https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

Brief Communication: A new drought monitoring network in the state of Brandenburg (Germany) using cosmic-ray neutron sensing

Daniel Altdorff[1,2,*], Maik Heistermann[1,*], Till Francke[1], Martin Schrön[2], Sabine Attinger[2], Albrecht Bauriegel[3], Frank Beyrich[4], Peter Biró[1], Peter Dietrich[2], Rebekka Eichstädt[5], Peter M. Grosse[1], Arvid Markert[3], Jakob Terschlüsen[1], Ariane Walz[6], Steffen Zacharias[2], and Sascha E. Oswald[1]

[1]Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany
[2]UFZ - Helmholtz Centre for Environmental Research GmbH, Permoserstr. 15, Leipzig, Germany
[3]Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg, Inselstraße 26, Cottbus, Germany
[4]Deutscher Wetterdienst, Meteorologisches Observatorium Lindenberg - Richard-Aßmann-Observatorium, Am Observatorium 12, 15848 Tauche, Germany
[5]Landesamt für Umwelt Brandenburg, Seeburger Chaussee 2, Potsdam, Germany
[6]Ministerium für Landwirtschaft, Umwelt und Klimaschutz, Henning-von-Tresckow-Straße 2-13, Potsdam, Germany
[*]These authors contributed equally to this work.

Correspondence: Maik Heistermann (maik.heistermann@uni-potsdam.de)

Abstract.

In the recent years, the German federal state of Brandenburg has been particularly impacted by soil moisture droughts. To support the timely and informed management of such water-related risks, we introduce a novel soil moisture and drought monitoring network based on cosmic-ray neutron sensing technology. This initiative is driven by a joint collaboration of research institutions and federal state agencies, and it is the first of its kind in Germany to have started operation. By mid 2024, eight sites were instrumented across Brandenburg; four more are planned for 2025. The data will be openly accessible to foster applications and collaboration right from the start.

1 Introduction

Soil moisture acts as a key state variable in the earth system: it exerts a major control on evapotranspiration, and hence the exchange of water and energy between soil and atmosphere. Furthermore, soil moisture affects the vitality of natural vegetation as well as the productivity of agricultural crops, and influences groundwater recharge, runoff formation, and the emission and sequestration of soil organic carbon.

The importance of soil moisture, and hence its monitoring, becomes specifically obvious in Brandenburg as one of the driest federal states in Germany. Large parts of the state are governed by relatively low annual precipitation sums (between 500 and 700 mm/a) and permeable sandy soils with low water retention capacity. This combination entails various drought-related hazards which became specifically obvious in the years 2018 to 2022. In this period, Brandenburg was affected by declining groundwater tables (Pohle et al., 2024; Warter et al., 2024), wild fires (Priesner et al., 2024), forest degradation (Horn et al., 2024; Priesner et al., 2024), and crop yield losses (Brill et al., 2024). While locations with a deep groundwater table are

https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

particularly prone to drought effects on vegetation, Brandenburg additionally features extensive lowland and wetland areas with a shallow groundwater table. In these areas, evapotranspiration in summer is particularly high, which causes a substantial pressure on water availability in lakes and rivers (Pohle et al., 2024; Warter et al., 2024). Again, this process is regulated by root-zone soil moisture.

Although the necessity of soil moisture monitoring is widely acknowledged (Oswald et al., 2024), it remains a notorious challenge to obtain timely and reliable data at useful spatio-temporal coverage and resolution. Conventional point-scale sensors are invasive and suffer from a lack of spatial representativeness, while remote sensing products are limited by shallow penetration depths, low overpass frequencies, and vegetation-related uncertainties (Babaeian et al., 2019; Schmidt et al., 2024; Oswald et al., 2024).

Within the past decade, cosmic-ray neutron sensing (CRNS) has emerged as a promising alternative. It allows for continuous and non-invasive monitoring of soil moisture with a measurement depth of tens of centimeters ("the root zone") and a footprint area of approximately 10 hectares (e.g. Schrön et al., 2017). When operated in mobile mode, the spatial extent of the CRNS measurement can be further increased, depending on the carrying vehicle (Altdorff et al., 2023).

With these features, CRNS is an ideal candidate to bridge the critical scale gap in soil moisture observations, as it enables robust estimates that are representative at the scale of agricultural fields, hydrotopes, or typical landscape parcels. In a densely instrumented agricultural research site near Potsdam (Brandenburg), Heistermann et al. (2023) already demonstrated the capability of multiple CRNS sensors to consistently capture the prolonged soil moisture droughts during the years 2019, 2020, and 2022.

So far, data from CRNS sites have been mainly used in research contexts. Some countries have already established long-term CRNS monitoring networks at the national scale (e.g., the United States, UK). For Germany, such a national-scale effort is not yet in place (although several academically-centered activities exist). In 2024, however, a consortium of research institutions and state agencies launched a CRNS-based soil moisture and drought monitoring network for the state of Brandenburg. In this paper, we describe the monitoring design of the stationary and mobile CRNS systems in Brandenburg, share first insights into the time series data, and discuss potential applications of such a network.

2 The monitoring network

In an effort that is, so far, unique in Germany, five institutions have combined their resources to establish a CRNS-based network for soil moisture and drought monitoring in Brandenburg: the Helmholtz Centre for Environmental Research (UFZ), the University of Potsdam (UP), the Ministry of Agriculture, Environment and Climate Protection (MLUK), the State Agency for Mining, Geology and Resources (LGBR), and the State Environment Agency (LfU). The actual implementation has also been supported by further research institutions and land owners. The network is designed as a long-term monitoring effort, facilitated by the close collaboration between federal state agencies and research institutions.

In the first half of 2024, nine locations (see Fig. 1 and Tab. 1) were equipped with a CRNS station. This includes a neutron detector, logger and telemetry, solar power supply, and sensors for barometric pressure, temperature, and humidity, as well as

https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

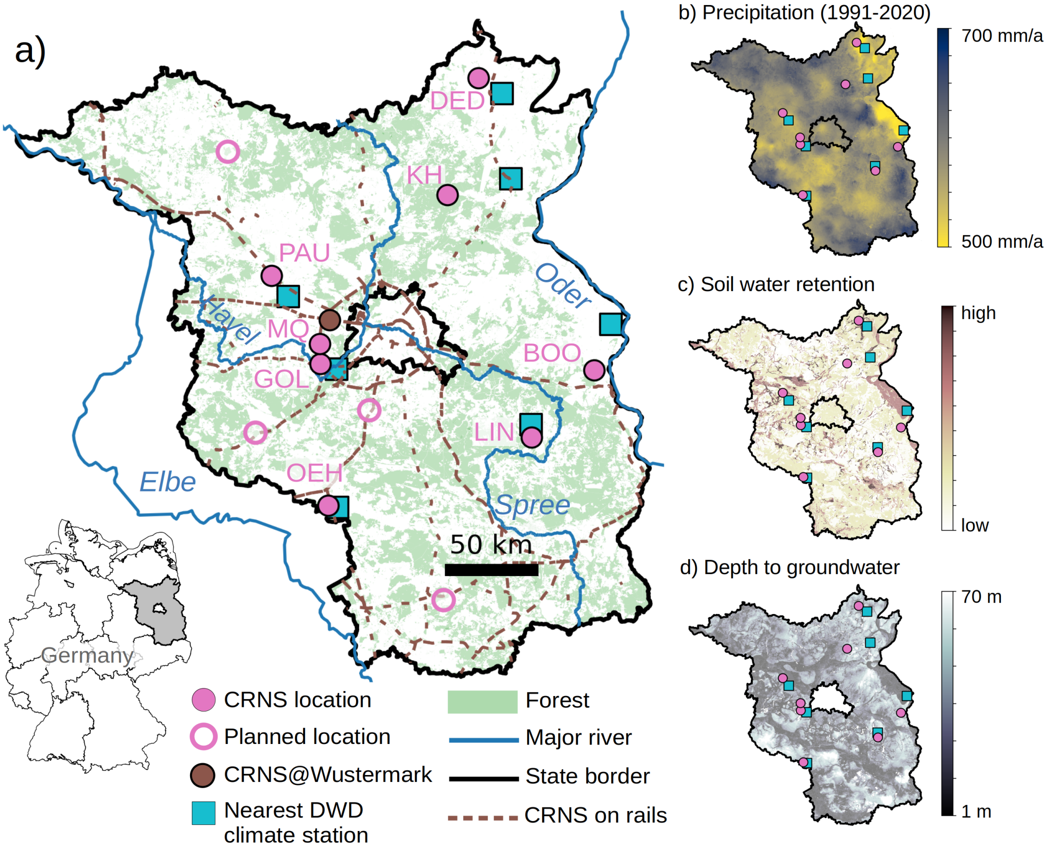

Figure 1. (a) Current locations in the CRNS-based soil moisture monitoring network (pink dots), nearest DWD climate stations (turquoise squares), forest coverage (green shade, © OpenStreetMap contributors, 2024, distribution under ODbL license), and rail-based CRNS network (brown). The labels show the location IDs in reference to Tab. 1. (b–d) Additional geographical features across Brandenburg: mean annual precipitation (1991-2020, based on DWD's HYRAS-PRE data), top soil water retention capacity (LBGR, 2024), and depth to the groundwater table (LfU, 2013).

conventional point-scale sensors of soil moisture in various measurement depths as an additional reference. Six of these stations were instrumented in the first half of 2024, three had already been operational before (Lindenberg since 2020, Marquardt and Oehna since 2022). Four additional locations are designated for instrumentation by early 2025. For the selection of sites, various criteria had to be accounted for:

- The locations should represent different combinations of landscape attributes such as land use (e.g., coniferous forest, meadow, cropland), soil types, or depth of the groundwater table.

https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

- Relative homogeneity of the sensor footprint with regard to these attributes simplifies the interpretation of the CRNS signal.
- Accessibility and permission of the land owner to place a sensor system.
- Availability of security measures against theft or vandalism, typically by fences and limited visibility of the equipment from roads and other public places.
- Existing instrumentation (e.g., by groundwater level sensors, lysimeters, climate gauges, complementary soil moisture measurements) was not mandatory, but advantageous.
- Another optional criterion was the relative proximity to railway tracks. A pilot study from the Harz mountains in central Germany has recently demonstrated that rail-based CRNS can monitor soil moisture along landscape transects of several kilometers at daily resolution (Altdorff et al., 2023). Building on this concept, four additional rail-based CRNS systems are now operational in Brandenburg (Fig. 1) and adjacent federal states. Almost each day, these systems collect soil moisture data along hundreds of kilometers (although the routes vary, depending on the operational schedule), and transmit the data in near real-time. Although this approach is still in its early stage, monitoring locations placed close to railway tracks will enable future comparisons of measurements by overlapping sensor footprints.

Table 1. Overview of CRNS-based monitoring locations; soil texture classes from BUEK300 (LBGR, 2024): Sl3: loamy sand, fSms: fine sand, mSfs: medium sand. "Additional instrumentation" indicates the availability of hydrometeorological or hydrological monitoring by the site owners (such as eddy flux towers, lysimeter, groundwater observation wells) in addition to the CRNS station itself.

ID	Location name	CRNS system	Land use	Soil texture	Depth to groundwater (m)	Additional instrumentation	Nearby rail track
BOO	Boßen	StyX S2	Cropland	Sl3	10	No	No
GOL	Golm	StyX S2	Grassland	fSms	1-2	No	Yes
PAU	Paulinenaue	StyX S2	Grassland	mSfs	2-3	Yes	Yes
DED	Dedelow	StyX S2	Cropland	Sl3	10	Yes	No
KH	Kienhorst	StyX S2	Pine forest	mSfs	5-7.5	Yes	No
MQ[1]	Marquardt	CRS-1000	Cropland	Sl3	10-15	Yes	Yes
LIN	Lindenberg	CRS-2000	Grassland	Sl3	3	Yes	No
OEH[2]	Oehna	CRS-1000	Cropland	Sl3	10-15	No	No
WUS[3]	Wustermark	StyX S2	Industrial	-	3	No	Yes

[1] not part of the CRNS cluster described by Heistermann et al. (2023); [2] intermittent pivot irrigation in dry periods;
[3] main reference location for rail-CRNS, internal use only

3 Conversion of CRNS observations to soil moisture

Cosmic-Ray Neutron Sensing (CRNS) is based on the detection of neutrons generated by the interaction of cosmic radiation with Earth's atmosphere. At ground level, the intensity of these neutrons is inversely related to the abundance of hydrogen in the near-surface environment (Desilets et al., 2010). While soil water typically constitutes the largest hydrogen pool, other occurrences of hydrogen might have to be accounted for (such as in vegetation, soil organic matter, or snow).

The retrieval of volumetric soil moisture estimates (m^3/m^3) from neutron intensities was outlined by Heistermann et al. (2024). In essence, the observed neutron intensities are converted to volumetric soil moisture by means of a non-linear transformation function. Before that conversion, however, the observations need to be corrected for the sensitivity of the neutron detector, the dynamic effects of incoming cosmic radiation (as quantified by the global neutron monitor database, NMDB), barometric pressure and atmospheric humidity (both recorded locally), as well as for the effects of other relevant hydrogen pools (which are typically assumed to be static). To that end, additional data need to be obtained to characterize the local measurement footprint, namely soil dry bulk density (kg/m^3), organic carbon content (kg/kg), and dry aboveground biomass density (kg/m^2), either from local field campaigns, soil maps, or literature.

4 Case study: learning from the combination of model and observation

Continuous soil moisture observations can provide valuable insights into terrestrial water storage and drought conditions. Yet, the usefulness of such data can be enhanced if combined with simulation models, which enable spatial and temporal extrapolation, and allow for a consistent representation of vertical water fluxes and the local water balance.

In a case study, we employed the Soil-Water-Atmosphere-Plant model (SWAP, van Dam et al., 2008) to simulate soil water dynamics at the monitoring locations, and to compare the results to preliminary soil moisture estimates as retrieved from the CRNS measurements. SWAP calculates vertical soil water movement by solving the Richards equation which accounts for processes such as infiltration and capillary rise. The simulation of evapotranspiration is based on Penman-Monteith's equation, and considers factors such as soil moisture content, interception by vegetation, root water uptake, and atmospheric conditions.

The model was parameterized to reflect surface conditions at the monitoring locations: soil hydraulic parameters were set by combining soil texture data from the state's soil map (BUEK300, LBGR, 2024) with a pedotransfer function (ROSETTA, Schaap et al., 2001); vegetation parameters such as seasonal leaf area index and rooting depth were set based on literature values. As atmospheric forcing, we used daily climate observations of the German Meteorological Service (Deutscher Wetterdienst, DWD henceforth) at the nearest climate station while for precipitation, DWD's radar-based quantitative precipitation product RADOLAN (DWD, 2022) was applied in order to better capture small scale convective rainfall during the 2024 summer season.

Fig. 2 shows the resulting dynamics for seven different variables: the observed (CRNS-based) soil moisture, the measurement depth of the CRNS, the vertically-weighted average of simulated soil moisture (using weights that mimic the vertical sensitivity of the CRNS), the soil water storage in the uppermost meter, and the cumulative fluxes of precipitation, evapotranspiration, and the flux across the depth of 2 m (often considered a proxy for groundwater recharge).

https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

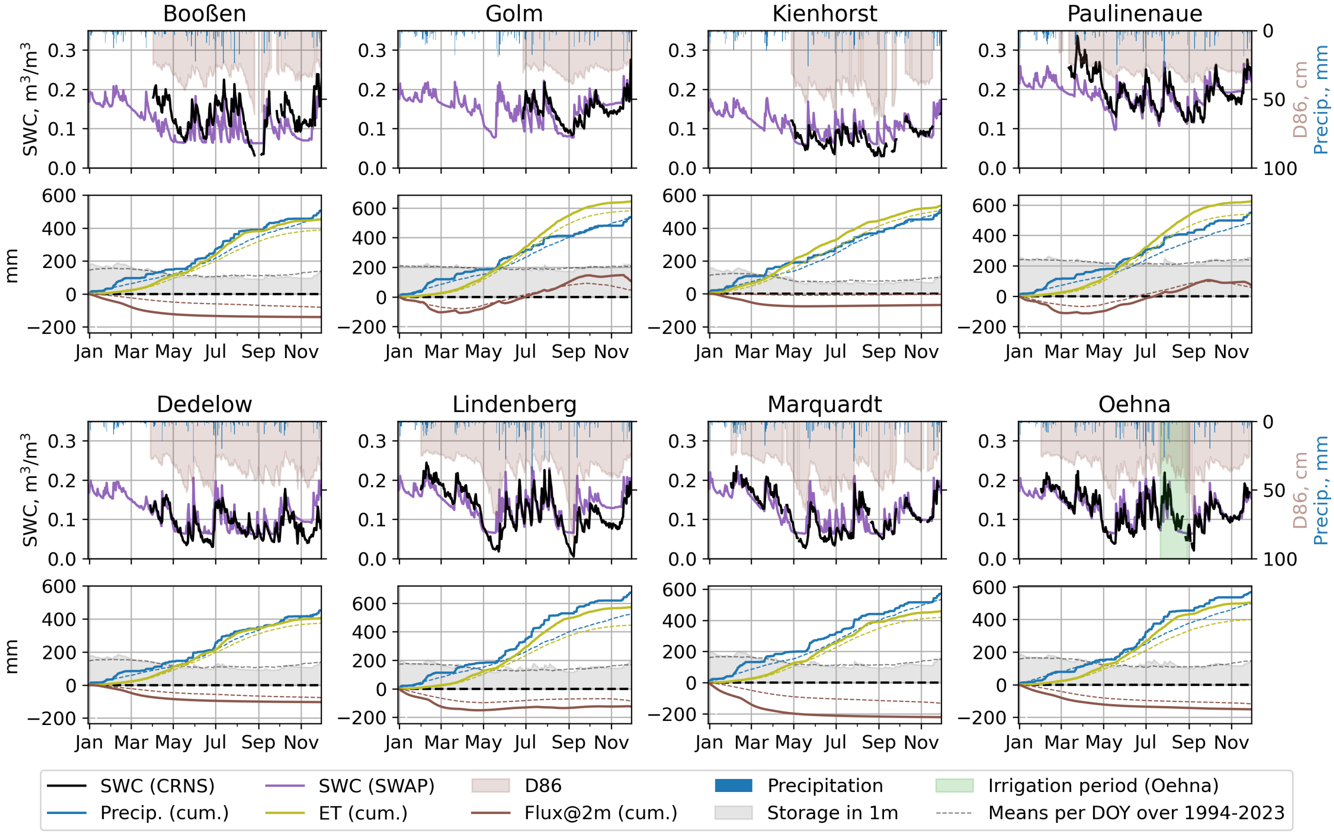

Figure 2. Soil water dynamics at the monitoring locations in 2024. Upper rows: observed (CRNS) and modelled (SWAP) soil water content (SWC), as well as CRNS measurement depth (D86, i.e. the depth that accounts for 86 % of the signal) and daily precipitation depths; note that CRNS-based SWC is not shown for January due to an extended snow episode during which soil moisture is difficult to estimate. Lower rows show the soil water balance as simulated by SWAP; solid lines: cumulative precipitation, evapotranspiration, and flux at 2 m depth; grey shade: soil water storage in the upper meter; the dashed lines refer to the water balance components of the same color, but represent as a reference the average values per day of year (DOY) over the last 30 years (1994–2023).

The figure provides an extensive set of details to examine. In the context of this study, we highlight only a few findings:

Given that no systematic model calibration was carried out, model and observation are quite consistent. This strengthens our confidence in the model's validity, so we can also appreciate the additional information it provides beyond what is captured by the observations. This includes temporal interpolation and extrapolation of soil moisture for periods before sensors were deployed or when data were missing. Furthermore, the model allows us to assess water storage at greater depths (e.g. down to 1 m), while CRNS-based soil moisture observations are typically limited to depths of 20 to 50 cm.

Additionally, the model enables us to infer water fluxes, such as evapotranspiration and percolation towards the groundwater. For instance, we can confirm relatively low percolation rates in forested areas (e.g., Kienhorst), seasonal shifts from downward to upward water fluxes at locations close to the groundwater table (e.g., Golm, Paulinenaue, and Lindenberg), or irrigation activities during the second half of August at the Oehna location (by comparing model and observation).

Still, we notice various types of discrepancies between model and observations, including systematic biases (e.g., Booßen, Paulinenaue), mismatches at very dry conditions (e.g., Lindenberg) or at moisture peaks (e.g., Kienhorst). These disagreements provide an intuitive guidance in which locations or periods the data need to be interpreted with particular caution. This, in turn, helps us to refine both, model *and* observation - as it should be kept in mind that our "observation" is an indirect measure of the target variable and subject to various uncertainties (Heistermann et al., 2024).

The dashed lines in the bottom rows of Fig. 2 also show the average seasonal cycles of soil water storage and water fluxes as obtained from SWAP simulations over the past 30 years (1994–2023). The comparison to the solid lines confirms that 2024 was a rather wet year. Still, a remarkable dry spell occurred in August.

Altogether, these initial findings demonstrate the potential of integrating instrumental and model-based soil moisture monitoring in Brandenburg while also highlighting several promising directions for future research and practical applications.

5 Opportunities for future research and applications

We consider the presented monitoring network as an important asset to address water-related risks in Brandenburg. To maximize its impact in research and applications, we are committed to openly provide both raw observational data and soil moisture estimates in near real-time, and to involve research institutions, authorities, and end users in an interdisciplinary collaboration. That way, various opportunities arise, which could include, but are certainly not limited to:

- **Hazard-specific monitoring products**: The integration of observation and model should allow to design products that address hazard-specific user requirements. For instance, different integration depths of soil water storage might be relevant in the context of wild fire hazards, agricultural management (e.g. timing of field operations, including irrigation), water resources management, or flood hazards (capacity for soil water retention, although flood generation is not a primary concern in Brandenburg). The design of such products should be subject to a continuous dialogue with potential users in the aforementioned sectors, including the involved federal state agencies, but also, e.g., farming or forestry companies.

- **Groundwater recharge**: Similarly, combining model and observational data should enable more accurate estimates of groundwater recharge rates under different conditions, including scenario analysis of land use and climate change.

- **Upscaling and transferablility**: the results of our case study demonstrate some validity of the model parameters (with regard to, e.g., soil and vegetation) at the monitoring locations. This suggests some level of transferability at least to similar location types. In addition to model-based upscaling, there are several promising opportunities for integrating soil moisture observations across larger spatial scales. While previous efforts focused on remote sensing, a more recent approach combines stationary CRNS observations with rail-borne CRNS. To this end, the University of Potsdam and

UFZ are partnering with the Havelländische Eisenbahn AG to equip locomotives with CRNS sensors. This allows for monitoring spatio-temporal soil moisture dynamics along selected railway tracks (see Fig. 1).

- **Improving soil moisture retrieval from CRNS**: as already shown in the case study, the long-term operation of CRNS sensors can help us to identify issues with the neutron measurements or the subsequent soil moisture retrieval. For example, the very low soil moisture estimates in Lindenberg under dry conditions suggest a weakness in the original transformation function (Desilets et al., 2010) for which Köhli et al. (2021) recently proposed an alternative. This new functional relationship could be particularly useful under the dry conditions in large parts of Brandenburg.
- **Network extension**: it is planned to expand the network in Brandenburg, and we encourage other institutions to integrate their sensors or to propose suitable locations for deployment. Similar efforts are underway in other federal states, e.g., Thuringia and Saxony. Collaboration and integration with these initiatives could be a pathway towards a prospective nation-wide monitoring.

6 Conclusions

In this study, we introduced a network for long-term soil moisture and drought monitoring in Brandenburg, using cosmic-ray neutron sensing (CRNS) technology. The launch of this network in 2024 resulted from a joint effort of research institutions and state government agencies that is, so far, unique in Germany. By mid 2024, eight locations were instrumented, and four more will follow until early 2025. The data will be openly shared in order to stimulate applications in various fields, but with a focus on water resources and drought risk management, e.g. with regard to monitoring and mitigation of wild fire hazards, agricultural yield losses, or hazards to natural ecosystems and groundwater recharge.

Obviously, the limited number of monitoring locations will not be able to capture all relevant combinations of landscape attributes and their inherent variability in Brandenburg. Hence, a key challenge will be to upscale the information obtained from this necessarily sparse network in order to unfold statewide benefits. This could be possible with the support of the railway CRNS system, remote sensing products, and hydrological models. A first case study has already shown the potential of combining the observations with the SWAP model.

Data availability. The raw CRNS observations as well as CRNS-based soil moisture estimates are openly available for download in near-real time under https://cosmic-sense.github.io/brandenburg.

Author contributions. DA, AB, AM, and SO designed and established the CRNS monitoring network, with contributions from all co-authors. MH and TF carried out the data analysis and modelling, created the figures and drafted the manuscript. All co-authors contributed to writing and reviewing the manuscript.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

Acknowledgements. This research was funded by the Helmholtz-Centre for Environmental Research GmbH - UFZ, the Ministerium für Landwirtschaft, Umwelt und Klimaschutz des Landes Brandenburg (MLUK, Ministry of Agriculture, Environment, and Climate Protection of the federal state of Brandenburg) as well as by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – research unit FOR 2694 "Cosmic Sense", project number 357874777.

We gratefully acknowledge the landowners and organisations granting access to the sites: Axel Behrendt, Gernot Verch (ZALF), Rainer Hentschel, Paul Reibetanz, Jens Hanneman (State Forestry Office Brandenburg), Ronny Henkel (Rail & Logistik Center Wustermark), Agro Uetz-Bornim GmbH, Oehnaland Agrar GmbH, Christiane Sengebusch, and Philip Golo. The authors furthermore acknowledge the support from the Havelländische Eisenbahn Gesellschaft (HVLE), Wustermark, Germany, particularly from Dirk Brandenburg, Uwe Wullstein and Stadler Rail, David Sorribes, and Bastian Weber.

We thank Markus Köhli and Jannnis Weimar (StyX Neutronica) for technical support with some of the sensors.

https://doi.org/10.5194/egusphere-2024-3848
Preprint. Discussion started: 12 December 2024

References

Altdorff, D., Oswald, S. E., Zacharias, S., Zengerle, C., Dietrich, P., Mollenhauer, H., Attinger, S., and Schrön, M.: Toward Large-Scale Soil Moisture Monitoring Using Rail-Based Cosmic Ray Neutron Sensing, Water Resources Research, 59, e2022WR033 514, https://doi.org/10.1029/2022WR033514, 2023.

Babaeian, E., Sadeghi, M., Jones, S. B., Montzka, C., Vereecken, H., and Tuller, M.: Ground, Proximal, and Satellite Remote Sensing of Soil Moisture, Reviews of Geophysics, 57, 530–616, https://doi.org/10.1029/2018RG000618, 2019.

Brill, F., Alencar, P. H. L., Zhang, H., Boeing, F., Hüttel, S., and Lakes, T.: Exploring drought hazard, vulnerability, and related impacts to agriculture in Brandenburg, EGUsphere, 2024, 1–34, https://doi.org/10.5194/egusphere-2024-1149, 2024.

Desilets, D., Zreda, M., and Ferré, T. P. A.: Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays, Water Resources Research, 46, W11 505, https://doi.org/10.1029/2009WR008726, 2010.

DWD: Historical hourly RADOLAN grids of precipitation depth, https://opendata.dwd.de/climate_environment/CDC/grids_germany/hourly/radolan/historical/, last accessed: 18 September 2024, 2022.

Heistermann, M., Francke, T., Scheiffele, L., Dimitrova Petrova, K., Budach, C., Schrön, M., Trost, B., Rasche, D., Güntner, A., Döpper, V., Förster, M., Köhli, M., Angermann, L., Antonoglou, N., Zude-Sasse, M., and Oswald, S. E.: Three years of soil moisture observations by a dense cosmic-ray neutron sensing cluster at an agricultural research site in north-east Germany, Earth System Science Data, 15, 3243–3262, https://doi.org/10.5194/essd-15-3243-2023, 2023.

Heistermann, M., Francke, T., Schrön, M., and Oswald, S. E.: Technical Note: Revisiting the general calibration of cosmic-ray neutron sensors to estimate soil water content, Hydrology and Earth System Sciences, 28, 989–1000, https://doi.org/10.5194/hess-28-989-2024, 2024.

Horn, K. H., Vulova, S., Li, H., and Kleinschmit, B.: Modelling Current and Future Forest Fire Susceptibility in north-east Germany, EGUsphere, 2024, 1–26, https://doi.org/10.5194/egusphere-2024-1380, 2024.

Köhli, M., Weimar, J., Schrön, M., Baatz, R., and Schmidt, U.: Soil Moisture and Air Humidity Dependence of the Above-Ground Cosmic-Ray Neutron Intensity, Frontiers in Water, 2, https://doi.org/10.3389/frwa.2020.544847, 2021.

LBGR: Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg, Bodenübersichtskarte des Landes Brandenburg im Maßstab 1:300,000, https://geo.brandenburg.de/?page=LBGR-Webservices, last accessed: 18 September 2024, 2024.

LfU: Landesamt für Umwelt Brandenburg, Mächtigkeit der ungesättigten Bodenzone, https://metaver.de/trefferanzeige?docuuid=06BE213C-BE2F-4009-8208-C58771700A33, last accessed: 18 September 2024, 2013.

OpenStreetMap contributors: Planet dump retrieved from https://planet.osm.org , https://www.openstreetmap.org, last access: October 2024., 2024.

Oswald, S. E., Angermann, L., Bogena, H., Förster, M., García-García, A., Lischeid, G., Paton, E. N., Altdorff, D., Attinger, S., Güntner, A., Hartmann, A., Franssen, H.-J. H., Hildebrandt, A., Kleinschmit, B., Orth, R., Peng, J., Ryo, M., Schrön, M., Wagner, W., and Wagener, T.: Hydrology on solid grounds? Integration is key to closing knowledge gaps concerning landscape subsurface water storage dynamics, Hydrol. Processes, 38, e1530, https://doi.org/10.1002/hyp.15320, commentary, 2024.

Pohle, I., Zeilfelder, S., Birner, J., and Creutzfeldt, B.: The 2018–2023 drought in Berlin: impacts and analysis of the perspective of water resources management, Natural Hazards and Earth System Sciences Discussions, 2024, 1–28, https://doi.org/10.5194/nhess-2024-187, 2024.

Priesner, J., Sakschewski, B., Billing, M., von Bloh, W., Fiedler, S., Bereswill, S., Thonicke, K., and Tietjen, B.: What if extreme droughts occur more frequently? – Mechanisms and limits of forest adaptation in pine monocultures and mixed forests in Berlin-Brandenburg, Germany, EGUsphere, 2024, 1–28, https://doi.org/10.5194/egusphere-2024-3066, 2024.

Schaap, M. G., Leij, F. J., and van Genuchten, M. T.: rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, Journal of Hydrology, 251, 163–176, https://doi.org/10.1016/S0022-1694(01)00466-8, 2001.

Schmidt, T., Schrön, M., Li, Z., Francke, T., Zacharias, S., Hildebrandt, A., and Peng, J.: Comprehensive quality assessment of satellite- and model-based soil moisture products against the COSMOS network in Germany, Remote Sensing of Environment, 301, 113 930, https://doi.org/10.1016/j.rse.2023.113930, 2024.

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H. R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S. E., Dietrich, P., Schmidt, U., and Zacharias, S.: Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity, Hydrology and Earth System Sciences, 21, 5009–5030, https://doi.org/10.5194/hess-21-5009-2017, 2017.

van Dam, J. C., Groenendijk, P., Hendriks, R. F., and Kroes, J. G.: Advances of Modeling Water Flow in Variably Saturated Soils with SWAP, Vadose Zone Journal, 7, 640–653, https://doi.org/10.2136/vzj2007.0060, 2008.

Warter, M. M., Tetzlaff, D., Marx, C., and Soulsby, C.: Impact of drought hazards on flow regimes in anthropogenically impacted streams: an isotopic perspective on climate stress, Natural Hazards and Earth System Sciences Discussions, 2024, 1–30, https://doi.org/10.5194/nhess-2024-44, 2024.