Supplement of Nat. Hazards Earth Syst. Sci., 25, 1293–1313, 2025
https://doi.org/10.5194/nhess-25-1293-2025-supplement

Natural Hazards and Earth System Sciences
Open Access

Supplement of

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

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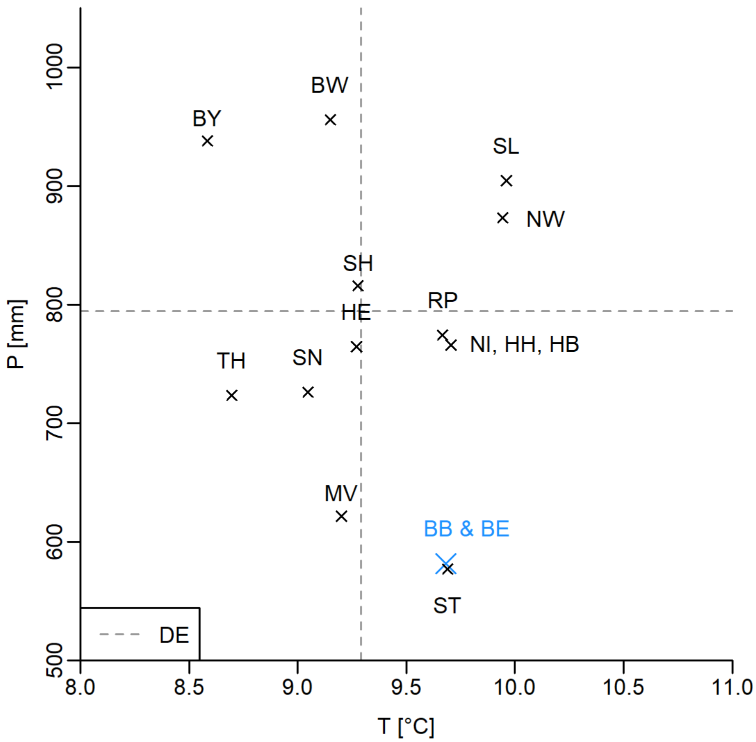

Fig. S1 Thermopluviogram for German Federal States and groups of Federal states based on annual mean air temperature (T) and total annual precipitation (P) in the period 1991-2020 for Brandenburg and Berlin (BB&BE), Baden-Württemberg (BW), Bavaria (BY); Mecklenburg-Western Pomerania (MV), Hesse (HE), Lower Saxony, Hamburg and Bremen (NI, HH, HB), North Rhine-Westphalia (NW), Rhineland-Palatinate (RP), Saarland (SL), Saxony (SN), Saxony-Anhalt (ST) and Thuringia (TH). Data: DWD: Annual regional averages of air temperature and precipitation (monthly mean), 2024))

Table S1 Overview of the data and monitoring stations shown. Abbreviations: P precipitation, T air temperature, ETP potential evapotranspiration, Vol storage volume, W water level, Q streamflow, BF soil moisture, Qin inflow, Qent withdrawal, C concentration, %Sew proportion of wastewater, DWD German Weather Service, LTV Saxon Dam Authority, LMBV Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, LfU Landesamt für Umwelt Brandenburg, WSA Federal Waterways and Shipping Administrations, SenMVKU Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt, BWB Berliner Wasserbetriebe.

Station	Variable	Data Source	Resolution	Period
Dahlem	P, T, ETP	DWD	1 d	1951-2023
Dahlem	BF	DWD	1 d	1991-2023
Spree catchment reservoirs sum of Quitzdorf, Bautzen, Lohsa I, Lohsa II,	Vol	LTV, LMBV, LfU	1 d	2018-2023

Bärwalde, Burghammer, Dreiweibern and Spremberg reservoirs)				
Waren, Müritz (Mecklenburger Oberseen)	W	WSA	1 d	1991-2023
Große Tränke UP (Spree)	Q	WSA	1 d	1991-2023
Wernsdorf OP (Oder-Spree Canal)	Q	WSA	1 d	1991-2023
Neue Mühle UP (Dahme)	Q	WSA	1 d	1991-2023
Borgsdorf (Obere Havel)	Q	WSA	1 d	1991-2023
Nauen Plateau / Grunewald area: 13 groundwater monitoring wells	W	SenMVKU	1 d*	2001-2023
Eastern Teltow Plateau: 13 groundwater monitoring wells	W	SenMVKU	1 d*	2001-2023
Warsaw-Berlin Glacial Spillway: 19 groundwater monitoring wells	W	SenMVKU	1 d*	2001-2023
Barnim Plateau: 17 groundwater monitoring wells		SenMVKU	1 d*	2001-2023
Groß Glienicker See	W	SenMVKU	1 d	1991-2023
Lübars (Tegeler Fließ)	W	SenMVKU	1 d	2008-2023
Röntgental (Panke)	W	SenMVKU	1 d	1986-2023
Eisenacher Straße (Wuhle)	W	SenMVKU	1 d	2008-2023
Wuhletal (Wuhle)	W	SenMVKU	1 d	2003-2023
Honsfelder Brücke (Wuhle)	W	SenMVKU	1 d	2021-2023
Krummendammbrücke (Neuenhagener Mühlenfließ)	W	SenMVKU	1 d	1983-2023
Fichtenau (Fredersdorfer Mühlenfließ)	W	SenMVKU	1 d	1991-2023
Hegemeisterweg (Fredersdorfer Mühlenfließ)	W	SenMVKU	1 d	1981-2023
Spandau OP	W	WSA	1 d	1991-2023
Total inflow to Berlin*	Q	SenMVKU		2003-2022

Total outflow from Berlin (sum of Tiefwerder and Kleinmachnow UP)	Q	SenMVKU, WSA		2003-2022
5 sewage water treatment plants	Sewage discharge	BWB	1 d	2003-2022
23 sites	Trace substance concentrations	SenMVKU, BWB	3 days	2019

* prior to 2004: partly daily instant readings

Table S2 Hydrological main values used in this study

Abbreviation	Description
HHW (HHQ)	Highest water level (discharge) ever recorded (given with date of occurrence)
HW (HQ)	Highest water level (discharge) in a specified time period
MHW (MHQ)	Mean high water level (discharge), i.e. mean of the highest water level (discharge) values of the individual years in a specified time period
MW	Mean water level (discharge), i.e. mean of daily average water level (discharge) values of the individual years within a specified time period
MLW	Mean low water level (discharge), i.e. mean of minimum average daily water level (discharge) values of the individual years within a specified time period
LW	Lowest average daily water level (discharge) in a specified time period
LLW	Lowest average daily water level (discharge) ever recorded (given with date of occurrence)

S1 BIBER model description

The model BIBER (Berechnungs- und Informationssystem Berliner Oberflächengewässer, computation and information system of Berlin's surface waters, IWU, 2019) is a 1D hydronumerical model to simulate the flow conditions in Berlin's hydrological system. BIBER is based on the 1D hydrodynamic model HYDRAX developed to simulate transient flow processes in river networks (Oppermann et al., 2015). HYDRAX is used to numerically solve the Saint Venant equations using the implicite finite difference scheme according to Preismann. Weirs and polders can be included in the model. Both steady-state and transient model runs are possible.

River cross sections are required as model parameters for the Saint Venant equations and the Bernoulli equation. To that end, horizontal and vertical coordinates as well as roughness values describe each cross-section. To account for variations in flow velocities perpendicular to the primary flow direction, five distinct flow zones can be identified: the main channel, left and right forelands, and left and right retention zones. As cross-sections can be structured, e.g. divided by an island, these zone types can occur several times per cross section. For each cross-section, ten flow zones with distinct roughness and distance to the next cross section (to account for meandering) can be considered. The model domain is discretised into river reaches, i.e. unbranched watercourse sections. The state variables of the model (water level, streamflow, flow velocity, cross sectional area and volume between two cross-sections) are calculated in relation to cross sections along a river reach. The boundary conditions for HYDRAX are inflows into the model domain, abstractions, transfers, precipitation and evaporation losses onto the river system as well as water levels. For a detailed model description of HYDRAX including equations please refer to Oppermann et al. (2015, in German).

BIBER, i.e. the HYDRAX model set up for Berlin, considers observed inflows of about 16 tributaries to Berlin including Große Tränke UP, Wernsdorf OP, Neue Mühle UP and Borgsdorf, which are explicitly mentioned, in the main text. The outflow from Berlin and the observed streamflow at selected cross-sections is also considered as input time series. Further, water levels in the impoundments are represented by a time series of one representative gauging station each. Four sewage treatment plants, which release their effluent into the main river network rather than into tributaries, as well as 14 abstractions for water supply and cooling water abstractions and discharges of 2 thermal power plants are considered. Three weather stations are used to derive rainwater discharges into the main river network as well as evaporation losses. Due to the availability of data from water users, BIBER simulations have were performed for the years 2003-2022 on a daily time step. Due to measurement errors of the time series included as well as influences in the main river network not explicitly captured by input time series, the water balance in the BIBER model domain is not always in equilibrium. To address this issue, an automatic error compensation is carried out in BIBER. To that end, the observed time series at Sophienwerder (final gauging station of the Spree upstream of its confluence with the Havel) and at Tiefwerder (first gauging station of the Havel downstream of the mouth of the Spree) are considered as optimisation target for error correction. All other time series are corrected in a specified range in order to meet the balance at these gauging stations. Especially during summer months, this may not be possible due to large measurement errors. In these cases, a manual quality control and adjustment of observed time series, including those at Sophienwerder and Tiefwerder, may be necessary. BIBER model results are balance corrected time series of the input variables as well as water level, streamflow, flow velocity, cross sectional area and volume between two cross-sections for 1400 cross-sections in Berlin's major river network. A detailed description of BIBER can be found in IWU (2019, in German).

References S1

IWU: Kurzdokumentation BIBER (Berechnungs- und Informationssystem Berliner Oberflächengewässer) Modellstand 2019 mit instationärem Bilanzausgleich und instationäre Berechnung der Jahresreihe 2003 bis 2018 (01.11.2002 bis 31.10.2018) Modellstand 2019, Berlin, 1–24 pp., 2019.

Oppermann, R., Schumacher, F., and Kirchesch, V.: Hydrax: ein hydrodynamisches 1-D Modell. Mathematisches Modell und Datenschnittstellen, BfG-1872, 1–54 pp., 2015.

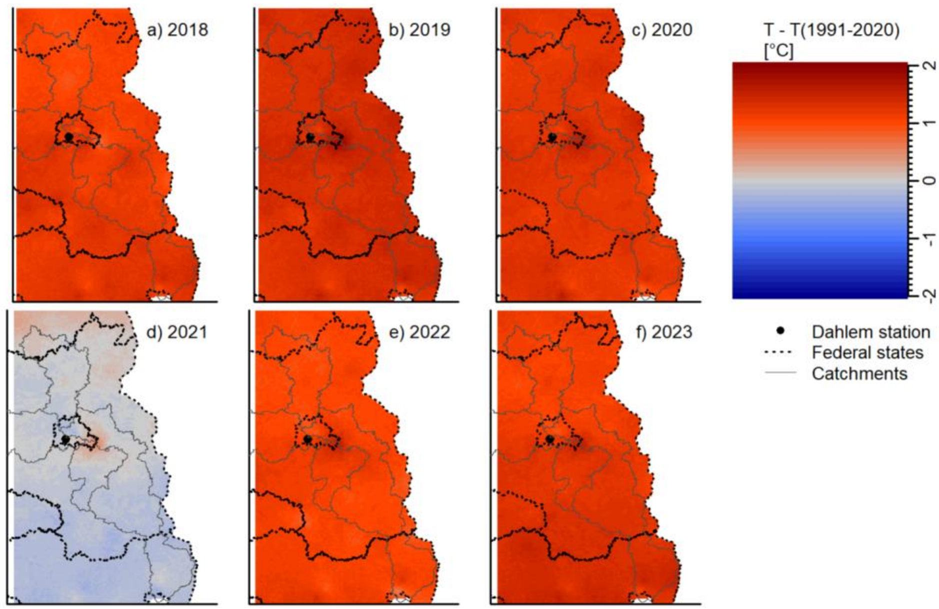

Fig. S2 Difference in annual air temperature compared to long-term mean annual air temperature (1991-2020): a) 2018, b) 2019, c) 2020, d) 2021, e) 2022, f) 2023. The map also shows the federal states (dark lines) and the catchments (grey lines) as well as the Dahlem weather station (point). Data: DWD Climate Data Center (CDC): Annual sum of monthly precipitation grids over Germany, version v1.0, Access date: 25th July 2024.

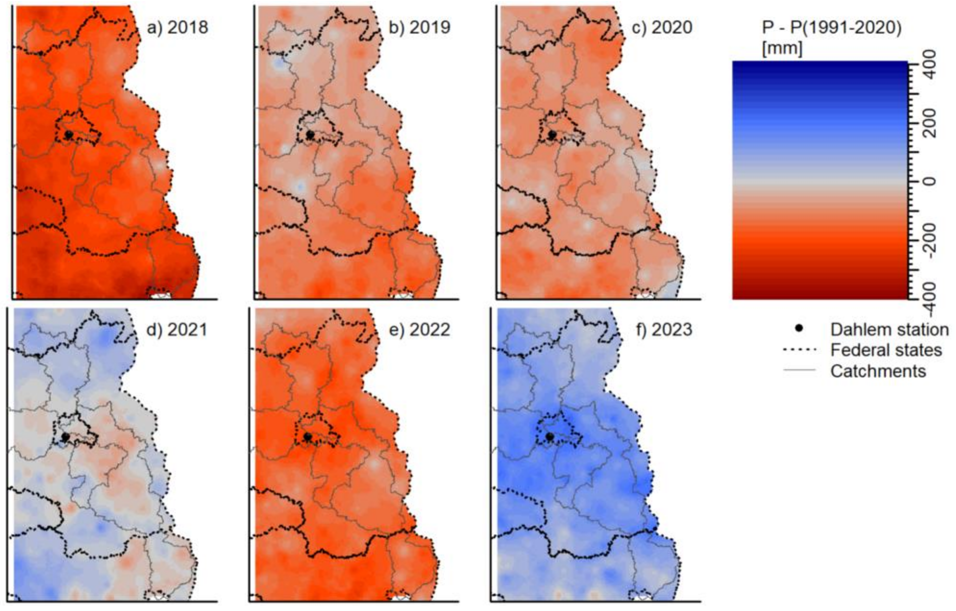

Fig. S3 Difference in annual precipitation compared to long-term means of annual precipitation (1991-2020): a) 2018, b) 2019, c) 2020, d) 2021, e) 2022, f) 2023. The map also shows the federal states (dark lines) and the catchments (grey lines) as well as the Dahlem weather station (point). Data: DWD Climate Data Center (CDC): Annual grids of monthly averaged daily air temperature (2m) over Germany, version v1.0. Access date: 25th July 2024.