UK Centre for Ecology & Hydrology

COSMOS-UK User Guide

Users' guide to sites, instruments and available data

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COSMOS-UK
UK Soil Moisture Monitoring Network

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1. Introduction

1.1 About the COSMOS-UK project

COSMOS-UK was established in 2013 and is therefore a relatively recent initiative which is still developing in terms of the services offered to users. Our ambition is to maintain, or slightly expand, our network and to enhance the information services provided. Visit the web site to learn about changes and improvements (cosmos.ceh.ac.uk).

The primary purpose of the COSMOS-UK project is to deliver soil moisture data in near real-time from a network of sites installed across the UK. The innovation provided by COSMOS-UK comes from the use of a sensor that exploits cosmic-rays to measure soil moisture over an area of up to 12 hectares (about 30 acres). The sensor sits above ground and operates automatically to deliver data from remote sites. This contrasts with other sensors that are intrusive, effectively point-scale, and require an on-site operator.

It is anticipated that publically accessible near real-time information will empower all kinds of applied environmental research: more accurate meteorological models; better water resource information of current and future conditions; increased resilience to natural hazards, for example by earlier flood warnings; improved water use efficiency in crop production and give better crop yield forecasts. It will enable a step change in fundamental science, particularly, meteorological predictability associated with soil moisture, and better models of greenhouse gas emissions from soils. COSMOS-UK will open up other environmental science areas where UK soil moisture data has not been available before, such as applications in ecosystem services.

The use of new technology is exciting and potentially rewarding but not without its challenges. There is research to do in interpreting the measurements obtained from the COSMOS-UK sites, e.g. adjusting raw measurements to give a reliable value of soil moisture, and relating to measurements derived from other techniques.

1.2 About this guide

This guide is intended for users and potential users of the COSMOS-UK data, both within UKCEH and externally.

The following sections give information on the COSMOS-UK sites, instrumentation, available data and information products including standard retrievals. Section 7 contains a fairly detailed description of the cosmic ray soil moisture method.

2. Sites

COSMOS-UK sites are listed in Table 2.1 with start dates, national grid references, and altitudes and shown mapped in Figure 2.1. There is a list with more site properties at the end of this guide in Appendix A.

Table 2.1 List of COSMOS-UK sites.

SITE_NAME	START_DATE	CALIBRATED	EAST	NORTH	ALTITUDE (M)
CHIMNEY MEADOWS	02-Oct-13	Y	436113	201160	65
SHEEPDROVE	24-Oct-13	Y	436039	181395	170
WADDESDON	04-Nov-13	Y	472548	216176	98
WYTHAM WOODS	21-Nov-13	Y	445738	208942	109
HOLLIN HILL	25-Mar-14	Y	468121	468811	82
MORLEY	14-May-14	Y	605826	298803	55
GLENSAUGH	14-May-14	Y	365870	780483	399
BALRUDDERY	16-May-14	Y	331643	732797	130
HARTWOOD HOME	20-May-14	Y	285476	658957	225
ROTHAMSTED	25-Jul-14	Y	511887	214048	131
EASTER BUSH	14-Aug-14	Y	324557	664463	208
GISBURN FOREST	15-Aug-14	Y	374899	458714	246
TADHAM MOOR	14-Oct-14	Y	342199	145692	7
NORTH WYKE	16-Oct-14	Y	265707	98832	181
THE LIZARD	17-Oct-14	Y	170940	19648	85
PLYNLIMON	05-Nov-14	Y	280322	285397	542
STIPERSTONES	06-Nov-14	Y	336086	298579	432
COCKLE PARK	21-Nov-14	Y	419544	591351	87
CRICHTON	02-Dec-14	Y	298903	573164	42
MOOR HOUSE	04-Dec-14	Y	369920	529470	565
SOURHOPE	09-Dec-14	Y	385562	620698	487
LULLINGTON HEATH	16-Dec-14	Y	554365	101634	119
PORTON DOWN	18-Dec-14	Y	422406	135670	146
BUNNY PARK	27-Jan-15	Y	458884	329606	39
BICKLEY HALL	28-Jan-15	Y	353112	347903	78
REDMERE	11-Feb-15	Y	564639	285846	3
CHOBHAM COMMON	24-Feb-15	Y	497737	164137	47
ALICE HOLT	06-Mar-15	Y	479950	139985	80
HARWOOD FOREST	20-May-15	Y	398505	591355	300
CARDINGTON	24-Jun-15	Y	507991	246422	29
STOUGHTON	18-Aug-15	Y	464641	300854	130
HENFAES FARM	17-Dec-15	Y	265750	371709	287
REDHILL	18-Feb-16	Y	569577	154326	91
EUSTON	31-Mar-16	Y	589619	279776	18
LODDINGTON	26-Apr-16	Y	479565	302022	186
RISEHOLME	04-May-16	Y	498425	374863	53
HILLSBOROUGH	14-Jun-16	Y	136345	513358	146
GLENWHERRY	15-Jun-16	Y	142962	556604	274
CWM GARW	29-Jun-16	Y	211350	231661	299

SITE_NAME	START_DATE	CALIBRATED	EAST	NORTH	ALTITUDE (M)
ELMSETT	11-Aug-16	Y	605122	248260	76
HADLOW	27-Oct-16	Y	562097	150263	33
SPEN FARM	23-Nov-16	Y	444887	441620	57
FINCHAM	07-Jun-17	Y	570068	305182	15
WRITTLE	04-Jul-17	Y	567062	206687	44
HEYTESBURY	16-Aug-17	Y	394535	144856	166
COCHNO	23-Aug-17	Y	249980	674651	168
HOLME LACY	11-Apr-18	Y	354663	236036	76
FIVEMILETOWN	26-Jun-18	Y	558510	502136	174
MORETON MORRELL	15-Nov-18	Y	429959	255776	53
SYDLING	27-Nov-18	Y	362917	103337	249
WIMPOLE	10-Sep-19	Y	533951	250013	30

Figure 2.1 Map of COSMOS-UK sites

2.1 Site selection criteria

The network has been designed to provide a UK-wide network of stations that sample the range of physical and climatic conditions across the UK (e.g., land cover, climate, soil type and geology). Some clustering of sites enables us to explore variability between sites at local, regional and national levels.

Listed below are factors used in the evaluation of potential sites, and whether they have a positive or negative influence. Some factors are both positive and negative influences on site selection; for example we are keen to sample locations not already represented in the network (a positive influence), but also to avoid undue duplication of site characteristics that are already well represented in the network (a negative influence).

Factors considered:

- Geographic location - providing desired spatial coverage within network. [Positive & negative]
- Environmental variables (e.g. climate, soil, geology, land cover and topography). [Positive & negative]
- High soil moisture variability. [Positive]
- Existing, relevant, on-going research and monitoring activities at the site. [Strong positive]
- Opportunities for COSMOS-UK data to directly satisfy research goals and foster collaboration, such as data assimilation into models, validation of remote sensing, and support of other monitoring programmes. [Positive]
- Proximity to open water or shallow/perched groundwater [Strong negative]
- Long-term permission for instrument installation and soil sampling. [Strong positive]
- Ease of access. [Strong positive]
- Risk of vandalism. [Strong negative]
- Mobile phone network coverage. [Positive]

3. Instrumentation

Instruments used by the COSMOS-UK network are listed in Table 3.1. Note that instrumentation has changed with time and that not all instruments are installed at all sites (see Table 3.2).

This information is provided for reference only and implies no endorsement of the specific instrument or supplier by UKCEH.

Table 3.1 Instruments used by COSMOS-UK.

Cosmic-Ray Neutron Sensor (CRNS) The sensor counts fast neutrons which can be converted to soil moisture after field calibration. Data processing accounts for variations in atmospheric pressure, humidity, and the intensity of incoming cosmic rays. The method is described in Section 7. The measurement volume of the sensor is many tens of meters horizontally (possibly up to 200m) although measurement is inversely related to distance from the sensor. The effective depth varies with soil moisture but is typically in the range 15-40cm. Köhli et al (2015) provide a recent discussion of the sensor footprint. Model: Hydroinnova CRS-2000/B and CRS-1000/B	
Digital weighing rain gauge Provides data on the amount and intensity of solid and liquid precipitation. On-board processing algorithms account for spurious changes due to temperature or wind speed. Model: OTT Pluvio²	

Tipping bucket rain gauge

Provides data on the amount of liquid precipitation at 0.2 mm resolution. Aerodynamically shaped to reduced wind-induced undercatch. Any solid precipitation collected in the funnel will be measured as it melts.

These were first installed at three sites in 2020, see Table 3.2.

Model: EML SBS 500

Point soil moisture sensor

Soil moisture sensors at various depths use the TDT (time domain transmissometry) technique and provide absolute volumetric water content and soil temperature.

Note that the soil moisture data are not calibrated to the site specific soil type, but rely on generic calibration information.

The sampling volume is a region around the waveguide which has a total length of 30cm. Blonquist et al (2005) suggest that the sampling volume is no greater than 15 cm (half length of wave guide) x 6 cm(horizontal) x3 cm(vertical)

All COSMOS-UK sites have a minimum of 2 TDT point soil sensors, those marked as having a ‘TDT array’ in Table 3.2 have 10.

Model: Acclima Digital TDT Soil Moisture Sensor

Profile soil moisture sensor

A profile probe with three sensors provides soil moisture at depths of 0.15, 0.40 and 0.65 m. The probe sits within a specially-designed access tube and is sensitive over a radius of around 0.10 m, although the region of highest sensor sensitivity is closest to the access tube. Sensors use the TDT (time domain transmissometry) technique.

Note that the soil moisture data are not calibrated to the site specific soil type, but rely on generic calibration information.

According to the manufacturer's documentation Each of the sensors has a measurement field of 11cm vertically and the effective penetration depth of the probe is 10cm (note that this is not uniform around the sensor but elliptical. Air gaps around the installation tube can have a detrimental effect on instrument accuracy.

For overall system operational reasons, it was decided in 2019 to withdraw the IMKO sensors.

Model: IMKO PICO-PROFILE Soil Moisture Sensor

Soil heat flux plate

Two heat flux plates at each site provide the soil heat flux at a depth of 0.03 m. These plates have a self-calibrating feature to maximise measurement accuracy; the in situ calibration is performed once a day.

Model: Hukseflux HFP01SC self-calibrating heat flux plate

Soil temperature sensor

The near-surface soil temperature is measured at five depths (0.02, 0.05, 0.10, 0.20 and 0.50 m) using a profile of thermocouples.

Model: Hukseflux STP01

Radiometer

A four-component radiometer measures the individual radiation components using upward and downward facing pyranometers (for the shortwave components) and pyrgeometers (for the longwave components). The net radiation is calculated as the sum of the incoming minus the outgoing components and is usually the dominant term in the surface energy balance. In the photo the radiometer is at the right-hand end of the horizontal support.

Model: Hukseflux four-component radiometer.

Automatic weather station

Air temperature and relative humidity are measured by a probe situated within a naturally aspirated radiation shield; barometric pressure is also measured.

Each COSMOS-UK site includes either this instrument or the barometric pressure and humidity sensors listed next.

Model: Rotronic HC2A-S3 within the Gill MetPak Pro Base Station

Barometric pressure sensor

A barometric pressure sensor which incorporates a Barocap® silicon capacitive pressure sensor encased in a plastic shell with an intake valve for pressure equalisation. Measures barometric pressure equivalent to an elevation range from below sea level to 4.5km.

Model: Vaisala PTB110 Barometric Pressure Sensor.

Temperature and humidity sensor

Humidity and air temperature are measured by a capacitive thin film HUMICAP© polymer sensor and resistive platinum sensor (Pt100) respectively. Both the humidity and temperature sensors are located at the tip of the probe protected by a removable filter.

Model: Vaisala HUMICAP HMP155A Humidity and Temperature Probe.

3D sonic anemometer

Monitors wind speeds of 0-50m/s (0-100mph), and wind direction.

Each COSMOS-UK site includes either this instrument or the 2D sonic anemometer below.

Model: Gill WindMaster 3D Sonic Anemometer

Integrated 2D sonic anemometer

High accuracy wind speed and direction integrated with automatic weather station

Model: Gill Integrated WindSonic

PhenoCam

A pair of cameras with almost 360° field of view provides visual information about the land cover, (e.g. when crops are harvested, greenness of vegetation - hence the name which is a contraction of “phenology camera”). It can also provide information on cloud cover, snow cover, surface ponding and atmospheric visibility.

Model: Motobotix S14 IP camera with hemispheric lenses

Snow depth sensor

Sonic rangefinder designed specifically to measure snow depth.

Model: Campbell Scientific SR50A

Snow water equivalent

The sensor records the intensity of downward-directed secondary cosmic-rays that penetrate the snow pack. This intensity is inversely proportional to the mass of snow traversed by cosmic-rays, and is related to soil water equivalent (SWE) through a calibration function.

Model: Hydroinnova SnowFox

Micrologger

Consists of measurement and control electronics, communication ports.

Model: Campbell ScientificCR3000

Table 3.2 Each COSMOS-UK site includes a selection of the sensors in Table 3.1. Depending on installation date and other factors, sites may implement a different type of anemometer, barometer, temperature and humidity sensor, point and profile soil moisture sensors, or rain gauge. This table lists the type of instrument installed at each site. Instruments included in Table 3.1 but not listed here are installed at all sites.

Site	3D sonic anemometer	2D sonic anemometer	Automatic weather station	Barometric Pressure sensor	Temperature and humidity sensor	Profile soil moisture	TDT array	Snow sensors	Tipping bucket rain gauge
Alice Holt[2]		X	X			X			
Balruddery	X		X			X			
Bickley Hall	X		X			X			
Bunny Park	X		X			X			
Cardington	X		X			X			
Chimney Meadows[1]	X	X	X	X	X	X	X		X
Chobham Common	X		X			X			
Cochno	X			X	X		X	X	
Cockle Park	X		X			X			
Crichton	X		X			X			
Cwm Garw	X			X	X		X	X	
Easter Bush	X		X			X		X	
Elmsett	X			X	X		X		
Euston	X			X	X		X		
Fincham	X			X	X		X		
Fivemiletown	X			X	X		X		
Gisburn Forest	X		X			X		X	
Glensaugh	X		X			X		X	
Glenwherry	X			X	X		X		
Hadlow	X			X	X		X		
Hartwood Home	X		X			X			
Harwood Forest[2]		X	X			X			
Henfaes Farm	X		X			X			
Heytesbury	X			X	X		X		
Hillsborough	X			X	X		X		
Hollin Hill	X		X			X			
Holme Lacy	X			X	X		X		
The Lizard	X		X			X			
Loddington	X			X	X		X		
Lullington Heath	X		X			X			
Moor House	X		X			X		X	
Morley	X		X			X			

Site	3D sonic anemometer	2D sonic anemometer	Automatic weather station	Barometric Pressure sensor	Temperature and humidity sensor	Profile soil moisture	TDT array	Snow sensors	Tipping bucket rain gauge
Moreton Morrell	x		x			x			
North Wyke	x		x			x			
Plynlimon	x		x			x		x	
Porton Down	x		x			x			
Redhill	x		x			x			
Redmere	x		x			x			
Riseholme	x			x	x				
Rothamsted	x		x			x			
Sheepdrove[1]	x	x	x	x	x	x	x		x
Sourhope	x		x			x		x	
Spen Farm	x			x	x				
Stiperstones	x		x			x			
Stoughton	x		x			x			
Sydling	x		x			x			
Tadham Moor	x		x			x			
Waddesdon[1]	x	x	x	x	x	x	x		x
Wimpole	x		x			x			
Writtle	x			x	x		x		
Wytham Woods[2]		x	x			x			

[1] These sites were upgraded in February 2020, thus replacing the 2D sonic anemometer and automatic weather station with a 3D sonic anemometer and upgraded barometric pressure sensor and temperature and humidity sensor. The extra 8 sensor 'TDT array' was also installed at these sites. The full record of sensor swaps is available upon request, see Appendix I.

[2] These sites were installed at pre-existing flux observation towers. Here meteorological sensors are located at the top of the tower above the vegetation canopy, whilst other equipment is installed at ground level. The digital weighing rain gauge (Pluvio²) receives rainfall collected at the top of the tower via a funnel and tube, and therefore does not accurately measure precipitation intensity. Precipitation accumulation data measured by the Pluvio² at these sites are corrected for the smaller aperture area of the funnel.

4. Available data

The data available from the COSMOS-UK network are listed below in Tables 4.1 & 4.2. As noted in Section 6 these data are subject to ongoing quality control and gap filling protocols together with changes in data processing and therefore their availability and value may change with time.

It is anticipated that further derived data sets will be made available in the future.

Table 4.1 Monitored data available from the COSMOS-UK network

VARIABLES	UNITS	RECORDING INTERVAL
Precipitation	mm	1 min
Absolute humidity[3]	gm^{-3}	30 min
Relative humidity	%	30 min
Air temperature	$°C$	30 min
Atmospheric pressure[4]	hPa	30 min
Incoming longwave radiation	Wm^{-2}	30 min
Incoming shortwave radiation	Wm^{-2}	30 min
Outgoing longwave radiation	Wm^{-2}	30 min
Outgoing shortwave radiation	Wm^{-2}	30 min
Wind direction	$degrees$	30 min
Wind speed	ms^{-1}	30 min
3D wind speed data (x3)	ms^{-1}	30 min
Snow depth	mm	30 min
Volumetric water content at three depths (15cm, 40cm, 65cm) (IMKO Profile)	%	30 min
Soil heat flux (x2)	Wm^{-2}	30 min
Soil temperature at five depths (2cm, 5cm, 10cm, 20cm, 50cm)	$°C$	30 min
Soil temperature and volumetric water content (10cm, and up to 4 other depths x2) (TDT)	$°C$ & %	30 min

[3] There was a small change in the derivation of absolute humidity in November 2019, so that the value is now calculated as part of data processing, rather than on the data logger. The change, which has been applied retrospectively to all data, makes an insignificant difference to the calculated value, but does improve the completeness of the data.

[4] Reported as recorded at altitude of instrument i.e. not corrected to sea level.

Table 4.2 Derived data available from the COSMOS-UK network

DERIVED VARIABLES	UNITS	NOTES
Net radiation	Wm^{-2}	30 min
Volumetric water content (CRNS)	%	Daily/hourly[5]
Typical sensing depth of CRNS (D86)	cm	Daily/hourly
Neutron counts from CRNS (corrected)	counts	Hourly
Potential evaporation[6]	mm	Daily
Atmospheric Pressure at sea level[7]	hPa	Daily/30min
Albedo[8]	Dimensionless	Daily
Soil moisture index (SMI)[9]	Dimensionless	Daily
Snow days[10]	Yes/No	Daily
Snow Water Equivalent (CRNS)	mm	Daily
Snow Water Equivalent (SnowFox)	mm	Daily

[5] Daily data are more reliable and complete than hourly data.

[6] Potential evaporation data are calculated using the Penman-Monteith method according to FAO 56, Allen et al., 1998.

[7] The correction of pressure to sea level is as recommended by WMO, 1964 p22 equation 2.

[8] Daily albedo is calculated as the mean ratio of outgoing to incoming short wave radiation in the period from 10:00 to 14:00.

[9] See Appendix H.

[10] See Section 7.5 for information concerning Snow days and Snow Water Equivalent.

5. Accessing COSMOS-UK data

COSMOS-UK data are available via the UKCEH Environmental Information Data Centre (EIDC) at http://eidc.ceh.ac.uk/.

These data are published by the EIDC in annual tranches and cover the period up to 1-2 years behind the date of the upload into the EIDC. Thus in September 2020 data are uploaded for the period up to 2018.

Requests for data not available via the EIDC will be considered but can only be met if the request is deemed reasonable in terms of the effort require to abstract and deliver the requested data. All data requests should be made to cosmosuk@ceh.ac.uk

All data supplied must be considered to be provisional, in that they may be subjected to further or revised quality control, and are supplied on the understanding that UKCEH accepts no liability for their use.

Data are supplied with a licence setting out the terms under which they can be exploited.

UKCEH also welcomes enquiries regarding collaborative research opportunities related to the COSMOS-UK project.

Data can be viewed as graphs on the data pages COSMOS-UK website (cosmos.ceh.ac.uk).

Several standard graphical retrievals are available, examples of which are presented in Appendix D.

6. Data processing

Data processing is required to ensure the quality of the COSMOS-UK data streams and to calculate derived data.

Derived data include the volumetric water content (VWC) calculated from the cosmic ray neutron sensor (CRNS). This is very obviously a derived product as the measured quantity (neutron counts) needs considerable processing, and combining with other data streams, to give a VWC. Even with this processing the underpinning data stream is noisy so that values of VWC derived from the counts over 30 minute intervals are not usable; some form of time-averaging is required to remove this noise and reveal the underlying signal. Research continues on how best to process the data from the CRNS. Section 7 provides information on the processing of neutron counts to volumetric water content.

Without getting too philosophical about it, most measurements are indirect and must be processed. For example, a weighing rain gauge does what it says and measures the mass of accumulated rainfall, which must be processed to give 1-minute rainfall depths in mm. Some of this processing is done in the instrument or data logger, so that the raw data are already in the form required.

COSMOS-UK sites also contain pairs of some instruments, i.e. heat flux plates and point soil moisture sensors. These are currently provided as separate data sets although users may decide to use the average value.

Data processing can also derive averages or accumulations over longer intervals than used to capture the data. So for example hourly or daily sets can be derived. Doing this requires some consideration about what to do with missing data. When aggregating to daily data, generally up to 2 hours of data are allowed to be missing.

6.1 Quality Control

Quality control procedures are subject to continuous development. Raw (level1) data are currently subject to two stages of quality control.

1. Automatically applied QC tests (see Table 6.1). Data that fail these tests are removed from the level 2 dataset. Tests are applied to specific variables, for details on which variables are subject to which test see Appendix F.
2. A daily visual inspection of all data on automatically generated plots showing 1 and 10 day time frames.

Raw data passing the level1 checks are copied into a level2 data set, i.e. the original data remain available for further review. The labels “LEVEL1” and “LEVEL2” are attached to variable names in some (but not all) of the references to, and labels for, COSMOS-UK data.

Table 6.1 Quality control tests applied to data. For details on which variables tests are applied to see Appendix G.

TEST	DESCRIPTION
ZERO DATA	Data equal to zero where this is not a possible value. For certain variables missing data is marked using a zero. For variables where this is true any zero values are removed as these are assumed to be missing.
TOO FEW SAMPLES	Data with too few half hourly samples. For variables that are a sum or average of numerous continuous readings in the preceding half hour period; if any of these readings are missing the measurement is unreliable and data are removed.
LOW POWER	Data recorded where battery voltage is low. Low battery power can mean measurements are missing or unreliable. If the battery pack voltage goes below 11V the associated data will be removed.
SENSOR FAULT	Data associated with a sensor that has a known fault
DIAGNOSTIC FLAG	Data that has been assigned a diagnostic flag by the instrument.
OUT OF RANGE	Data that are outside an acceptable range for that variable. Each variable measured at each site has a minimum and maximum value set. If the measurement of this particular variable goes out of this range it will be removed.
SECONDARY VARIABLE	Data dependant on another variable and the other variable is incorrect. Some measurements are dependent on the measurements of another variable being reasonable. For example measurements of the components of radiation are not reliable when the body temperature (of the radiometer) measurement is out of the acceptable range. This test will remove values from the dependent variables if the main variable is not correct.
SPIKE	Data that are greater than a threshold value smaller/larger than the neighbouring values. If a value is greater than a certain threshold away from its neighbouring values this is removed.
ERROR CODES	Data where the logger programme has assigned an error code value due to a sensor/programme fault. When there is a fault with the sensor for some variables the logger programme can record a value of 7999.

6.2 Gap filling

Gaps can occur in the data because of instrument failure, failure in data logging or telecommunications, and failure at quality control.

Currently no gap-filling is undertaken.

7. Processing the CRNS data

In this section is a description of cosmic rays, how they interact with the atmosphere and soil, and how counting neutrons is the basis for deriving soil moisture. This is followed by a discussion of the noise in the cosmic ray derived soil moisture data and what this implies for the temporal resolution of the data.

7.1 About cosmic-rays

Primary cosmic-rays are high-energy sub-atomic particles that originate from outer space and continuously bombard the Earth. The intensity of cosmic-rays arriving at the top of the Earth's atmosphere varies with the events that generate them (distant astronomical events) and factors such as variations in the solar magnetosphere. The particles are mostly (90%) protons with a typical energy of around 1 GeV.

When these particles enter the Earth's atmosphere they collide with atoms in the air and create a shower of secondary cosmic-ray particles (including neutrons), which may or may not interact with other particles before reaching the Earth's surface. Each collision causes the particle (neutron) to lose energy. The energy spectrum of these neutrons at the Earth's surface contains a number of peaks. At around 100 MeV are high energy neutrons, which interact with air and soil to produce a second peak, at around 1 MeV, of fast neutrons, also known as evaporated neutrons (that is not evaporation as understood by hydrologists but the "release" of neutrons following the collision of a high energy particle, e.g. a proton or neutron, with the nucleus of an atom).

Further collisions cause a further reduction in the energy of the neutrons until they become 'thermalised' i.e. in thermal equilibrium with the environment; that is they can neither lose more energy nor regain lost energy. These thermalized, or thermal, neutrons, have typical energies of around 0.1 eV. Neutrons with energies greater than thermal neutrons may be referred to as epi-thermal, generally meaning greater than 0.5 eV; fast neutrons are therefore within the epi-thermal range. Köhli et al. (2015) provide an illustration of this energy spectrum, reproduced below as Figure 7.1.

The themalisation of neutrons (also known as moderation) is highly dependent on the properties of the particles (elements) the cosmic rays hit. Hydrogen is the most efficient element in terms of its stopping power of fast neutrons; 18 collisions with hydrogen will thermalize a fast neutron whereas this takes 149 collisions with oxygen. This is explained by the fact that the light hydrogen nucleus, comprising just one proton, can absorb a lot of the energy from the neutron in a collision (much like when two billiard balls collide) whereas when a neutron hits a large nucleus it bounces off retaining most of its energy (like a billiard ball hitting the cushion on the snooker table, this nice analogy is from Zreda et al., 2012). This stopping power combined with the abundance of hydrogen in air and soil means that the process of thermalisation is largely determined by the presence of hydrogen.

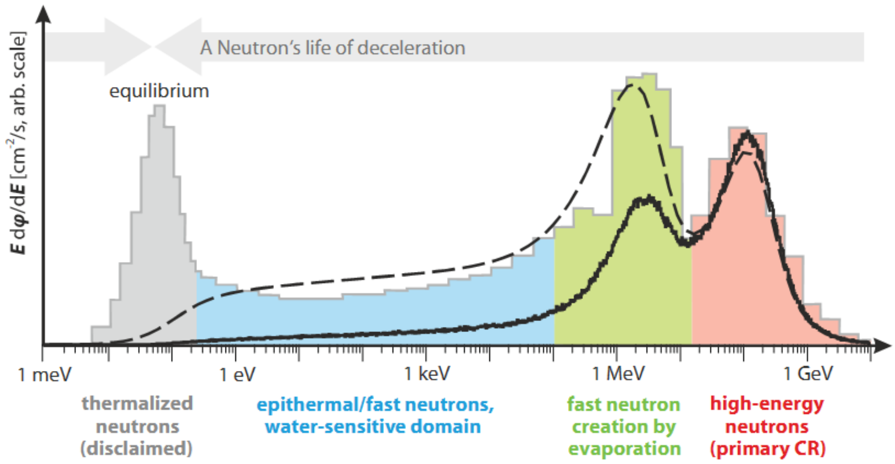

Figure 1. Neutron energy spectra at the surface: exemplary measurement by *Goldhagen et al.* [2002] (grey) and simulated by *Sato and Niita* [2006] (dashed). After subtracting the ground reflected component over pure water, we obtain a pure incoming component (continuous black line), which is used as the source spectrum in this study. Colors illustrate the deceleration of initial high-energy neutrons (red), which interact with heavy atoms leading to the evaporation spectrum (green). Energy is lost by elastic collisions with light atoms in the regime where the detector is particularly sensitive (blue) until neutrons arrive energetically in a thermal equilibrium (light grey).

Figure 7.1 Neutron energy spectra reproduced from Köhli et al (2015)

These collisions result in neutrons being scattered in all directions, i.e. between and within the air and soil, and the process of thermalisation is effectively instantaneous because of the high energy/velocity of the fast neutrons. The concentration of fast neutrons therefore very quickly reaches an equilibrium in both the soil and the air, and a key factor in determining the concentration is the amount of hydrogen that is present.

This is the basis of the cosmic-ray soil moisture method. A sensor at the land surface will count more fast neutrons when there is little hydrogen (water) present and fewer fast neutrons when there is more hydrogen to remove energy from the neutrons leading to their themalisation.

7.2 Converting counts to soil moisture

The neutron counter is basically a tube containing a gas that can convert thermal neutrons into detectable electrons by ionisation; higher energy neutrons pass through the tube without interacting with the gas. In its "bare" format the sensor therefore counts themalised rather than fast neutrons, although there is not a sharp cut-off in its detection limit.

A "moderated" tube contains the same sensor embedded in a material that causes the themalisation of neutrons and therefore counts neutrons in a higher energy range, although some lower energy neutrons are also likely to be counted.

Andreasen et al., 2015 presents figures showing part of the neutron energy spectrum sampled by bare and moderated detectors, reproduced below as Figure 7.2.

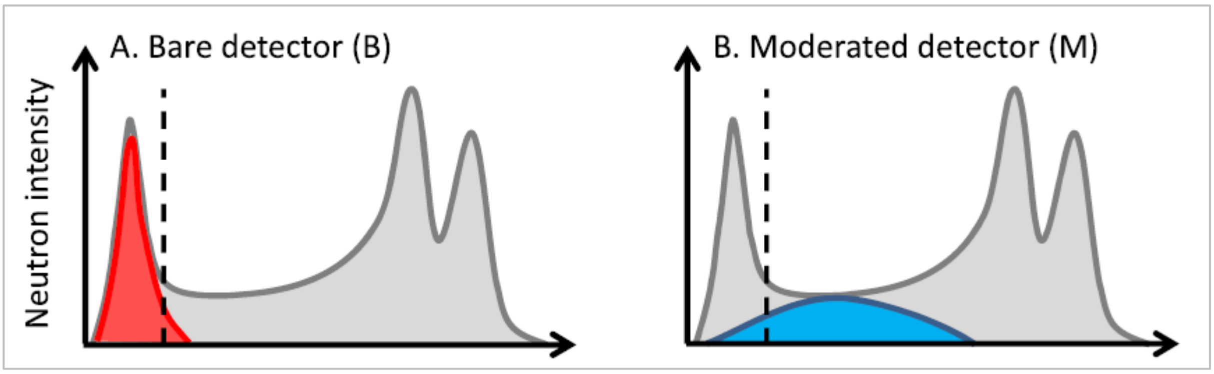

Figure 7.2 Sampling of neutron energy spectra by bare and moderated detectors, from Andreasen et al. (2016). The dashed line represents 0.5eV.

Zreda et al (2012) suggest that the moderated tube is used to measure soil moisture and that the bare tube is potentially useful for water that is present above the land surface in snow, vegetation etc. COSMOS-UK prototype sites were equipped with both types of tubes; sites installed subsequently only have moderated tubes.

From the above there is an understanding, in principle at least, of how the intensity of cosmic ray derived neutrons measured at the Earth's surface is influenced by water contained within in soil. The processing of neutron counts to derive volumetric water content has been described in, for example, Evans et al. (2016) and what follows is a brief overview.

Firstly, correction factors are applied to the recorded neutron counts to account for variations in background cosmic ray intensity (as measured by a high altitude reference site at Junfraujoch, Switzerland), altitude, atmospheric pressure and atmospheric water vapour. This adjusted number of counts is known as the 'corrected counts'.

There are currently three methods that can be used to derive water content from the corrected counts: (1) Site specific N_0 method, (2) universal calibration method (also known as hydrogen molar fraction (HMF) method), and (3) neutron transport modelling (e.g. MCNP, COSMIC, URANOS). These methods are described in Baatz et al. (2014) and Bogena et al. (2015). The first of these methods is the most straightforward to apply and as a consequence the most widely used. Baatz et al. (2014) conclude that all three methods estimate soil water content with acceptable errors when compared to estimates determined using soil sampling and laboratory analysis.

COSMOS-UK uses the first of these methods in which a *reference soil water content* is obtained from field calibration, see Franz (2012) and Zreda et al. (2012). This reference value is then used in combination with an equation relating corrected counts to soil water content (with parameters applicable for a generic silica soil matrix; see Desilets et al. (2010)), to calculate a site specific N_0 calibration coefficient. The COSMOS-UK procedure also follows the procedures in Zreda et al. (2012) and Franz et al. (2013) to account for the effects of lattice and bound water (structural water associated with clay minerals in the soil) and soil organic carbon (a minor constituent of mineral soils, but the major constituent of peat soils).

Even within the site specific N_0 method there is scope to vary the implementation. Through time changes have been made to the method used by COSMOS-UK, to improve the overall quality of the data set.

7.3 Averaging to reduce noise in soil moisture

As noted in Evans et al. (2016), although the counts are recorded by COSMOS-UK on an hourly basis "the noise associated with the cosmic-ray technique … (in) UK conditions" means that averaging at 6 hours or 24 hours is recommended. The UK conditions referred to here are the general wetness of the UK soils, low altitude and high soil organic carbon at particular sites, which reduce the number of neutron counts; from the background above it will be noted that this is the basis of the measurement technique but the wetness of the UK soils was outside the range observed in the USA where the method originated. In practice processing on an hourly basis can lead to values of soil moisture of greater than 100% or less than 0%, hence the necessity to censor or average values at some stage in the processing.

The COSMOS-UK recommendation is that generally the hourly data are too noisy to be useful and that daily data should be used. As with the processing from counts to water content, there are many ways in which an average value can be obtained.

The COSMOS-UK method is to derive an average number of hourly counts for the day and use this to derive the daily VWC; this method results in only a tiny percentage of values greater than 100% and no negative values.

However, this data set can still contain values that are unbelievably high, either through noise, or because water detected by the CRNS is incorrectly interpreted as soil moisture when it is in fact above the soil surface. This can occur during snow events, and a correction is applied to the daily VWC when a snow day is detected (see Section 7.5).

7.4 The CRNS footprint

A key characteristic of the CRNS method is its large footprint (perhaps up to 300m from the sensor), and under dry conditions deep penetration below the soil surface

(0.76m given by Zreda et al. (2008) for dry soils in the USA). However, these characteristics are not constant but vary with soil moisture. As with the calculation of VWC there have been developments in how best to estimate these footprint characteristics, and indeed how this feeds back into the site calibration required by the N_0 method. Footprint characteristics are based on the volume of soil from which 86% of the detected neutrons originate.

COSMOS-UK now uses recommendations of Köhli et al. (2015) regarding calibration and estimating sensing depth. They conclude that the source of neutrons sampled by the sensor is dependent on both water content and distance from the sensor, and provide a means to estimate the decreasing penetration depth with increasing distance from the sensor.

COSMOS-UK now uses this method to provide depth values (known as D86) at six selected distances from the CRNS. The distances selected correspond with the four calibration soil sampling distances (1, 5, 25 and 75 m) along with the anticipated minimum (150 m) and maximum (200 m) footprint radii calculated for typical wet and dry UK conditions. A comparison of the effective depth from Franz et al. (2013) and the D86 values from Köhli et al. (2015) is presented below for the COSMOS-UK site at Rothamsted.

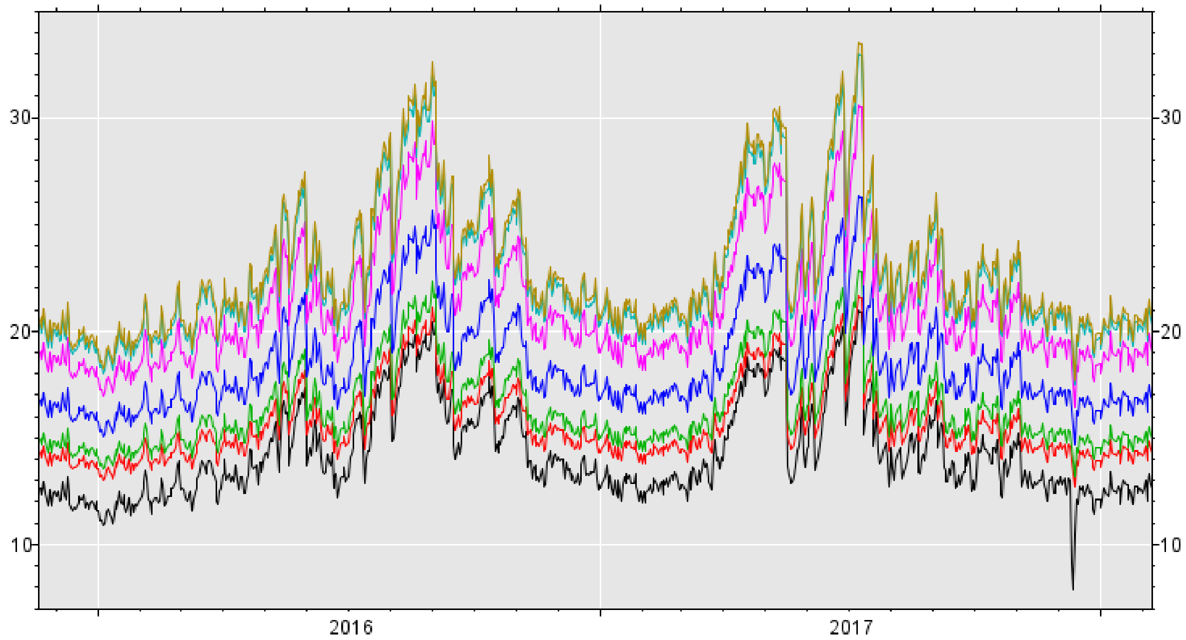

Figure 7.3 Variation in effective depth at Rothamsted: black is effective depth others are D86 from top to bottom at 1m (brown), 5m (cyan), 25m (pink), 75m (blue), 150m (green) and 200m (red) from the sensor.

COSMOS-UK has made the somewhat arbitrary decision to use the 75m D86 (blue in the above figure) as a single indicator to illustrate the variation of the sensor footprint penetration depth with soil wetness.

7.5 Estimation of Snow Water Equivalent using CRNS and SnowFox counts

The neutron count rates detected by both the CRNS and SnowFox are sensitive to presence of water held in a snow pack. Because of this, both sensors can be used to estimate the snow water equivalent (SWE), while the VWC calculated from the CRNS during days with snow cover will typically be overestimated.

For a given day, the presence or absence of snow cover is first established using the average value of the albedo between the times of 10:00 and 14:00 GMT. A period of snow cover is deemed to begin if average albedo exceeds a threshold of 50%, and end when it falls below 35%. These threshold values where chosen with the aim of only classifying a day as a snow day if a potentially detectable amount of snow is present (e.g. at least 2-3mm of SWE).

To estimate the SWE, for both CRNS and SnowFox sensors, the count rate from before the start of the snow event is used to estimate a count rate for snow-free conditions. Then the difference between the measured daily average count rate and the snow-free estimate are used to calculate the SWE. The method is described in full as Method 1 in Wallbank et al. (2020).

Wallbank et al. (2020) also used the method of triple collocation to compare neutron based SWE estimates with alternatives, either based on measurements from the snow depth sensors, or based on a modelled SWE estimate using the temperature and precipitation. Importantly, the SnowFox SWE estimate was found to be biased compared to the other estimates by a factor of approximately 1.7. This bias has not been corrected, primarily because there remains the possibility of at least some bias in the other SWE estimates. Because of this it is suggested that SnowFox SWE estimates are divided by 1.7 before being used. Representative uncertainties (one standard error) of less than 4mm were obtained for both the CRNS and SnowFox SWE estimates. The uncertainty should be expected to, (i) increase as the event progresses, (ii) show some increase for larger snow depth, and (iii), for the CRNS only, increase if the underlying soil moisture is high. Also note that the footprint of the SnowFox (e.g. <1m) is much smaller than that of the CRNS making this estimate sensitive to inhomogeneity in the snowpack. Finally, significant forest cover within the CRNS footprint (e.g. at the sites Alice Holt, Gisburn Forest, Harwood Forest, and Wytham Woods) is also expected to complicate CRNS based estimates of SWE.

7.6 Introduction of revised processing

It will be appreciated that various alternative methods can be adopted to derive the VWC and D86 from the counts recorded by the CRNS, at hourly and daily intervals, and that the preferred methods of doing so will change with time.

It is therefore likely that there will be further changes to the processing of these data. Whenever such changes are made to the processing method they are applied to the entire data set, i.e. at all sites back to the start of operation, to ensure consistency within and between each data series. In some instances calculations using legacy methods continue in the background.

7.7 A comparison with data from TDT sensors

The signal from the CRNS is noisy which is caused by the variability in the number of neutrons counted by the sensor tube in the monitoring interval; there's a lot of randomness in the process generating these neutrons. A bigger tube, or using several tubes at the same site would reduce the noise but, obviously, be more expensive.

The CRNS data (counts) are logged at 30 minute intervals but most of the processing starts with hourly accumulations. Without going into the details of the processing hourly VWC data are routinely derived, as a starting point for further processing.

Below is a plot of some data from the COSMOS-UK site at Rothamsted for September and October 2016 (Figure 7.4). The black crosses are the one hourly VWC from the CRNS; the noise is obvious. Simple ways of trying to identify the signal from the noise are to average the data either using a running mean or over a fixed period. For this period the running mean data clearly still contain some noise; the daily data look noise-free but for other times at other sites this is not the case.

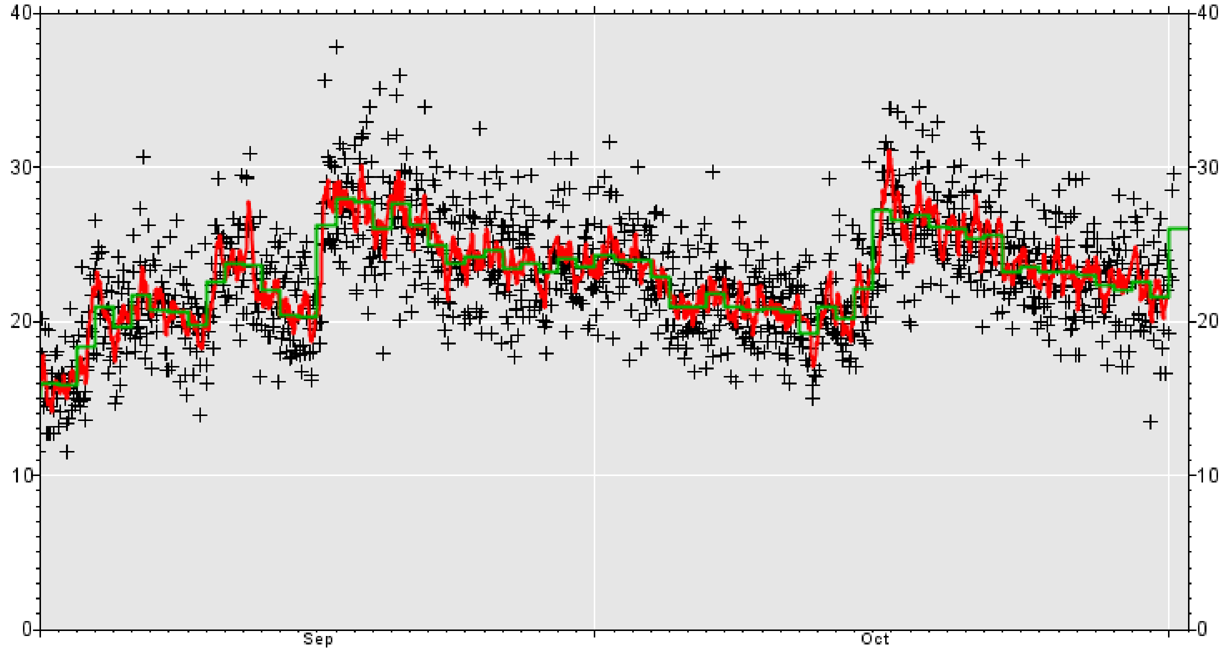

Figure 7.4 A comparison of VWC data from the CRNS: hourly (black), 7-hour moving average (red) and daily (green).

At COSMOS-UK sites we have other instruments also measuring VWC. These sample small volumes of soil but are far less noisy. The data from the two TDT probes are generally reliable; these probes are at about 10cm depth and are approximately 2m apart. The 30 minute data from the two TDTs are shown with the hourly data from the CRNS in Figure 7.5 for the same site and period as in Figure 7.4.

Firstly, it's clear that the data from the TDT probes are far less noisy that those from the CRNS, although some averaging is probably still justified. Secondly the two TDTs are in good general agreement as over this period they agree to with a few percent of VWC. It is not certain that these differences are genuine differences in soil moisture around the sensor and not the result of differences between the sensors. It is however reasonable to assume that the differences are caused by differences in actual VWC around the sensor. If they are genuine then it is the case that the differences vary through time, i.e. generally the red line is above the green line, but this is not the case for the second half of September. And at the beginning of October there is a small increase in VWC in the red data, but not the green data; there is perhaps a similar event around September 10 which causes the red and green lines to diverge slightly.

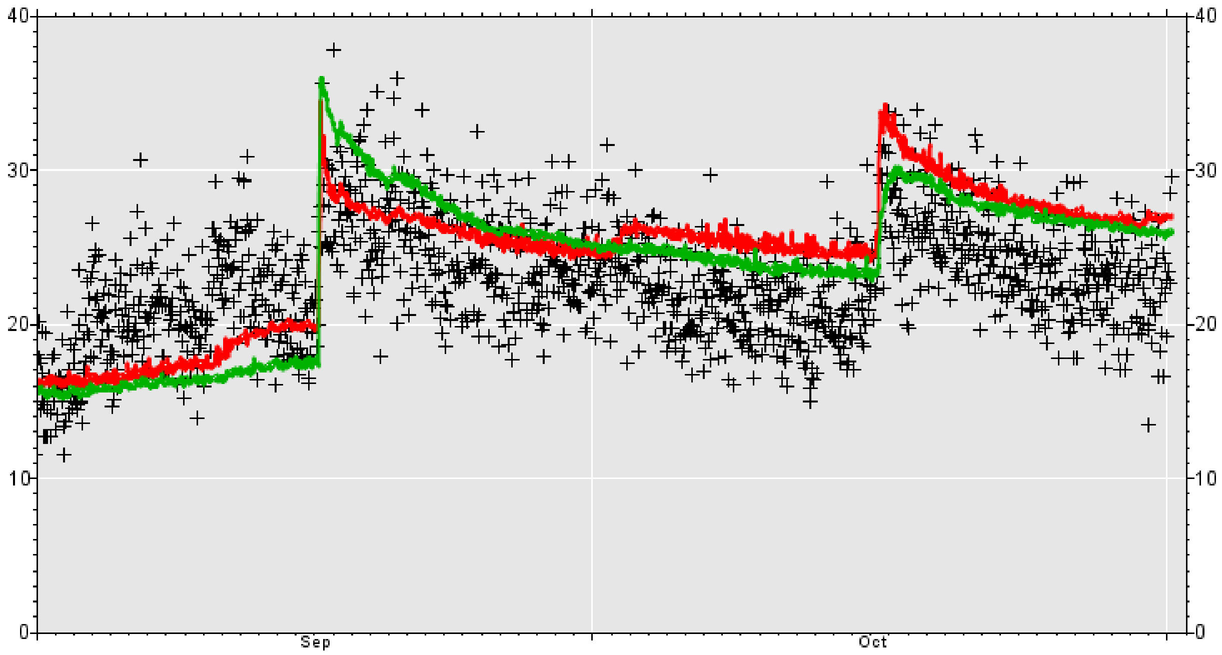

Figure 7.5 A comparison of hourly data from the CRNS (black), with 30 minute data from two TDT sensors (red and green).

A third point to be noted from Figure 7.5 is that the CRNS and TDT data are in broad agreement, but sometimes the TDTs are at the low end of the variability of the CRNS data (1-15 September), in the centre of the CRNS data (20-30 September), and sometimes at the top end of the CRNS data (8-15 October). One explanation of this is that the CRNS data are not from small volumes of soil around the sensor but sample a much larger volume of soil around the sensor.

It is partly because of the high spatial variability of soil moisture that the CRNS is appealing as a measurement technique (there are other reasons too). The CRNS has a large footprint possibly several hundred metres in diameter, and it also samples water above, at, and below the surface down possibly to 20cm or deeper if the soil is dry, as discussed in Sections 7.4 and 7.6.

Figure 7.6 compares the TDT data with the daily mean data from the CRNS. There are periods of close agreement and periods of divergence. Possible explanations include: different sampling volumes; different sampling periods, differences between measurement techniques; noise in the data.

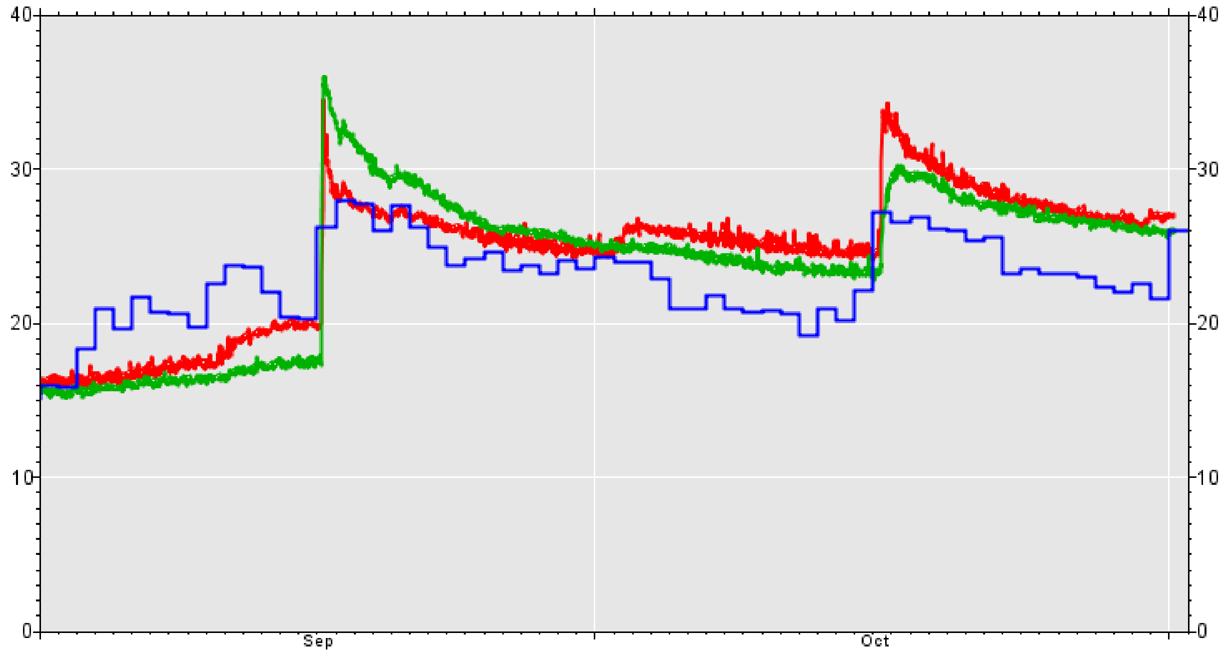

Figure 7.6 A comparison daily VWC data from the CRNS (blue) with 30 minute data from the two TDTs (red and green).

Thus far analysis of the COSMOS-UK have been largely subjective in nature, as in this note. Comprehensive objective analysis will follow based on all COSMOS-UK sites, longer periods of record, data from a “test and validation” site, and published developments from other users of CRNS technology.

It is anticipated that a key output from these analyses will be information and guidance about the spatial and temporal resolution of VWC data from the CRNS, including corrections for water measured by the sensor but which is not in the soil (e.g. surface ponding and in vegetation). At this stage it seems this may vary between sites, soil type and land use.

8. Acknowledgements

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Agroco Farms

Bangor University

Berks, Bucks and Oxon Wildlife Trust (BBOWT)

British Geological Survey (BGS)

Cheshire Wildlife Trust

College of Agriculture, Food and Rural Enterprise

Defence Science and Technology Laboratory

Euston Estate

Farmcare

Forest Research

Game and Wildlife Conservation Trust

G's Naturally Fresh

Hadlow College

James Hutton Institute (JHI)

Met Office

Morley Agricultural Foundation

The National Trust

Natural England

Newcastle University

Redhill Farm Estate

Rothamsted Research

Scotland's Rural College (SRUC)

Sheepdrove Organic Farm

Surrey Wildlife Trust

Sweet Lamb Complex

University of Glasgow

University of Leeds
University of Lincoln
The University of Nottingham
Waddesdon Estate
Writtle University College

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Appendix A Expanded Site List

SITE_NAME	SITE_ID	START DATE	END DATE	CALIBRATED	EAST	NORTH	LATITUDE	LONGITUDE	ALTITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER (%)	LAND COVER
ALICE HOLT	ALIC1	06-Mar-15		Y	479950	139985	51.154	-0.858	80	Mineral soil	0.85	8.4	Broadleaf woodland
BALRUDDERY	BALRD	16-May-14		Y	331643	732797	56.482	-3.111	130	Mineral soil	1.34	4.6	Arable and horticulture
BICKLEY HALL	BICKL	28-Jan-15		Y	353112	347903	53.026	-2.701	78	Mineral soil	1.31	4.0	Grassland
BUNNY PARK	BUNNY	27-Jan-15		Y	458884	329606	52.861	-1.127	39	Mineral soil	1.55	3.2	Arable and horticulture
CARDINGTON	CARDT	24-Jun-15		Y	507991	246422	52.106	-0.425	29	Mineral soil	1.14	8.0	Improved grassland
CHIMNEY MEADOWS	CHIMN	02-Oct-13		Y	436113	201160	51.708	-1.479	65	Calcareous mineral soil	1.36	5.4	Acid grassland
CHOBHAM COMMON	CHOBH	24-Feb-15		Y	497737	164137	51.368	-0.597	47	Organic soil over mineral soil	0.9	6.2	Heather grassland
COCHNO	COCHN	23-Aug-17		Y	249980	674651	55.941	-4.404	168	Mineral soil	0.83	13.6	Improved grassland
COCKLE PARK	COCLP	21-Nov-14		Y	419544	591351	55.216	-1.694	87	Mineral soil	1.21	6.6	Arable and horticulture
CRICHTON	CRICH	02-Dec-14		Y	298903	573164	55.043	-3.583	42	Mineral soil	1.15	9.0	Improved grassland
CWM GARW	CGARW	29-Jun-16		Y	211350	231661	51.951	-4.747	299	Mineral soil	0.96	9.6	Improved grassland
EASTER BUSH	EASTB	14-Aug-14		Y	324557	664463	55.867	-3.207	208	Mineral soil	1.1	6.6	Improved grassland
ELMSETT	ELMST	11-Aug-16		Y	605122	248260	52.095	0.993	76	Calcareous mineral soil	1.26	4.4	Arable and horticulture
EUSTON	EUSTN	31-Mar-16		Y	589619	279776	52.336	0.796	18	Mineral soil	1.27	5.8	Improved grassland
FINCHAM	FINCH	07-Jun-17		Y	570068	305182	52.618	0.511	15	Calcareous mineral soil	1.33	4.0	Arable and horticulture
FIVEMILETOWN	FIVET	26-Jun-18		Y	55851	502136	54.299	-7.292	174	Mineral soil			
GISBURN FOREST	GISBN	15-Aug-14		Y	374899	458714	54.024	-2.385	246	Mineral soil	0.82	12.2	Coniferous woodland
GLENSAUGH	GLENS	14-May-14		Y	365870	780483	56.914	-2.562	399	Organic soil	0.44	40.6	Heather
GLENWHERRY	GLENW	15-Jun-16		Y	142962	556604	54.838	-6.005	274	Organic soil	0.54	30.6	Improved grassland
HADLOW	HADLW	27-Oct-16		Y	562097	150263	51.229	0.320	33	Mineral soil	1.22	6.2	Improved grassland
HARTWOOD HOME	HARTW	20-May-14		Y	285476	658957	55.810	-3.829	225	Mineral soil	1.02	8.6	Improved grassland
HARWOOD FOREST	HARWD	20-May-15		Y	398505	591355	55.216	-2.024	300	Organic soil	0.33	60.0	Coniferous forest

SITE_NAME	SITE_ID	START DATE	END DATE	CALIBRATED	EAST	NORTH	LATITUDE	LONGITUDE	ALTITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER (%)	LAND COVER
HENFAES FARM	HENFS	17-Dec-15		Y	265750	371709	53.225	-4.012	287	Mineral soil	0.97	15.4	Acid grassland
HEYTESBURY	HYBRY	16-Aug-17		Y	394535	144856	51.203	-2.080	166	Calcareous mineral soil	0.88	13.2	Arable and horticulture
HILLSBOROUGH	HILLB	14-Jun-16		Y	136345	513358	54.447	-6.068	146	Mineral soil	1.15	8.4	Improved grassland
HOLLIN HILL	HOLLN	25-Mar-14		Y	468121	468811	54.111	-0.960	82	Mineral soil	1.06	6.4	Improved grassland
HOLME LACY	HLACY	11-Apr-18		Y	354663	236036	50.021	-2.662	76	Mineral soil	1.24	4.4	Improved grassland
LODDINGTON	LODTN	26-Apr-16		Y	479565	302022	52.610	-0.826	186	Mineral soil	1.16	7.2	Arable and horticulture
LULLINGTON HEATH	LULLN	16-Dec-14		Y	554365	101634	50.794	0.189	119	Calcareous mineral soil	0.90	8.6	Heather grassland
MOOR HOUSE	MOORH	04-Dec-14		Y	369920	529470	54.659	-2.468	565	Mineral soil	0.76	15.2	Heather grassland
MORLEY	MORLY	14-May-14		Y	605826	298803	52.548	1.034	55	Mineral soil	1.53	3.4	Acid grassland
MORETON MORRELL	MOREM	15-Nov-18		Y	429959	255776	52.199	-1.563	53	Mineral soil	1.22	7.00	Arable and horticulture
NORTH WYKE	NWYKE	16-Oct-14		Y	265707	98832	50.773	-3.906	181	Mineral soil	1.12	7.4	Improved grassland
PLYNLIMON	PLYNL	05-Nov-14		Y	280322	285397	52.453	-3.763	542	Organic soil	0.62	19.6	Improved grassland
PORTON DOWN	PORTN	18-Dec-14		Y	422406	135670	51.120	-1.681	146	Calcareous mineral soil	0.97	9.8	Acid grassland
REDHILL	REDHL	18-Feb-16		Y	569577	154326	51.263	0.429	91	Calcareous mineral soil	1.26	4.8	Arable and horticulture
REDMERE	RDMER	11-Feb-15	20-Sep-18	Y	564639	285846	52.446	0.421	3	Organic soil	0.60	47.6	Orchard
RISEHOLME	RISEH	04-May-16		Y	498425	374863	53.262	-0.526	53	Calcareous mineral soil	1.27	6.4	Improved grassland
ROTHAMSTED	ROTHD	25-Jul-14		Y	511887	214048	51.814	-0.378	131	Mineral soil	1.33	4.2	Arable and horticulture
SHEEPDROVE	SHEEP	24-Oct-13		Y	436039	181395	51.530	-1.482	170	Mineral soil	1.04	11.8	Improved grassland
SOURHOPE	SOURH	09-Dec-14		Y	385562	620698	55.480	-2.230	487	Mineral soil	0.65	17.2	Improved grassland
SPEN FARM	SPENF	23-Nov-16		Y	444887	441620	53.869	-1.319	57	Calcareous mineral soil	1.41	3.8	Arable and horticulture
STIPERSTONES	STIPS	06-Nov-14		Y	336086	298579	52.581	-2.945	432	Organic soil	0.62	20.8	Arable and horticulture
STOUGHTON	STGHT	18-Aug-15		Y	464641	300854	52.602	-1.047	130	Mineral soil	1.33	5.4	Grassland
SYDLING	SYDLG	27-Nov-18		Y	362917	103337	50.828	-2.527	249	Mineral soil	1.17	7.0	Acid grassland
TADHAM MOOR	TADHM	14-Oct-14		Y	342199	145692	51.208	-2.829	7	Organic soil	0.32	62.8	Grassland
THE LIZARD	LIZRD	17-Oct-14		Y	170940	19648	50.033	-5.200	85	Mineral soil	0.95	11.6	Grassland
WADDESDON	WADDN	04-Nov-13		Y	472548	216176	51.839	-0.948	98	Mineral soil	1.11	6.8	Improved grassland

SITE_NAME	SITE_ID	START DATE	END DATE	CALIBRATED	EAST	NORTH	LATITUDE	LONGITUDE	ALTITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER (%)	LAND COVER
WIMPOLE	WIMPL	10-Sep-19		Y	533951	250013	52.132	-0.044	30	Mineral soil	1.22	7.0	Arable and horticulture
WRITTLE	WRTTL	04-Jul-17		Y	567062	206687	51.734	0.418	44	Mineral soil	1.26	7.0	Improved grassland
WYTHAM WOODS	WYTH1	21-Nov-13	01-Oct-16	Y	445738	208942	51.777	-1.338	109	Mineral soil	1.05	5.6	Broadleaf woodland

Appendix B Period of record data availability

The figure below is an indication of data availability and completeness for the period of record for all sites. Availability shown is from date of site installation until 31/12/2018 i.e. sites that were installed mid-year will show data availability between the date of installation and the end of the calendar year.

Note that the data from the IMKO (if installed) are not included within the “soil” group.

Table B.1 Variable groups used to report data availability/completeness

GROUP	VARIABLES
MET	PRECIP_LEVEL2 Q_LEVEL2 RH_LEVEL2 TA_LEVEL2 PA_LEVEL2 LWIN_LEVEL2 LWOUT_LEVEL2 SWIN_LEVEL2 SWOUT_LEVEL2 WD_LEVEL2 WS_LEVEL2
SOIL	G1_LEVEL2 G2_LEVEL2 STP_TSOIL2_LEVEL2 STP_TSOIL5_LEVEL2 STP_TSOIL10_LEVEL2 STP_TSOIL20_LEVEL2 STP_TSOIL50_LEVEL2 TDT1_TSOIL_LEVEL2 TDT2_TSOIL_LEVEL2 TDT1_VWC_LEVEL2 TDT2_VWC_LEVEL2
VWC	COSMOS_VWC *NB: Uncalibrated sites will show ‘No data’ for this group.*

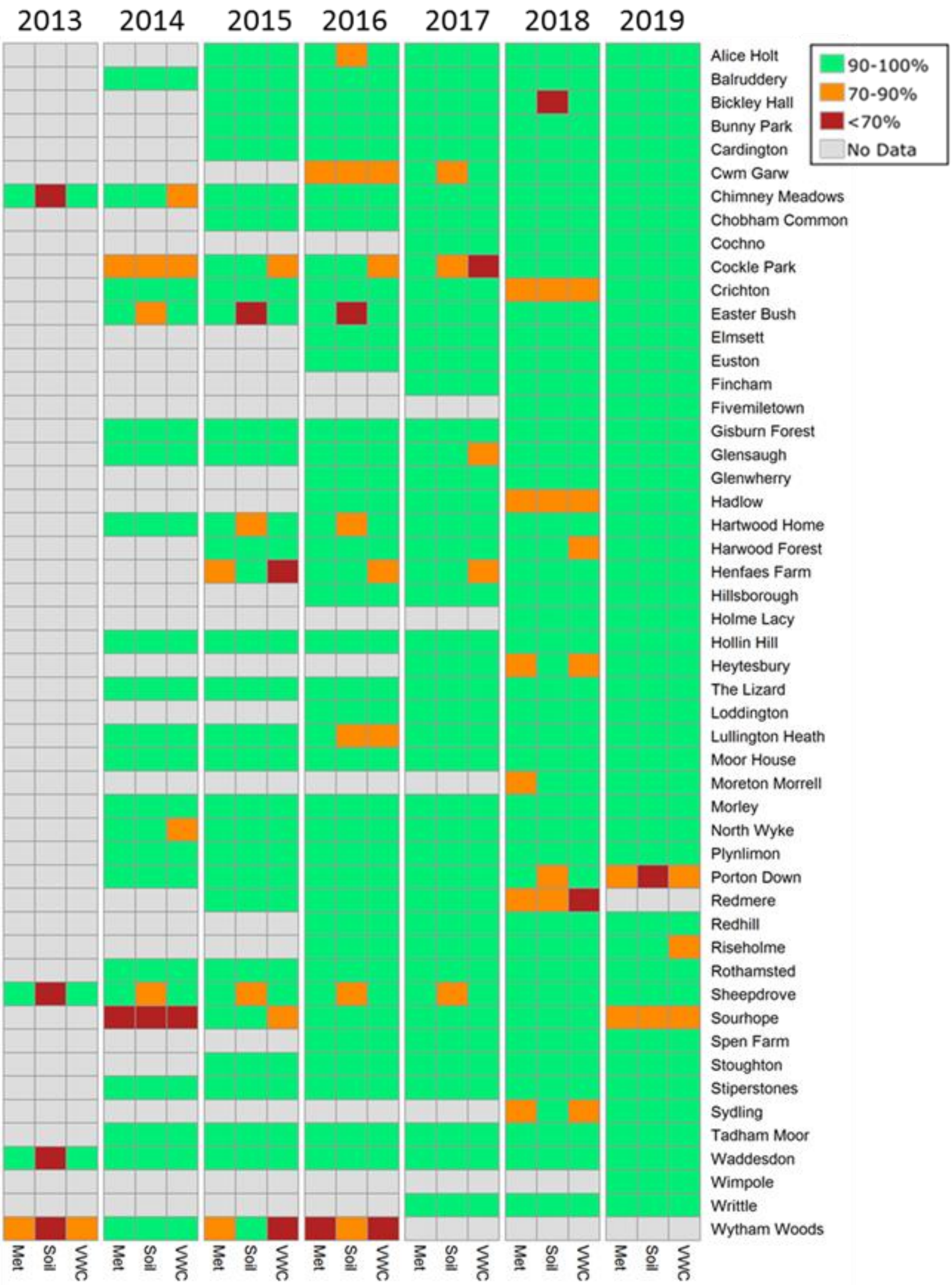


Figure B.1 Data availability/completeness for period of record for all sites. Cells indicate the percentage of 30 minute (or 1 hour for VWC) values received for the groups of variables compared to the number expected in the given year.

Appendix C Phenocam images

The two wide-angle lens cameras are intended to capture qualitative information about the environment around the COSMOS-UK site. Of particular interest are seasonal changes in vegetation since these will have an influence on soil moisture (i.e. the state and changes in vegetation influence water uptake by the vegetation and depletion of soil moisture via evapo-transpiration) and the counts recorded by cosmic-ray sensor (i.e. the sensor detects hydrogen ions in the vegetation as well as in the soil). The study of these seasonal changes is called phenology – hence the shorthand name for the cameras.

The phenocams are programmed to record five images per day and are captured as image pairs as in the example below (Figure C.1). The cameras are directed due south (left hand image) and due north.

Note that not all images are successfully captured and stored, so images may be missing or incomplete. Images may also be of poor quality, for example because of water or dirt on the camera lens.

The resolution of the image is either 1600x600 pixels or 2560x960 pixels. The higher resolution images are achieved following a switch in modem introduced at new sites from 2017, and subsequently being rolled out to all sites.

Figure C.1 Example pair of phenocam images.

In the top right hand corner of the image is a date and time stamp, so this image was apparently taken at 14:20:03 on 31-05-2015: nothing in the image indicates the site from which it comes.

The image is transferred from the camera to the data logger which creates an image file timestamped with the current data logger date and time (at the moment that the image is received by the data logger, some minutes after the image was taken by the camera).

In this case, the telemetered filename would have been:

BALRD_1517.jpg [with a timestamp of 31-05-2015 13:42 GMT]

This timestamp information (unchanged, and in GMT/UTC) is written into the filename of the image by a computer script which renames the file only after it is received by the telemetry server at UKCEH. The final file name that includes the site name and the date and time, has the format:

SITE_YYYYMMDD_HHMM_IDnnnn.jpg

Where,

SITE: COSMOS-UK Station Site Code (five upper case letters)

YYYY: 4 digit year

HH: hour (GMT/UTC)

MM: minutes

ID: 'ID' two fixed characters

nnnn = integer image number – this is NOT a fixed length string, and could range from n to nnnnnn. Note this is of little value to the user.

In the above example, the final filename is:

BALRD_20150531_1342_ID1517.jpg

The difference between the two date/time stamps is caused by (a) clock drift in the camera and (b) the transfer delay between camera and logger. The camera is intended for use in an environment in which it can regularly connect to the internet and synchronise with a time server, but within the COSMOS-UK instrument setup this cannot be achieved on most current systems; however, work is underway to provide a camera time server connection on selected upgraded sites. The data logger however is synchronised to internet time on a daily basis and is therefore reliable.

The important point here is to use the file name as being the approximate time at which the phenocam images were taken and not the time in the images themselves.

As well as recording changes in vegetation, the phenocam images can provide qualitative information about lying snow (Figure C.2) and standing water (Figures C.3 and C.4). The phenocam images can therefore be used as a means of screening to detect periods with unusual ground conditions, or as a way of investigating unusual data recorded by other COSMOS-UK instrumentation.

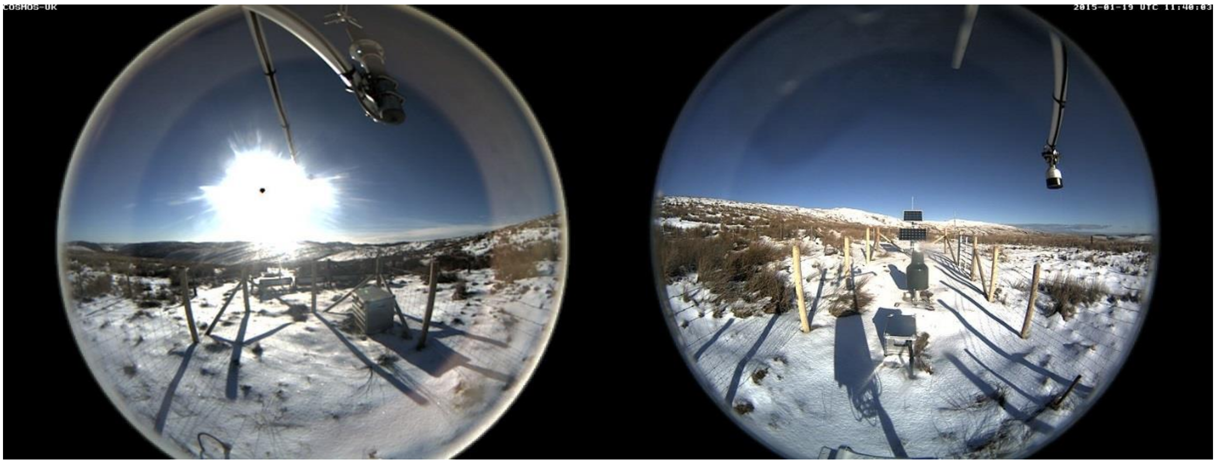


Figure C.2 Snow as recorded by the phenocam at Plynlimon. Note also the burning on the south facing image on the left caused by the camera pointing directly at the sun on a clear day.

Figure C.3 A rare, large but short lived, body of standing water at Easter Bush.

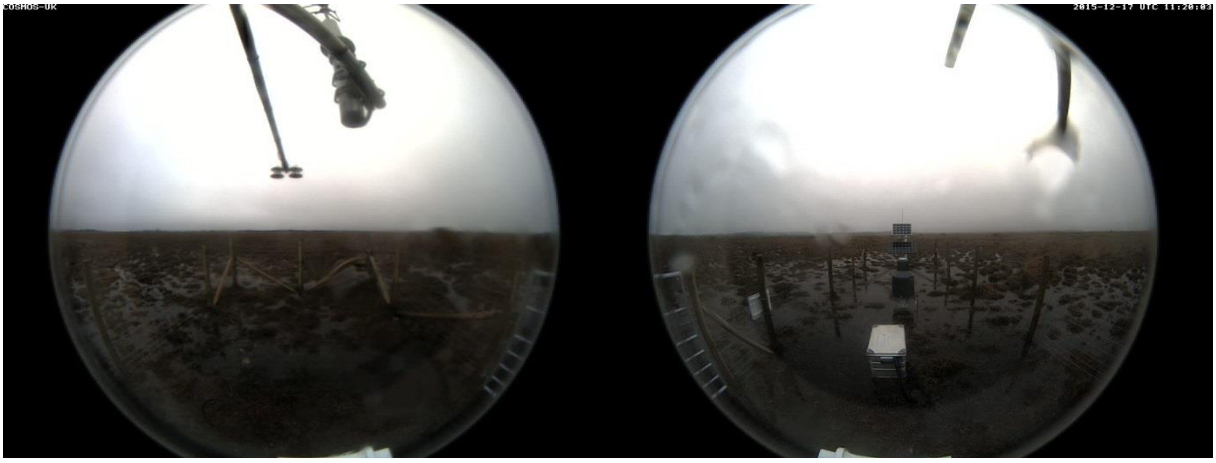


Figure C.4 Surface water ponding is not unusual after heavy rainfall at The Lizard which has a peaty top soil.

Appendix D Standard graphical retrievals

Several standard graphical retrievals are available, examples of which are presented in the following pages.

Figure D.1 Monthly summary of daily data

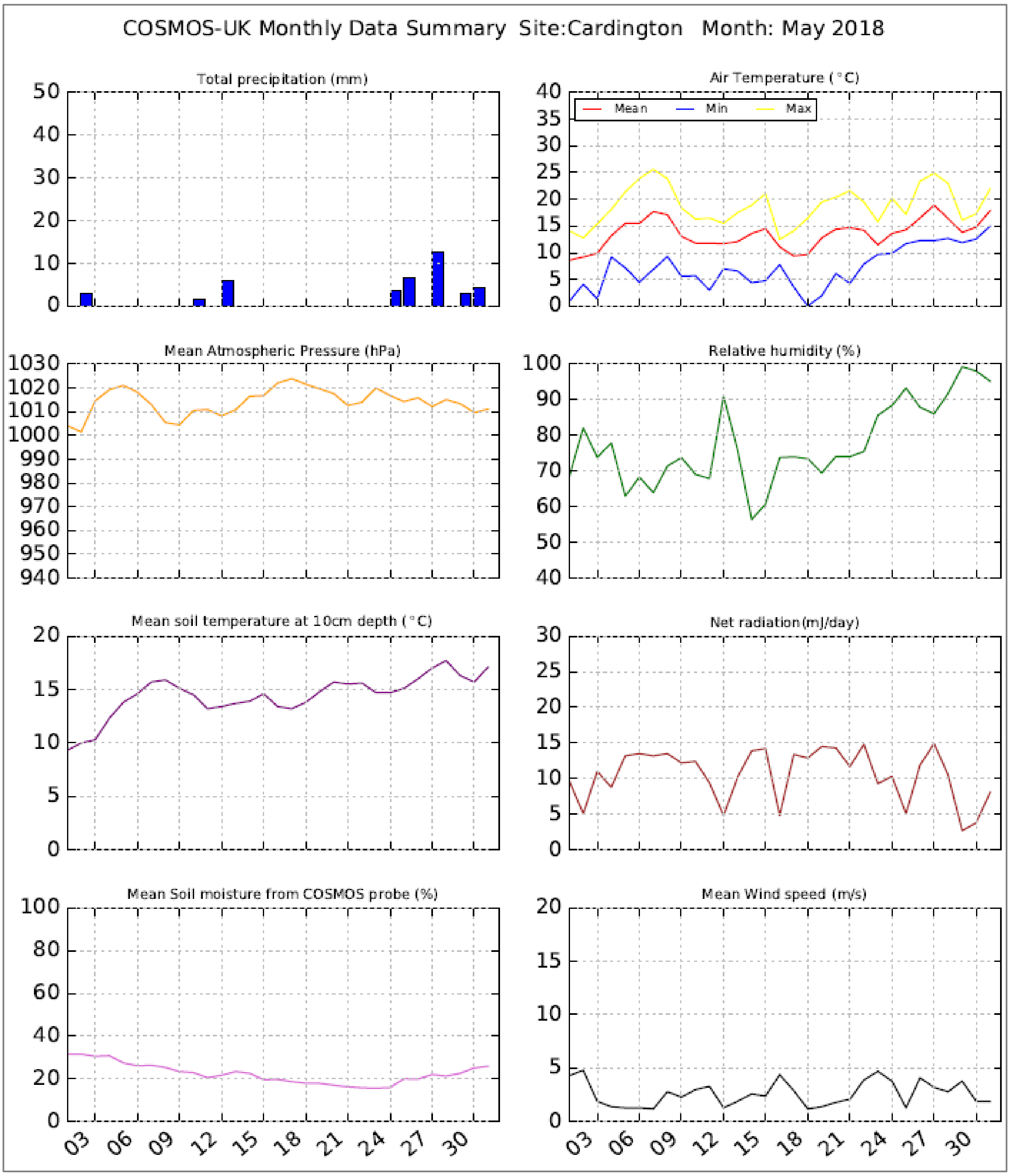
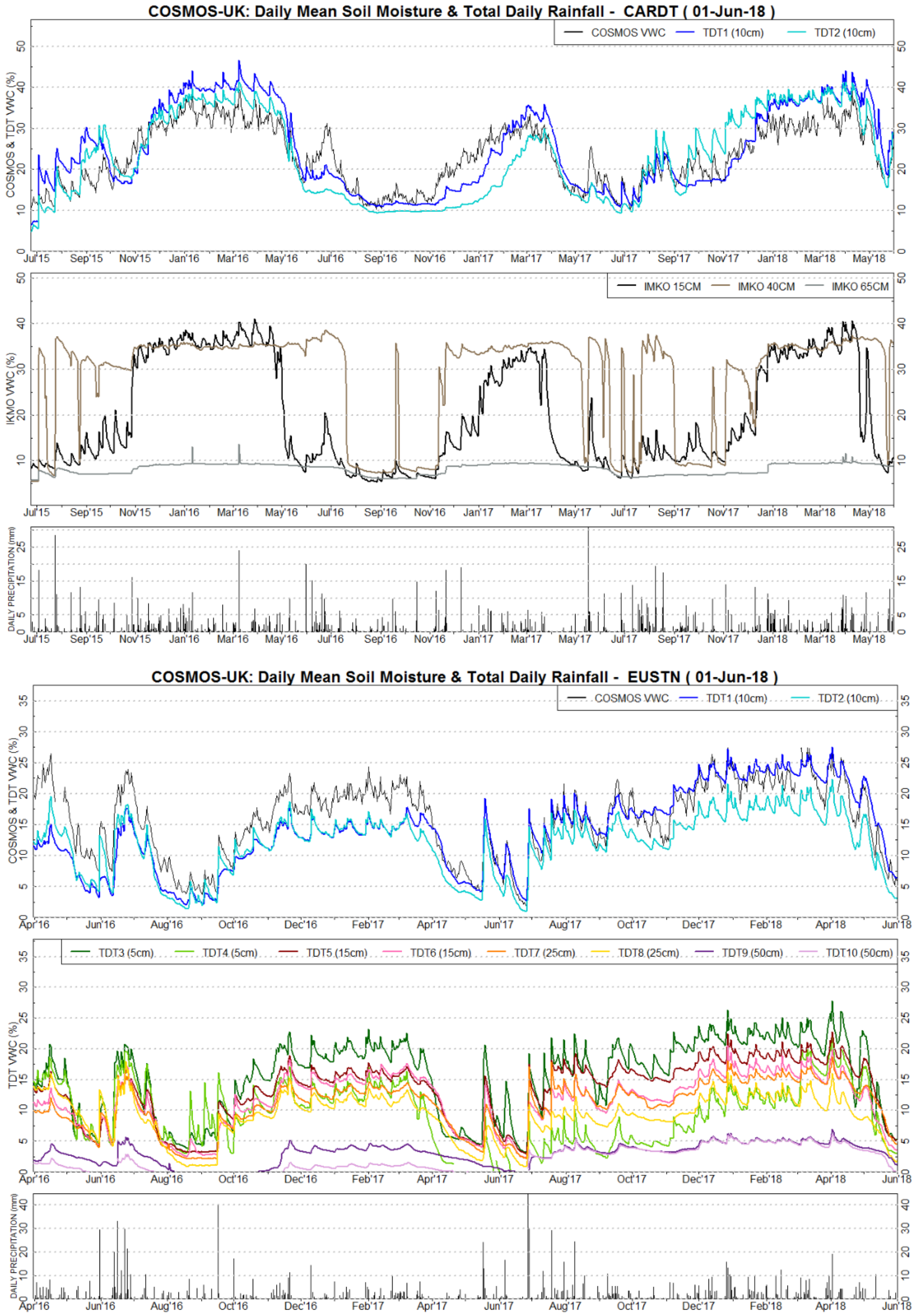


Figure D.2 Period of record soil moisture data from all COSMOS-UK instruments (top IMKO, bottom TDT array)



Quality control plots

Two rather content-dense quality control plots are routinely produced and archived; they contain data for 1 day and 10 days.

Figure D.3 Daily quality control plot

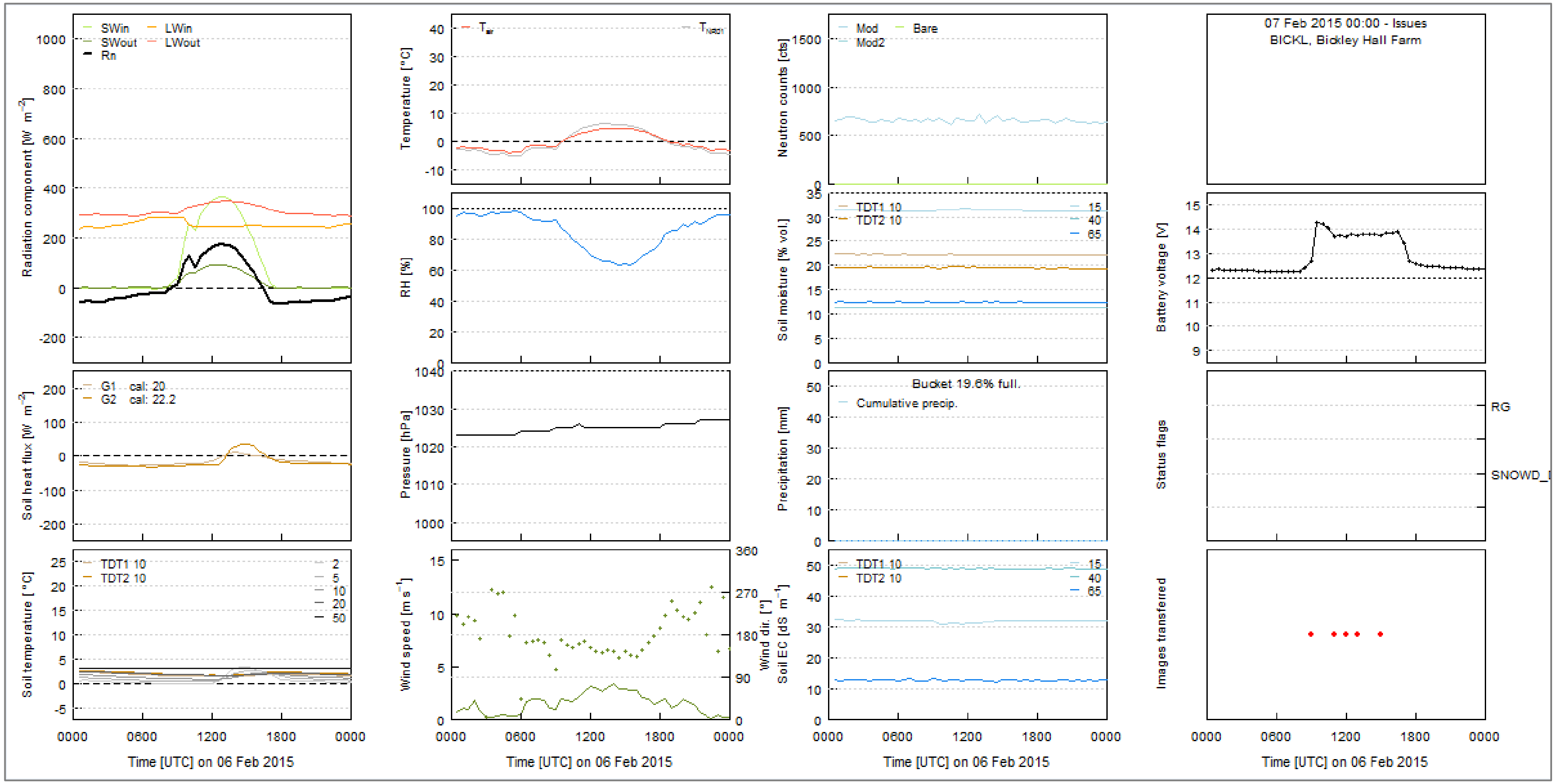
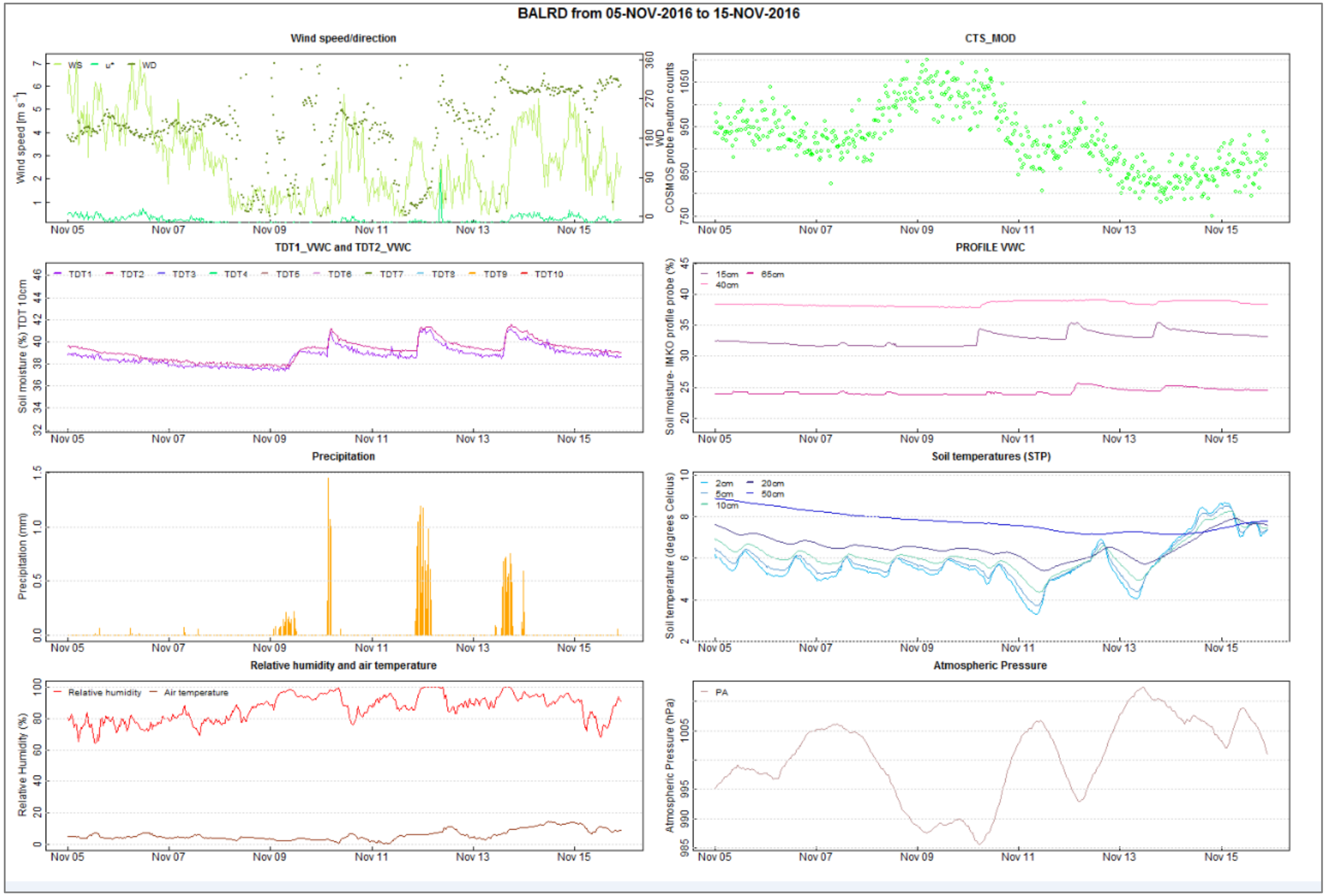


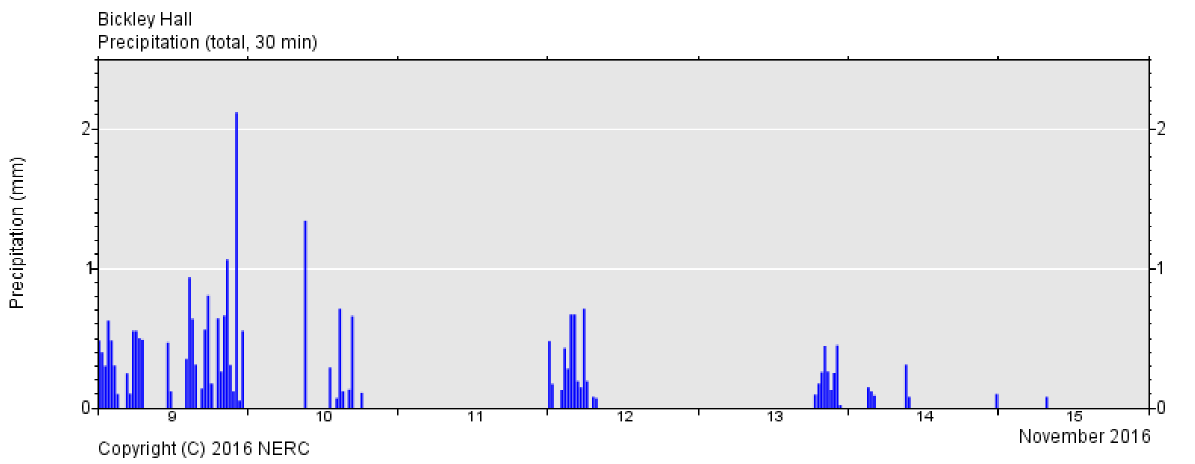
Figure D.4 10 Day quality control plot



Appendix E Embedding COSMOS-UK data plots in a website

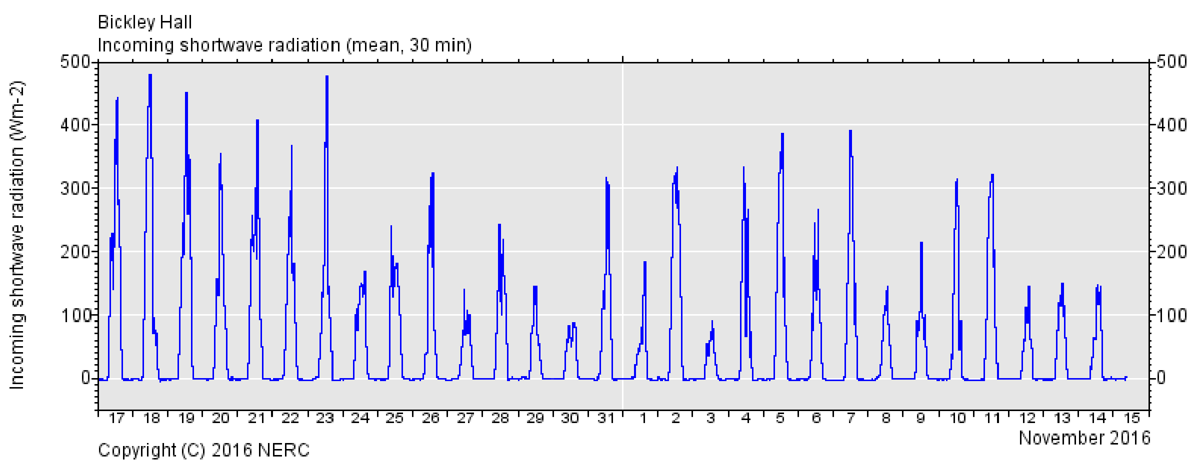
Users can use the url below to run an application that will produce a graph on a web page, in this case seven days of 30 minute rainfall are shown.

http://nrfaapps.ceh.ac.uk/nrfa/image/cosmos/graph.png?db-level=2&site=BICKL&parameter=PRECIPITATION_LEVEL2&days=7&w=800&h=300



This generates a picture of the graph which is displayed in the browser as a png (portable network graphics) file. Here's another example showing 30 days of short wave radiation, which corresponds with sunshine, i.e. it's easy to distinguish day from night and cloudy conditions from clear skies.

http://nrfaapps.ceh.ac.uk/nrfa/image/cosmos/graph.png?db-level=2&site=BICKL&parameter=SWIN_LEVEL2&days=30&w=800&h=300



If the detail within the data is finer than the resolution of the final image then data can be lost in the production of the png, and what's more this can happen in a random way. For COSMOS-UK plots this become apparent for rainfall which is displayed using a vertical bar.

There are six arguments passed to the app.

Argument	Function
db-level	Indicates QC level of data: should be specified as 2
site	Five letter code for the COSMOS-UK sites (see Appendix A)
Parameter code	See table below
days	Number of day up to the present day to display
w	Width of plot in pixels
h	Height of plot in pixels

Note that some combinations of values for days and width may result in a horizontal axis that has poor or unreadable labelling.

Parameter codes

Parameter	Code	Notes
Precipitation	PRECIPITATION_LEVEL2	
Air temperature	TA_LEVEL2	
Radiation	SWIN_LEVEL2 SWOUT_LEVEL2 LWIN_LEVEL2 LWOUT_LEVEL2	SWIN is short wave incoming radiation which is most like sunshine. Other radiation fluxes are SWOUT, LWIN, LWOUT, i.e. there are four fluxes: short and long wave, incoming and outgoing.
	RN_LEVEL2	Net radiation derived from above components
Relative humidity	RH_LEVEL2	
Absolute humidity	Q_LEVEL2	
Atmospheric pressure	PA_LEVEL2	This is at the altitude of the instrument i.e. not corrected to sea level.
Atmospheric pressure	MSLP	Derived parameter. Atmospheric pressure adjusted to mean sea level.
Wind speed	WS_LEVEL2	

Parameter	Code	Notes
Wind direction	WD_LEVEL2	This is in degrees from north i.e. 0 and 360 are both north. Data can look odd (jumpy) if the wind direction varies around northerly.
Components of wind direction	UX_LEVEL2 UY_LEVEL2 UZ_LEVEL2	
Soil temperature	STP_TSOILxx_LEVEL2	From soil temperature profile sensor: xx is the depth in cm and can be 2, 5, 10, 20 or 50
	TDTx_TSOIL_LEVEL2	From TDT sensor: x is the identifying number of the TDT. All sites have 2 TDTs at 10cm depth (TDT1 and TDT2). Those specified as having a TDT array in Table 3 have 10 TDTs (including the two at 10cm) installed between 5 and 50cm depth (TDT3-TDT10).
Soil heat flux	G1_LEVEL2 G2_LEVEL2	Heat flux from two sensors
Soil moisture	TDTx_VWC_LEVEL2	From TDT sensor: x is the identifying number of the TDT. All sites have 2 TDTs at 10cm depth (TDT1 and TDT2). Those specified as having a TDT array in Table 3 have 10 TDTs (including the two at 10cm) installed between 5 and 50cm depth (TDT3-TDT10).
	PROFILE_VWCxx_LEVEL2	From profile soil moisture sensor: xx is the depth in cm and can be 15,40 or 65
	COSMOS_VWC (hourly) COSMOS_VWC_1DAY (daily) COSMOS_VWC_1DAY_RAW (daily)	Derived from CRNS counts. Daily values are capped at saturation by default or limited to 100% (RAW).
D86 (depth to which 86% of the	D86_xxM (hourly) D86_xxM_1DAY (daily)	Derived from CRNS counts.

Parameter	Code	Notes
detected cosmic-ray neutrons had contact with constituents of the soil)		Where xx is distance from the CRNS probe in metres and can be 1, 5, 25, 75, 250 (suggested nominal distance 75m)
Corrected neutron counts from CRNS	CTS_MOD_CORR_LEVEL2	
Potential evaporation	PE_LEVEL2	Derived parameter
Albedo	ALBEDO_DAILY_MEAN	Derived parameter
Snow days	SNOW_DAY	Derived parameter: 1 on snow day.
Snow water equivalent	SWE_CRNS_1DAY	Derived parameter: only present on snow day.

What are the most recent data I can view?

Most of the COSMOS-UK data are recorded every 30 minutes: rainfall is recorded every minute but the above url access 30 minute data. These data are logged on site.

The data are transferred back to UKCEH at Wallingford using the mobile phone network. Every hour the site switches on its modem ready to receive a request for the data. Wallingford then tries to connect to the site: if this is successful the data are transferred, if not there will be repeated attempts to connect for 30 mins. If these fail then the data remain on the logger at the site and there will be a fresh attempt to access them during the following hour.

The data that are received at Wallingford are transferred from their raw format into a database, and then subject to quality control that creates a cleaned version of the data in which dubious data have been removed (this is termed LEVEL2 data). Both of these steps run automatically.

The graphing application provided by the url described above accesses the data from the data base when it is run, so there will always be a delay between data being recorded at a site and it being displayed in the graph. The length of the delay will depend on whether the automatic processes completed properly or not. The best case is for a time lag of under two hours, but it could be considerably longer.

Once the graph has been displayed on a web page it will not update itself but it can be refreshed manually (press F5). However, frequent refreshing could cause problems with the underpinning services as each refresh request generates a request through to the live COSMOS-UK data base.

Why are there sometimes gaps in the data?

Gaps can occur for a number of reasons, for example sensor faults, data logging issues, telecommunication problems, or a failure to pass quality control.

Some gaps may be infilled later, for example data may be retrieved by visiting the site if the gap has been caused by a communication problem.

But gaps can also be introduced later. This could happen if manual quality control, which happens after the automatic quality control, identifies an issue that was not trapped by the automatic algorithms.

How can this image be embedded in a web site?

The image can be embedded within a web page by using the following example html, within which the image url is included within the src attribute:

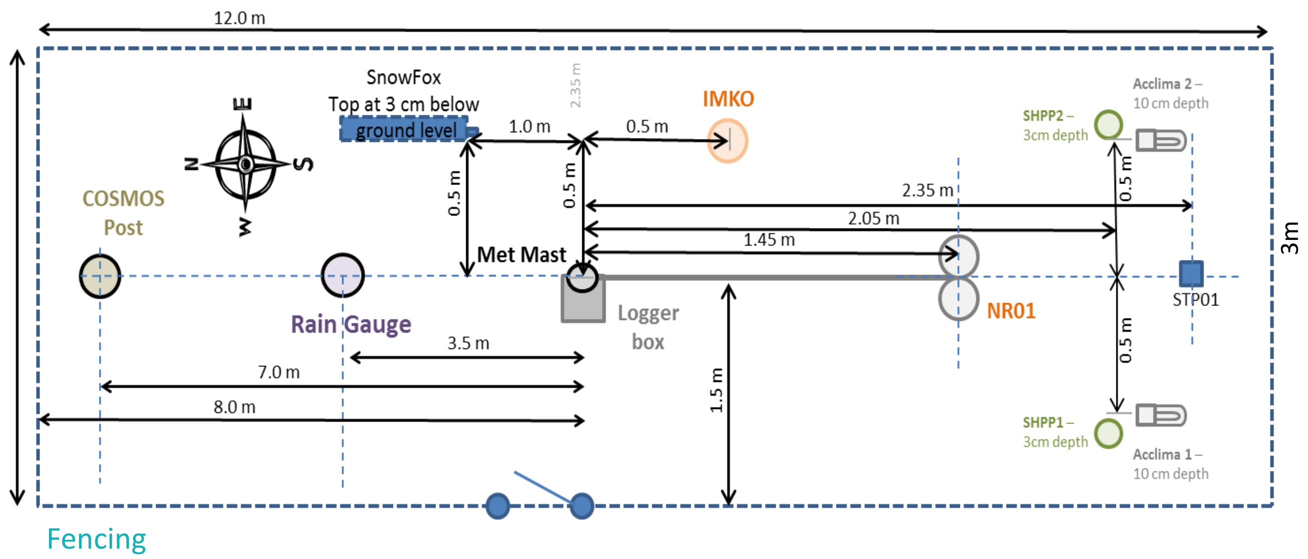
<img src="http://nrfaapps.ceh.ac.uk/nrfa/image/cosmos/graph.png?db-level=2&site=BICKL&parameter=PRECIPITATION_LEVEL2&days=7&w=800&h=300" width="800" height="300" alt="Rainfall graph" title="Graph of precipitation at Bickley Hall for the last 7 days">

Note that this image has its width and height set explicitly to those of the image requested from the application; if they are set differently the text within the image may appear distorted. The "alt" attribute sets the text that appears if the image is not available (or while the page is waiting for it to be produced). The "title" attribute sets the "tooltip" text that is visible when hovering over the graph.

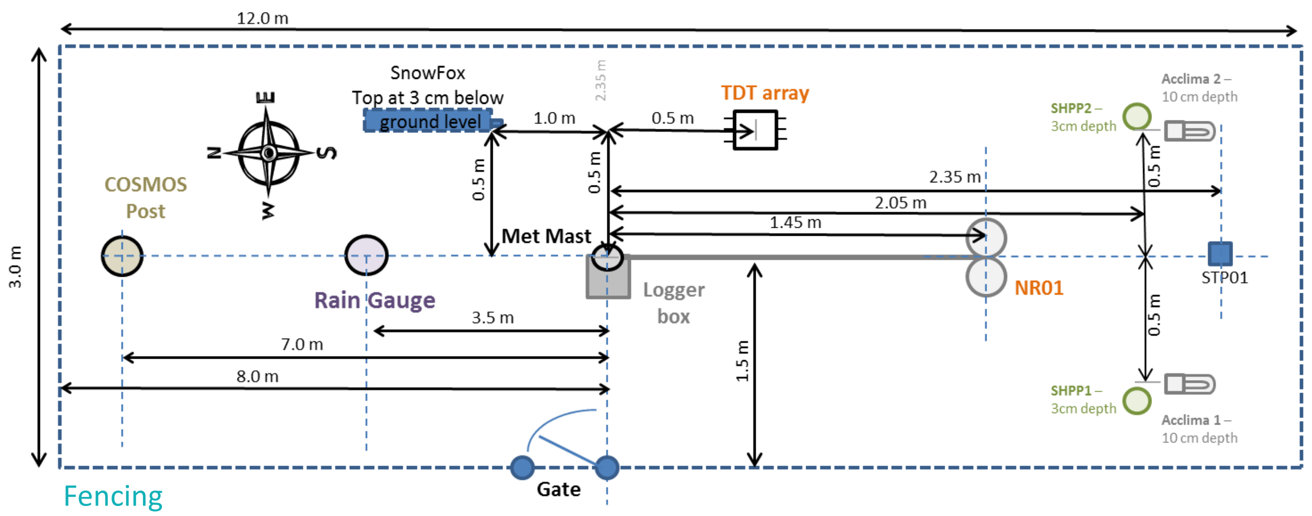
The html can be previewed by pasting the text into one of the many available online html editors, e.g. http://www.onlinehtmleditor.net or http://scratchpad.io .

Appendix F Site Layout

Original Layout - note that a SnowFox is not installed at all sites. Acclima1 and 2 are TDT sensors.



Post 2016 - TDT array replaces IMKO



NOT TO SCALE

Appendix G Quality control tests applied to data

Only measured variables included in ingested data shown. See Table 4 for more information about each of the tests, and Section 7 to decode PARAMETER_ID.

PARAMETER_ID	ZERO	SAMPLES	POWER	SENSOR_FAULT	DIAGNOSTIC	RANGE	SECONDARY_VAR	SPIKE	ERROR_CODE
G1		x	x	x		x	x		x
2		x	x	x		x	x		x
LWIN	x	x	x	x		x	x		x
LWOUT	x	x	x	x		x	x		x
PA	x	x	x	x		x		x	x
PRECIP		x	x	x	x	x			x
PROFILE_SOILEC15	x		x	x		x			x
PROFILE_SOILEC40	x		x	x		x			x
PROFILE_SOILEC65	x		x	x		x			x
PROFILE_VWC15	x		x	x		x			x
PROFILE_VWC40	x		x	x		x			x
PROFILE_VWC65	x		x	x		x			x
Q	x	x	x	x		x			x
RH	x	x	x	x		x			x
RN			x	x		x			x
SNOWD_DISTANCE_COR			x	x		x			x
STP_TSOIL10		x	x	x		x			x
STP_TSOIL2		x	x	x		x			x
STP_TSOIL20		x	x	x		x			x

PARAMETER_ID	ZERO	SAMPLES	POWER	SENSOR_FAULT	DIAGNOSTIC	RANGE	SECONDARY_VAR	SPIKE	ERROR_CODE
STP_TSOIL5		x	x	x		x			x
STP_TSOIL50		x	x	x		x			x
SWIN	x	x	x	x		x	x		x
SWOUT	x	x	x	x		x	x		x
TA		x	x	x		x			x
TDT1_TSOIL			x	x		x			x
TDT1_VWC	x		x	x		x			x
TDT2_TSOIL			x	x		x			x
TDT2_VWC	x		x	x		x			x
UX			x	x		x			x
UY			x	x		x			x
UZ			x	x		x			x
WD		x	x	x		x			x
WS	x	x	x	x		x			x

Appendix H Soil Moisture Index

Volumetric water content (VWC) provides an absolute measure of water content in the soil, which reflects characteristics of the soil as well recent weather conditions. Soil characteristics determine minimum and maximum water content values, whereas recent whether determines the status between these two extremes.

There are a number of well-established reference points for soil moisture that may be defined by a water content (%), or a soil moisture potential often expressed as a pressure/suction in kPa.

Wilting Point (WP) and Permanent Wilting Point (PWP) represent dry reference value sfor water content at which plants begin to wilt and beyond which may not recover. Air Dryness (moisture content after drying at 40^{o}C for 48 hours) and Oven Dryness (moisture content after heating in an oven at 105^{o}C), represent drier reference states than WP and PWP. Whereas WP represents a probable minimum to soil deep within the soil profile, soil at the surface may dry below the WP towards Air Dryness.

Saturation (SAT) is a wet water content reference point that corresponds to soil porosity.

Two processes are at work as a soil dries. Firstly, water drains under gravity from the larger pores in the soil. However, a point is reached in the smaller pores at which the gravitational force is balanced by the surface tension forces. At this point water no longer drains, but can be removed by plants through evapotranspiration. Drainage is a relative fast process that may last just a few days, whereas evapotranspiration is a much slower process, indeed plants can survive for considerable periods sustained by the water held in the soil. This boundary point is termed Field Capacity (FC) and may be seen as a plateau value at which soil moisture sits during relatively wet periods, e.g. winter in temperate climates when evapotranspiration is very low or zero.

FC is used to derive another measure of soil water content, soil moisture deficit (SMD) which is the depth of water in mm required to return soil moisture to FC. If soil moisture is above FC, SMD is zero.

These reference points provide a means to convert VWC to a soil moisture index (SMI) by, for example setting the SMI to zero when VWC is at WP, and setting SMI to one when VWC is at SAT. SMI provides a more convenient way to compare the relative wetness between sites, where soil and other site characteristics differ.

The SMI used by COSMOS-UK uses a dry reference of WP for zero and SAT as the wet reference corresponds to an SMI of 2. An intermediate point is defined by FC which has a SMI value of 1.

Values of WP, FC and SAT can be obtained from the analysis of soil samples in the laboratory, and these values have been derived for a great many sites across the UK.

For COSMOS-UK sites soil samples have been taken as part of the calibration process and have been analysed to determine bulk density and organic carbon content. A total of 90 soil samples from 5 depths and 18 locations within the CRNS footprint are taken and average values are presented in the table in Appendix A.

As already noted, porosity provides an appropriate estimate for SAT, and for mineral soils porosity, *f*, can be estimated from bulk density, ρ:

$$f = 1 - (\rho/2.65)$$

This equation uses the particle density of quartz (2.65 gm cm^{-3}) and is therefore only valid for mineral soils.

The value of SAT obtained from the bulk density can be compared with the distribution of observed VWC values.

Using the example of Chimney Meadow bulk density is 1.36 gm cm^{-3}, giving an estimated porosity of 49%. The maximum observed VWC is 57.2%, but this value is not a reliable estimate soil moisture as it corresponds to a day with lying snow. The 99^{th} percentile VWC is 50.1%, so an estimated value of SAT of about 50% would seem reasonable.

At the other end of the distribution the minimum VWC at Chimney Meadow is 18.2% and the 1^{st} percentile is 19.9%. The minimum is a rather better estimate of a dry reference point as it cannot be influence by short lived events such as snow or the ponding of the water at the surface. Whether it is a reasonable reference point depends on the record length and the conditions experience. Chimney Meadow was installed in 2013 and was operating through the very dry summer of 2018. A minimum reference point of around 18% seems appropriate.

Some indication of a likely value for FC can also be obtained from inspecting the distribution since as noted above FC represents the plateau value reached in most winters. Putting data in 5% bins suggests the mode of the distribution is 35-40%, which corresponds roughly to the 70^{th} percentile of the distribution.

An example of the distributions of observed VWC is shown in Figure H.1 for the Easter Bush site (EASTB). The histogram shows the distribution is slightly skewed with fewer observed values above the mode than below it. The upper two plots plot the ordered VWC values on a linear scale (middle plot) and against a normal reduced variate (upper plot). If the data were well represented by a normal distribution (which we know they are not) the data would plot as a straight line in the upper plot.

This upper plot very clearly shows the lower limit of the observed VWC values during the period of record (~18%). At the wet end of the scale there are two small steps in the VWC values: the values above these steps are probably the result of days when there was standing water or snow lying. VWC values corresponding to 99%, 99.5% and 99.9% are 47.2%, 53.8% and 64.7% respectively. An initial estimate of SAT would be that it is probably in the range 45-50%.

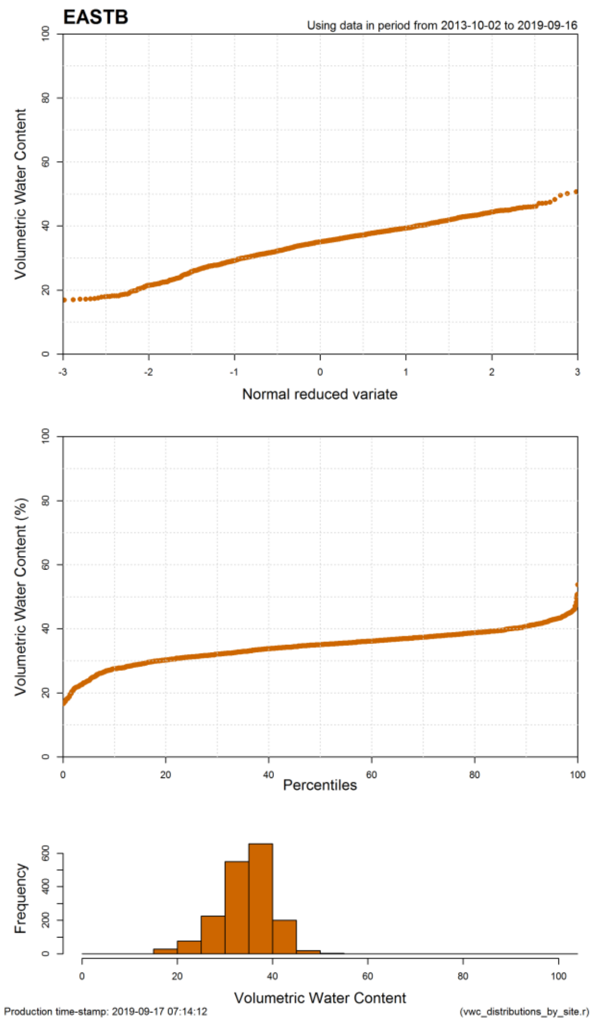


Figure H.1 Distributions of observed VWC at Easter Bush

Using these values as a guide a simple 1-dimensional model has been applied to all COSMOS-UK sites using precipitation and potential evaporation as inputs to simulate VWC. This model has WP, FC, and SAT as parameters and the values obtained by inspection from the distribution can be tested. The model-based approach cannot validate the values but does provide a check, and possibly an adjustment to the values obtained from the distribution, and in the case of SAT the value estimated from porosity.

The values of WP, FC and SAT obtained in this way are used to derive the COSMOS-UK SMI. Because the approach is very much data-driven, the analyses to set these values must be repeated as more data are collect to further test the adopted reference point values.

Appendix I Instrument swaps

Instruments get swapped for two reasons. Firstly, a faulty instrument is replaced either by another instrument of the same make or model, or possibly an upgraded or replacement model. Secondly, some instruments require periodic recalibration and must be removed from the field for this purpose; the instrument is replaced to ensure no loss of data, and once recalibrated the removed instrument may be redeployed elsewhere.

Both of these could cause a discontinuity in the recorded data, which may or may not be problematic. An example where this is obvious and problematic is the replacement of the TDT sensors at Waddesdon on 4th October 2018 (Figure I.1). Here there is a gap in the record prior to the new instruments being installed. The data from the newly installed sensors is not consistent with the previously recorded data probably as a consequence of the new instruments requiring some time to "settle in" after installation. This settling-period is quite usual after the installation of TDTs.

Table I.1 lists the instrument swaps in an example year (2019) by site and date. Table I.2 lists any new instruments added to a site post installation. This table comprises the earliest three COSMOS-UK sites, which were upgraded to higher performance sensors in February 2020. Table I.3 lists the instruments permanently removed from sites. The full record of sensor changes is available on request.

Users of COSMOS-UK data are urged to be mindful of instrument swaps, and contact us regarding unexplained discontinuities in the data.

Figure I.1 Soil moisture (VWC %) from the CRNS (black), TDT1 (red) and TDT2 (green) showing the dramatic effect of instrument swap.

Table I. 1 Instruments swapped due to fault or recalibration during 2019.

SITE_ID	SWAP_DATE	INSTRUMENT_NAME
ALIC1	10/10/2019	Weighing Raingauge
BALRD	28/08/2019	Automatic Weather Station
BALRD	28/08/2019	Four-component radiometer
BALRD	28/08/2019	Weighing Raingauge
BICKL	14/02/2019	3D Sonic Anemometer
BICKL	10/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
BICKL	27/11/2019	Weighing Raingauge
BUNNY	27/06/2019	Hygroclip (relative humidity component of MetPak). Improved model.
BUNNY	11/09/2019	3D Sonic Anemometer
BUNNY	11/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
BUNNY	03/10/2019	Weighing Raingauge
BUNNY	18/11/2019	Weighing Raingauge
CARDT	24/10/2019	Hygroclip (relative humidity component of MetPak). Improved model.
CGARW	11/06/2019	Relative humidity sensor
CGARW	11/06/2019	Snowfox COSMOS tube
CGARW	11/06/2019	Weighing Raingauge
CGARW	17/09/2019	Relative humidity sensor
CGARW	17/09/2019	Snow depth sensor
CHIMN	25/06/2019	Phenocam lens 1
CHIMN	25/06/2019	Phenocam lens 2
CHIMN	17/12/2019	Cosmic-ray soil moisure sensor (Moderated)
CHOBH	27/11/2019	Four-component radiometer
CHOBH	27/11/2019	Hygroclip (relative humidity component of MetPak). Improved model.
CHOBH	27/11/2019	TDT sensor 2
COCHN	17/10/2019	Relative humidity sensor
COCHN	17/10/2019	Snow depth sensor
COCLP	31/10/2019	3D Sonic Anemometer
COCLP	31/10/2019	Four-component radiometer
COCLP	31/10/2019	Hygroclip (relative humidity component of MetPak). Improved model.
CRICH	03/09/2019	3D Sonic Anemometer
CRICH	03/09/2019	Automatic Weather Station
CRICH	03/09/2019	Four-component radiometer
CRICH	03/09/2019	Phenocam lens 1
CRICH	03/09/2019	Phenocam lens 2
EASTB	29/10/2019	Snow depth sensor
EASTB	29/10/2019	Automatic Weather Station
EASTB	29/10/2019	Hygroclip (relative humidity component of MetPak). Improved model.
EASTB	29/10/2019	Four-component radiometer
EASTB	29/10/2019	Phenocam lens 1
EASTB	29/10/2019	Phenocam lens 2
ELMST	19/08/2019	Weighing Raingauge
ELMST	27/09/2019	Relative humidity sensor
EUSTN	25/09/2019	Barometric Pressure Sensor

EUSTN	25/09/2019	Relative humidity sensor
EUSTN	20/11/2019	Weighing Raingauge
FINCH	23/09/2019	Relative humidity sensor
FIVET	18/09/2019	Relative humidity sensor
GISBN	29/08/2019	3D Sonic Anemometer
GISBN	04/12/2019	Automatic Weather Station
GISBN	04/12/2019	Hygroclip (relative humidity component of MetPak). Improved model.
GISBN	04/12/2019	Snow depth sensor
GLENS	18/06/2019	3D Sonic Anemometer
GLENS	27/08/2019	Automatic Weather Station
GLENS	27/08/2019	Four-component radiometer
GLENS	27/08/2019	Snow depth sensor
GLENW	22/08/2019	Barometric Pressure Sensor
GLENW	22/08/2019	Relative humidity sensor
GLENW	05/12/2019	Relative humidity sensor
HADLW	22/03/2019	Relative humidity sensor
HADLW	21/11/2019	Barometric Pressure Sensor
HADLW	21/11/2019	Relative humidity sensor
HARTW	30/08/2019	Automatic Weather Station
HARTW	30/08/2019	Four-component radiometer
HENFS	18/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
HILLB	21/08/2019	Barometric Pressure Sensor
HILLB	21/08/2019	Relative humidity sensor
HILLB	21/08/2019	Weighing Raingauge
HLACY	12/08/2019	Relative humidity sensor
HOLLN	22/05/2019	Four-component radiometer
HOLLN	03/12/2019	Automatic Weather Station
HOLLN	03/12/2019	Four-component radiometer
HOLLN	03/12/2019	Hygroclip (relative humidity component of MetPak). Improved model.
HYBRY	01/08/2019	Weighing Raingauge
HYBRY	26/11/2019	Barometric Pressure Sensor
HYBRY	26/11/2019	Relative humidity sensor
LIZRD	25/05/2019	3D Sonic Anemometer
LIZRD	13/12/2019	Automatic Weather Station
LIZRD	13/12/2019	Hygroclip (relative humidity component of MetPak). Improved model.
LODTN	13/08/2019	Barometric Pressure Sensor
LODTN	13/08/2019	Relative humidity sensor
LULLN	10/10/2019	Weighing Raingauge
LULLN	22/11/2019	Hygroclip (relative humidity component of MetPak)
MOORH	31/07/2019	Weighing Raingauge
MOORH	04/09/2019	Four-component radiometer
MOORH	04/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
MOORH	04/09/2019	Snow depth sensor
MOORH	18/09/2019	3D Sonic Anemometer
MOREM	20/05/2019	Weighing Raingauge
MOREM	13/09/2019	Relative humidity sensor
MORLY	24/09/2019	3D Sonic Anemometer

MORLY	24/09/2019	Automatic Weather Station
MORLY	24/09/2019	Four-component radiometer
MORLY	24/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
MORLY	24/09/2019	Weighing Raingauge
NWYKE	20/11/2019	Weighing Raingauge
NWYKE	12/12/2019	Automatic Weather Station
NWYKE	12/12/2019	Hygroclip (relative humidity component of MetPak). Improved model.
NWYKE	12/12/2019	Four-component radiometer
NWYKE	12/12/2019	Weighing Raingauge
PLYNL	19/09/2019	3D Sonic Anemometer
PLYNL	19/09/2019	Automatic Weather Station
PLYNL	19/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
PLYNL	19/09/2019	Four-component radiometer
REDHL	04/10/2019	Weighing Raingauge
RISEH	26/06/2019	Phenocam lens 1
RISEH	26/06/2019	Phenocam lens 2
RISEH	07/08/2019	TDT sensor 3
RISEH	10/10/2019	Barometric Pressure Sensor
RISEH	10/10/2019	Relative humidity sensor
ROTHD	23/10/2019	3D Sonic Anemometer
ROTHD	23/10/2019	Automatic Weather Station
ROTHD	23/10/2019	Four-component radiometer
ROTHD	23/10/2019	Hygroclip (relative humidity component of MetPak). Improved model.
SHEEP	24/06/2019	Weighing Raingauge
SHEEP	03/10/2019	Weighing Raingauge
SOURH	01/01/2019	Automatic Weather Station
SOURH	30/10/2019	Four-component radiometer
SOURH	30/10/2019	Hygroclip (relative humidity component of MetPak). Improved model.
SOURH	30/10/2019	Snow depth sensor
SPENF	05/09/2019	Relative humidity sensor
SPENF	19/09/2019	Weighing Raingauge
STGHT	12/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
STIPS	20/09/2019	Automatic Weather Station
STIPS	20/09/2019	Four-component radiometer
STIPS	20/09/2019	Hygroclip (relative humidity component of MetPak). Improved model.
SYDLG	25/07/2019	Weighing Raingauge
SYDLG	10/12/2019	Relative humidity sensor
TADHM	11/12/2019	3D Sonic Anemometer
TADHM	11/12/2019	Automatic Weather Station
TADHM	11/12/2019	Four-component radiometer
TADHM	11/12/2019	Hygroclip (relative humidity component of MetPak). Improved model.
WRTTL	19/06/2019	Relative humidity sensor
WRTTL	20/11/2019	Barometric Pressure Sensor
WRTTL	20/11/2019	Relative humidity sensor

Table I. 2 New instruments installed providing new datasets.

SITE_ID	START_DATE	INSTRUMENT_NAME
CHIMN	12/02/2020	3D Sonic Anemometer
CHIMN	12/02/2020	Tipping bucket raingauge
CHIMN	12/02/2020	TDT sensor 3
CHIMN	12/02/2020	TDT sensor 4
CHIMN	12/02/2020	TDT sensor 5
CHIMN	12/02/2020	TDT sensor 6
CHIMN	12/02/2020	TDT sensor 7
CHIMN	12/02/2020	TDT sensor 8
CHIMN	12/02/2020	TDT sensor 9
CHIMN	12/02/2020	TDT sensor 10
SHEEP	13/02/2020	3D Sonic Anemometer
SHEEP	13/02/2020	Tipping bucket raingauge
SHEEP	13/02/2020	TDT sensor 3
SHEEP	13/02/2020	TDT sensor 4
SHEEP	13/02/2020	TDT sensor 5
SHEEP	13/02/2020	TDT sensor 6
SHEEP	13/02/2020	TDT sensor 7
SHEEP	13/02/2020	TDT sensor 8
SHEEP	13/02/2020	TDT sensor 9
SHEEP	13/02/2020	TDT sensor 10
WADDN	13/02/2020	3D Sonic Anemometer
WADDN	13/02/2020	Tipping bucket raingauge
WADDN	13/02/2020	TDT sensor 3
WADDN	13/02/2020	TDT sensor 4
WADDN	13/02/2020	TDT sensor 5
WADDN	13/02/2020	TDT sensor 6
WADDN	13/02/2020	TDT sensor 7
WADDN	13/02/2020	TDT sensor 8
WADDN	13/02/2020	TDT sensor 9
WADDN	13/02/2020	TDT sensor 10

Table I. 3 Instruments removed and not replaced.

SITE_ID	END_DATE	INSTRUMENT_NAME
ALIC1	29/01/2020	Soil moisture profile sensor
BALRD	28/08/2019	Soil moisture profile sensor
BICKL	10/09/2019	Soil moisture profile sensor
BUNNY	11/09/2019	Soil moisture profile sensor
CARDT	22/10/2019	Soil moisture profile sensor
CHIMN	12/02/2020	Soil moisture profile sensor
CHOBH	27/11/2019	Soil moisture profile sensor
COCLP	31/01/2018	Soil moisture profile sensor

CRICH	03/09/2019	Soil moisture profile sensor
EASTB	29/10/2019	Soil moisture profile sensor
GISBN	18/11/2015	Soil moisture profile sensor
GLENS	27/08/2019	Soil moisture profile sensor
HARTW	30/08/2019	Soil moisture profile sensor
HARWD	19/12/2018	Soil moisture profile sensor
HENFS	18/09/2019	Soil moisture profile sensor
HOLLN	05/04/2016	Soil moisture profile sensor
LIZRD	13/12/2019	Soil moisture profile sensor
LULLN	22/11/2019	Soil moisture profile sensor
MOORH	05/11/2015	Soil moisture profile sensor
MORLY	24/09/2019	Soil moisture profile sensor
NWYKE	02/11/2015	Soil moisture profile sensor
PLYNL	09/04/2016	Snow depth sensor
PLYNL	19/09/2019	Soil moisture profile sensor
PORTN	28/01/2020	Soil moisture profile sensor
RDMER	19/09/2018	Soil moisture profile sensor
REDHL	30/01/2020	Soil moisture profile sensor
ROTHD	23/10/2019	Soil moisture profile sensor
SHEEP	11/02/2020	Soil moisture profile sensor
SOURH	30/10/2019	Soil moisture profile sensor
STGHT	12/09/2019	Soil moisture profile sensor
STIPS	08/03/2016	Soil moisture profile sensor
TADHM	11/11/2015	Soil moisture profile sensor
WADDN	13/02/2020	Soil moisture profile sensor
WYTH1	30/09/2016	Soil moisture profile sensor

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