model across spatial scales could enable the testing of adaptive strategies to mitigate the effects of hydrological extremes in diverse environmental contexts.

CRediT authorship contribution statement

Jakub Langhammer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jana Bernsteinová:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Jakub Langhammer reports financial support was provided by Ministry of Education Youth and Sports of the Czech Republic. Jakub Langhammer reports financial support was provided by Technology Agency of the Czech Republic. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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