The 2018-2023 drought in Berlin: impacts and analysis of the perspective of water resources management

Ina Pohle[1], Sarah Zeilfelder[1], Johannes Birner[1], Benjamin Creutzfeldt[1]

[1]Department of Integrative Environmental Protection (II), Senate Department for Urban Mobility, Transport, Climate Action
and the Environment, Berlin, 10179, Germany

Correspondence to: Ina Pohle (Ina.Pohle@senmvku.berlin.de)

Abstract. The years 2018 to 2023 were characterised by extreme hydrometeorological conditions, with record-high average annual air temperatures and record-low annual precipitation, affecting the hydrogeological and hydrological conditions in Berlin and the catchments of its tributaries, mainly the Spree and Obere Havel. To combat the impact of the drought, various water resources management measures were implemented in Berlin and the Spree and Obere Havel catchments.

We analysed observed and modelled time series of hydrometeorological, hydrogeological and hydrological variables in Berlin and the Spree and Obere Havel catchments to characterise the years 2018-2023 also in comparison with long-term averages.

We found that the meteorological drought propagated into soil moisture drought and hydrological drought, e.g. in terms of record-low groundwater and surface water levels and streamflow, with smaller rivers drying up. Due to the intensity and duration of the drought, water resources management was only able to partially counteract the drought situation, so that water use was partially limited, e.g. in terms of shipping. Enhanced proportions of sewage water and reverse flow were associated with detectable concentrations of trace substances. However, Berlin's water supply was always guaranteed and represents a stable system.

Climate change is expected to lead to more frequent meteorological droughts, which will have more severe hydrological impacts in the future due to socioeconomic changes in Berlin (increasing population) and the catchments (termination of mining discharges). Therefore, water resource management in the Spree and Obere Havel catchments and in Berlin needs to be adapted to combat such situations, taking into account the lessons learned from the 2018-2023 drought and possible future developments.

1 Introduction

Droughts as periods with water availability significantly below average are natural disasters affecting ecology, economy and society (Van Loon and Laaha, 2015). Drought propagates in the hydrological cycle (Van Loon, 2015) whereby drought conditions typically emerge from precipitation deficit (meteorological drought), and can subsequently lead to soil moisture deficit (agricultural drought), low flows and low water levels in surface and groundwater (hydrological drought), in consequence limiting water availability for various water users (socio-economical drought). Drought further affects water

quality in terms of e.g. nutrients and trace substances (e.g. Winter et al., 2023; Wolff and van Vliet, 2021). Hence aquatic ecosystems can be under stress due to reduced water quantity and deteriorated water quality (Chow et al., 2022; Lennox et al., 2019). Managing droughts, low flows and water scarcity are therefore essential tasks of water resources management.

In Germany and throughout Europe, the 2018-2023 drought was characterised by extreme heat and precipitation deficit (Kaspar and Friedrich, 2020; Vogel et al., 2019), severe soil moisture drought (Boeing et al., 2022; Toreti et al., 2019), low groundwater levels and long and intense low flow periods (Boergens et al., 2020; Bonaldo et al., 2023; Trauth and Haupt, 2022). Various economic sectors, such as agriculture (Conradt et al., 2023), energy production (Shyrokaya et al., 2024) and water supply (Rickert et al., 2022; Schwandt et al., 2022) were strongly affected by the drought.

In Berlin, 74 % of the drinking water comes from bank filtration and groundwater recharge and only 26 % directly from groundwater. In contrast, 63 % of drinking water nationwide is obtained from groundwater and only 16 % from bank filtration and recharge (StaBuA, 2022). So, in contrast to many regions in Germany, Berlin's water supply is predominantly dependent on surface water and hence, from the Spree and Obere Havel catchments. These catchments are especially vulnerable to water scarcity due to (i) low natural water availability, (ii) declining mining discharges from open-pit lignite mines in the Spree catchment (Pohle et al., 2019), (iii) a groundwater deficit of billions of cubic meters in the Lusatian lignite mining region due to the pumping of mine water and subsequently the filling of open-pit lakes and (iv) intense water usage in the Spree and Obere Havel catchments and in Berlin for agriculture, industry and energy production.

The 2018-2023 meteorological drought resulted in both severe soil moisture and groundwater deficit and affected Berlin's water quantity and water quality. Thus, targeted water management measures were carried out both in Berlin itself and the Spree and Obere Havel catchments.

Unlike floods, which are managed through legal (Floods Directive, Federal Water Act (Wasserhaushaltsgesetz WHG)) and administrative (German Working Group on water issues of the Federal States and the Federal Government, LAWA and River Basin Community (RBC) Elbe) instruments at EU, national and river basin level, comparable instruments have so far been lacking for the management of drought, water shortages and low flows. At the political level, the German Conference of the Environment Ministers (UMK) therefore decided to develop an overarching framework for managing drought risks at state level (UMK 101/102 umk_endgueltiges_ergebnisprotokoll_1719251905.pdf, umweltministerkonferenz.de). The strategic framework was set at the German national level through the National Water Strategy (BMUV, 2023). The Berlin-Brandenburg Water Strategy and the Water Masterplan address the issue at regional level. The topic of water resource management has been addressed in the work programme of the German Working Group on water issues of the Federal States and the Federal Government (LAWA). For example, a LAWA subgroup on water shortage and competing uses has been formed in 2023 to develop guidelines for prioritising water use during periods of water shortage and for dealing with conflicts of use. The German Association of Towns and Municipalities has already presented an example of how to limit the use of drinking water during hot summers in the form of a handout.

Understanding the causes and impacts of drought in Berlin is a prerequisite for assessing the consequences of a potentially warmer and drier future. This provides a basis for adapting water resource planning and management and for developing appropriate technical, legal and administrative instruments in a timely manner.

This manuscript analyses the 2018-2023 drought period in Berlin focusing on water quantity under consideration of complex water management measures in Berlin and the Spree and Obere Havel catchments. The manuscript further addresses the following questions: How did the 2018-2023 drought propagate in Berlin and how does it compare to previous drought periods? Does the 2018-2023 drought give a taste of the future? What does the 2018-2023 drought imply for future water resources management in Berlin and the Spree and Obere Havel catchments?

2 Study area

Berlin is the capital and largest city of Germany in terms of population (currently around 3.9 million and growing) and area (892 km²). As a city-state, Berlin is surrounded by the state of Brandenburg. Together, the Berlin-Brandenburg region has a population of about 6.2 million and covers about 30,500 km². The hydrological situation of Berlin is influenced by the meteorological processes in Berlin itself, but especially by its major tributaries, the Spree and Obere Havel. This study thus not only focuses on Berlin, but also considers the effects of the 2018-2023 drought on the Spree and Obere Havel catchments mainly in Brandenburg, also covering parts of the Czech Republic, Saxony and Mecklenburg-Western Pomerania (Fig. 1). The region, shaped by its glacial history, is characterised by predominantly sandy soils and flat topography. The dominant land uses are agriculture (ca. 43 % of the state of Brandenburg, most important crops are maize, winter wheat, rye and winter barley) and forestry (ca. 37 % of the state of Brandenburg, mainly Scots pine). Urban areas are concentrated in and around Berlin. Open-pit lignite mining significantly influences the Spree catchment with active mines, recultivation areas, and post-mining lakes.

2.1 Hydrometeorological characteristics

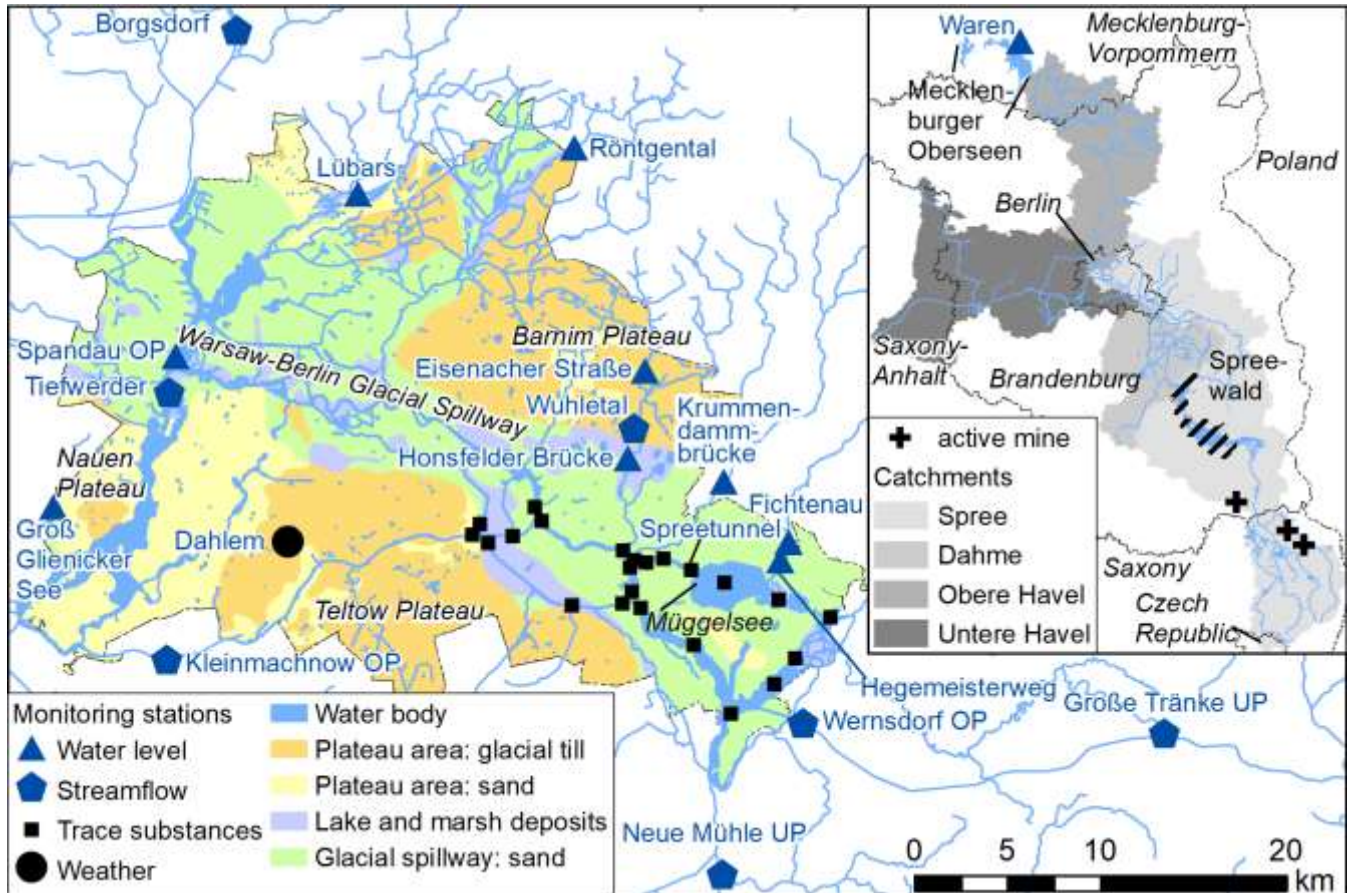
The climate in the Berlin-Brandenburg region is humid continental with annual average temperatures around 9.7 C (reference period: 1991-2020, January mean: 0.8°C and July mean: 19.3°C) and annual precipitation around 579 mm (reference period: 1991-2020, January: 47 mm, July: 75 mm, see supplement S 1 based on (Annual regional averages of air temperature and precipitation (monthly mean), 2024)). In comparison with other German regions, Berlin-Brandenburg appears as one of the driest but also relatively warm (see S1). The region has undergone climatic changes in recent decades, such as air temperature increases (Gädeke et al., 2017). While annual precipitation did not change significantly, precipitation shifts from summer to winter (Murawski et al., 2016) and longer dry periods and more drought months in summer (Paton et al., 2021) have been observed. Overall, the region, which has relatively low natural water availability, has become even drier as temperature-induced evaporation increases have not been by changes in annual precipitation. Declining groundwater recharge as well as lower lake levels have been reported as a result of climatic and land cover changes (Kaiser et al., 2015; Natkhin et al., 2012).

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Figure 1 Map of Berlin including the monotoring stations analysed in this study. The inset shows Berlin within the Spree (including Dahme) and Obere Havel as well as Untere Havel catchments. Data: BfG. DWD, LfU, SenMVKU, WSA

2.2 Water management in the Spree and Obere Havel catchments

The Spree has its source in Saxony; its headwater catchment also includes parts of the Czech Republic. The Spree then flows
100   through Saxony, Brandenburg and Berlin where it joins the Havel upstream of Tiefwerder. The Spree catchment has an area
of around 10,100 km²; its landscape features include reservoirs (Bautzen, Quizdorf and Spremberg), the Lusatian lignite mining
region and the Spreewald wetland. Mining discharges from large-scale open-pit mining and reservoir management result in
elevated streamflow volumes and reduced temporal streamflow variability of the Spree (Pohle et al., 2019). Open-cast lignite
mining in the Spree River catchment peaked in the 1980s and declined after 1990 due to German reunification. Currently,
105   three mines are still operating which produced 42 million tons of lignite in 2023 (Daten und Fakten 2023, 2024). To extract
lignite, groundwater levels have to be lowered and pumped groundwater is released into the river system resulting in
significantly elevated streamflow, i.e. up to a factor of ten during low flow periods in the 1980s (Grünewald, 2001; Koch et
al., 2005). Decreasing mining activities thus also led to significant decreases in streamflow of the Spree since the 1990s.

Another influence on the flow of the Spree are high evaporation losses in the wetland Spreewald during summer (Dietrich et
110 al., 2007). Furthermore, water transfers between catchments (e.g. between the Spree and the Schwarze Elster and Lusatian Neisse) and abstractions (e.g. for inland fisheries) influence streamflow variability in space and time. Water resources management in the Spree catchment is based on harmonised management principles of the working group River Basin Management Spree, Schwarze Elster and Lusatian Neisse (AG Flussgebietsbewirtschaftung Spree, Schwarze Elster und Lausitzer Neiße (AG FGB)) consisting of the German Federal States of Berlin, Brandenburg and Saxony. These management
115 principles consider water quantity, e.g. required minimum flows (e.g. 8 m³/s for the Spree upstream of Berlin at the Große Tränke UP gauging station), and aspects of mining-related water quality with respect to iron and sulphate concentrations. Water management is generally prioritised with water abstraction (under consideration of required minimum flow and water quality requirements) being the highest priority. Second priority is given to replenishing reservoirs, third priority to maintaining the water levels of the Oder-Spree canal and fourth priority to flooding of post-mining lakes.

120 The Havel River is a right tributary of the Elbe River in north-eastern Germany which originates in the state of Mecklenburg-Western Pomerania upstream of the Mecklenburger Oberseen. The Havel catchment has a total area of ca. 23,900 km². Its upper part, the Obere Havel catchment, stretches up to the Spandau impoundment (gauging station Spandau OP in Fig. 1) and has an area of ca. 3,400 km². Streamflow variability of the Obere Havel is dominated by the management of the Mecklenburger Oberseen, a group of lake reservoirs (Plauer See, Petersdorfer See, Malchower See, Fleesensee, Kölpinsee and Müritz lakes)
125 which is managed as a reservoir with outlets towards both the Obere Havel to the south-east and the Elde to the west. The streamflow of the Obere Havel is further influenced by 14 river impoundments (Ebner von Eschenbach et al., 2021). Unlike in the Spree catchment, water resources management in the Havel catchment does not yet follow formalised management principles. The minimum flow required by Brandenburg for the Havel downstream of Berlin is 10 m³/s.

The water resources management in the Spree and Obere Havel catchments and in Berlin has been adapted to combat the 2018-
130 2023 drought. In the Spree catchment, the working group "ad-hoc extreme situation" has been set up between the Federal States of Berlin, Brandenburg and Saxony and the mining cooperatives to coordinate operational water management (AG FGB, 2023). These measures include limiting water abstractions, public information on water saving, optimised water management in the Spreewald wetland, adaptation of minimum flows and immission limits for sulphate and optimised reservoir management.

135 In the Obere Havel catchment, various measures have been implemented, including in some areas a restriction of public surface-water use and an increased release from the Mecklenburger Oberseen reservoir into the Obere Havel. In Berlin, the weirs have been closed as far as possible and lock operations were limited and special monitoring programmes were set up (Creutzfeldt et al., 2021). Measures to counteract the fall in water levels in the Spandau impoundment, which is crucial for Berlin's water supply, included reduced outflows, increased transfers of waste water and suspending the targeted reduction of
140 water levels to summer operational level (Creutzfeldt et al., 2023).

2.3 Hydrogeology, hydrology and water management in Berlin

Tertiary and quaternary glacial processes shaped the (hydro-) geological setup of Berlin, resulting in an aquifer system of a total thickness of approx. 150 m. This system consists of alternating layers of unconsolidated sediments with varying hydraulic conductivity such as gravel and sand, which form the aquifers and glacial till, silt and clay, which, in turn, form the aquitards.

145 These layers can be differentiated into four aquifers (Limberg, A., Thierbach, 1997). Depending on regional sedimentation and erosion processes, some aquifers are in direct contact with each other without a separating aquitard or have been eroded by glacial-fluviatile processes. In this study, only the groundwater levels of the "main aquifer" (from the Saale glacian period) are considered, as this aquifer holds economic importance for water resource management. On the Barnim Plateau and the eastern part of the Teltow Plateau (Fig. 1), the main aquifer is confined, being covered by glacial till from the ground moraine.

150 In the area of the Warsaw-Berlin glacial spillway, the main aquifer is covered by Weichselian sediments with high hydraulic conductivity, resulting in unconfined groundwater conditions. Also in most of the Nauen Plateau and the western part of the Teltow Plateau where the sediments of the aquifer are largely characterised by very thick meltwater sand sequences (SenStadt, 2013), the groundwater is unconfined.

The general groundwater flow direction is from the recharge areas on the Barnim Plateau (in the north-east) and the Teltow

155 Plateau (in the south) to the Warsaw-Berlin glacial spillway, which serves as the discharge area with effluent conditions to the Spree. The depth to water table ranges between 7 m and up to 40 m on the Plateau areas and only several meters along the Warsaw-Berlin glacial spillway (SenStadt, 2010). Along the Warsaw-Berlin glacial spillway, groundwater levels are influenced by the Spree and its artificial regulation. The public water-supply wells are primarily located along the Spree and Lake Müggelsee in the eastern part of the city, as well as along the Havel in the western area of the Teltow Plateau. To evaluate

160 the development of groundwater levels, it is essential to distinguish between the data sets of these (hydro-) geological regions due to the heterogeneity of the study area.

Berlin is characterised by around 140 km of larger and 75 km of smaller rivers as well as both fluvial and groundwater-fed lakes and also ponds. The main tributaries (i.e. Spree, Dahme and Obere Havel) are connected by a number of canals and regulated by weirs, resulting in a branched surface water system in Berlin. Due to weir operations, there is little intra-annual

165 variation in water levels despite large variations in streamflow. Low streambed and water level gradients and wide river cross-sections result in near-zero flow velocities especially during drought periods. Berlin's water users, i.e. water supply and wastewater disposal, inland navigation, abstractions and cooling water discharges by thermal power plants, depend on the streamflow situation as well as the controlled water levels in Berlin.

3 Data and Methods

3.1 Data

The hydrometeorological situation was analysed using the example of the Berlin-Dahlem weather station of the German Weather Service (DWD, location see Fig. 1). We used daily values of observed precipitation and air temperature as well as derived potential evapotranspiration (grass reference evapotranspiration). We further used gridded annual air temperature and precipitation data provided by the German Weather Service for the Spree and Obere Havel catchments. Reservoirs in the Spree catchment were analysed in terms of the daily total storage of eight reservoirs; these data were provided by the Saxon Dam Authority (LTV), Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV) and Landesamt für Umwelt Brandenburg (LfU). The Mecklenburger Oberseen in the Obere Havel catchment was considered by daily water levels at the Waren (Müritz) gauging station provided by the Federal Waterways and Shipping Administration (WSA). Inflows to Berlin were analysed based on discharges at the gauging station Große Tränke UP (Spree), Wernsdorf OP (Oder-Spree Canal), Neue Mühle UP (Dahme) and Borgsdorf (Obere Havel) provided by WSA.

Soil moisture in Berlin was taken into account by model results of the AMBAV model (Löpmeier, 1994) for grass and sand between 0 cm and 60 cm depth at the Berlin-Dahlem weather station (DWD Climate Data Center: Calculated daily values for different characteristic elements of soil and crops. Version v19.3, 2024). Groundwater levels were analysed using daily data from monitoring wells representing four geological regions, i.e. the Nauen Plateau / Grunewald area (13 wells), the Eastern Teltow Plateau (13 wells), the Warsaw-Berlin glacial spillway (19 wells) and the Barnim Plateau (17 wells). All of the monitoring wells are measuring the groundwater levels of the "main aquifer" which is the relevant aquifer with regard to water resources management. The hydrological situation in Berlin was analysed using around 60 surface water quantity (water level and or flow) monitoring stations, those which are explicitly mentioned in the manuscript are shown in Fig. 1. The drought impact on Berlin's water quality was assessed by concentrations of trace substances measured at 23 sites on three sampling days in summer 2019. For an overview of the monitoring stations please refer to supplement S 1.

3.2 Statistical Analysis

Metrics describing the hydrometeorological situation, the hydrogeological situation and the hydrological situation as well as water management in the drought years 2018-2023 are shown and compared to long-term averages (typically 1991-2020). If not mentioned otherwise, hydrological years (in Germany 1 November of the previous year up to 31 October of the respective year) are used, whereby hydrological summer refers to 1 May to 31 October of the respective year.

The hydrometeorological situation is represented by thermopluviograms, relating mean annual temperature to annual precipitation totals, and evapopluviograms relating potential evapotranspiration to precipitation. The latter includes diagonals representing isolines of the climatic water balance, which is calculated as difference between precipitation and potential evapotranspiration.

200   To compare annual courses of the respective hydrogeological and hydrological variables of several years, we chose diagrams combining hydrographs of the hydrological years of interest (shown in colour) and percentiles for each calendar day in the reference period (shown in grey scale) based on the R code provided by Zappa et al. (2014). These figures also show long-term monthly averages. These plots may also contain hydrological main values of water level (W) or discharge (Q), i.e. highest values recorded (HHW, HHQ), highest values in a time period (HW, HQ), mean high values (MHW, MHQ), mean values

205   (MW, MQ), mean low values (MLW, MLQ), lowest values in a time period (LW, LQ) and lowest values recorded (LLW, LLQ). Please refer to supplement S 3 for a detailed description of the hydrological main values.

The low flow situation was described using mean average minimum water level or discharge over 7 (MAM7), 30 (MAM30), 60 (MAM60) and 90 days (MAM90). Stream flow intermittency was described in terms of dry periods during which water levels drop below the threshold detectable at the water level gauges.

210   Groundwater levels were considered as median deviations from long-term averages for each geological region. For each well, monthly median water levels were calculated from daily values, and the monthly deviation to the long-term medians (2001-2020) of each observation well was calculated. Following from this, the monthly deviations were then averaged across all monitoring wells within each respective hydrogeological region.

Drought propagation was summarised following Peters et al. (2006) and Van Loon (2015) in terms of sequence of monthly

215   precipitation, climatic water balance, soil moisture, groundwater levels and streamflow in relation to long-term averages.

3.3 Modelling

The 1 D hydronumerical model BIBER (computation and information system of Berlin's surface waters, IWU, 2019) which is based on the HYDRAX model (Oppermann et al., 2015) was used to determine streamflow at cross-sections in Berlin's surface water systems that are not monitored. BIBER considers daily values of inflows, water levels in Berlin's river

220   impoundments, discharges of sewage treatment plants, waterworks withdrawals, withdrawals and cooling water discharges of the thermal power plants, precipitation and evaporation to simulate water level, discharge, flow velocity, cross-sectional area and flow volume for 1400 cross sections in Berlin's main river network. A balance adjustment is calculated for all these components. Please see supplement S 4 for a description of BIBER. Due to data availability issues, BIBER simulations were carried out for the period 2003-2022.

225   **4 Results**

4.1 Hydrometeorological conditions

The hydrological years 2018-2023 were very warm and characterised by low precipitation in the Spree and Obere Havel catchments. At the Berlin-Dahlem weather station, the annual mean air temperature ranged between 11.0 °C and 11.2 °C (except 2021: 10.1 °C), markedly exceeding the 1991-2020 average of 9.9 °C (Fig. 2a). With the exception of 2021, the Spree

230   and Obere Havel catchments were on average 1.1 to 1.4 °C warmer than the 1991-2020 average (standard deviation of ≤ 0.1 °C

in individual years, see supplement S 5). From 2018 to 2022, annual precipitation at Dahlem ranged between 402 mm (2018, 2022) and 508 mm (2019) and was lower than the l991-2020 average of 585 mm. Only 2023 showed an above-average precipitation of 638 mm. The precipitation deficit during the 2018-2023 drought accumulated to 360 mm in the Spree catchment and 260 mm in the Obere Havel catchment (supplement S 6). Precipitation differences from the 1991-2020 period

235   varied in space (standard deviation up to 40 mm based on 1 km² cells in each catchment, supplement S 6) and time. 2018 and 2022 were the driest years with an average precipitation deficit of 200 mm and 140 mm, respectively, in the Spree and 180 mm and 140 mm in the Obere Havel catchment. In 2021, the Spree catchment had around average precipitation and the Obere Havel catchment above-average precipitation (48 mm) while 2023 showed above average precipitation in both catchments.

The hydrological summers were characterised by above-average temperatures and (except 2023) below-average precipitation

240   (Fig. 2b). The hydrological summers of 2018 and 2022 showed higher temperatures (17.6 °C and 17.0°°C) and lower precipitation (140 mm and 183 mm, respectively) than previously recorded at this station. Potential evapotranspiration in each year 2018-2023 exceeded the 1991-2020 average of 640 mm, with 2018 displaying the highest ETP on record (755 mm, Fig. 2c). As a result, the climatic water balance was negative, with 2018 showing the lowest CWB since records began (-352 mm, 1991-2020: -55 mm). Precipitation varied widely between months, with March 2022 being almost dry and all summer months

245   of 2022 below average. In the recent past, there has been a clear alternation between years of high and low precipitation, resulting in phases of positive and negative climatic water balance (Fig. 2e). In contrast, the 2018-2023 drought was the longest consecutive period of negative annual CWB resulting in a strong decrease in cumulative CWB.

4.2 Hydrological conditions in the Spree and Obere Havel catchments

Reservoir contents in the Spree and Obere Havel catchments typically vary seasonally with higher storage volumes in summer

250   than in winter (Fig. 3). The reservoirs in both the Spree and Obere Havel catchments were still well filled by the beginning of the 2018 hydrological summer. At the end of the hydrological years 2018, 2019 and 2020, the reservoir volumes in the Spree catchment were lower than 25 hm³ (Fig. 3a). During the 2020 winter, the reservoirs filled to only half their capacity. The water level of the Mecklenburger Oberseen reservoir has remained below the upper operating water level of 62.35 m since March 2018. It fell below the lower operating water level of 61.80 m a.s.l (above sea level) for extended periods (September 2018 to

255   January 2020, July 2019 to January 2020 and August 2020 to January 2021, Fig. 3b). Since 1990, the only other longer periods during which water levels fell below the lower operating water level were in 1991 (September to December) and 2003 (August to December). During two weeks in September 2019, water levels even reached the lowest operating water level of 61.60 m. From September 2018 to August 2021, the reservoir volumes of the Mecklenburger Oberseen were lower than the 90th percentile of exceedance compared to long-term mean values of the respective months between 1991 and 2020.

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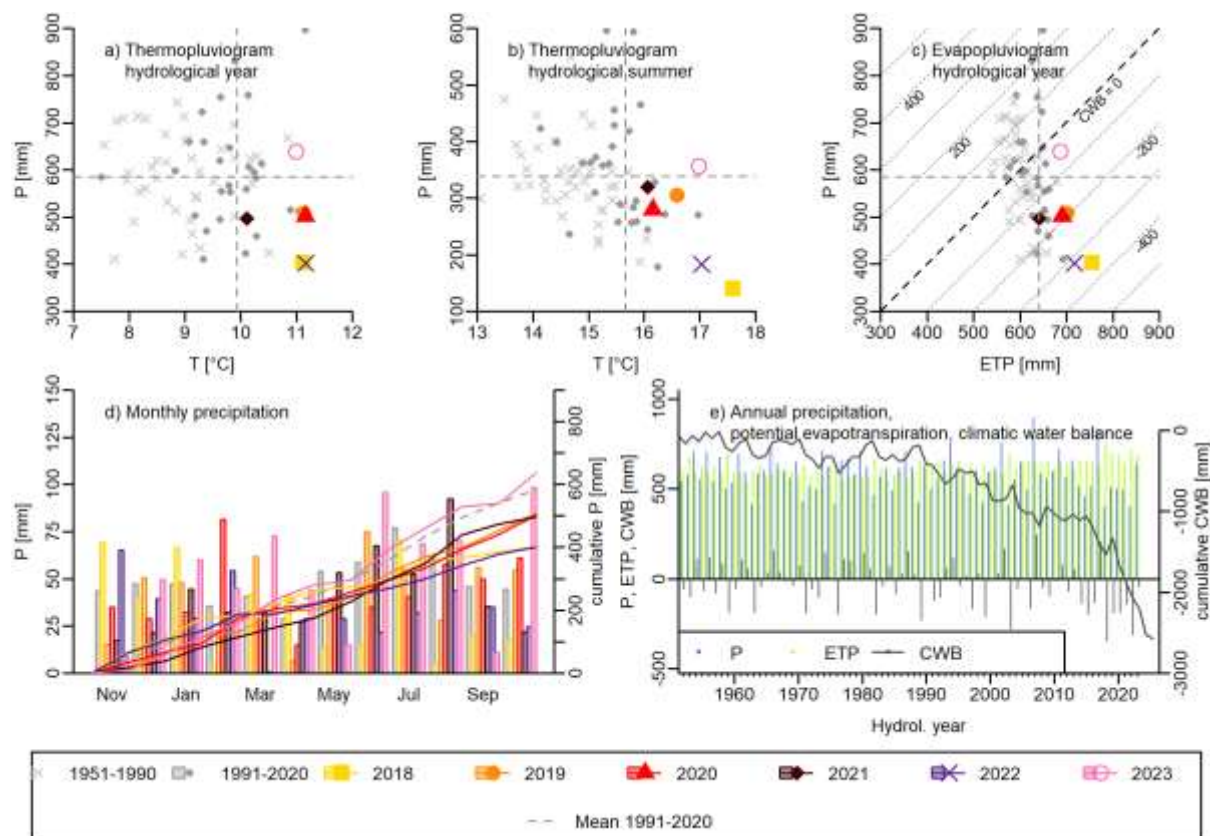


Figure 2 Hydrometeorological situation at the example of the Dahlem weather station: a) thermopluviogram based on air temperature (T) and precipitation (P) for hydrological years, b) thermopluviogram for hydrological summer (May – October), c) evapopluviogram based on potential evapotranspiration (grass reference evapotranspiration; ETP) and P for hydrological years, d) monthly precipitation depths and cumulated precipitation for hydrological years, e) annual totals of P, ETP and climatic water
265 **balance (CWB) and cumulated climatic water balance. Data: DWD**

The inflows from the Spree and Obere Havel catchments showed extended low-flow periods (Fig. 4). The lowest annual averages on record occurred in 2019 at Borgsdorf (Obere Havel, 6.97 m³/s compared to the 1991-2020 average of 12.1 m³/s) in 2020 at Neue Mühle UP (Dahme, 2.82 m³/s compared to 8.83 m³/s) and in 2022 at Große Tränke UP (Spree, 8.56 m³/s compared to 12.0 m³/s). Compared to the reference period 1991-2020, streamflow was mostly below the respective long-term
270 monthly averages and below the median of the respective calendar days. During summer, streamflows were partially even lower than the 90th percentile of the respective calendar days, sometimes even lower than the minima in the reference period. Streamflow often fell below the average minimum flow MLQ, with the longest periods below MLQ occurring between May and September 2019 at Große Tränke UP and Wernsdorf OP, between April and September 2020 at Neue Mühle UP and between June and September 2022 at Borgsdorf. In many cases, e.g. between May and September 2018 and 2022, the flow
275 requirement at Große Tränke UP of 8 m³/s could not be met. The most intensive low-flow periods were observed in 2019 at Große Tränke UP (for MAM30, MAM60, MAM90) and in 2022 at Wernsdorf OP and Borgsdorf (all MAM values).

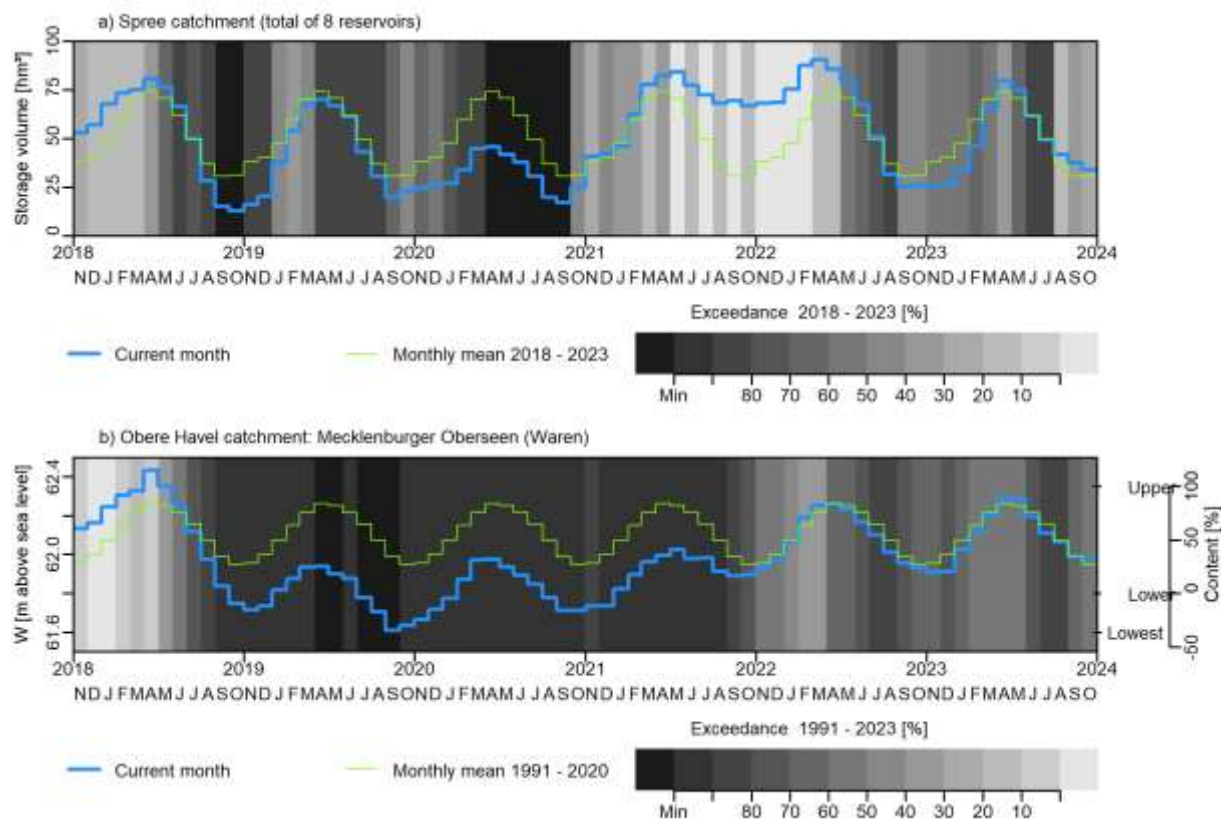



Figure 3: Reservoir contents as monthly mean values during the 2018-2023 drought compared to long-term monthly means. a) Spree
280 **catchment: total active storage volume of eight reservoirs compared to monthly mean values in 2018-2023, b) Obere Havel**
catchment: water level of the Mecklenburger Oberseen at Waren gauging station compared to long-term monthly mean values in
1991-2020. The left-hand y-axis shows upper, lower and lowest operational levels and relative reservoir content. Data: LTV, LMBV,
LfU, WSA

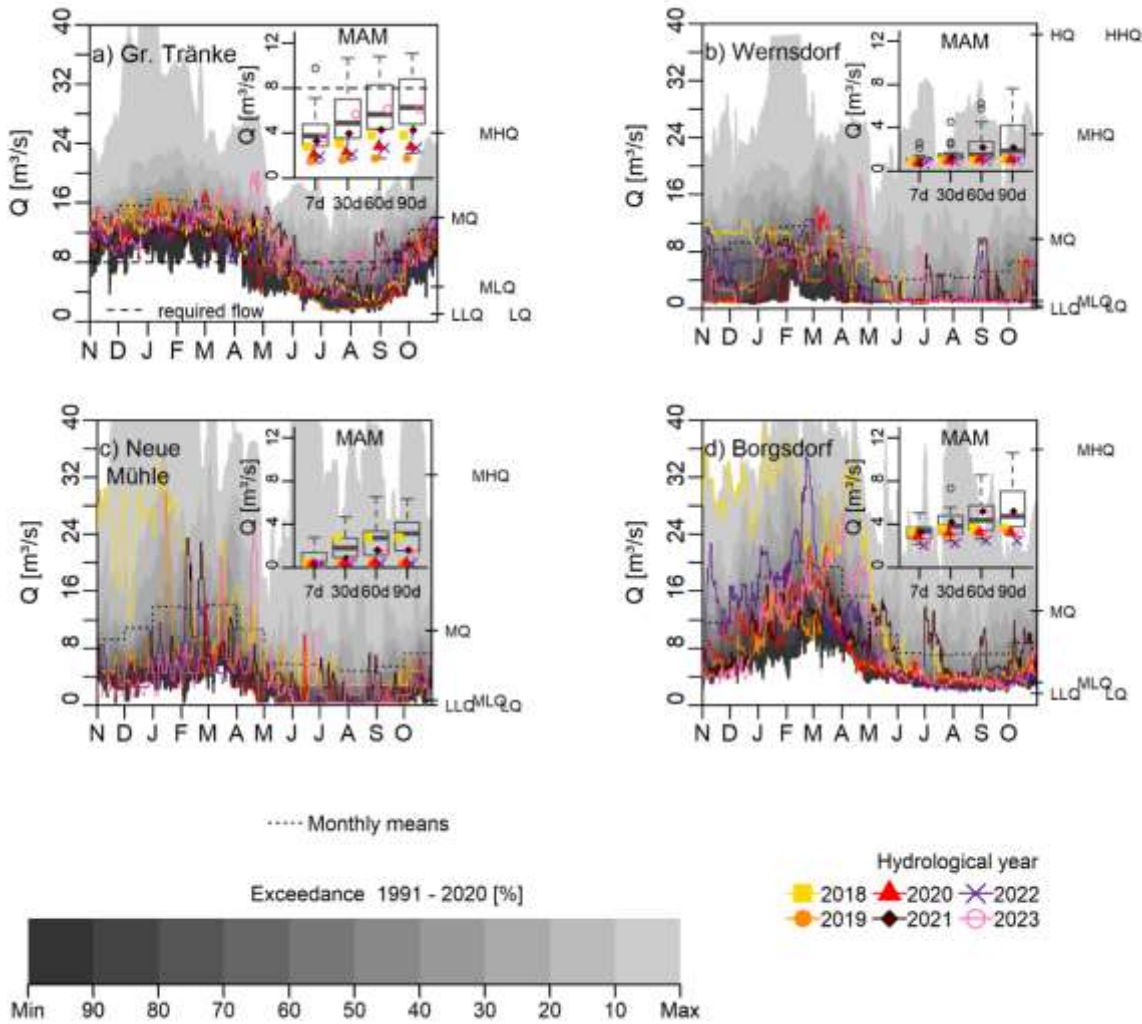



Figure 4 Inflows (Q) to Berlin as percentiles for calendar dates and long-term monthly mean values for the hydrological years 1991-
2020 and daily values in the hydrological years 2018-2023. The right-hand y-axes show hydrological main values in specific time
periods: Große Tränke UP (Spree, 1962-2020, LLQ: 3 August 2001), b) Wernsdorf OP (Oder-Spree-Canal, 1962-2020, LLQ: 7th
May 1905, HHQ: 6 February 2011), c) Neue Mühle UP (Dahme, 1955-2020, LLQ: February 1954) and d) Borgsdorf (Obere Havel,
1976-2020, LLQ: 29 September 2009). The insets show the low-flow characteristics MAM7, MAM30, MAM60 and MAM90 as
boxplots for the hydrological years 1991-2020 and points for 2018-2023. Data: WSA

4.2 Hydrogeological and hydrological conditions in Berlin

Soil moisture shows pronounced seasonality with the highest values around 100 % of the available water capacity during
January to March (Fig. 5). In the spring of 2018, soil moisture decreased to below 25 %. Since then, soil moisture above the
long-term monthly averages has only been reached after rain events and in January and February. Compared to the 1991-2020
reference period, the values in 2018-2023 are generally below the median values of the respective calendar days, partially

reaching or even falling below the minimum values of the reference periods. The longest periods of particularly dry soils occurred between April and December 2022 with 247 consecutive days below 50 % soil moisture for grass and sand at Dahlem.

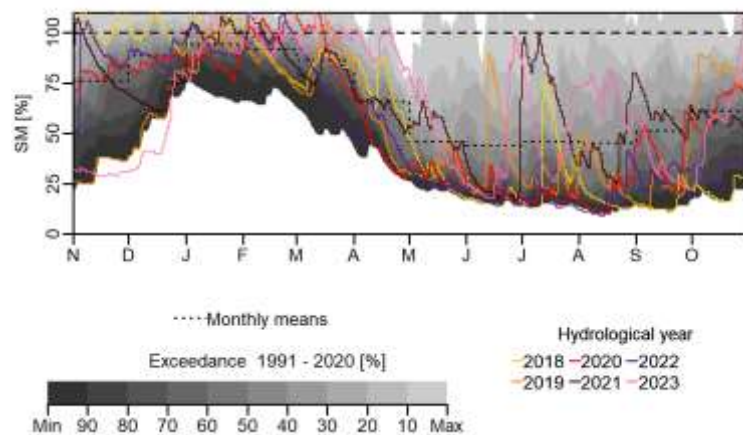



Figure 5 Soil moisture (SM; percent of the available water capacity) for grass and sand at the Dahlem weather station shown as percentiles for calendar dates and long-term monthly mean values for the hydrological years 1991-2020 and daily values in the hydrological years 2018-2023. Data: DWD

At the start of the hydrological year 2018, groundwater levels were considered normal to high throughout almost all four geological regions due to heavy precipitation events in summer 2017 and the delayed reaction of the aquifers in the plateau areas. Groundwater levels continued to rise through the end of the hydrological winter in 2018. However, during the hydrological summers of the years 2018 to 2020, groundwater levels decreased subsequently each year without being balanced by a comparable rise during the groundwater recharge season of the following hydrological winter. While a seasonal pattern is recognizable in the areas of the Barnim Plateau and the Warsaw-Berlin glacial spillway, it is not evident in the eastern part of the eastern Teltow Plateau, indicating low groundwater recharge in that area. In the Nauen Plateau / Grunewald area, groundwater levels decreased considerably stronger than they rose during the years of 2018 to 2020. In 2021, groundwater levels showed a more balanced tendency with no major rises or declines. However, a slight decrease persisted in the eastern Teltow Plateau. Throughout the hydrological summer of 2022, groundwater levels decreased again, especially in the Barnim Plateau due to low precipitation in the winter period of 2021/2022. Across all geological regions, groundwater levels of the analysed observation wells reach their minimum in 2022. In the subsequent hydrological winter of 2023, groundwater levels rose moderately across all regions except the eastern Teltow area. A recovery of groundwater levels occurred only in the Warsaw-Berlin glacial spillway, while in the other areas, groundwater levels remained below the range of the reference period.

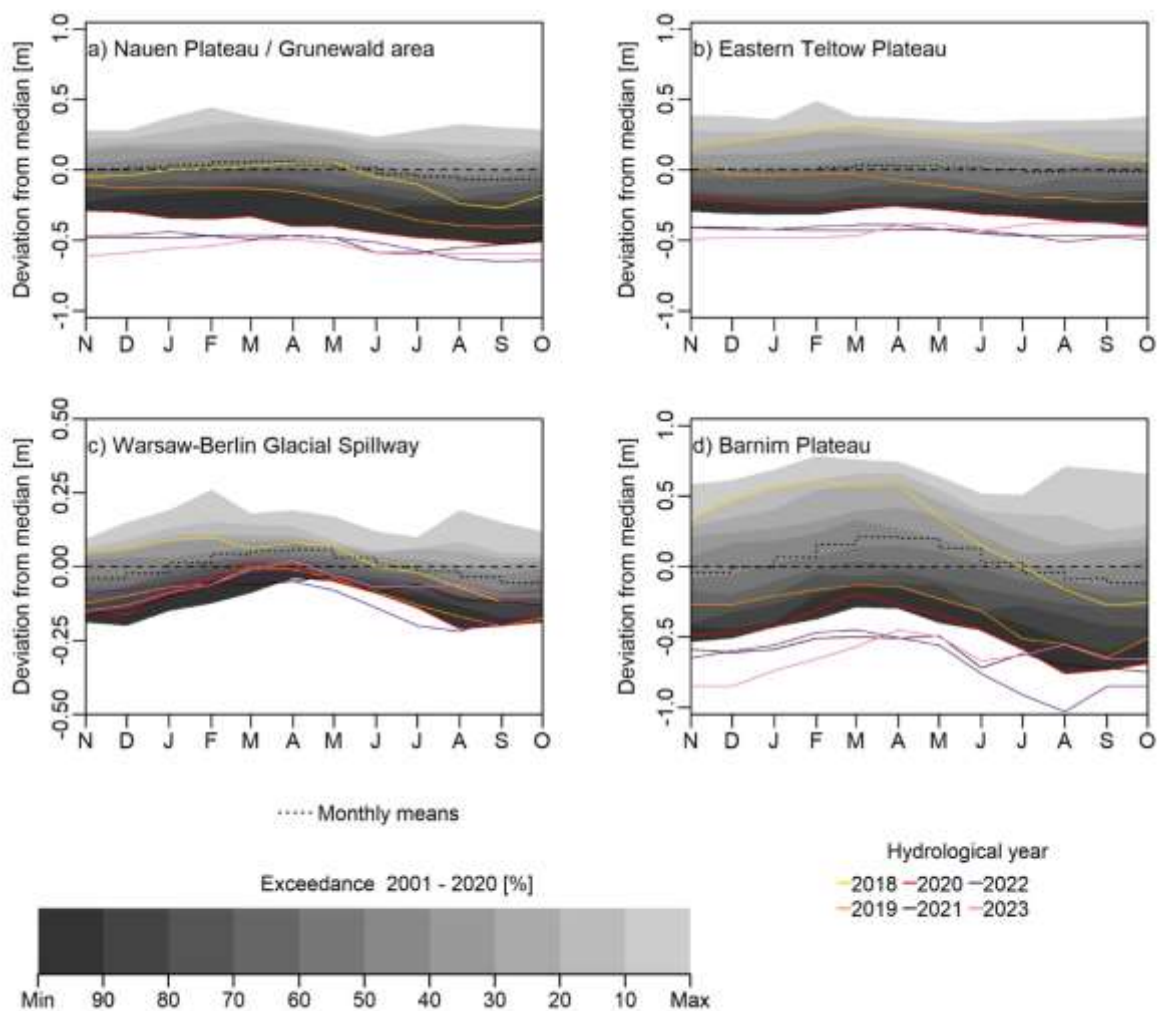



Figure 6 Groundwater level as deviation from the long-term (2001-2020) median as percentiles for months and long-term monthly mean values for the hydrological years 2001-2020 and monthly values in the hydrological years 2018-2023: a) Nauen Plateau / Grunewald area (median of 13 wells), b) Eastern Teltow Plateau (median of 13 wells), c) Warsaw-Berlin glacial spillway (median of 19 wells), d) Barnim Plateau (median of 17 wells). Data: SenMVKU

Groundwater-fed lakes partially recorded some of the lowest water levels since observations started, e.g. for Groß Glienicker See water levels fell between the previous LLW (lowest water ever recorded: 30.32 m in October and November 2016) so that the new LLW of 29.63 m occurred in October-November 2022 and 2023 (Fig. 7). The water level of Groß Glienicker See has been decreasing since the 1990s, but the downward tendency has increased since 2018 with water levels generally below average low water level (MLW). Compared to the calendar months of the reference period 1991-2020, the water levels have been consistently below the 90th percentile of exceedance since the beginning of the hydrological year 2018.

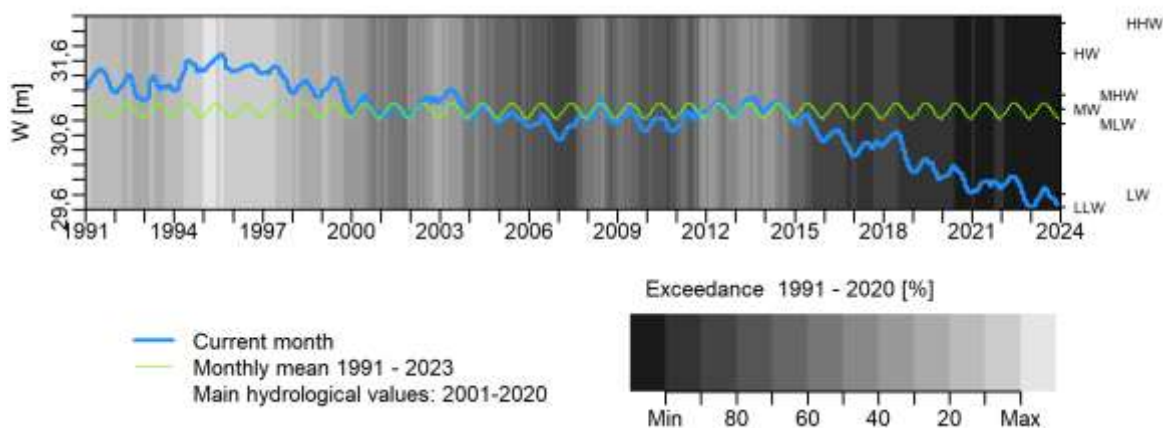



Figure 7 Lake water level (W) of the Groß Glienicker See as percentiles for months and long-term monthly mean values for the hydrological years 1991-2020 and monthly values in the hydrological years 1991-2023. The right-hand y-axis shows hydrological main values (first occurrence of LLW: 10 October 2022, HHW 23 April 1970). Data: SenMVKU

Summer streamflow in Berlin's river network was lower than average (Fig. 8). Conversely, sewage water discharges were slightly above average (e.g. in 2021 15% higher compared to the long-term summer average) also contributing to a higher sewage water proportion in the river network. The flow direction of the Teltow Canal and the Spree at Spreetunnel downstream of Lake Müggelsee reversed during the summers. In 2019, the Spree experienced reverse flows on 81 days, so that in total 5.8 hm³ of downstream water reached the Müggelsee. In 2020, the Spree had its lowest summer streamflow of 2.15 m³/s in the city centre (around 25% of the long-term average) and 7.03 m³/s (around 40 % of the long-term average) upstream of its confluence with the Havel. Similarly, the Havel had its lowest summer streamflow in 2020 (2.15 m³/s upstream of the mouth of the Spree and 9.04 m³/s downstream, each slightly above one third of the long-term summer average). The driest periods for inflow and outflow occurred in the summers of 2019, 2021 and 2022 so that also the required minimum total outflow of 10 m³/s was not met for consecutive periods of 82, 59 and 52 days, respectively.

Smaller streams (e.g. the Tegeler Fließ and Wuhle rivers) had their lowest summer streamflows in 2022, in some cases 80% below long-term summer averages (fig 8). In 2022 and 2023, many smaller streams ran dry, sometimes for the first time on record (e.g. Wuhle river at Honsfelder Brücke and Erpe river at Krummendammbrücke) or for longer than before. At the Fredersdorfer Mühlenfließ River, streamflow only occurred after pronounced rainfall events.

4.3 Water resources management and water quality

Berlin's drinking water supply was unrestricted at all times during the 2018-2023 drought. Berlin's water balance, however, and the importance of its individual components was altered during the drought years, so that total inflow and outflow, precipitation and abstractions as well as discharges from thermal power plants were below long-term averages (Fig. 8). Raw water abstractions and sewage water discharge were relatively high, e.g. in summer 2019 5 % and 11 % higher than the long-term summer averages (Fig. 8). Hence, the proportion of sewage water to surface water in the hydrological network was

relatively high and also spatially heterogeneous (Fig. 9a for July-September 2019). For example, the Teltow Canal showed sewage proportions close to 100 % (e.g. at Adlergestell). Return flows of the Spree from the city centre led to high sewage proportions at the Spreetunnel (Fig. 9b). Sewage proportions correlate with detectable trace substance concentrations, as shown

355 in Fig. 9c for the radiographic contrast agent iomeprol. During summer 2019, these concentrations increased locally (Fig. 9d-f).

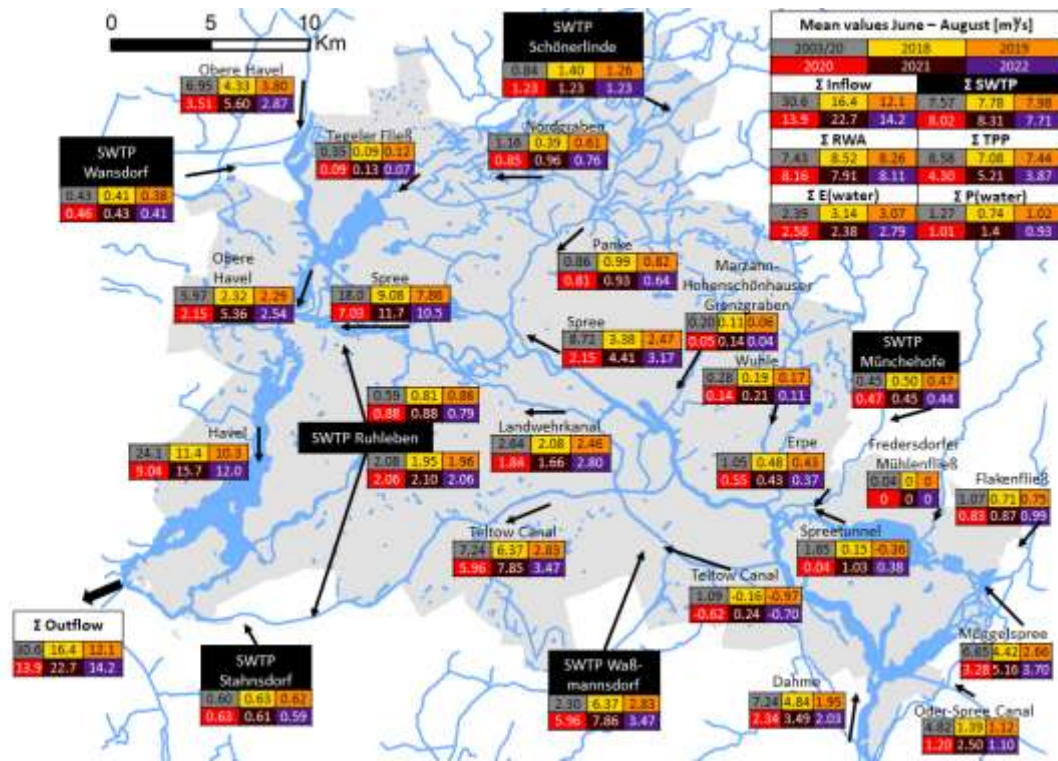
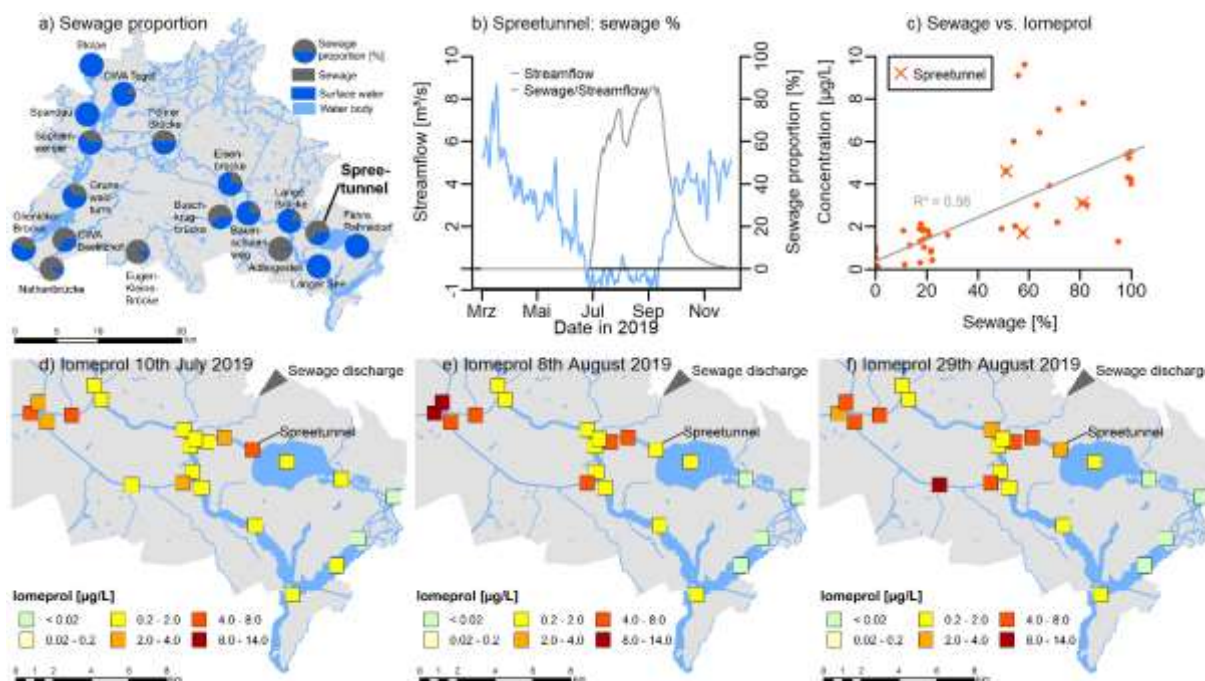



Figure 8 Streamflow situation in Berlin's hydrological network (BIBER model results) and water balance components: total inflow to Berlin, total sewage water treatment plant (SWTP) discharges, total raw water abstractions (RWA), total thermal power plant
360 **abstractions and discharges (TPP), evaporation (E) and precipitation (P) of the major river network as well as total outflow (sum of streamflow at Tiefwerder and Kleinmachnow). Data: BWB, DWD, SenMVKU, Vattenfall, WSA**

Table 1: Gauging stations of rivers which temporally ran dry during the hydrological years 2018-2023. Data: SenMVKU

Gauging Station	Dry at W* [cm]	First occurrence	Dry: Number of days per hydrological year						
			1991-2020	2018	2019	2020	2021	2022	2023
Lübars (Tegeler Fließ)	≤ 0	2017	0**	0	0	0	0	17	0
Röntgental (Panke)	≤ 28 ***	2001	9	0	0	0	0	17	0
Eisenacher Straße (Wuhle)	≤ 33	2008	11**	37	22	0	98	114	134
Wuhletal (Wuhle)	≤ 29	2006	18**	61	85	126	97	163	182

Honsfelder Brücke (Wuhle)	≤ 9	2021	-	-	-	-	22	78	42
Krummendammbrücke (Erpe)	<= 6	2022	0	0	0	0	0	82	3
Fichtenau (Fredersdorfer Mühlenfließ)	≤ 17	1991	82	160	297	213	237	259	304
Hegemeisterweg (Fredersdorfer Mühlenfließ)	≤ 0	1998	97	165	344	333	357	351	364

* above gauge datum, ** since observations started, *** before 1994: ≤ 0 cm

365 **Figure 9 Wastewater percentage (BIBER model results) and water quality: a) percentage of treated wastewater in streamflow (dark grey) averaged between July and September 2019, b) streamflow and percentage of treated wastewater (grey) at the Spreetunnel between March and November 2019, c) relationship between wastewater percentage and concentrations of the radiographic contrast agent iomeprol at 24 monitoring points and 3 sampling dates in 2019, iomeprol concentrations on 10 July 2019 (d), 8 August 2019 (e), and 29 August 2019 (f). Data: BWB, SenMVKU.**

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The water level at the Spandau impoundment, which is crucial for Berlin's water supply as it is home to three waterworks, fell below the operational targets for extended periods (Fig. 10). In the spring of 2018 and 2019, the water level was lowered from winter to summer operational level. In these years, the water level in the Spandau impoundment fell below summer operational

level from the end of July until the end of October and reached winter operational level in December. In subsequent years, the
375 water level was not deliberately lowered to summer operational target. Water levels fell below the original summer operational
target between July and October 2020, in June 2021, between June and October 2022 and in September and October 2023.
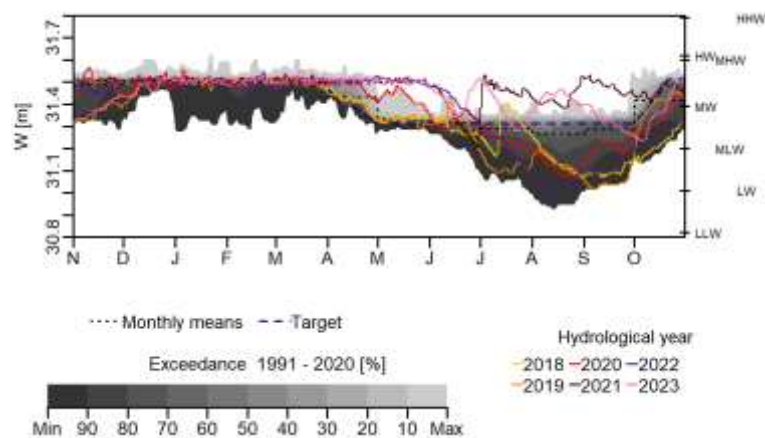
Figure 10 Water level (W) at the Spandau OP gauging station to Berlin as percentiles for calendar dates and long-term monthly
380 **mean values for the hydrological years 1991-2020 and daily values in the hydrological years 2018-2023. The right-hand y-axis shows**
hydrological main values in the period 2010-2020 (LLW: 10 August 1911, HHW: 22 January 1906), the blue dashed line shows the
operation target (winter: 31.514 m, summer: 31.314 m). Data: WSA

5 Discussion

5.1 Propagation and classification of the 2018-2023 drought in Berlin

385 The years 2018-2023 years are characterised as meteorological drought, resulting in both a soil moisture drought and
hydrological drought, setting new records in hydrometeorological, hydrogeological, and hydrological characteristics.
Meteorological drought (precipitation deficit, synchronous low climatic water balance, Fig. 2e, see also supplement S 7a,b)
occurred mainly in summer and autumn 2018, autumn 2019 and summer 2020 and 2022. For example, 2022 had the highest
mean annual temperature on record, followed by 2020. Both 2018 and 2022 were characterised by the lowest precipitation and
390 the highest and second highest potential evapotranspiration, respectively, and were thus the years with the two lowest values
for annual climatic water balance since observations began (Fig. 2e). The sequence of drought years exceeded previous
observations, as indicated by the strong decrease in the cumulative water balance. The summers generally showed a high
influence of evapotranspiration in the region which was also reflected by the isotopic composition (Kuhlemann et al., 2020).
During summer days, high evaporation in the Spreewald wetland led to a depletion of water from the Spree and lower outflow
395 from the Spreewald than inflow (AG FGB, 2023). Yet, precipitation showed a stronger deviation from long-term averages
than evapotranspiration, so that meteorological drought in terms of precipitation is in phase with that expressed by climatic

water balance (Fig. 2e, supplement S 7 a,b). Conradt et al. (2023) describe a similar temporal pattern of the 2018-2019 meteorological drought in the German part of the Elbe catchment.

Soil moisture drought slightly lagged meteorological drought (Fig 5, supplement S 7 c) and was most pronounced in summer and autumn 2018, summer 2020 and summer 2022 to winter 2023. As 2017 was a particularly wet year in the Berlin-Brandenburg region (Caldas-Alvarez et al., 2022), 2018 started with relatively high soil moisture, groundwater levels and streamflow. While the onset of soil moisture drought generally lags behind meteorological drought (Zhang et al., 2022), this lag was relatively short in our study as sandy soils were considered. However, soil moisture drought lasted longer than meteorological drought. Soil moisture drought in 2018-2022 further led to agricultural drought in Brandenburg (Brill et al., 2024).

Hydrological drought is visible from 2019 for groundwater and from 2018 for surface water. Since then, groundwater levels on the plateaus have remained in the range of the minima in the 2001-2020 reference period (Fig. 6, supplement S 7 d-g). In line with total water deficit shown by GRACE-FO (Boergens et al., 2020), we also observed more pronounced groundwater deficits in 2019 compared to 2018 despite less severe soil moisture drought which can be attributed to low groundwater recharge in the 2018/2019 winter due to low precipitation.

The hydrometeorological influence on the hydrological situation is most obvious for the groundwater-fed lake Groß Glienicker See, which showed a decreasing water level synchronous with the decline in cumulative water balance (compare Fig. 7 and Fig. 2e) so that hydroclimatic drivers appear as dominant factor of decreasing lake levels. However, other authors (Somogyvari et al., n.d.) report that also other factors such as large-scale groundwater dynamics as well as vegetation growth and changes in rainwater and sewage water management influenced lake level dynamics of the Groß Glienicker See. Declining lake water levels in the Berlin-Brandenburg region have already been a concern in recent decades and have in part been attributed to climatic conditions (Kaiser et al., 2015; Natkhin et al., 2012). Streamflow typically shows delayed and buffered response to meteorological drought (Bhardwaj et al., 2020; Van Loon and Laaha, 2015), in Berlin visible for both smaller and larger rivers with streamflow consistently below the long-term averages (Fig. 4, Fig. 8, see also supplement S 7 h-j). Streamflow is impacted by drought effects on different time scales, i.e. lack of rainfall-runoff events and declining groundwater levels, the latter leading to declining baseflow in the Berlin-Brandenburg region (Warter et al., 2024). In turn, despite a similar hydrometeorological situation, smaller rivers experienced lower flows and dried up for longer periods in 2022 than in 2018 (Tab. 1).

Water resources management largely influenced the drought propagation to Berlin's major streams but was also affected by the drought in the Spree and Obere Havel catchments and Berlin itself. Due to the intense and prolonged drought in the Spree and Obere Havel catchments, the reservoirs were depleted and not fully filled during the winters (Fig. 3), limiting the ability to mitigate low flows. In turn, the inflows from the Spree and Obere Havel catchments were the lowest on record in terms of lowest mean annual averages and lowest MAM values mostly in either 2019 or 2022 (Fig. 4). Consequently, stream flow in Berlin was very low and reverse flow occurred in parts of the Spree and the Teltow Canal. Furthermore, sewage proportions were relatively high so that trace substances concentrations were detected. Berlin's water supply was secured despite the unprecedented low streamflow and is a stable system, particularly due to the partially closed circuits.

5.2 The 2018-2023 drought – a taste of the future?

Future climate change will further impact the inflows to Berlin and the hydrological processes in Berlin itself. It is expected that future temperatures will rise, whereas future precipitation changes in central Europe are subject to high uncertainties (Evin et al., 2021; Moghim et al., 2022). While 2018 was an extreme drought across Europe, such hydrometeorological situations might be common by the middle of the 21st century (Hari et al., 2020; Toreti et al., 2019). Temperature increases might cause more frequent rather than longer soil moisture droughts (Aalbers et al., 2023). Groundwater levels in Germany might further decline in future (Wunsch et al., 2022), but with high uncertainty as groundwater recharge is extremely difficult to measure and model and therefore to predict. As a result of climatic changes and decreasing mining discharges, future inflows to Berlin are likely to decrease (Pohle et al., 2016). However, uncertainty in precipitation projections results in a wide range of streamflow projections of the Spree (Gädeke et al., 2014; Roers and Wechsung, 2015). It has to be noted, that since the publication of these studies, newer climate scenarios have been developed. In 2020, the decision was taken to phase out coal by 2038 which will lead to an end of mining discharges. Investigating the impacts of these changes in relation to more recent scenarios and taking appropriate action is currently part of the AG FGB work programme.

The 2018-2023 drought was as severe as climate change impact studies expect for future decades only. For example, the streamflow of the Spree at the Große Tränke UP gauging station was partly lower than expected for the middle of the century under scenarios of decreasing precipitation (STAR 2K, Orlowsky et al., 2008) and declining mining discharges (compare Fig. 4a and Fig. 8 in Pohle et al. (2016)). In the future, hydrometeorological conditions similar to the 2018-2023 drought would lead to more intense hydrological droughts, because of declining mining discharges and higher evaporation rates from mining pit lakes. Potentially lower groundwater levels (Wunsch et al., 2022) would have stronger consequences for streamflow, with smaller rivers drying up more frequently. Further socioeconomic changes in the region might influence water use (Harrison et al., 2019), e.g. through increased water demands due to structural change in the Spree catchment and from a growing population in the Berlin/Brandenburg metropolitan region, and hence future streamflow.

For Berlin, it can therefore be assumed that the inflow and water supply will decrease in the future. A stress test assuming a further sharp decline in future inflows, showed that water levels in Berlin's impoundments can be maintained, with the exception of the Spandau impoundment (SenUVK, 2021). In Berlin's main river network, water can be retained and recirculated thanks to the water level regulation. In this way, wastewater from sewage treatment plants supports the water levels in the impoundments. However, this leads to an increase in the proportion of wastewater in surface water and the associated increased concentrations of trace substances if no measures (e.g. fourth purification stage) are taken. The quantitative reduction in the inflow and water supply with an increase in water demand, leads to a latent water quality issue, whereby other water quality (combined sewer overflows, etc.) and biological (algae growth, changes in bank structure) aspects must be taken into account or play an important role here (Creutzfeldt et al., 2021).

5.3 Consequences for water resources management

The impacts of the 2018-2023 drought on Berlin are the result of a number of factors, the most important of which are the hydrometeorological situation and water resources management in the Spree and Obere Havel catchments and in Berlin itself.

465 However, in a perspective of multi-hazards and their interactions in space and time, the drought situation is also linked to the 2022 Oder environmental disaster, due to which transfers from the Oder to the Oder-Spree Canal were limited resulting in even further reduced inflows to Berlin at Große Tränke UP and Wernsdorf OP. Also, low abstractions and discharges from thermal power plants can not solely be explained by hydrometeorological drivers but are mostly related to the global energy crisis (2021–2023). The impact of water resources management measures during the 2018-2023 drought can be seen at the

470 example of the water levels of the Spandau impoundment. Allthough the inflows to the Spandau impoundment (streamflow at Borgsdorf, see Fig. 4d) in 2019 were similar to those in 2020 and 2022, the water levels at Spandau OP in 2019 fell below summer operational target much earlier and remained below this target for a longer period. This can mainly explained by the suspension of the targeted reduction of water levels to summer operational level since 2020 (meaning that around 2 million m³ of water have not been deliberately released in spring) among a number of other measures (Creutzfeldt et al., 2023). To evaluate

475 water resources management measures, the complexity and interlinkages between different influences on Berlin's hydrological system need to be taken into account. It is therefore necessary to analyse the effect of measures not only based on observations, but also using model simulations of combinations of different environmental factors and different management scenarios both in the Spree and Obere Havel catchments and in Berlin using appropriate models.

Water resources management in Berlin and the Spree and Obere Havel catchments will face further challenges as a result of

480 climate change, lignite-mining phase-out and other aspects of regional structural change and population growth in the Berlin/Brandenburg metropolitan region. Sewage discharge already plays a major role in Berlin's hydrological system, noticeable e.g. by the occurrence of trace substances also in drinking water protection areas such as Lake Müggelsee which are linked to reverse flows (Fig. 10, see also Creutzfeldt et al. (2021) and Reith et al. (2024). This issue will become even more relevant in the future as the streamflow in the Spree is likely to decline and reverse flows may occur more often. To prepare

485 for more frequent and more intense droughts in the future, water resources management needs to be adapted both in terms of water quantity as well as water quality. In Berlin, measures for a sustainable future water resources management are being brought together under the framework of the Masterplan Wasser (Masterplan Wasser, SenUVK, 2021). Based on the results of a risk analysis, five areas of action (water management, wastewater infrastructure, water supply, cross-cutting measures and strategies) were identified, from which 32 specific measures were derived. These include amongst others an optimised sewage

490 water treatment, e.g. removal of trace substances in the sewage water treatment plants. Decentralised rainwater management (e.g. green roofs, infiltration throughs) is expected to locally increase groundwater recharge in Berlin and thus will slightly counteract the tendency towards potentially declining groundwater recharge under changing climatic conditions. The dominance of inflows for the hydrological system in Berlin rather than of local rainfall-runoff processes, also illustrated by the synchronous pattern of inflow from major tributaries and outflow, underlines the importance of interstate and federal-state

495 collaboration in the regional water resources management. The Water Strategy Capital Region 2050 Brandenburg and Berlin (MLUK, 2023) aims to achieve closer cooperation between the Federal States of Brandenburg and Berlin in the areas of water supply and wastewater disposal. The interstate collaboration in the Spree and its neighbouring Schwarze Elster and Lusatian Neisse catchments was further strengthened in 2022 when the new mandate of the AG FGB was signed. Staffing the office of the AG FGB in 2024 represents another important milestone in the context of federal cooperation in the Spree catchment. In

500 2023, the German Federal States of Mecklenburg-Western Pomerania, Brandenburg and Berlin and the Federal Republic of Germany represented by the Waterways and Shipping Agency signed a cooperation agreement on river basin management in the Obere Havel catchment, which will provide the basis for harmonised management principles in the future. Starting in 2024, the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde, BfG) is developing models to provide the technical basis for deriving management principles and objectives for the Obere Havel catchment.

505 The 2018-2023 drought highlights the need to improve the legal and administrative framework for dealing with droughts as natural hazards. At the European level, Blauhut et al. (2022) proposed a EU drought directive for future drought regulation. At the national level, a guideline or legal framework for drought management needs to consider, for example, the harmonisation of technical conventions (e.g. definition of usable water supply and indicators of drought/water scarcity) and the resolution of conflicts of use and the prioritisation of water uses, taking into account the interests of upstream and downstream users. To

510 that end, it is necessary to look beyond national borders, e.g. to France (Ministre de la transition ecologique et de la cohesion des territoires, 2023) or the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2021).

6 Conclusion and Outlook

While each of the years 2018-2023 was warm and dry, the consecutive years of drought constitute an unprecedented hydro-meteorological situation since records began. The integrative and interdisciplinary analysis of the 2018-2023 drought illustrates

515 the vulnerability of the state of Berlin to droughts. We show that particularly long dry spells cause critical hydrogeological and hydrological situations in Berlin characterised by extremely low soil moisture, groundwater and lake water levels and river flows. While smaller rivers dry up, larger rivers regulated by weirs such as the Spree partially reverse their flow direction. As a result, the water quality deteriorates in terms of high water temperatures, high levels of sewage percentage and enrichment of point sources. Low water levels also limit the passability of small rivers for fish and aquatic invertebrates. Some heavy

520 rainfalls during the 2018-2023 drought caused combined sewer overflows. Due to low river flows, these were not sufficiently diluted resulting in oxygen depletion and hitherto fish kills.

Various water management measures to combat the 2018-2023 drought in Berlin and the Spree and Obere Havel catchments included adapted reservoir management, e.g. the suspension of the scheduled reduction of the water level of the Spandau impoundment to summer operational level from 2020 onwards. While the drought situation led to restrictions for some water

525 users such as shipping, Berlin's drinking water supply was not affected.
The 2018-2023 drought may give a taste of future effects of drought intensification and prolongation due to climate change and other factors. Similar hydrometeorological situations in the future will cause even more intense low-flow periods as mining discharges into the Spree continue to decline. Water resources management in Berlin will need to be adapted to meet these challenges, e.g. wastewater management needs to be further improved. The dominance of inflows on Berlin's streamflow situation requires further cooperation between decisions makers at both federal and state level within the Spree and Obere Havel catchments.

Code availability

The analyses are written in R. Code can be made available upon request.

Data availability

Hydrogeological and hydrological monitoring data of the state of Berlin are available at https://wasserportal.berlin.de/. Meteorological data has been obtained from the German Weather Service and is available via https://opendata.dwd.de/climate_environment/CDC/. Storage contents of the reservoirs have been obtained from the Landesamt für Umwelt Brandenburg, the Saxon Dam Authority and the Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH and are not publicly available. Water levels and discharges at the monitoring stations of the Federal Waterways and Shipping Administration are in part available via https://www.pegelonline.wsv.de.

Author contribution

IP and BC designed the concept. IP and SZ, JB carried out the data analysis. IP, SZ and BC prepared the manuscript with contributions from JB.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank German Weather Service, Landesamt für Umwelt Brandenburg, Saxon Dam Authority, Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, Berliner Wasserbetriebe as well as the Federal Waterways and Shipping Administrations for data provision.

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