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# *STH-net*: a model-driven soil monitoring network for process-based hydrological modelling from the pedon to the hillslope scale

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**Abstract.** The *Schäfertal hillslope* site is part of the TERENO Harz/Central German Lowland Observatory and its soil water dynamics is being monitored intensively as part of an integrated, long-term, multi-scale and multi-temporal research framework linking hydrological, pedological, atmospheric and biodiversity-related research to investigate the influences of climate and land use change on the terrestrial system. Here, a new soil monitoring network, indicated as *STH-net*, has been recently implemented to provide high-resolution data about the most relevant hydrological variables and local soil properties. The monitoring network is spatially optimized, based on previous knowledge from soil mapping and soil moisture monitoring, in order to capture the spatial variability of soil properties and soil water dynamics along a catena across the site as well as in depth. The *STH-net* comprises eight stations instrumented with time-domain reflectometry (TDR) probes, soil temperature probes and piezometers. Furthermore, a weather station provides data about the meteorological variables. A detailed soil characterization exists for locations where the TDR probes are installed. All data are measured at a 10-minutes interval since January 1st, 2019. The *STH-net* is intended to provide scientists with high-quality data needed for developing and testing modelling approaches in the context of vadose-zone hydrology at spatial scales ranging from the pedon to the hillslope. The data are available from the EUDAT portal (https://b2share.eudat.eu/records/e2a2135bb1634a97abcedf8a461c0909) (Martini et al., 2020).

## 1 Introduction

Soils are embedded in the larger environment, coupled to vegetation and atmosphere at the land surface and to groundwater at its lower end. This gives rise to a suite of physical, chemical, and biological dynamics most of which are highly non-linear and varying in time and space. Soils provide crucial ecosystem functions such as water storage and filtering, food and other biomass production, recycling of carbon and nutrients, biological habitat and gene pool, as well as physical and cultural heritage, source of raw materials and platforms for human life (United Nations, 2014; Vereecken et al., 2016). Soils are widely distributed on the Earth surface, but the strongest gradients in soil systems occur in the vertical direction. Therefore, despite the relevance of soils for global phenomena, the relevant soil processes are rather local. Here, one aspect that complicates the picture is the heterogeneity of the soil properties, as soils are heterogeneous at all spatial scales. Another one is the non-linearity of soil processes, hence numerical models are needed for the comprehensive representation of the states and estimation of the fluxes towards an improved understanding of the hydrological system.

Recently, Vogel (2019) provided a comprehensive discussion about the scales and scaling issues in the context of soil hydrological research and remarked the need for looking at small-scale soil properties (at the pedon scale, at which soil physics is capable of describing states and fluxes with sufficient accuracy) as a necessary step towards understanding and summarizing the processes at larger scales, with the landscape being the typical scale of application of hydrological research at which, however, high-resolution measurements of the relevant states and properties cannot be achieved. In this context, the intermediate scale is crucial for linking the detailed process understanding to larger scale dynamics, recognizing hillslopes as key landscape features that organize water availability on land (Fan et al., 2019). Hypotheses testing and falsification in vadose zone hydrology can be facilitated if observations are merged with models that honour the relevant nonlinear interactions. In this respect, coupling state of the art hydrological modelling approaches with high-resolution subsurface characterization can lead to an accurate quantification of the soil water dynamics in the vadose zone (Vereecken et al., 2015).

The physical description of the small-scale water movement through the soil's porous structure is typically achieved using the Richards equation. However, the detailed description of the material properties is needed and cannot be fully resolved by direct sampling. Thus, inverse modelling can be a powerful tool for the estimation of the soil hydraulic parameters (e.g., Vrugt et al., 2008), including the recent developments in data assimilation approaches (e.g., Bauser et al., 2016, 2020; Botto et al., 2018). These require dense (in the direction of the dominant flow, typically orthogonal to the soil surface) measurements of soil water content with high temporal resolution and of high quality. Furthermore, *in situ* sensors can experience all the processes affecting the measured state variables in their natural environment (Wollschläger et al., 2009), which is an important advantage with respect to sample-based determinations from the laboratory.

The performances of hydrological models can be improved by various measured data with high spatial and temporal resolution (Clark et al., 2017). Bronstert (1999) remarked the importance of linking experimental knowledge to the experience gained from numerical modelling applications as a very valuable synergistic combination. Technological advances in our ability to measure soil hydrological states efficiently at the hillslope scale and beyond are one possible way to gain the much needed improved understanding of processes that challenge the comprehensive understanding of field-scale hydrology. Critical Zone Observatories (e.g., Brantley et al., 2007; Anderson et al., 2008; White et al., 2015), environmental research platforms focusing on the interconnection between physical, chemical and biological processes affecting Earth surface, offer the opportunity to integrate information about different compartments of the environment, scales, and knowledge from different disciplines, which can potentially lead to the enhanced understanding of soil processes (e.g., Guo and Lin, 2016).

In the research framework of the TERENO Harz/Central German Lowland Observatory, the *Schäfertal hillslope* represents a benchmark site for developing and testing the integration of state-of-the-art monitoring techniques with advanced modelling approaches. This offers the opportunity to gain a more detailed understanding of processes and to quantify and predict water and matter fluxes at nested spatial scales in the context of climate and land use change. Specifically, the approach followed at the site accounts for the soil spatial variability through detailed soil mapping and is designed to provide *in situ* data of, to our knowledge, the best quality available to date, with high temporal resolution and dense coverage in the vertical direction, about the soil water dynamics in the vadose zone and of its boundary conditions. With this design tailored to the needs of vadose zone modelling, we aim at feeding physical models with ideally all the data needed for quantifying and predicting the soil water fluxes at spatial scales ranging from the pedon to the hillslope scale, with important implications, in terms of methodological advance and process understanding, for catchment-scale processes.

Here, we present the first 21 months of the comprehensive dataset measured by the monitoring network *STH-net*, recently implemented at *Schäfertal Hillslope* site, part of an intensive hydrological observatory. The data set includes hourly time series of the meteorological forcing, soil water content measured *in situ* at different locations and at multiple soil depths along a hillslope transect, soil physical and physicochemical properties.

## 2 Site description

The Schäfertal experimental site is a small headwater catchment (1.44 km$^2$) located in the Lower Harz Mountains, in Central Germany (51°39’ N, 11°3’ E). Environmental research at the Schäfertal catchment was initiated at the end of the 1960s with the implementation of a hydro-meteorological station (Reinstorf et al., 2010) and the infrastructure has continuously been expanded since then. Since 2010, the Schäfertal catchment is one of the highly instrumented intensive research sites within the TERENO Harz/Central German Lowland Observatory (Zacharias et al., 2011, Wollschläger et al., 2018). Due to the geographical settings of the Harz region, the Schäfertal catchment receives only 630 mm of precipitation per year. The average annual air temperature is 6.9°C, with a subcontinental superimposed on the climate (Reinstorf, 2010). The geology of the catchment is dominated by Devonian argillaceous shales and greywackes, covered by periglacial sediments (Borchardt, 1982). Near-surface compacted horizons within the basal layer are known to induce interflow processes in the unsaturated zone (Borchardt, 1982; Gräff et al., 2009). Dominant soil types in the Schäfertal are Gleysols occurring in the valley bottom as well as Luvisols and Cambisols on the loess-covered slopes (Ollesch et al., 2005). The slopes of the catchment are intensively used for agriculture, whilst meadow occupies the valley bottom (Schröter et al., 2015).

Since 2012, a smaller hillslope area named *Schäfertal Hillslope* site, located downstream of the Schäfertal gauging station, was instrumented for detailed investigations of the hydrological processes in the unsaturated zone. From 2012 to 2017, the wireless soil moisture monitoring network *SoilNet* has delivered information about the soil water dynamics at three depths within the unsaturated zone with high spatial coverage. In 2018, the *SoilNet* has been disposed and a new soil monitoring network, named *STH-net*, has been installed aiming to improve the resolution in the vertical direction at a fewer locations selected based on the knowledge about the soil spatial variability and soil water dynamics gained from the previous monitoring experience (see Martini et al., 2015; 2017a; 2017b). The *STH-net* is described in the following sections of this manuscript and its data are now available through the data portal EUDAT. The *Schäfertal Hillslope* site includes north- and south-exposed slopes divided by the creek (*Schäferbach*) in the valley bottom (Fig. 1). In contrast to the slopes upstream of the gauging station, which are primarily covered by cropland, this grassland transect is used as pasture and is not affected by agricultural practices except that the grass is mowed typically once per year. The spatial extent of the hillslope is approximately 250 by 80 m and presents various topographical and pedological features. The *STH-net* is designed to cover the spatial variability of the soil properties as well as the soil layering with high resolution.

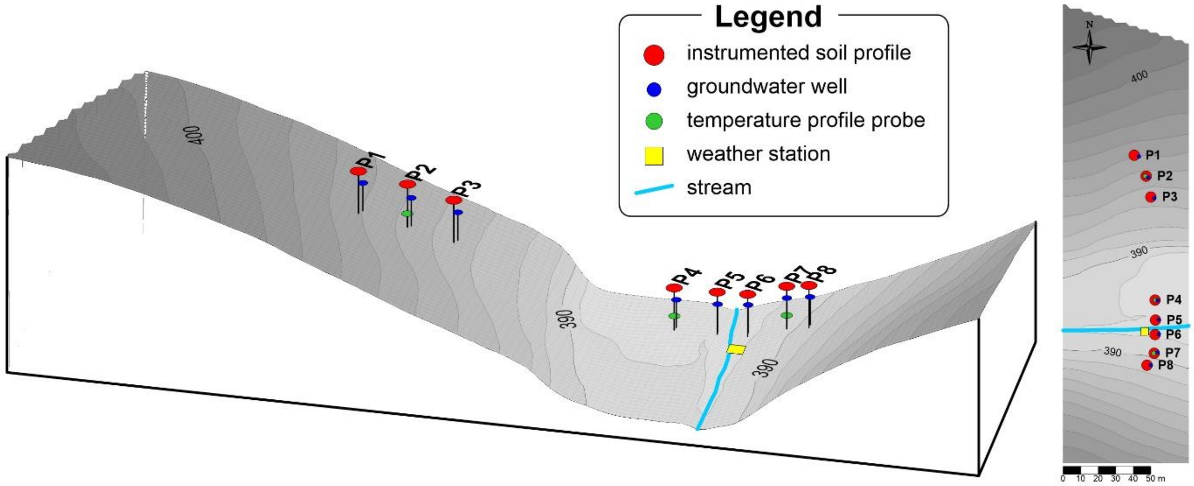

**Figure 1: Spatial map in 3D and aerial view of the *Schäfertal hillslope* site and location of the *STH-net* monitoring stations.**

## 3 Monitoring design and measurement techniques

The *STH-net* comprises eight monitoring stations (named as P1 to P8) arranged along a transect centred within the *Schäfertal Hillslope* site and aligned along the slope direction (Fig.1). The stations P1, P2 and P3 are located within the Northern (i.e., South-facing) slope; the stations P4 and P5 fall into the valley bottom; P6, P7 and P8 cover the lower part of the Southern (i.e., North-facing) slope. Every station features a soil profile instrumented with Time-Domain Reflectometry (TDR) probes installed every 0.1 m along the vertical direction. A sketch showing the design of a reference monitoring station is presented in Fig. 2. Each of the instrumented soil profiles located on the hillslopes features seven TDR probes installed at the depths of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7 m, whilst the profiles at P4 and P5 feature additional TDR probes at the depths of 0.8, 0.9, 1 and 1.1 m in order to cover the deeper soils. In a few cases, the depths of the probes were adjusted to avoid installing the TDR probe at or too close to the boundaries between soil horizons. The exact depth of every TDR probe is reported in the file "STH-net_Soils.txt" and displayed in Fig. 3.

At every station, a piezometer for monitoring the groundwater level was installed ca. 2 m to the East of the instrumented soil profiles. One station for every topographic unit (i.e., Northern slope, valley bottom and Southern slope) was further instrumented with sensors measuring the soil temperature at six depths between 0.05 and 1 m.

A weather station is located in the centre of the hillslope transect next to the creek.

All measurement systems comprising the *STH-net* collect measurements every 10 minutes.

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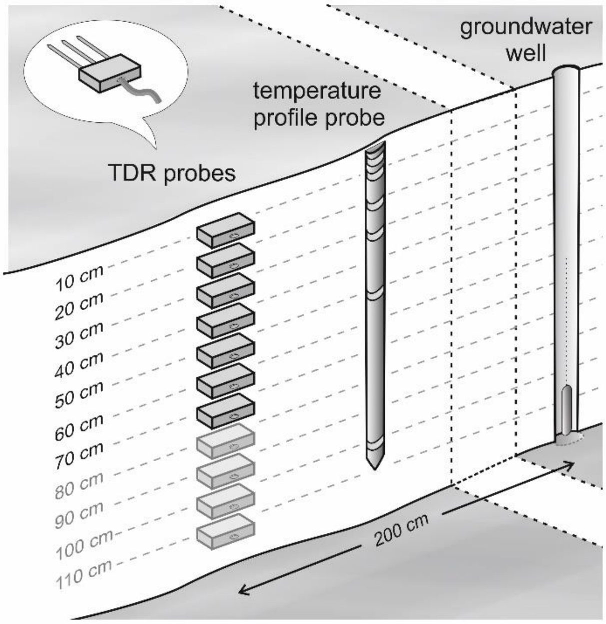

**Figure 2: Sketch of a representative monitoring station of the *STH-net*.**

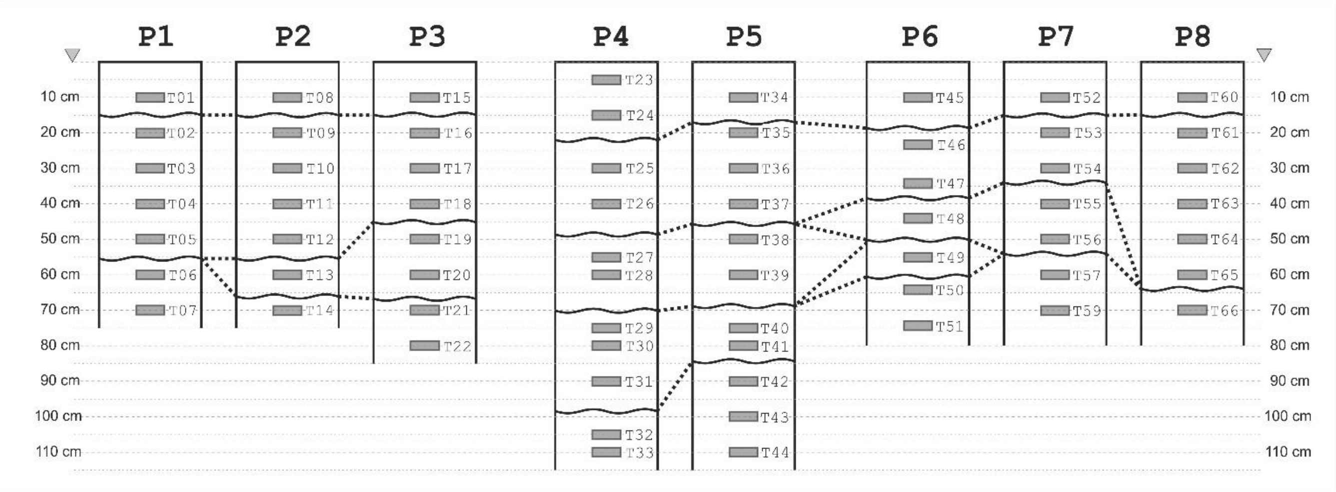

**Figure 3: Sketch of the soil profiles showing the mapped soil horizons and the depth of the TDR probes (see labels).**

## 3.1 TDR measurements

The TDR probes are arranged in clusters of 22 probes for the Northern slope and the valley bottom, whilst only 21 probes were installed at the Southern slope, for a total of 65 TDR probes. Each cluster consists of one TDR device (TDR100 for the station North, TDR200 for the stations Valley and South, Campbell Scientific Inc., Logan, UT, United States) and a data logger (CR1000 for the station North, CR6 for the stations Valley and South, Campbell Scientific Inc., Logan, UT, United States). The clusters are powered by safety extra low voltage cables buried ca. 0.3 m below the ground and cased in HDPE (i.e., high-density polyethylene) tubes and an AGM (i.e., absorbent glass mat) battery capable of supplying the required power in case of power cut-off. Every TDR probe is connected to its station master by a 22-m long low loss coaxial cable, tested to be the optimal length providing good signal quality while enabling enough flexibility in terms of network design. The TDR probes have three 0.2 m-long rods, were self-produced and calibrated through measurements in air and in water with different salt concentrations for water content and electrical conductivity estimation. The probes were installed horizontally in soil pits which were carefully refilled after the installation. The installation was carried out between June and August 2018 and all the measurements collected until the end of December 2018 were discarded to allow the soil to re-compact naturally during the first rainy season.

From the TDR traces, the dielectric permittivity $\varepsilon$ of the medium is calculated as:

$$\sqrt{\varepsilon} = \frac{\left(\sqrt{\varepsilon_{air}} - \sqrt{\varepsilon_{water}}\right)(t - t_{water})}{t_{air} - t_{water}} + \sqrt{\varepsilon_{air}} \quad (1)$$

based on the calibration measurements of travel time and dielectric permittivity in air ($t_{air}$, $\varepsilon_{air}$) and water ($t_{water}$, $\varepsilon_{water}$), where $t$ is the travel time estimated for the measured trace. The volumetric water content $\theta$ is calculated according to the complex refractive index model (CRIM) following Roth et al. (1990) as:

$$\theta = \frac{\sqrt{\varepsilon} - \sqrt{\varepsilon_{soil}} - \phi\left(\sqrt{\varepsilon_{air}} - \sqrt{\varepsilon_{soil}}\right)}{\sqrt{\varepsilon_{water}} - \sqrt{\varepsilon_{air}}} \quad (2)$$

where $\phi$ is the porosity which was calculated from the soil bulk density and $\varepsilon_{soil}$ is set to 4.6. Fig. 4 shows the hourly time series of soil water content. Characteristic differences in the soil water dynamics are evident for the distinct soil profiles and depths to be attributed, e.g., to the differences in soil texture and soil layering or, locally to groundwater dynamics.

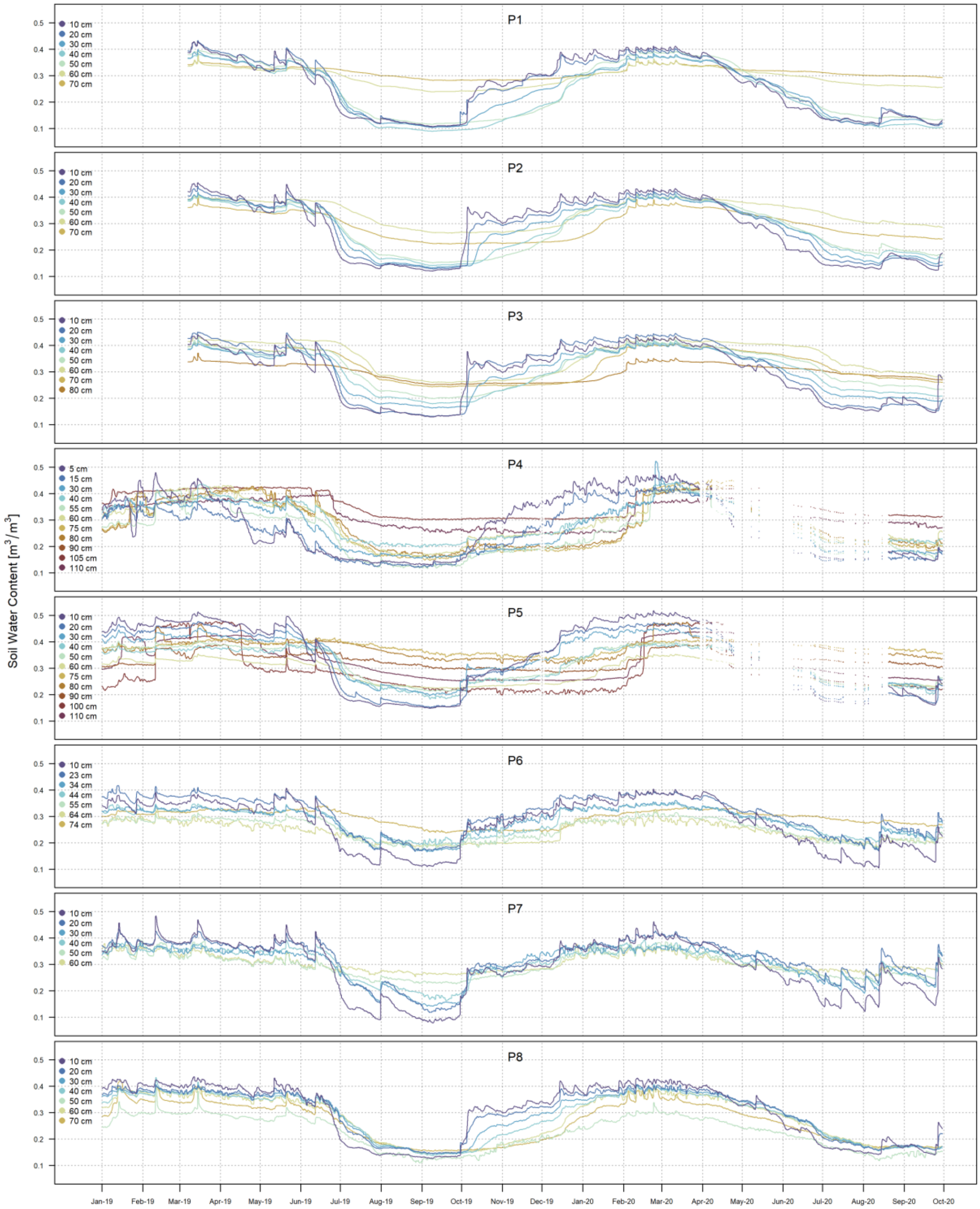

**Figure 4: Time series of hourly soil water content data. The plots were made using the data set as it appears in the online archive. The data are plotted using a scientific colour scale from Crameri (2018) chosen according to the principles described in Crameri et al. (2020).**

### 3.2 Soil temperature

The stations P2, P4 and P6 are instrumented with one Th3-s soil temperature profile probe (UMS GmbH, Munich, Germany) each, located nearby the instrumented soil profiles (Fig. 2) and connected via SDI-12 to the same data loggers and power supply. The probes consist of six temperature sensors cased inside a tube made of glass-fibre reinforced plastic and placed at the fixed depths of 5, 10, 20, 30, 50 and 100 cm. Soil temperature is measured at the same times as the TDR traces. The measured data are shown in Fig. 5. The influence of the geographical exposure of the slopes is particularly evident, e.g. overall higher temperature and stronger dynamics for the south-exposed slopes compared to the other areas, as well as the strongest dynamics near the surface compared to the deepest sensors.

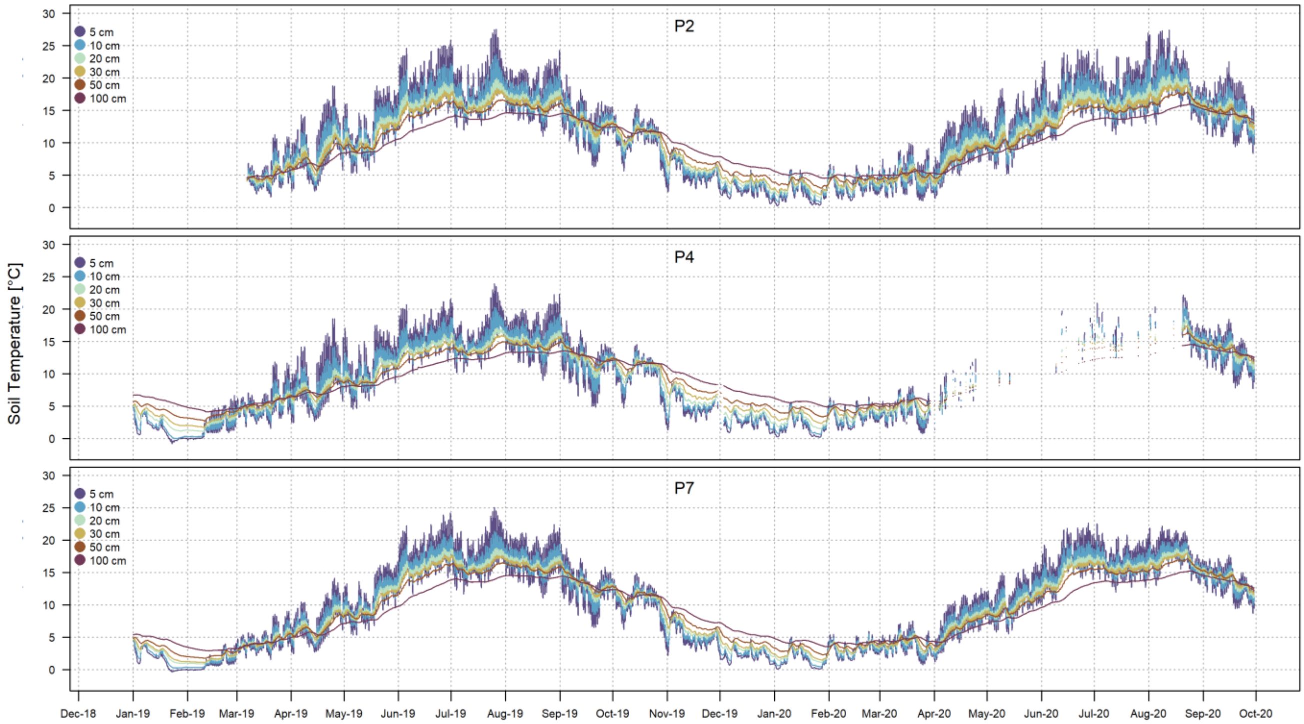

**Figure 5: Time series of hourly soil temperature data. The plots were made using the data set as it appears in the online archive. The data are plotted using a scientific colour scale from Crameri (2018) chosen according to the principles described in Crameri et al. (2020).**

### 3.3 Groundwater level

Every station of the *STH-net* is equipped with a monitoring well consisting of a LDPE (i.e, low-density polyethylene) tube drilled to the maximum depth of 2 m and screened in the depth interval 1 - 2 m. Due to an initial malfunctioning of the piezometers, only the data measured since March 2020 are available (not displayed).

## 3.4 Meteorological data

In the central part of the Schäfertal Hillslope site, a WXT 520 weather station (Vaisala Oyj, Laskutus, Finland) equipped with a CMP3-L pyranometer (Kipp & Zonen, Delft, Netherlands) installed at the height of 2 m measures the wind vector, air temperature and pressure, relative humidity, liquid precipitation, hail and solar radiation. The system is fully integrated with the data logger of the central monitoring station and the meteorological variables are measured at the same times as the TDR and soil temperature profile probes. Fig. 6 shows the hourly time series of rainfall intensity, air temperature and solar radiation.

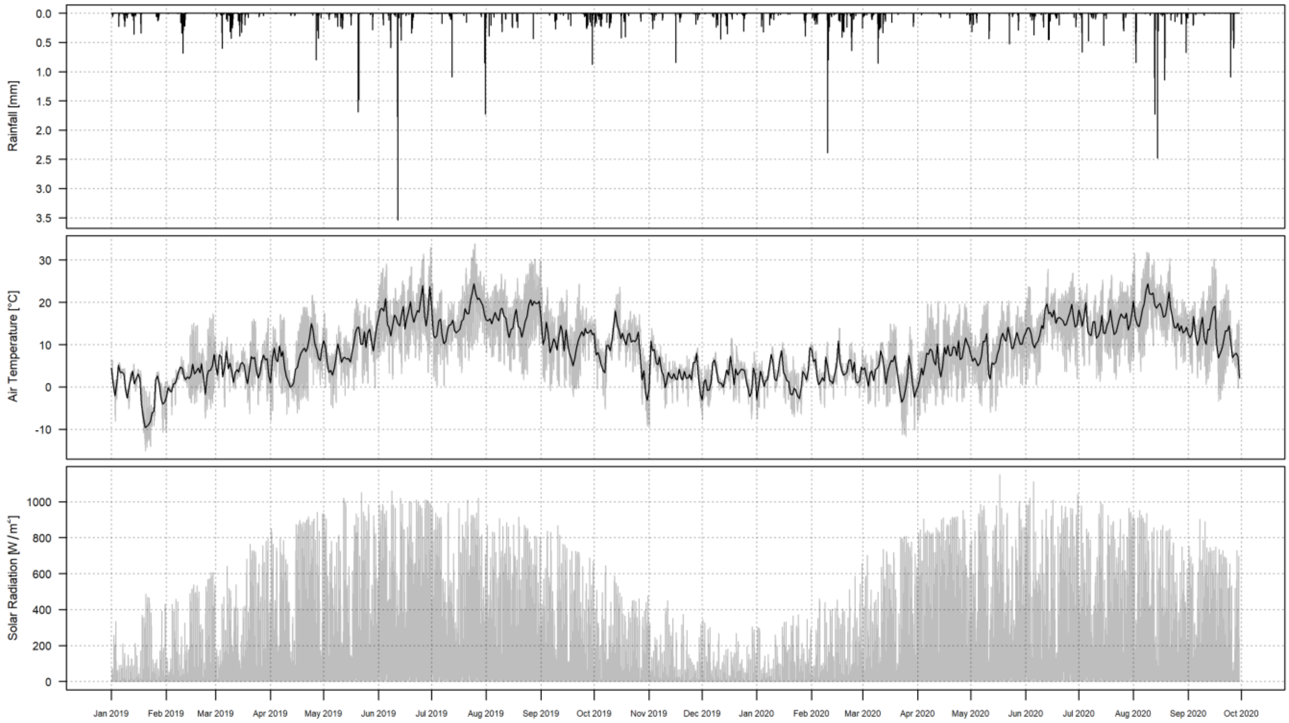

**Figure 6: Time series of the most relevant meteorological variables measured at the *Schäfertal Hillslope* site. The black line in the second plot shows the daily temperature while all other data are in hourly time steps. The plots were made using the hourly data set as it appears in the online archive.**

## 3.5 Soil properties

During the installation of the STH-net, one bulk soil sample and one volumetric soil sample were collected at every soil pit at the same depth as each of the TDR probes installed. From the bulk samples, the percentage of sand, silt and clay in the fine earth fraction was determined in the laboratory using the pipette method. The volumetric soil samples were collected with a stainless stain ring and used for the soil bulk density estimation. Fig. 6 shows the classification of the soil samples according to the German soil textural classes (Ad-hoc-AG Boden, 2005), considered suitable for the soil parameterization for physically-based hydrological modelling (Bormann, 2007).

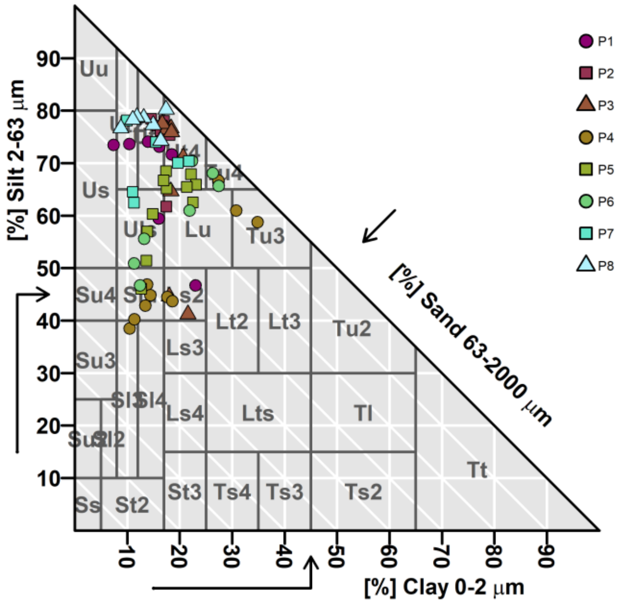

**Figure 7: Soil textural classification according to the German *Bodenkundliche Kartieranleitung* (Ad-hoc-AG Boden, 2005) grouped by soil profiles (P1 to P8). *Ss*: pure sand; *Su2*: slightly silty sand; *Sl2*: slightly loamy sand; *Sl3*: medium loamy sand; *St2*: slightly clayey sand; *Su3*: medium silty sand; *Su4*: highly silty sand; *Slu*: loamy silty sand; *Sl4*: highly loamy sand; *St3*: medium clayey sand; *Ls2*: slightly sandy loam *Ls3*: medium sandy loam; *Ls4*: highly sandy loam; *Lt2*: slightly clayey loam; *Lts*: clayey sandy loam; *Ts4*: highly sandy clay; *Ts3*: medium sandy clay; *Uu*: pure silt; *Us*: sandy silt; *Ut2*: slightly clayey silt; *Ut3*: medium clayey silt; *Uls*: loamy sandy silt; *Ut4*: highly clayey silt; *Lu*: silty loam; *Lt3*: medium clayey loam; *Tu3*: medium silty clay; *Ts2*: slightly sandy clay; *Tu4*: highly silty clay; *Tu2*: slightly silty clay; *Tl*: loamy clay; *Tt*: pure clay. The figure was created in RStudio with the package "The Soil Texture Wizard" (https://CRAN.R-project.org/package=soiltexture) by Julien Moeys. The data are plotted using a scientific colour scale from Crameri (2018) chosen according to the principles described in Crameri et al. (2020).**

## 4 Data management

The *STH-net* data stored by the three data loggers are accessed and downloaded remotely using the software *Loggernet* (Campbell Scientific Inc., Logan, UT, United States). The data files are regularly quality checked and processed using a custom-made code running on RStudio (RStudio Team, 2019). The original files are averaged to hourly values and uploaded to the EUDAT record *STH-net* (https://b2share.eudat.eu/records/e2a2135bb1634a97abcedf8a461c0909), where they remain available for download. For soil water content data only, the full resolution data were denoised using a moving average smoothing (width of 12-hours) prior to the hourly aggregation. This procedure was compared to others and proved to be effective in removing the measurement noise while keeping the dynamic component of the signal.

## 5 Data sets

The *STH-net* data are archived as separate text files for the different data types: soil water content, soil temperature, and meteorological variables. Furthermore, the geographic coordinates of the measurement locations and the soil information are available for download. The time series data start from January 1st, 2019 and continue with hourly time steps until the most recent update. At the time of the manuscript submission, the latest entry refers to September 30th, 2020.

## 6 Data availability

The *STH-net* data are available under a dynamic identifier DOI 10.23728/b2share.e2a2135bb1634a97abcedf8a461c0909 (Martini et al., 2020) at the time of the manuscript submission (from there, all future versions of the archive can be easily accessed) under the Creative Commons Attribution license (CC-BY 4.0).

## Author contribution

Edoardo Martini: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, visualization, writing – original draft preparation, writing – review & editing.
Simon Kögler: conceptualization, data curation, methodology.
Manuel Kreck: data curation, methodology, writing – review & editing.
Kurt Roth: conceptualization, resources, writing – review & editing
Ulrike Werban: conceptualization, funding acquisition, resources, writing – review & editing
Ute Wollschläger: conceptualization, writing – review & editing
Steffen Zacharias: conceptualization, funding acquisition, resources, writing – review & editing

## Competing interests

The authors declare that they have no conflict of interest.

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*net* data. Edoardo Martini received funding from the German Research Foundation (DFG) through the research grant MA 7936/1-1.

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