



Standard Observation SOHYD_168

Soil water content and soil temperature

Version 0.11

September 29, 2026

NOTE: THIS PROTOCOL IS STILL UNDER REVIEW.



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The eLTER Standard Observation protocol can be cited as:

Schrön, M., N. Cools, C. Schütze, S. Zacharias (2026): eLTER Standard Observation protocol SOHYD_168 – Soil water content and soil temperature. Version 0.11

**Prepared under contract from the European Commission
Grant agreement No. 871128
EU Horizon 2020 Research and Innovation action**

Project acronym: **eLTER PLUS**
Project full title: **European long-term ecosystem, critical zone and socio-ecological systems research infrastructure PLUS**
Start of the project: Feb 2020
Duration of the project: 60 months
Project coordinator: Jaana Bäck
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<https://elter-ri.eu/elter-plus>

By the end of January 2026 the further work on the protocol was handed over to and executed by the provisional eLTER Head Office and Topic Centre on Interoperability of the emerging eLTER ERIC.

Version Status		Date	Authors
0.1	Draft	Dec 2024	N. Cools, M. Schrön, S. Zacharias, C. Schütze
0.2	Revised Draft	Mar 2025	S. Zacharias, N. Cools, M. Schrön, C. Schütze
0.3	Revised draft	Jun 2025	S. Zacharias
0.4	Review	Sep 2025	T. Dirnböck, H. Barral, S. Nied
0.5	Revised draft	Nov 2025	S. Zacharias
0.6	Revised and reformatted	Nov 2025	S. Zacharias
0.7	Typos corrected	Feb 2026	S. Zacharias
0.8	Global Cosmos Reference added	Mar 2026	S. Zacharias
0.9	Project acknowledgements revised	Aug 2026	S. Zacharias
0.10	CRNS specification for data availability/transmission added	Sep 2026	S. Zacharias
0.11	CRNS accuracy update, added link to processing toolbox specification, minor improvements and clarifications	Sep 2026	M. Schrön

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SO variable overview

Habitat:

Applies to all eLTER habitat groups except of Coastal (transitional) habitats

Variable(s):

- **Soil temperature (ST):** Reporting unit: °C
- **Volumetric soil water content (SWC):** Reporting unit: Vol%

Contents

1	Introduction	5
2	BASIC method	5
2.1	Scope and data product	5
2.2	Method	6
2.3	Measurement design	6
2.3.1	Spatial design	6
2.3.2	Sampling depths	6
2.3.3	Temporal resolution	7
2.4	Installation	7
2.5	Sensor protection	8
2.6	Sensor calibration	8
2.7	Maintenance	8
2.8	Data processing	9
3	PRIME method	9
3.1	Scope and data product	9
3.2	Scientific method	10
3.3	Measurement accuracy	10
3.4	Measurement design	12
3.4.1	Spatial design	12
3.4.2	Record period	12
3.5	Installation	12
3.6	Sensor calibration	12
3.7	Maintenance	13
3.8	Data processing	14
4	Data validation	15
5	Data and metadata format	15
5.1	Data format	15
5.2	Reporting format	16

1 Introduction

Soil moisture controls the partitioning of precipitation and snow water into groundwater recharge, plant available water storage, evaporation, and runoff. Hence, volumetric soil water content (SWC) is a key variable in hydrological, climatological, and environmental studies and its monitoring is essential to investigate soil-water-plant relationships, hydrological and nutrient fluxes. SWC and soil temperature (ST) are some of the most important controls for a wide variety of geochemical and ecological processes in the vadose zone (VZ).

SWC is also a key variable of the climate system, as it governs the energy fluxes between the land surface and the atmosphere through its impact on evapotranspiration (Bogena et al. 2017). Soil temperature (ST) (°C) measurements provide information on the soil thermal characteristics such as the depth of frost penetration into the soil and the duration that the soil remains frozen. ST affects surface runoff infiltration and snowmelt. ST drives the soil component of the fluxes of greenhouse gases and energy, for example through its effect on soil microbial activity and chemical reaction rates, while it also affects plant root activity and water uptake (Op de Beeck et al. 2018).

Suitable models for describing and quantifying the water balance at the watershed scale typically operate on a horizontal scale of 100 to 1000 m and also consider the water dynamics of the unsaturated zone, including the root zone. Therefore, the parameterization of such models also requires observational data that are representative of the model. Most soil moisture measurements are based on sensors that either operate on the point scale, thus being prone to small-scale heterogeneity (e.g., soil sampling or Time-domain reflectometry (TDR)), and/or which measure only the upper few centimeters of the soil, thus being influenced by surface roughness and vegetation (e.g., remote sensing data). The basic method of this protocol measures SWC profiles at the point scale, while the prime method requires additional SWC measurements beyond the point scale using the Cosmic-Ray Neutron Sensor (CRNS). The method of cosmic-ray neutron sensing can be used to monitor the average snow and soil water content at the hectare scale and in typical root zone depths. The above-ground sensor technology is non-invasive, autarkic, and requires low maintenance. Recommended read: Zreda et al. (2012), Andreasen et al. (2017), Bogena et al. (2022), and Köhli (2026).

On Cat-1 sites with focus on the hydrosphere, the Basic method at the point scale is complementing the CRNS at the plot scale.

2 BASIC method

2.1 Scope and data product

The eLTER SO BASIC method records the SWC and ST on the point scale. The point measurements are done on a continuous basis with sensors permanently installed in the soil at pre-defined soil depths. All measurements of the soil water content and soil temperature at one eLTER site must be done with the same sensor model to ensure the same elevation. The utilisation of a sensor system that combines ST and SWC measurements is possible.

SWC (Vol%) and ST (°C) are measured at the same depth whenever possible. The SWC should only be measured in soil layers that are not permanently saturated with water so should not be measured below the minimum groundwater table depth. The ST may be measured below this depth to monitor the temperature in the permanently water-saturated soil layer.

Site category	2 or 1 (if hydrosphere is not one of the focal spheres)
Raw data	Volumetric soil moisture content (m^3/m^3) (depending on the type of sensor) Soil temperature (ST) ($^{\circ}\text{C}$)
Data products	Volumetric soil moisture content (Vol%) Soil temperature (ST) ($^{\circ}\text{C}$)

2.2 Method

All sensors must be designed for long-term burial operation.

SWC must be measured with dielectric sensors. For both, ST and SWC, single sensors and profile probes fulfilling the following specifications are allowed.

- Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), Amplitude Domain Reflectometry (ADR), capacitance method
- The minimum measurement accuracy is set at $\leq 0.05 \text{ m}^3/\text{m}^3$, as indicated by the manufacturer in the sensor specifications, valid for the type of soil and over the entire SWC range expected at the site where the sensor is installed

ST must be measured with Resistance Temperature Detectors or thermistors with the following specifications:

- measurement accuracy $\leq 0.25 \text{ }^{\circ}\text{C}$, as indicated by the manufacturer in the sensor specifications
- measurement range exceeding the soil temperature range at the site of installation

A data logger is needed for logging sensor output and in case of large distance among sampling points multiple data loggers can be used. Flexible tubing or cable ducts should be foreseen to pull through surfacing sensor cables in order to protect them from rodents or other disturbances, and enclosures for the data loggers to protect them from rain, animals and dust.

2.3 Measurement design

2.3.1 Spatial design

The BASIC method applies to all eLTER habitat groups except of “coastal (transitional) waters”. SWC and ST is measured in close vicinity of meteorological measurement stations (meteo station, SOATM_027). At each meteo station SWC/ST is measured at 1 plot with minimum 2 points for each layer for soil temperature and minimum 3 for soil water content. The number and spatial arrangement of meteo stations (and SWC/ST measurement plots) at each site depend on site characteristics (habitat(s), size of the site). The principles for selecting the locations for the meteorological measurements are described in the SOATM_027 protocol.

2.3.2 Sampling depths

Depths of sensors are always expressed relative to the local zero reference level. In mineral soils, this is the boundary between the surface organic horizon (O-horizon following the FAO definition) and the underlying mineral horizon. If a surface organic horizon is not present, such as in tilled croplands, the local zero reference is the soil surface. In organic soils, such as found at mire stations, the local zero reference is the top of the surface organic horizon (H-horizon following the FAO definition).

To decide on the number of depths and the depths itself, the following aspects need to be taken into account:

- The SWC/ST profile should cover a depth up to 100 cm. If limited by the presence of bedrock or a water-impermeable layer, the ST and SWC profile can be less deep.
- The maximum number of measured depths is set to 4. If limited by the presence of bedrock or a water-impermeable layer, the ST and SWC profiles can be limited to fewer measurement depths.
- The first measurement is as close as possible to 5 cm. Three more depths covered are at 20, 50, and 100 cm. If the soil properties suggest this, the depths of measuring points below the first 5 cm-measurement can also be selected based on the soil profile characteristics. At mire stations, the 2nd SWC/ST measurements are mandatory done at 10 cm depth.

2.3.3 Temporal resolution

The ST, SWC sensors are all logged continuously at 1-minute time resolution (i.e. every 60 seconds a value is recorded).

2.4 Installation

This protocol describes SOHYD_168 on soil water content and temperature. However, if your site is a Cat-1 site with a focus on the atmosphere, the installation of soil heat flux plates (SOATM_098) should be included in the design.

The installation of the SWC sensors requires the excavation of a soil pit (not necessary for profile probes). This opportunity should be used to sample the undisturbed soil core for calibration in the laboratory. If applicable, it is useful to colocate (at ± 2 to 3 m distance) the SWC and ST profiles with the water table depth measurement, which is part of the SOHYD_006 bundle where the hydraulic head is used as an indicator of the depths of the water table.

- **The excavation pit should be slightly wider than the distance between the outermost sensors and a few centimetres deeper than the deepest planned sensor position.** The trench length should be adjusted as required to allow proper installation of all sensors.
- **Mark the contours of the pit on the ground before excavation.** On sloping terrain, the wall designated for sensor installation should be located on the uphill side of the pit.
- **Store the excavated soil on site in stratified layers until the pit is backfilled.** Prior to installing the sensors, carry out a description of the soil profile according to pedogenetic horizons (SOGEO_001) and collect soil samples – both intact cores for calibration and loose samples for soil characterisation – either at fixed depths or following the identified horizons.
- **Insert the sensors carefully and horizontally into the pit wall.** A dummy probe can be used to pre-drill the ground and ensure optimal contact between the sensor rod and the surrounding soil. A horizontally installed probe at a given depth provides an average soil water content (SWC) over approximately ± 1.5 cm at that depth.
- **Use a measuring tape to determine and record the exact position of each sensor before installation.** For the shallow sensors placed close together, install them diagonally rather than vertically aligned. Avoid areas with visible stones, gravel, roots or burrows created by soil fauna within the sensor's sampling volume.
- **Gently press each sensor into the wall until its head is flush with the wall surface.** Insert the sensors parallel to the local slope of the ground surface. Avoid rocking the sensor during installation to prevent the formation of air gaps around the rods or tines. If necessary, drill pilot holes. Ensure good physical contact between the sensor and the soil, for example by lightly moistening the soil after installation.
- **Install the sensors** starting from the lowest depth and refill the pit each time with soil until the next installation depth.
- **Refill the soil pit.** As mentioned above, after installing the sensor(s) at a certain depth, refill the pit with the excavated soil to the next installation depth. Respect the horizon sequence.

Fill the pit as close as possible to the original conditions. Run sensor cables and wires some distance down or horizontally away from the sensors before bringing them to the surface. This will prevent heat conduction and water running down the cables and wires towards the sensors. Saturate the plot area with water to ensure good contact between the soil and the sensors.

2.5 Sensor protection

Like any other field-operated sensor, protection by fencing or enclosures might be needed, but always without interfering with vegetation, the radiation regime (fence shading) and grazing (if present). Ground sensor cables can be protected from rodent damage by running the cables through flexible electrical tubing or through cable ducts.

In managed arable and grassland, cables to and from buried sensors should either be temporarily removed when field machinery is in the field or buried in ditches well below the maximum depth of tillage during crop growth. It is good practice to clearly mark the location of soil sensors to avoid disturbance (including standing in the area).

2.6 Sensor calibration

A soil-specific calibration of the sensors will reduce measurement inaccuracy associated with the differences in soil bulk density, texture, and salinity between the soil in which the sensors are installed and the soils used for factory calibration. As a rule, sensor-specific calibration procedures and recalibration intervals both in field and laboratory are described by the manufacturer.

SWC sensors require sensor-specific calibration prior to long-term operation. The calibration procedure involves comparing sensor readings with gravimetric measurements, which serve as the accuracy standard. Gravimetric methods typically provide highly accurate soil moisture data, with an accuracy of approximately ≤ 0.03 g/g. Values can be converted from gravimetric to volumetric soil moisture using the soil bulk density as a factor: $\theta_{vol} (m^3/m^3) = \rho_s \cdot \theta_{grv} (g/g)$. These measurements should be performed on representative soil samples extracted from the field that span the full range of SWC expected at the installation site. All gravimetric measurements follow the SOGEO_048 protocol.

Calibration can be conducted using soil samples that are saturated in the laboratory and then allowed to dry gradually, or the reverse sequence. Moreover, calibration may be established individually for each sensor deployed in the field, or a single calibration may be applied to multiple sensors, for example, those installed within the same soil horizon. Examples of calibrations of SWC sensors are given by De Vos et al. (2021) and Bogaen et al. (2017).

Soil temperature (TS) sensors can operate with the factory calibration and do not require any (initial) site-specific calibration. However, if quality control routines reveal long-term sensor drift, recalibration of the TS sensors might be needed. This in fact applies to all soil-meteorological sensors (Op de Beeck et al. 2018).

2.7 Maintenance

The lifetime of components should be known so that the exchange of spare parts can be performed in time. A modular construction of instruments enables easy replacement of spare parts and reduces data loss.

Installed sensors do not require specific maintenance, but the following checks have to be done at least weekly in grazed grasslands and at least biweekly in all other ecosystems:

- Check the soil-meteorological locations for damage or disturbances (wildlife, vandalism, etc).
- Check surfacing power and data cables for damage (rodents, etc).

At mire stations, sensor depths should be checked at the start and end of each growing season, as the distance of the sensors to the local zero reference level changes in time through the continuous accumulation of organic material at the soil surface. The position of the sensors should be adjusted if needed.

At stations in agricultural ecosystems where the soil is tilled between two crops, all sensors are removed from the soil prior to tillage and reinstalled later. Sensor removal during harvesting should be avoided unless sensors risk being damaged by engines during crop management activities (e.g. mechanical weeding, ...).

If the Quality Control routines on the sensor's output indicate sensor failure, the sensor should be dug. If the failing sensor cannot be repaired in one week, it should be replaced with a spare sensor of the same model. The failing sensor can be sent to the factory for repair and after reparation reused as spare.

If replacing a sensor that is at the end of its lifetime but still functions well, this sensor and the new sensor have to run in parallel for at least 12 months.

2.8 Data processing

After the field data are collected and transferred to the computing environment, the next steps are to validate and process the data.

The raw signal (X) of each ST sensor and each SWC sensor is converted to ST (in °C) and SWC (in Vol%), with:

$$ST = f_{cal,ST}(X)$$

$$SWC = f_{cal,SWC}(X)$$

The calibration factors f_{cal} are generated by:

- Recording sensor signal X at known reference values (ST, SWC).
- Mathematical fitting of a suitable function between X and ST or SWC.
- Optimization of the parameters so that the deviation is minimal.

3 PRIME method

3.1 Scope and data product

The eLTER SO PRIME method requires monitoring of SWC on the plot scale using Cosmic-Ray Neutron Sensing (CRNS). In addition, two profile measurements of SWC and ST based on eLTER SO BASIC method are carried out within the CRNS sensor footprint. CRNS is a non-invasive method for measuring soil moisture over a spatial footprint of approximately 100–200 meters in diameter and a depth of 10–50 cm, depending on soil moisture content and soil porosity. The technique relies on detecting natural background neutrons produced by cosmic rays interacting with the Earth's atmosphere and the ground. Since fast neutrons are moderated (slowed down) primarily by hydrogen atoms, and soil moisture is the dominant source of hydrogen in the soil, the measured neutron intensity inversely correlates with soil moisture content. CRNS provides continuous, real-time data with minimal disturbance, making it valuable for hydrology, agriculture, and climate research.

The PRIME method is the mandatory measurement method for Cat-1 sites for monitoring soil moisture (except of Coastal (transitional) habitats).

Site category	1
Raw data	Neutron in counts per hour (cph) Air pressure in hPa Air relative humidity in % Air temperature in °C
Data products	Corrected neutrons in cph Gravimetric water equivalent (incl. snow) in g/g Volumetric soil moisture in m ³ /m ³

3.2 Scientific method

The standard CRNS systems measure the epithermal neutron flux rate in counts per hour together with auxiliary measurements of air pressure, air humidity, and air temperature. In the ground, neutrons can travel tens of decimeters, while in air, the travel distance can be hundreds of meters. Hence, the neutron radiation above the ground is a mixed gas which carries information of nearby hydrogen pools within the root zone and an area of several hectares.

The main radiation source is the high-energy cosmic radiation flux, which depends on the solar activity, the geographical location on Earth, and the local atmospheric and geomagnetic conditions. Therefore, in order to extract the soil moisture component from the CRNS signal, appropriate corrections are required. The corrected neutron signal is then converted to gravimetric soil moisture. The product can further be corrected for offset hydrogen pools, such as lattice water or organic water equivalent, and eventually be converted to volumetric soil moisture using soil bulk density information.

Cosmic-ray neutron sensing (CRNS) is a passive method based on detectors to measure the background radiation of cosmogenic neutrons. Cosmic radiation is omnipresent on Earth, interacts with the soil and it significantly responds to water. The interaction with the hydrogen nucleus is most effective in slowing down the neutrons, which leads to a smaller number of neutrons above wet soil. In contrast, elastic scattering on heavy nuclei corresponds to more neutrons above dry soil. All in all, CRNS measurements of soil moisture make use of the intensity of cosmic-ray neutrons that are generated in the near-surface layer of the soil and relate it to the concentration of hydrogen atoms in the sensor footprint (recommended read: Zreda et al. 2012).

A typical CRNS station consists of a data logger and a neutron detector component. For eLTER sites, only recordings of epithermal neutrons (energy range from 1 eV to 10⁵ eV) are required for soil moisture measurement, which is typically implemented by a high-density polyethylene shield (HDPE).

3.3 Measurement accuracy

The final CRNS data products are (i) neutrons corrected for relevant influencing factors, (ii) gravimetric water equivalent which includes soil moisture, snow pack, intercepted, and ponded water, and (iii) the estimated volumetric soil moisture. While the direct CRNS measurement product is gravimetric soil moisture, it can be converted to volumetric soil moisture using local average soil bulk density: $\theta_{vol} \text{ (m}^3/\text{m}^3) = \rho_s \cdot \theta_{grv} \text{ (g/g)}$. The basic processing of the raw data is suggested to be carried out on the basis of the Global Cosmos Reference (Global COSMOS Consortium 2025), while it is noted that the processing requirements can become more complex depending on the heterogeneity in the footprint. Here, scientific consultation is recommended.

The achievable accuracy of the neutron measurement and derived soil moisture information depends directly on the neutron count rate N and is given by the Poissonian counting statistics as $\sqrt{N}$. The relative neutron uncertainty is $1/\sqrt{N}$ and translates nonlinearly to soil moisture uncertainty (Jakobi

et al. 2020; Weimar et al. 2020). Hence, the maximum soil moisture accuracy that can be achieved will eventually depend on the local count rate N , which depends on the detector efficiency and size (increases N), but also on temporal aggregation (increases N) and environmental conditions, such as soil wetness or air humidity (decreases N) or geographic location like altitude (increases N) and latitude (increases N). The higher the local count rate N , the lower is the minimum required detector count rate at reference conditions to achieve a given target accuracy of soil moisture.

As a minimum requirement for eLTER sites, the gravimetric soil moisture product should have an uncertainty of less than ± 0.02 g/g for a **2 hour** temporal resolution window and under conditions of **5 g/m³** air humidity and **0.25 g/g** total soil water content (including water in organic material, biomass, clay lattice, etc.). This corresponds to a minimum count rate of about **1350 cph** under reference conditions (50°N, 10°E, sea level, SWC=0.10 g/g, h=5 g/m³).

Note 1: As mentioned, the necessary minimum count rate may also change depending on location, e.g., under the conditions above, it may vary across Europe (1150–2750 cph) and elevations (550–1350 cph).

Note 2: With the above count rate, the soil moisture uncertainty of such a system would range from ± 0.01 g/g at 0.10 g/g soil moisture to ± 0.06 g/g at 0.40 g/g soil moisture. Hence, if lower uncertainties are desired for wet sites, for instance, higher count rates may be adequate.

Recommendation: To find the minimum count rate for your specific location and uncertainty requirements, it is recommended to use the CRNS accuracy calculator at <https://neptoon.web.app.ufz.de/Uncertainties>.

Detector sensitivity	Highest sensitivity to epithermal neutrons (1eV to 10 ⁵ eV), typically implemented by HDPE shielding.
Protection against water	IP66 (IEC 60529 / DIN EN 60529)
Cell Modem	GSM or Iridium or Ethernet if applicable
Measurement accuracy	± 0.02 g/g minimum soil moisture accuracy for 2 hour temporal resolution at 5 g/m ³ air humidity and 0.25 g/g total soil water content. This corresponds to >1350 cph neutron count rate at 50°N, 10°E, sea level. <i>Note: individual site conditions may require higher count rates, see recommendation above.</i>
Data availability/transmission	Raw data shall be stored on an SD card in ASCII format and remain fully accessible on-site. SD card capacity must accommodate at least two years of continuous full operation. During sensor operation, raw data shall be accessible on-site via standard interfaces (USB or Bluetooth) and communication protocols (e.g., UART), using freely available terminal software. Raw data transmission to the eLTER data portal is preferably automated via cellular modem, antenna, or Ethernet, occurring at least once per day. A standard 15 cm antenna is typically sufficient; however, forest sites may require larger antennas (>1 m) to strengthen cellular signal reception. Automated raw data transmission must support MQTT and FTP protocols, with configurable APN parameters. If automated transmission is not feasible, data shall be provided manually via the SD card slot.

3.4 Measurement design

3.4.1 Spatial design

The CRNS probe should be located (where possible) in homogeneous terrain to minimize the influence of site-heterogeneity and to simplify the calibration and validation effort. If any site-specific land use is located in the footprint (e.g., buildings or vegetation), exact information about the size, distances, and hydrogen content need to be provided. It's recommended to operate the sensor in vicinity of meteorological measurement stations (meteo station, SOATM_027). The CRNS pre-processing of the raw data requires knowledge of air pressure, air temperature, and air humidity. If no other meteorological sensor is in place, CRNS stations should be provided with an external sensor for air pressure, air temperature, and air humidity.

One CRNS instrument is the minimum requirement for sites smaller than **10 hectares**. For very large sites more sensors are recommended to cover parts the field-scale heterogeneity.

Each CRNS station must additionally be equipped with at least **two in situ soil moisture profiles** following the BASIC method protocol. The profiles should be distributed in the near field around the sensor (**1-25 m** distance, at least one within **1 m** distance). The corresponding sensors could be connected with the CRNS data logger to achieve a streamlined data set. The measurements in at least **3 depths** in 0-5, 5-15, and 15-30 cm are required to resolve the soil moisture profile states in the area. If the site already operates in-situ profiles with this vertical density, no additional sensors are required.

3.4.2 Record period

The minimum record period of the raw measurement should be **5 Minutes** in order to resolve short-term events like heavy rainfall or solar particle showers. Note that accurate soil moisture measurements at this resolution are not realistic (see section 3.3), so the temporal resolution for soil moisture measurements *after* data processing may be higher.

Temporal resolution	5 minutes
Data transmission period	1 day (near real-time)

3.5 Installation

The sensor should be mounted on a pole between **1 m and 2 m** height in order to avoid strong influence of local effects. Anti-theft protection is recommended. The attachment of further sensors or components (e.g. solar panel, external sensors, etc) is possible since they usually do not influence the measurement. The pole needs to have a storm-proof attachment to the ground (on the mast or anchor).

3.6 Sensor calibration

In order to find a relation between local neutron counts and soil moisture, it is necessary to provide a "true value" calibration at least once for a CRNS site. The calibration should be performed under constant weather conditions and the CRNS sensor must be active and counting during this period.

Number of calibration campaigns	at least 1 per 10 years
Campaign protocol	Date and time (UTC) Duration (in hours) Average neutron counts (in cph)

It is recommended to determine the relevant soil moisture values using gravimetric samples. The carefully taken samples should be weighed, dried, and weighed again to determine the density and water content Method sheets SA04 and SA14 in Annex I of Cools and De Vos (2020). Special high-temperature ovens can be used to determine bound water in organic and clay materials (Ref). Above-ground and below-ground biomass is to be estimated. Data to be provided for each sample are:

Sampling location	Latitude (°N) Longitude (°E) Altitude (m) Sample depth (m from surface, e.g., 0.00–0.05 m)
Soil moisture	Gravimetric water content (g/g)
Soil properties (if not available from other sources)	Soil bulk density (kg/m ³) Lattice water (g/g) or clay content (%) Soil organic carbon (g/g)
Vegetation (if not available from other sources)	Estimation of above-ground biomass (kg/m ²) Estimation of below-ground biomass (kg/m ²) Vegetation height (m)

The vertical sampling design should cover the upper 50 cm (for typically dry sites) or 30 cm (for typically wet sites). The samples should also aim at resolving the uppermost layers of the soil in highest detail, i.e., soil samples in 0–0.05 m and 0.05–0.10 m are mandatory, while the resolution could be reduced towards deeper depths. The soil moisture values determined from the samples need to be averaged for each individual profile location using vertical weighting functions, as documented in Global COSMOS Consortium (2025) and Schrön et al. (2017).

The horizontal sampling design should resemble the site-specific heterogeneity around the CRNS station. Choose one of three options:

1. Divide the area into homogeneous sub-areas and take 3–6 profiles in each area depending on spatial extend. Average the profile-average soil moisture values equally in each subarea, then average the resulting values of each subarea according to their signal contribution (Schrön et al. 2023).
2. When the identification of such homogeneous subareas is not possible, divide the area into annuluses of equal contribution and take 3–10 samples each depending on spatial heterogeneity (see Figure 1). Average profile-average soil moisture values equally in each annulus, then average the resulting values equally (Schrön et al. 2017).
3. If the identification of those subareas is not possible, arbitrary profile locations in the footprint may be chosen (at least 3 within 5 m distance) and their profile-average values averaged using horizontally weighting functions (Schrön et al. 2017).

At the end of the calibration campaign, the field-average water content could be used to determine the free parameter N_0 in the neutron to soil moisture conversion function. The estimation of relevant subareas and the weighting of data could be supported by the CRNS online toolbox https://neptoon.web.app.ufz.de/Footprint_Analysis. Further good practice guidance on CRNS sensor calibration has been published by the SOMMET project, Oswald et al. (2026).

3.7 Maintenance

The CRNS system requires comparably low maintenance, as the method is passive (no generation of signals), non-invasive (no disturbance by soil operations), and autarkic (solar power supply). In rare cases, the battery or electronics may fail due to periods of low solar radiation, snow coverage,

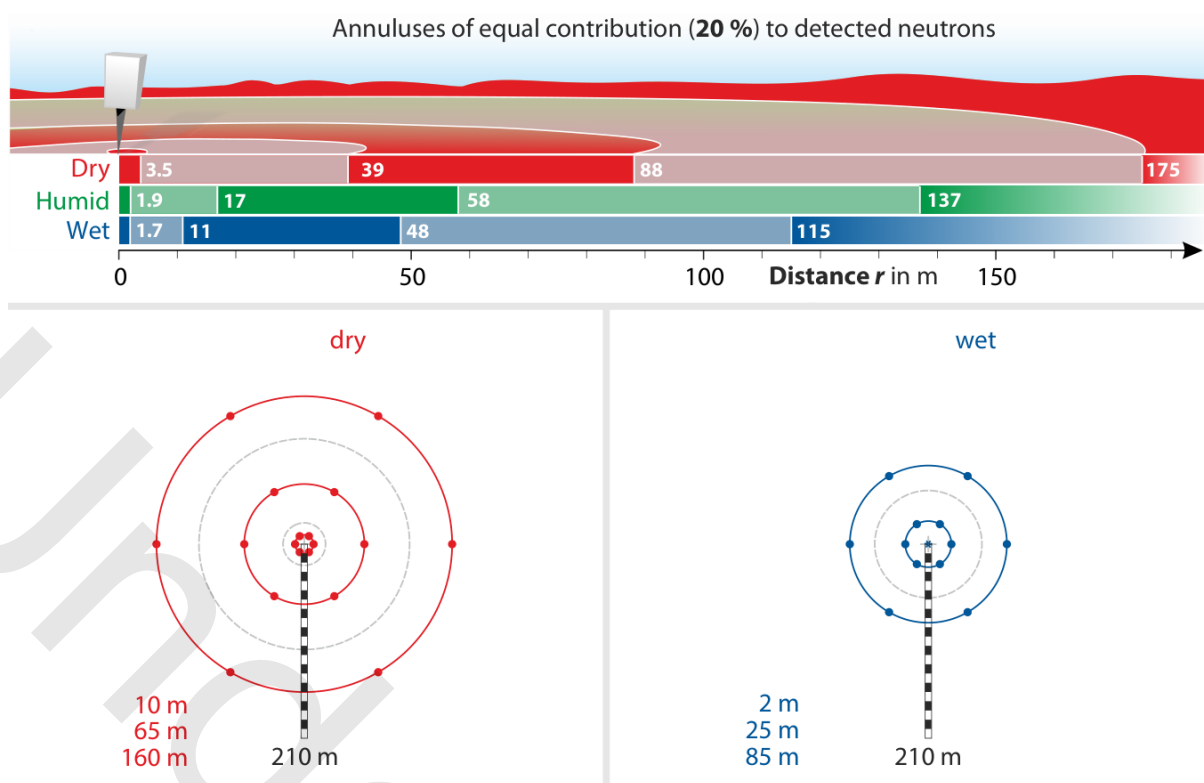


Figure 1: Illustration of regions of equal contribution (20 % quantiles) to the neutron signal for three climates, from Schrön et al. (2017)

or accumulation of air humidity inside the device.

Weekly	Battery check (remotely)
Wet/humid periods	Renew moisture removal packs inside
Winter months	Remove snow from solar panel

Activities such as agricultural harvesting, tillage, irrigation, grazing, but also the presence of a large group of people in the vicinity of the sensor can lead to "abrupt" changes in the hydrogen pools within the footprint. In these cases, it is recommended to log the information in the protocol that may support data interpretation later on.

Upon agricultural activities	Move sensor if required, log harvest and plowing into protocol
Upon site visits	Log date, times, number and distance of people into protocol

3.8 Data processing

CRNS data processing will be centrally organized and conducted by eLTER services. It includes the application of meteorological correction (air pressure, air humidity), correction for incoming reference cosmic rays (download of real-time data from external neutron monitors), correction for soil properties, and the application of latest flagging and filtering methods. The processing routine follows basic principles outlined in the Global Cosmos Reference document (Global COSMOS Consortium

2025)¹ but may be changed depending on local site complexity. The implemented workflow makes use of the tool "Neptoon" (Neutron data processing tool in python) which is freely available for local applications (<https://www.neptoon.org> or via an online service (<https://neptoon.web.app.ufz.de/>). Once the site-specific processing parameters and steps have been determined, Neptoon will be operated centrally to generate CRNS soil moisture products. eLTER will share the processing parameters as a file which anyone could use to reproduce the results.

4 Data validation

Data validation is used to determine whether the collected data have an acceptable completeness and reasonableness and to eliminate erroneous values. This step transforms raw data into validated data and is crucial to maintain high rates of data completeness during the monitoring program. There are many causes of erroneous data: damaged or malfunctioning sensors, broken wire connections, damaged hardware, data logger malfunctions, static discharges, sensor calibration drift, icing conditions among others. Therefore the data must be validated as soon as possible within a few days after transfer. It is very important to store the original raw data; the validation steps should be made on a copy of the original data set.

Data can be validated manually or automatically using computer software. The two main parts of data validation are data screening and data verification. Data screening may be performed using a series of validation routines or algorithms to screen all the data for questionable or erroneous values. It is recommended to print a data validation report which lists the suspect values. Data verification requires a case-by-case decision on what to do with the suspect values – retain them as valid, reject them as invalid or replace them with redundant valid values. A qualified person familiar with monitoring equipment and the local meteorology should make this part of data validation.

General system checks. Two simple tests may be performed to evaluate the completeness of the collected data. A check of whether the number of data fields is equal to the number of measured parameters for each record and a check of whether there are any missing sequential data values. Measured parameter checks. These tests consist of range tests, relational tests and trend tests.

Range tests are the simplest and most commonly used validation tests. The measured data are compared to allowable upper and lower limiting values. If the value meets a criterion then it is considered as valid. It is recommended to have several criteria checks because a single criterion is unlikely to detect all problems. Relational tests are based on expected physical relationships between various variables and ensure that physically improbable situations are not reported in the data without verification. Trend tests are based on the rate of change in a value over time.

Missing or invalid data (outcome of the plausibility checks) is flagged accordingly and as such reported.

5 Data and metadata format

5.1 Data format

For the temperature sensors, both the raw signal in instrument units and the TS value in physical units (°C) must be submitted. If the raw signal is not retrievable from the sensors, TS suffices.

For the SWC sensors, both the raw signal in instrument units and the SWC value in physical units (%) must be submitted. If the raw signal is not retrievable from the sensors, SWC suffices.

For the CRNS sensor, the raw signal (neutron counts) need to be reported. Meteorological data

¹The Global Cosmos Reference is currently still under review

required for the pre-processing and signal correction are either reported via the SOATM_027 or need to be reported additionally.

Data information can be provided as text format (e.g. csv or txt) in UTF-8 encoding.

5.2 Reporting format

Reporting is conducted in accordance with the rules and conventions specified in Peterseil and Geiger (2020)² regarding file naming, file formats, and metadata scope.

²Document is currently under revision.

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