Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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 recent initiative which is still developing in terms of the number of sites deployed and services offered to users. Our ambition is to 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 CEH 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	N	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	N	55851	502136	174

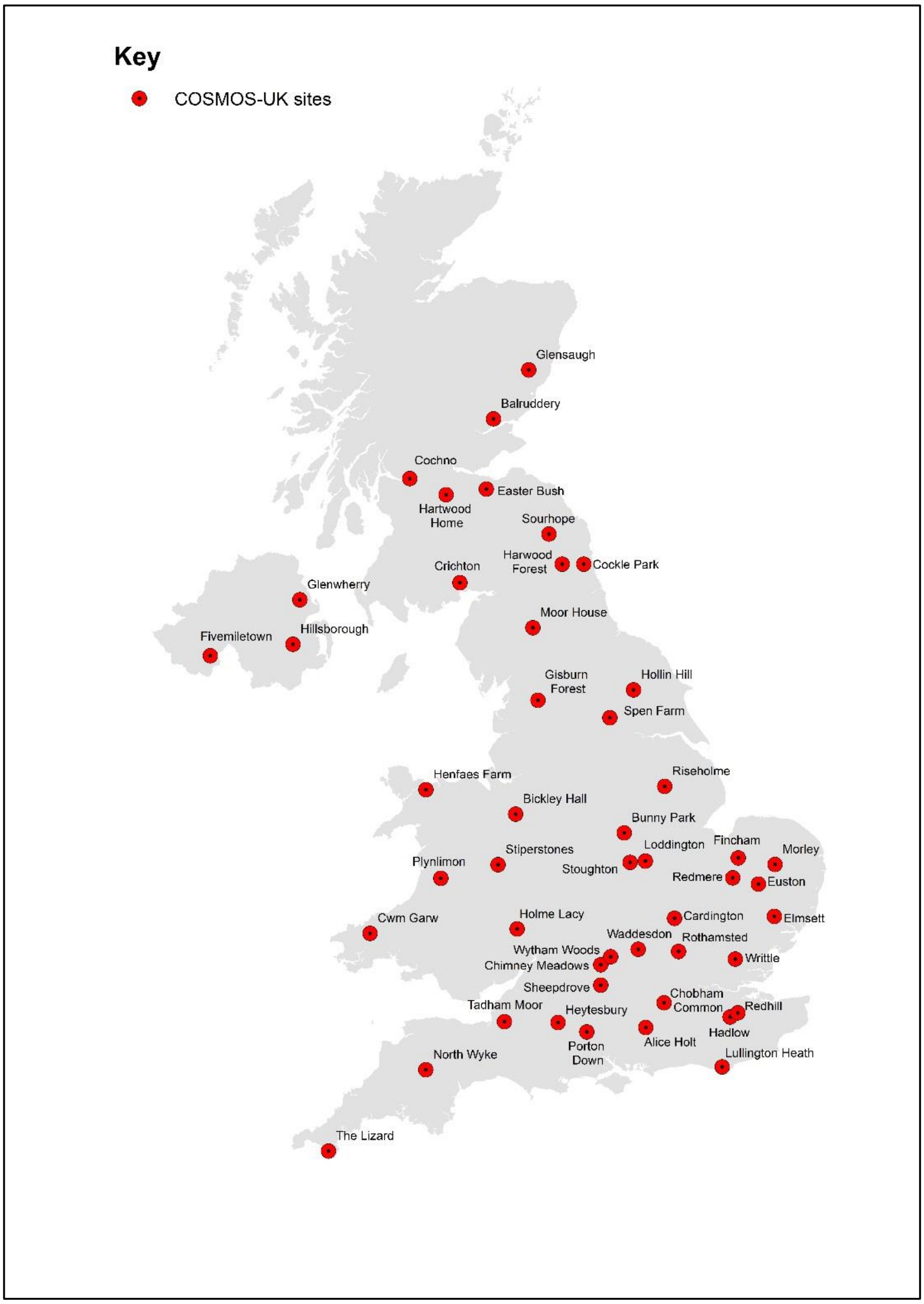

Figure 2.1 Map of COSMOS-UK sites

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 CEH.

Table 3.1 Instrument 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 and CRS-1000/B

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

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 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.

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.

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

Phase 3 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.

Phase 3 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.

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 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 Instruments installed at COSMOS-UK sites.

Site	3D sonic anemometer	2D sonic anemometer	Automatic weather station	Phase 3 Barometric Pressure sensor	Phase 3 Temperature and humidity sensor	Profile soil moisture	TDT array	Snow sensors
Alice Holt		x	x			x		
Balruddery	x		x			x		
Bickley Hall	x		x			x		
Bunny Park	x		x			x		
Cardington	x		x			x		
Chimney Meadows		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		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		
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		x	x			x		
Sourhope	x		x			x		x
Spen Farm	x			x	x			
Stiperstones	x		x			x		
Stoughton	x		x			x		
Tadham Moor	x		x			x		
Waddesdon		x	x			x		
Writtle	x			x	x		x	
Wytham Woods		x	x			x		

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	gm^{-3}	30 min
Relative humidity	%	30 min
Air temperature	$°C$	30 min
Atmospheric pressure[1]	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	-
Snow water equivalent[2]	mm	-
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

Table 4.2 Derived data available from the COSMOS-UK network

DERIVED VARIABLES	UNITS	NOTES
Net radiation (derived from above)	Wm^{-2}	30 min
Volumetric water content (CRNS)	%	Daily/hourly[3]
Typical sensing depth of CRNS (D86)	mm	Daily/hourly
Neutron counts from CRNS (corrected)		Hourly
Potential evaporation[4]	mm	Daily

[1] Reported as recorded at altitude of instrument i.e. not corrected to sea level.
[2] Data not currently being processed.
[3] Daily data are more reliable and complete than hourly data.
[4] Potential evaporation data are calculated using the Penman-Monteith method according to FAO 56, p.24.

5. Accessing COSMOS-UK data

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

These data are uploaded to 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 2018 data are uploaded for the period up to 2016.

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 CEH accepts no liability for their use.

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

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

Data can be viewed as graphs on the live data page COSMOS-UK website. At present the web site only displays precipitation, air temperature and soil moisture from the CRNS, or neutron counts if the site is not yet calibrated, and over a 6-month period back from the present day. There are plans to completely redevelop this page to allow more variables to be displayed over a user-specified period.

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 raingauge 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 daily data 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. Kohli 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.

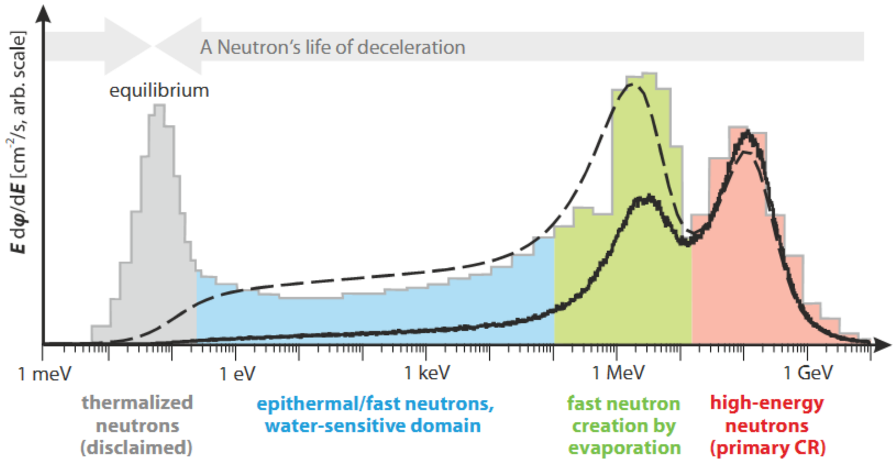

Figure 1. Neutron energy spectra at the surface: exemplary measurement by *Goldhagen et al.* [2002] (grey) and simulated by *Sato and Niita* [2006] (dashed). After subtracting the ground reflected component over pure water, we obtain a pure incoming component (continuous black line), which is used as 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 Kohli 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.

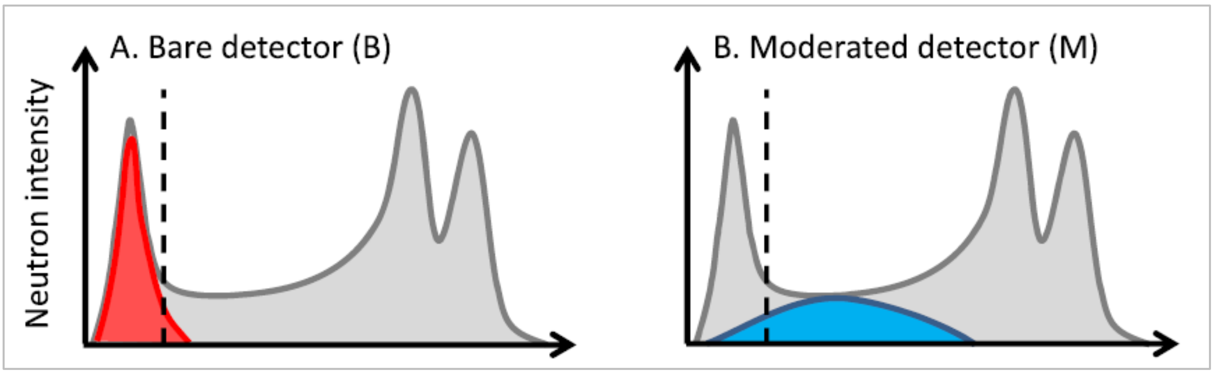

Figure 7.2 Sampling of neutron energy spectra by bare and moderated detectors, from Andreasen et al. (2016). The dashed line represents 0.5eV.

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).

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 using standard equations as referenced above 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. In fact some 1.2% of all hourly VWC values were greater than 100%, whereas less than 0.01% of values were less than 0%. Note that hourly VWC data could also be unavailable because of missing data, i.e. the numbers of counts or those variables needed to derive the corrected counts.

COSMOS-UK has employed several variations in methods of data processing and by late 2016 had generally adopted a method that censored (filtered) hourly values with >100% or <0% water content and then averaged as appropriate, e.g. to give a daily mean. An arbitrary decision had to be made about how many hourly values could be missing for a daily mean to be considered acceptable (generally one missing value was allowed). The COSMOS-UK recommendation was that generally the hourly data were too noisy to be useful and that the daily mean data should be used. Because of the filtering, the daily VWC could not be outside the range 0-100%, but could approach these limits and therefore not be considered sensible measurements of soil moisture. Data supplied to users alerted then to these issues and advised caution in their use.

Across all sites the changes to the averaging and VWC calculation methods have improved the number of daily VWC values calculated from 84% to 92%. However, the degree of improvement varies between sites with the biggest improvement being at the sites with high soil organic carbon content such as Redmere where the changes have led to a 60% improvement on the number of daily days of data generated.

Note that the problems associated with high VWC generally relate to sites with peat soils in which higher VWC values are expected. VWC data from mineral soils with lower water content are more reliable; problems are rare in the daily data from mineral soils, although the hourly data are still noisy.

7.4 The CRNS footprint

The characteristics of the sensor footprint were understood to vary relatively little with distance from the sensor as soil wetness changes, but the sensor penetration depth below the ground surface decreases markedly with soil water content. This variation has been characterised by the soil depth from which 86%[5] of the measured neutron counts have originated (effective depth). Franz et al. (2013) provide a way of

[5] 86% represents two e-fold drops or $1-1/e^2$ (Zreda et al., 2008)

calculating an average effective depth which was initially used by COSMOS-UK. In the wettest conditions this depth can be as little as 0.08m, very much less than the 0.76m given by Zreda et al. (2008) for dry soils in the USA. At this time the sensor footprint was considered to be roughly 300m in radius (i.e. 86% of measured neutrons were generated from within this footprint).

These footprint characteristics informed the field soil sampling protocol used to obtain the *reference soil water content* mentioned above.

Kohli et al. (2015) published a re-evaluation of the sensor footprint and changes to way in which calibration data are used to calculate the *reference soil water content*. A key finding was that 50% of the neutrons counted came from within 50m of the sensor, and that the sensor showed “extraordinary sensitivity” to the closest few meters to the sensor.

While this result led to a change in the field sampling protocol used by COSMOS-UK (i.e. the protocol was changed to take samples closer to the sensor), this in itself has little impact as the COSMOS-UK sites have been selected to have similar characteristics over the larger footprint. There is no reason to suspect that soil moisture varies significantly with distance from the sensor.

Kohli et al. (2015) also suggested other changes which relate to the way averaging of soil moisture and bulk density is performed both for calibration of the sensor and the derivation of water content. Of these changes the biggest impact comes from using the bulk density averaged across all samples rather than using just those samples corresponding to the effective depth at the time of the field sampling. This has a particular impact in peat soils in which bulk density increases considerably with depth.

7.5 Revised method for daily averaging

Introducing the above changes to the method of deriving VWC further reduced the number of hourly VWC values that were below zero, or greater than 100%, by about 30%. It has been decided to set negative values to zero but to leave values greater than 100% in the data set, so that the user should determine how to handle data considered unreliable.

However, whilst making these changes it was decided to change the way in which daily averages were derived. The “old” method was to filter counts to avoid out of range values of VWC and then average to daily. The new method is to derive an average number of hourly counts for the day and use this to derive the daily VWC; this method resulted in only a tiny percentage of values greater than 100% and no negative values. These >100% values are left in the data set with the user advised to check all high VWC values. Again it was decided that the daily mean number of counts could be used even with some hourly counts missing. After inspecting the data for missing values, which could arise from any of the required variables being missing, it was decided to allow up to two missing hourly values in deriving daily mean VWC.

The figures below demonstrate how these changes impact on the daily data. Firstly, at Rothamsted which is a mineral soil, the difference is just a few percent, and in this case VWC is increased, probably just for some quirk in the way the bulk density was calculated.

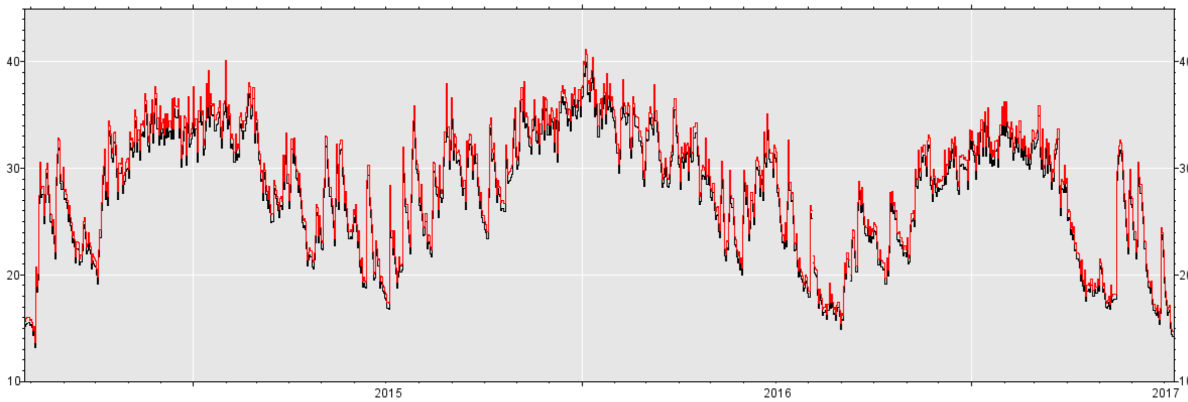

Figure 7.3 VWC as percentage at Rothamsted comparing original method (black) and revised method (red) – the difference is tiny, just a few percent.

At sites with peat soils the difference is more noticeable. The graph below shows data from Glensaugh were the laboratory analysis of soils gave an average organic matter content of 40.6%. In comparision with Rothamsted the soils are wet as can be seen form the scaling of the two graphs. Note also how during 2015 the soil moisture showed no seasonal variation. The original method generated values of VWC greater than 100% even when averaged over a day. Filtering was introduced in the original processing to remove these unrealistically high values but led to a data set with many gaps. The revised method generates no daily values greater than 100% at Glensaugh. Further research is required on how best to process the data from peat soils but in the meantime VWC values from sites with peat soils should be used with care.

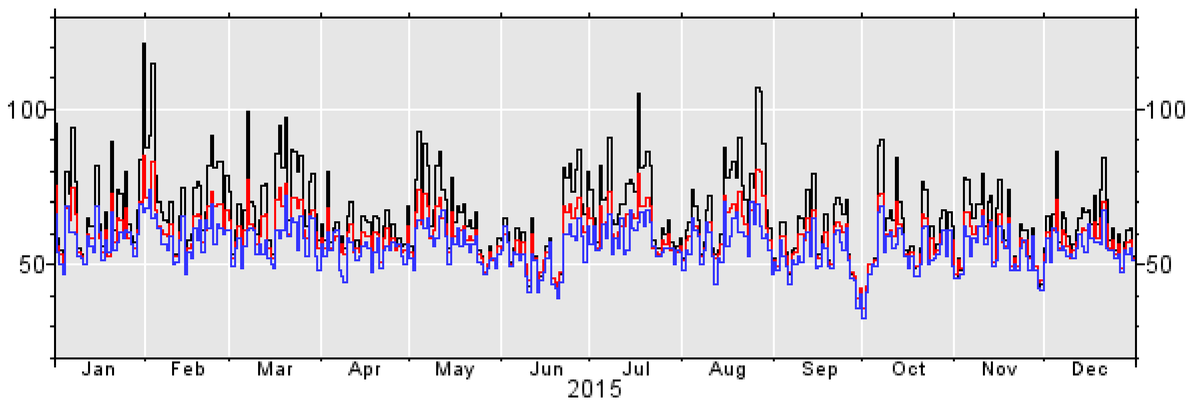

Figure 7.4 VWC as percentage at Glensaugh comparing original method without filtering (black), original method with filtering (blue) and revised method (red).

7.6 Revised effective depth estimation

As mentioned above, a feature of the CRNS is that since the neutrons resulting from cosmic rays penetrate the soil, the derived VWC represents a depth averaged value. Franz et al. (2012) provide a method of estimating an effective depth for the sensor. This depth is dependent on VWC and has an approximate range from 10 cm in wet soils to 80 cm in dry soils. This effective depth was calculated for COSMOS-UK sites and made available with the VWC.

The same study that proposed a reduction to the spatial footprint of the sensor, also reviewed depth penetration of the sensor (Kohli et al., 2015; termed D86). 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 distance from the sensor.

COSMOS-UK now uses this method to provide D86 values at six selected distances from the CRNS instead of the previously calculated single distance-invariant effective depth. 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 previously derived effective depth and the D86 values is presented below for the COSMOS-UK site at Rothamsted.

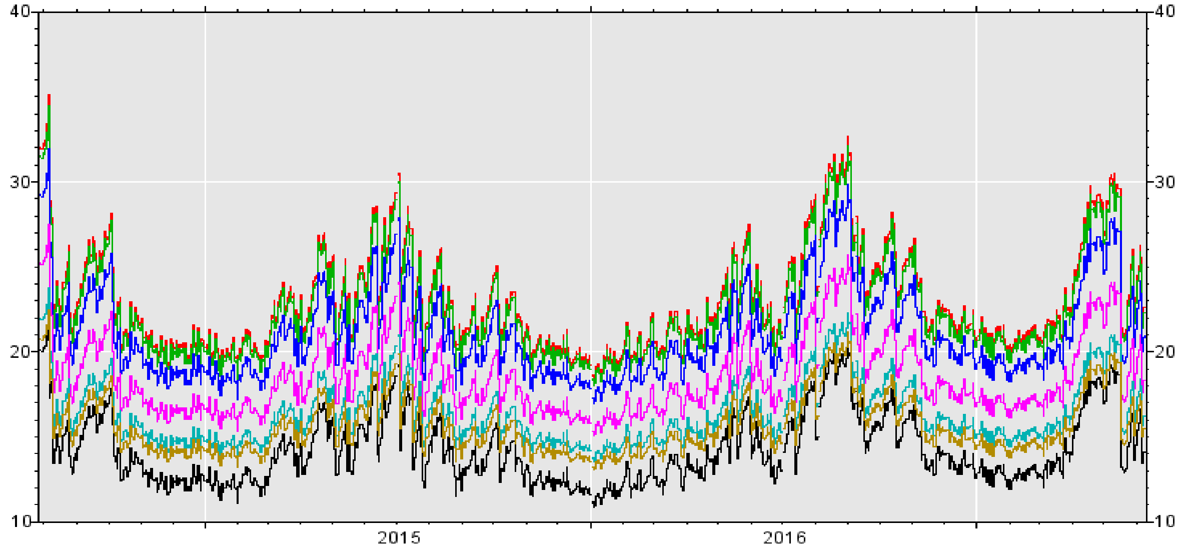

Figure 7.5 Variation in effective depth at Rothamsted: black is effective depth others are D86 from bottom to top at 1m (brown), 5m (cyan), 25m (pink), 75m (blue), 150m (green) and 200m (red) from the sensor.

From the figure it is obvious that the D86 values are all greater than the effective depth. This is a consequence of the revised derived VWC, the form of the new D86 equation and the way in which soil properties are averaged in the revised method. COSMOS-UK has made the somewhat arbitrary decision to use the 75m D86 (pink in the above figure) as a single indicator to illustrate the variation of the sensor footprint penetration depth with soil wetness.

7.6 A new correction factor

As noted in Section 7.2, a correction factor is applied to the counts recorded by the CRNS to adjust for fluctuations in incoming cosmic rays. This factor is of the form

$$F_i = \gamma\left(\frac{I_{ref}}{I_{ref}'} - 1\right) + 1$$

in which ɣ is a scaling factor to adjust for geomagnetic effects and differences between the CRNS and the reference counter. Until 2018 the scaling factor was always set to unity and the correction factor reduces to

$F_i = I_{ref} / I_{ref}'$

In 2018, following an investigation into spurious trends in the derived VWC data an empirical method of deriving site-specific ɣ values was introduced to remove these trends. This working model to correct for difference between COSMOS-UK sites and sensors, and the characteristics of the Jungfrau reference sensor is the subject of a paper currently in preparation.

7.7 Introduction of revised processing

It will be appreciated that various alternative methods can be adopted to derive the VWC from the counts recorded in the cosmic ray neutron sensor. It is possible that there will be further changes to the processing of these data.

Whenever changes are made to the processing method they are introduced to the entire data set, i.e. at all sites back to the start of operation, to ensure consistency in each data series. In some instances calculations using legacy methods continue in the background.

7.8 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 7.6). 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.

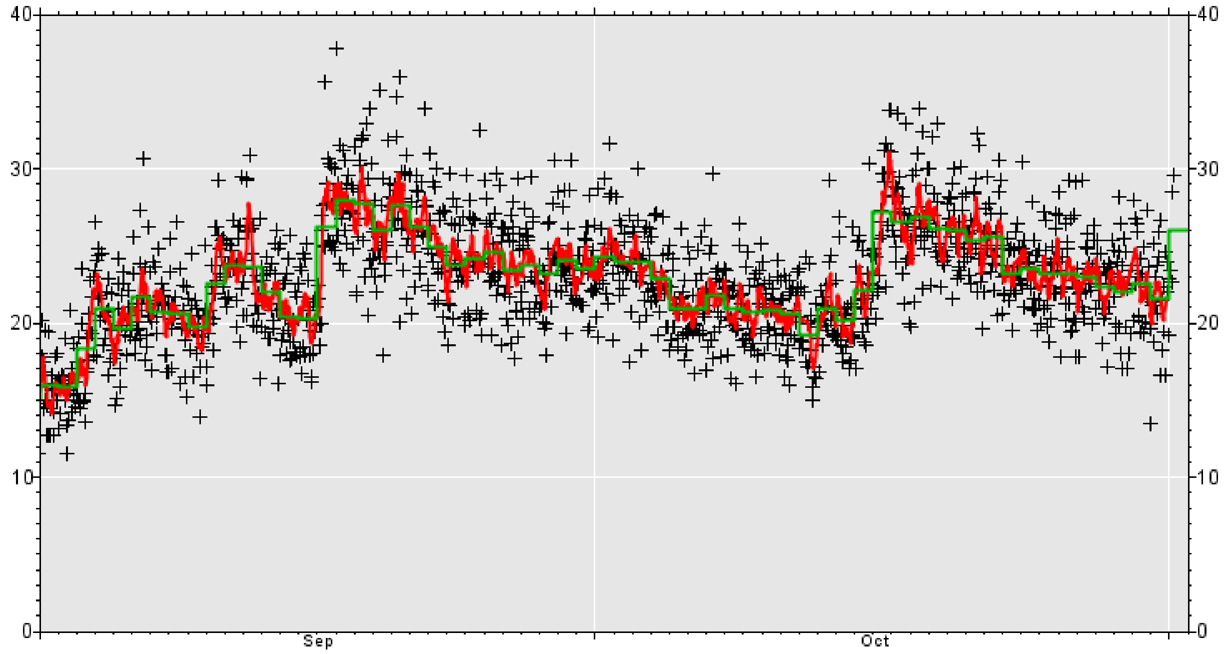

Figure 7.6 A comparison of VWC data from the CRNS: hourly (black), 7-hour moving average (red) and daily (green).

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 7.7 for the same site and period as in Figure 7.6.

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.

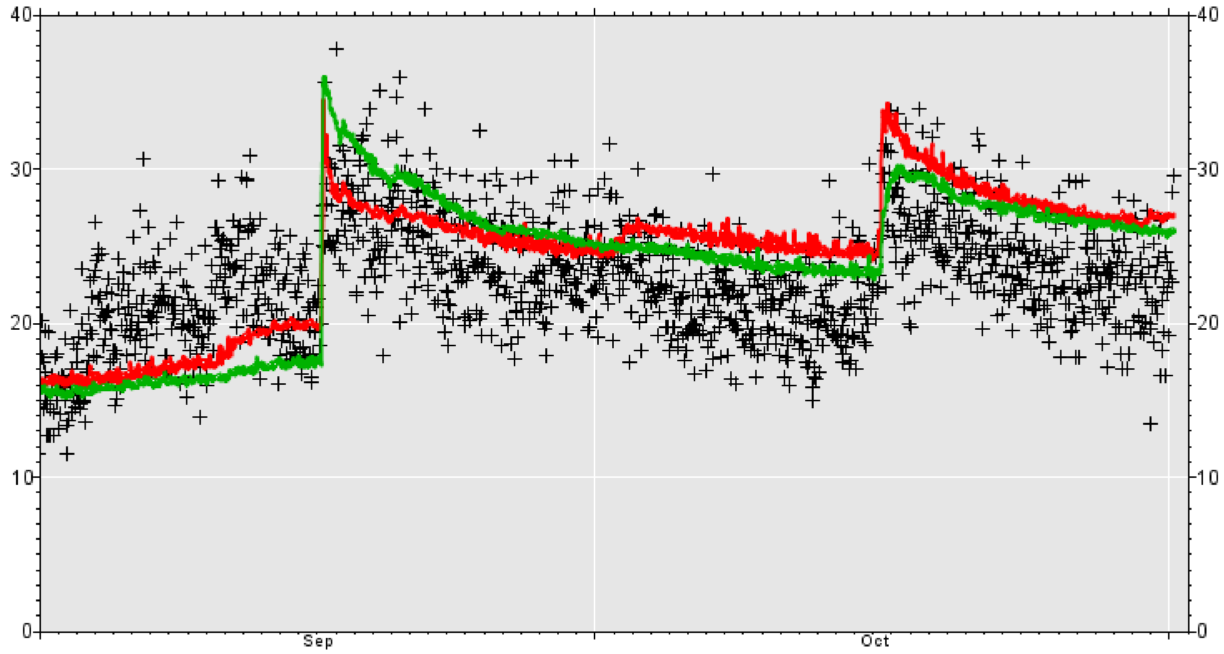

Figure 7.7 A comparison of hourly data from the CRNS (black), with 30 minute data from two TDT sensors (red and green).

A third point to be noted from Figure 2 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 7.8 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.

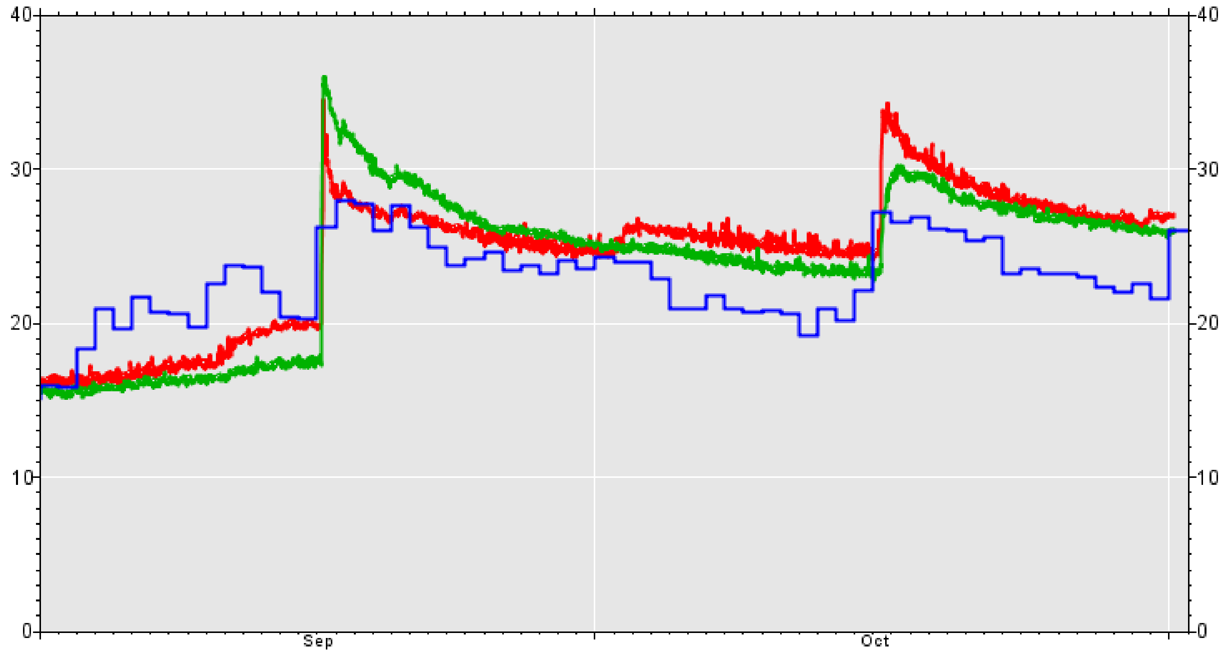

Figure 7.8 A comparison daily VWC data from the CRNS (blue) with 30 minute data from the two TDTs (red and green).

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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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
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	CALIB-RATED	EAST	NORTH	LAT-ITUDE	LONG-ITUDE	ALT-ITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER	INFORMAL SOIL DESCRIPTION	LAND COVER
ALICE HOLT	ALIC1	06-Mar-15	Y	479950	139985	51.154	-0.858	80	Loam to Clay	0.85	8.4	Typical mineral soil; lower bulk density may be due to higher clay and/or organic content or macropores from tree roots	Deciduous Broadleaf Forest
BALRUDDERY	BALRD	16-May-14	Y	331643	732797	56.482	-3.111	130	Sandy Loam	1.34	4.6	Typical mineral soil	Farmland
BICKLEY HALL	BICKL	28-Jan-15	Y	353112	347903	53.026	-2.701	78	Sand to Sandy Loam	1.31	4	Typical mineral soil	Improved Grassland
BUNNY PARK	BUNNY	27-Jan-15	Y	458884	329606	52.861	-1.127	39	Sand to Sandy Loam	1.55	3.2	Typical mineral soil with high bulk density	Arable
CARDINGTON	CARDT	24-Jun-15	Y	507991	246422	52.106	-0.425	29	Clayey Loam to Sandy Loam	1.14	8	Typical mineral soil	Grassland
CHIMNEY MEADOWS	CHIMN	02-Oct-13	Y	436113	201160	51.708	-1.479	65	Clay to Sandy Loam (deep)	1.36	5.4	Calcareous mineral soil (around 20% calcium carbonate)	Grassland
CHOBHAM COMMON	CHOBH	24-Feb-15	Y	497737	164137	51.368	-0.597	47	Sand to Loam	0.9	6.2	Highly variable soil, with a mix of organic soil/material of variable thickness overlying mineral soil; low lattice and bound water	Heath
COCHNO	COCHN	23-Aug-17	Y	249980	674651	55.941	-4.404	168	Clayey loam to sandy loam	0.83	13.6	Mineral soil with high soil organic carbon	Improved Grassland
COCKLE PARK	COCLP	21-Nov-14	Y	419544	591351	55.216	-1.694	87	Loam to Clay	1.21	6.6	Typical mineral soil	Grassland and Arable
CRICHTON	CRICH	02-Dec-14	Y	298903	573164	55.043	-3.583	42	Clayey Loam to Sandy Loam	1.15	9	Typical mineral soil	Grassland
CWM GARW	CGARW	29-Jun-16	N	211350	231661	51.951	-4.747	299	Mudstone, Siltstone and Sandstone				Grassland
EASTER BUSH	EASTB	14-Aug-14	Y	324557	664463	55.867	-3.207	208	Clayey Loam to Sandy Loam	1.1	6.6	Typical mineral soil	Grassland
ELMSETT	ELMST	11-Aug-16	Y	605122	248260	52.095	0.993	76	Loam and clay	1.26		Calcareous mineral soil (around 5% calcium carbonate)	Arable
EUSTON	EUSTN	31-Mar-16	Y	589619	279776	52.336	0.796	18	Sandy loam	1.27	5.8	Typical mineral soil; low lattice and bound water	Improved Grassland

SITE_NAME	SITE_ID	START DATE	CALIB-RATED	EAST	NORTH	LAT-ITUDE	LONG-ITUDE	ALT-ITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER	INFORMAL SOIL DESCRIPTION	LAND COVER
FINCHAM	FINCH	07-Jun-17	Y	570068	305182	52.618	0.511	15	Freely draining lime-rich loamy soil	1.33		Calcareous mineral soil	Arable
FIVEMILETOWN	FIVET	26-Jun-18	N	55851	502136	54.299	-7.292	174					Arable
GISBURN FOREST	GISBN	15-Aug-14	Y	374899	458714	54.024	-2.385	246	Clayey Loam to Silty Loam	0.82	12.2	Mineral soil with high soil organic carbon, most likely from decomposed forest litter	Coniferous Woodland
GLENSAUGH	GLENS	14-May-14	Y	365870	780483	56.914	-2.562	399	Sand to Sandy Loam	0.44	40.6	Extremely organic soil with little mineral material, i.e. very high soil organic carbon and extremely low bulk density	Grass and Heather Moorland
GLENWHERRY	GLENW	15-Jun-16	Y	142962	556604	54.838	-6.005	274	Peat	0.54	30.6	Organic soil, i.e. very high soil organic carbon and low bulk density	Grassland
HADLOW	HADLW	27-Oct-16	Y	562097	150263	51.229	0.320	33	Loam and clay	1.22	6.2	Typical mineral soil	Improved Grassland
HARTWOOD HOME	HARTW	20-May-14	Y	285476	658957	55.810	-3.829	225	Clayey Loam to Sandy Loam	1.02	8.6	Typical mineral soil	Grassland/ Woodland
HARWOOD FOREST	HARWD	20-May-15	Y	398505	591355	55.216	-2.024	300	Clayey Loam to Silty Loam	0.33		Extremely organic forest soil with little mineral material	Coniferous Woodland
HENFAES FARM	HENFS	17-Dec-15	Y	265750	371709	53.225	-4.012	287	Silty Loam to Silt	0.97	15.4	Mineral soil with very high organic matter	Semi-Natural Grassland
HEYTESBURY	HYBRY	16-Aug-17	Y	394535	144856	51.203	-2.080	166	Shallow, lime-rich over chalk or limestone	0.88		Highly calcareous mineral soil with high soil organic carbon	Grassland
HILLSBOROUGH	HILLB	14-Jun-16	Y	136345	513358	54.447	-6.068	146	Glacial clay till	1.15	8.4	Typical mineral soil	Grassland/ Woodland
HOLLIN HILL	HOLLN	25-Mar-14	Y	468121	468811	54.111	-0.960	82	Clay to Loam	1.06	6.4	Typical mineral soil	Grassland
HOLME LACY	HLACY	11-Apr-18	Y	354663	236036	50.021	-2.662	76	Free draining slightly acidic and loamy	1.24		Typical mineral soil	Grassland
LODDINGTON	LODTN	26-Apr-16	Y	479565	302022	52.610	-0.826	186	Loam to clay	1.16	7.2	Typical mineral soil; lattice and bound water appears somewhat high	Arable
LULLINGTON HEATH	LULLN	16-Dec-14	Y	554365	101634	50.794	0.189	119	Chalky, Silty Loam	0.90	8.6	Highly calcareous mineral soil (around 66% calcium carbonate); lattice and bound water is lower than for a typical mineral soil	Grassland/Heath
MOOR HOUSE	MOORH	04-Dec-14	Y	369920	529470	54.659	-2.468	565	Clayey Loam to Silty Loam	0.76	15.2	Mineral soil with very high organic matter, i.e. high soil organic carbon and low bulk density	Cotton Grass/Heather
MORLEY	MORLY	14-May-14	Y	605826	298803	52.548	1.034	55	Loam to Clayey Loam	1.53	3.4	Typical mineral soil with high bulk density	Arable

SITE_NAME	SITE_ID	START DATE	CALIB-RATED	EAST	NORTH	LAT-ITUDE	LONG-ITUDE	ALT-ITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER	INFORMAL SOIL DESCRIPTION	LAND COVER
NORTH WYKE	NWYKE	16-Oct-14	Y	265707	98832	50.773	-3.906	181	Loam to Silty Loam	1.12	7.4	Typical mineral soil	Grassland/Pasture
PLYNLIMON	PLYNL	05-Nov-14	Y	280322	285397	52.453	-3.763	542	Loam	0.62	19.6	Organic soil with some mineral material, i.e. high soil organic carbon and low bulk density	Semi-Natural Grassland
PORTON DOWN	PORTN	18-Dec-14	Y	422406	135670	51.120	-1.681	146	Chalky, Silty Loam	0.97	9.8	Highly calcareous mineral soil (around 82% calcium carbonate); lattice and bound water is lower than for a typical mineral soil	Grassland
REDHILL	REDHL	18-Feb-16	Y	569577	154326	51.263	0.429	91	Sand to Sandy Loam	1.26	4.8	Slightly calcareous mineral soil (around 7% calcium carbonate)	Improved Grassland
REDMERE	RDMER	11-Feb-15	Y	564639	285846	52.446	0.421	3	Peat	0.60	47.6	Extremely organic soil, perhaps somewhat compacted, i.e. very high soil organic carbon and higher than expected but still low bulk density; lattice and bound water appears somewhat high	Shallow Arable
RISEHOLME	RISEH	04-May-16	Y	498425	374863	53.262	-0.526	53	Shallow loam	1.27	6.4	Calcareous mineral soil (around 21% calcium carbonate)	Improved Grassland
ROTHAMSTED	ROTHD	25-Jul-14	Y	511887	214048	51.814	-0.378	131	Clayey Loam	1.33	4.2	Typical mineral soil	Crops and Grassland
SHEEPDROVE	SHEEP	24-Oct-13	Y	436039	181395	51.530	-1.482	170	Chalky Silty Loam: intermediate -shallow	1.04	11.8	Mineral soil with fairly high soil organic carbon; slightly calcareous	Grassland
SOURHOPE	SOURH	09-Dec-14	Y	385562	620698	55.480	-2.230	487	Loam to Sandy Loam	0.65	17.2	Mineral soil with very high organic matter, i.e. high soil organic carbon and low bulk density	Coarse Grassland
SPEN FARM	SPENF	23-Nov-16	Y	444887	441620	53.869	-1.319	57	Clayey loam to silty loam	1.41		Calcareous mineral soil (around 22% calcium carbonate), with high bulk density	Arable and horticulture
STIPERSTONES	STIPS	06-Nov-14	Y	336086	298579	52.581	-2.945	432	Shallow Loam	0.62	20.8	Organic soil with some mineral material, i.e. high soil organic carbon and low bulk density	Heathland
STOUGHTON	STGHT	18-Aug-15	Y	464641	300854	52.602	-1.047	130	Loam to Clayey Loam	1.33	5.4	Typical mineral soil	Arable
TADHAM MOOR	TADHM	14-Oct-14	Y	342199	145692	51.208	-2.829	7	Peat (deep)	0.32	62.8	Extremely organic soil with little mineral material, i.e. very high soil organic carbon and extremely low bulk density	Grassland
THE LIZARD	LIZRD	17-Oct-14	Y	170940	19648	50.033	-5.200	85	Loam to Silty Loam	0.95	11.6	Mineral soil with high soil organic carbon; bulk density is notably lower towards the surface (0-10/15 cm)	Grassland/Heath
WADDESDON	WADDN	04-Nov-13	Y	472548	216176	51.839	-0.948	98	Clay to Loam (deep)	1.11	6.8	Typical mineral soil	Grassland
WRITTLE	WRTTL	04-Jul-17	Y	567062	206687	51.734	0.418	44	Loamy and clayey soil	1.26		Typical mineral soil	Arable and horticulture

SITE_NAME	SITE_ID	START DATE	CALIB-RATED	EAST	NORTH	LAT-ITUDE	LONG-ITUDE	ALT-ITUDE (M)	SOIL TYPE	BULK DENSITY	ORGANIC MATTER	INFORMAL SOIL DESCRIPTION	LAND COVER
									with impeded drainage				
WYTHAM WOODS	WYTH1	21-Nov-13	Y	445738	208942	51.777	-1.338	109	Loam to silty loam: intermediate	1.05	5.6	Typical mineral soil	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 01/08/2017 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.*

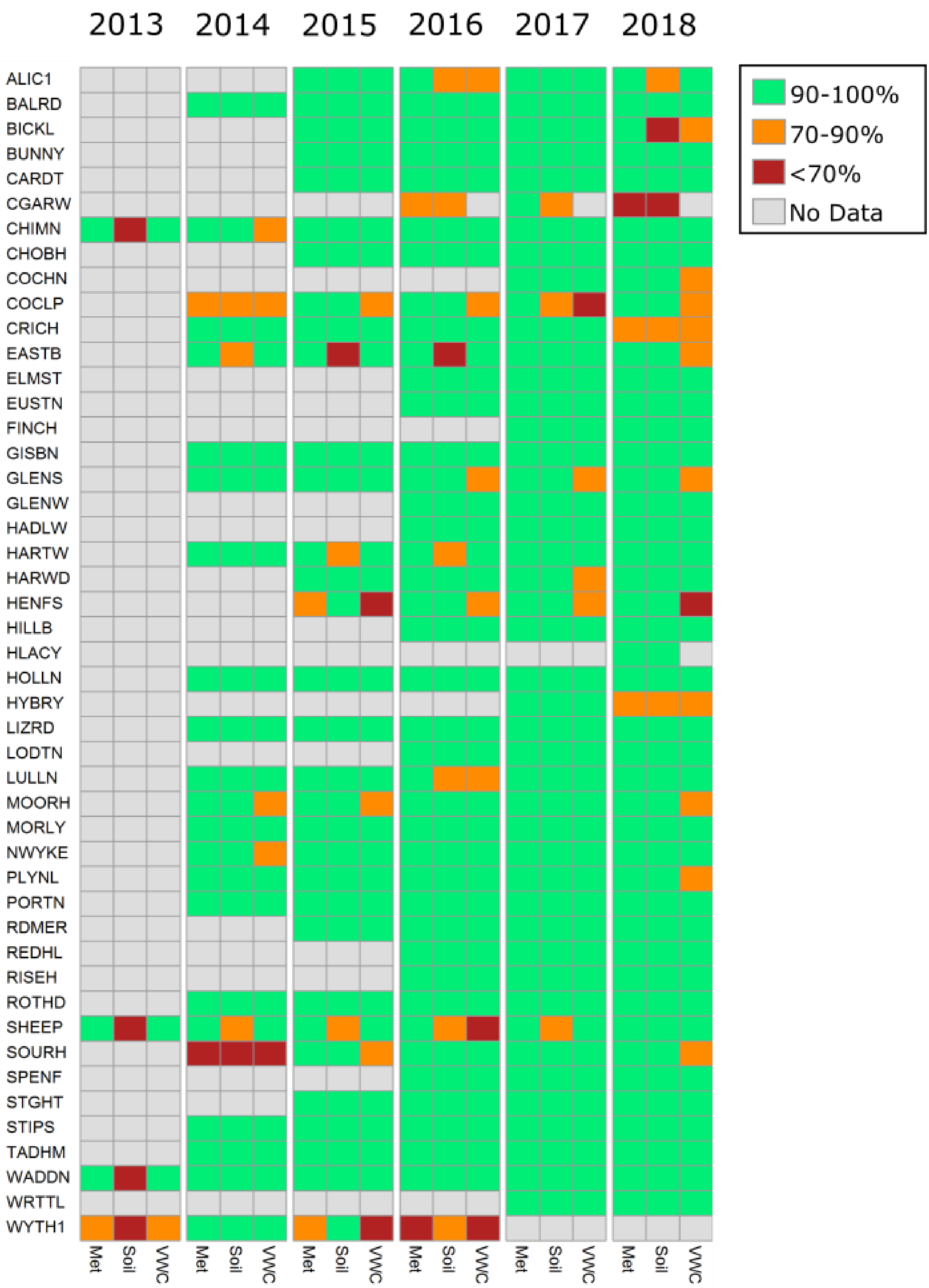


Figure B.1 Data availability/completeness for period of record for all sites. Cells indicate the percentage of 30 minute (or 1 hour for VWC) values received for the groups of variables compared to the number expected in the given year.

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 an 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 CEH. 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.

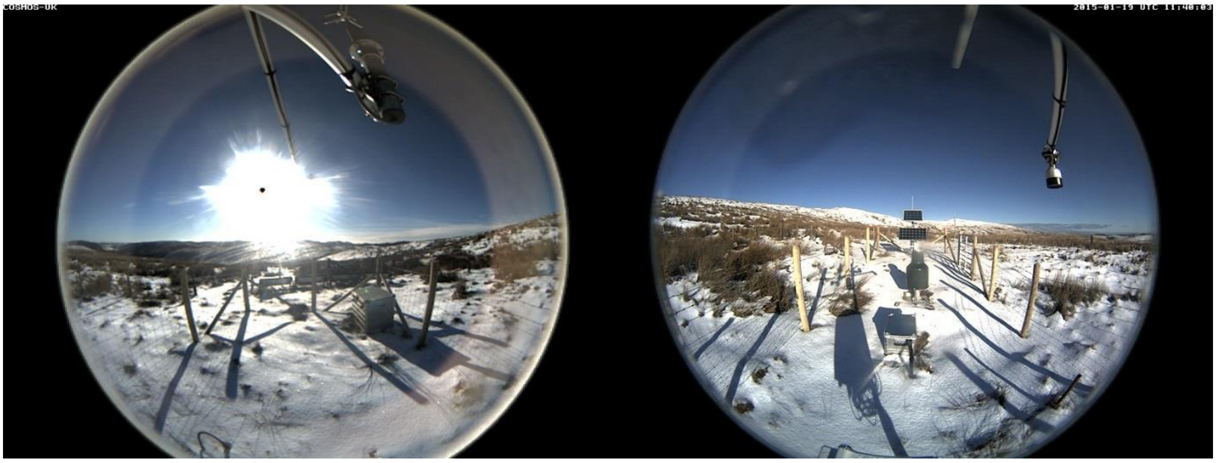


Figure C.2 Snow as recorded by the phenocam at Plynlimon. Note also the burning on the south facing image on the left caused by the camera pointing directly at the sun on a clear day.

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

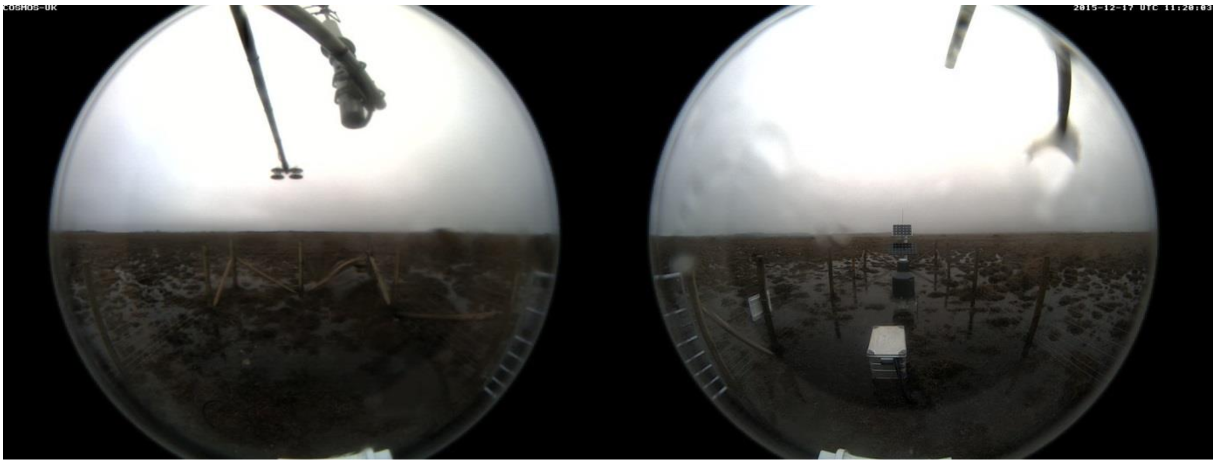


Figure C.4 Surface water ponding is not unusual after heavy rainfall at The Lizard which has a peaty top soil.

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

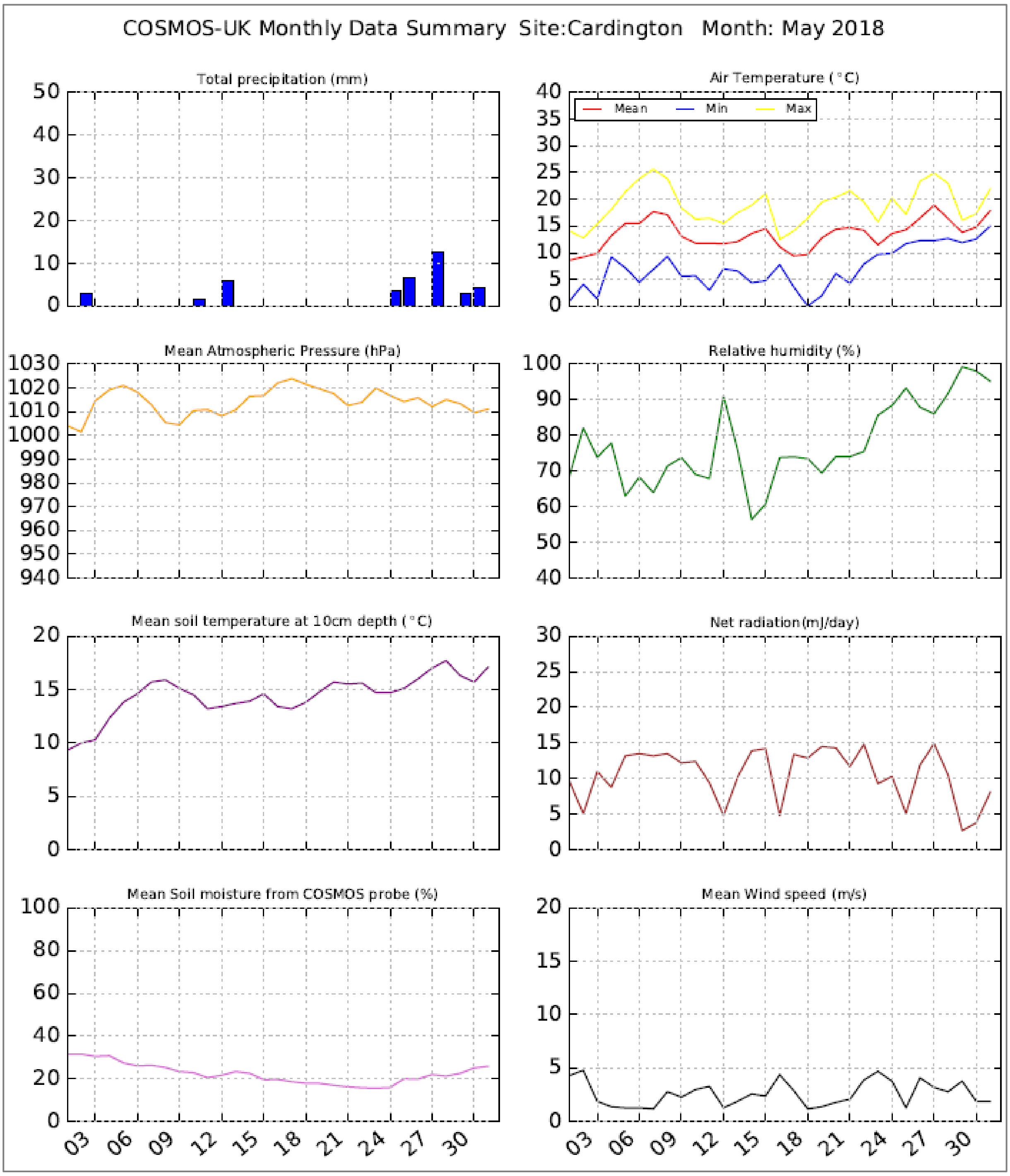
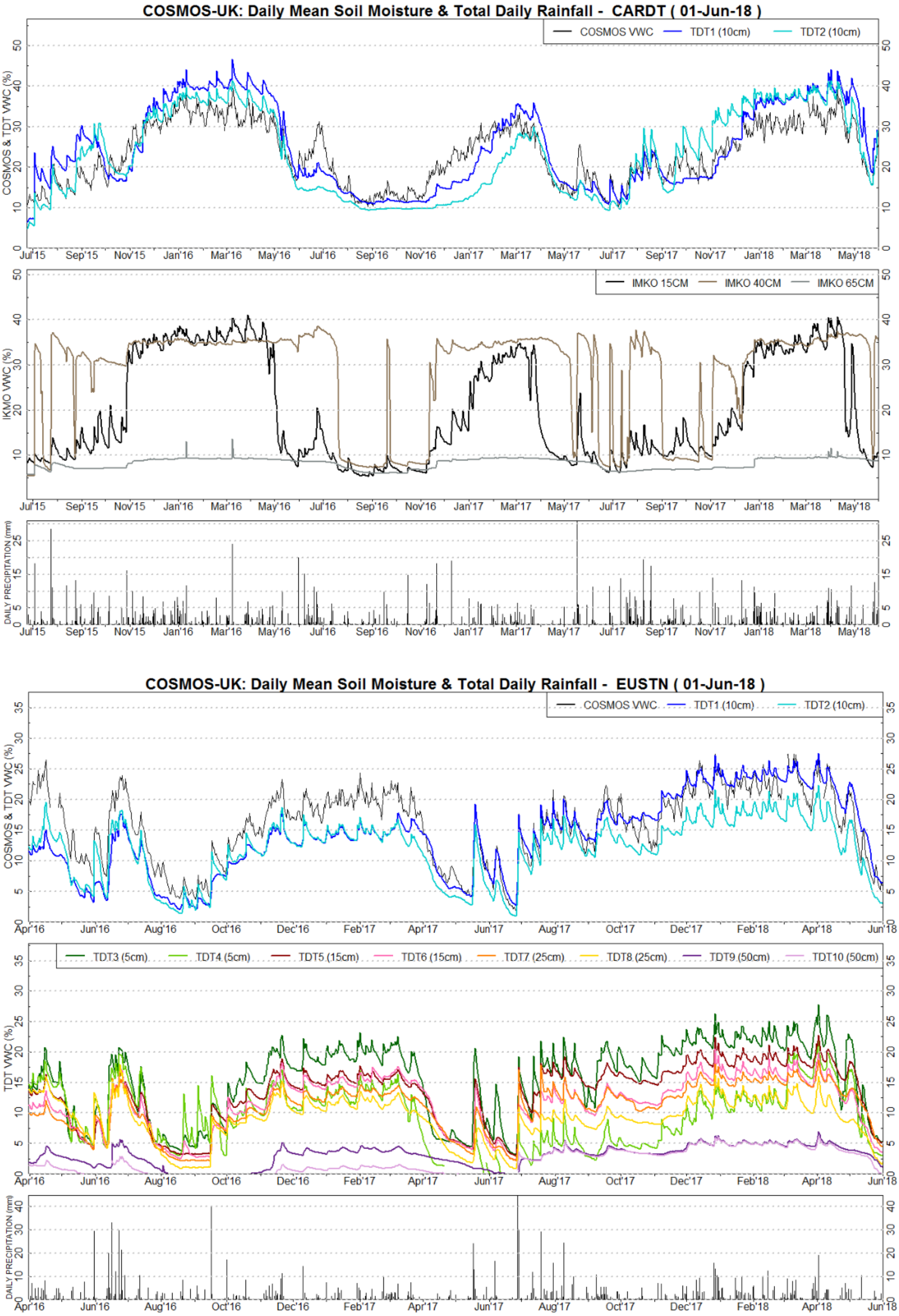


Figure D.2 Period of record soil moisture data from all COSMOS-UK instruments (top IMKO, bottom TDT array)



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

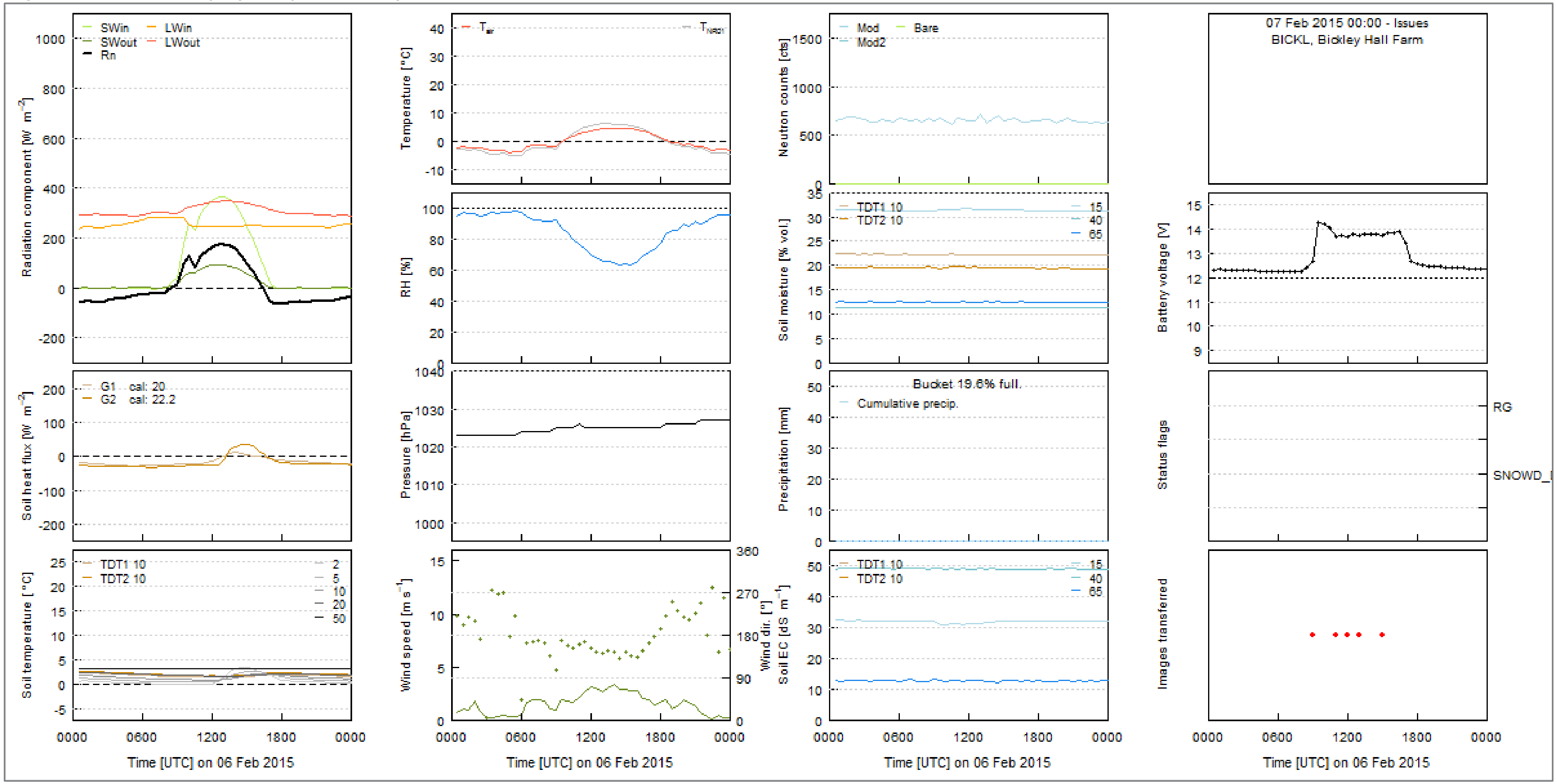
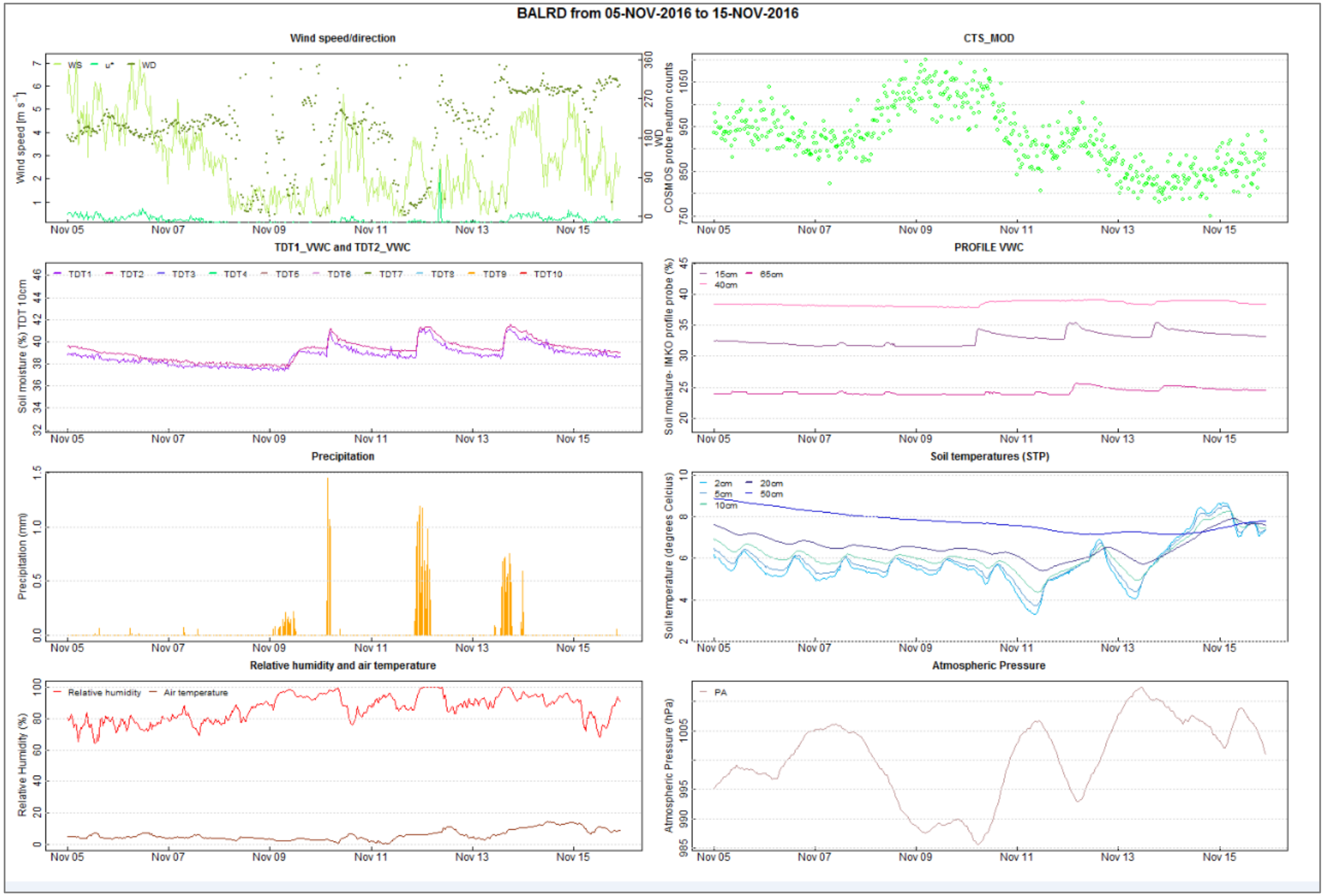


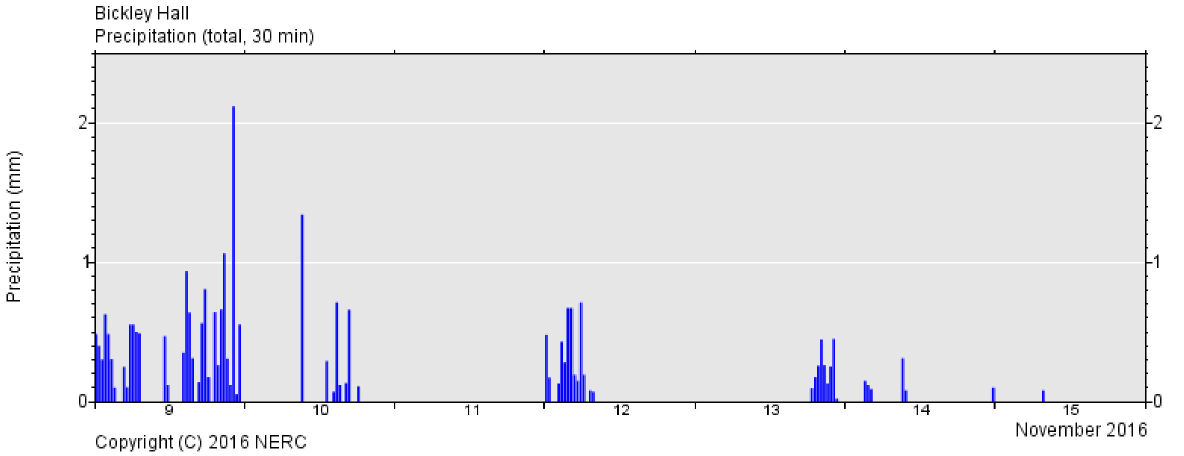
Figure D.4 10 Day quality control plot



Appendix E Embedding COSMOS-UK data plots in a website

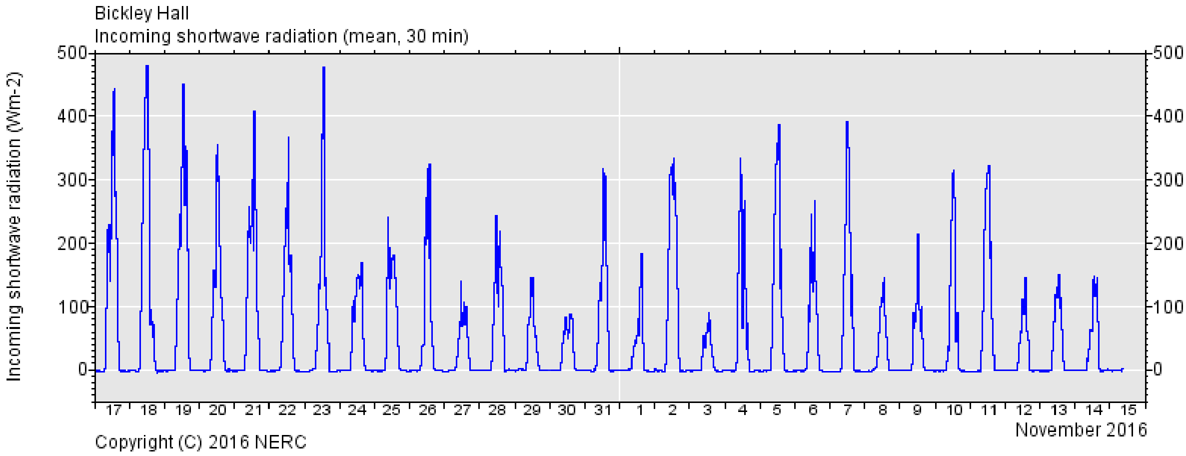
Users can use the url below to run an application that will produce a graph on a web page, in this case seven days of 30 minute rainfall are shown.

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.
Wind speed	WS_LEVEL2	
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	

Parameter	Code	Notes
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)	Derived from CRNS counts
D86 (depth to which 86% of the detected cosmic-ray neutrons had contact with constituents of the soil)	D86_xxM (hourly) D86_xxM_1DAY (daily)	Derived from CRNS counts. 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

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 CEH 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:

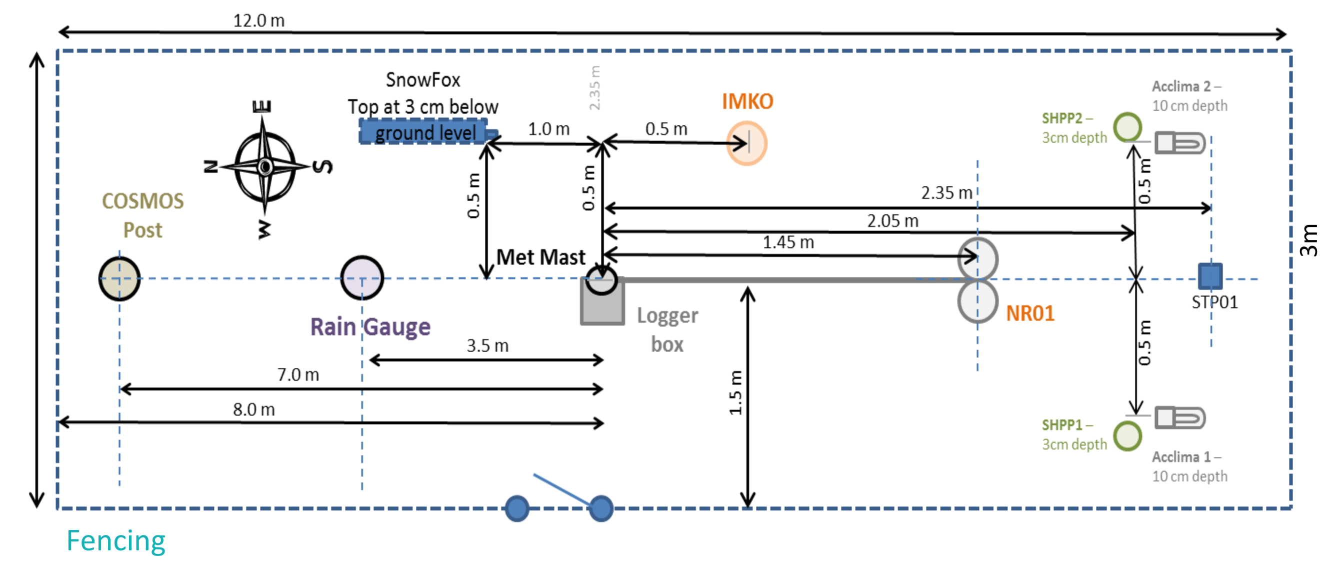
<img src="http://nrfaapps.ceh.ac.uk/nrfa/image/cosmos/graph.png?db-level=2&site=BICKL&parameter=PRECIPITATION_LEVEL2&days=7&w=800&h=300" width="800" height="300" alt="Rainfall graph" title="Graph of precipitation at Bickley Hall for the last 7 days">

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.

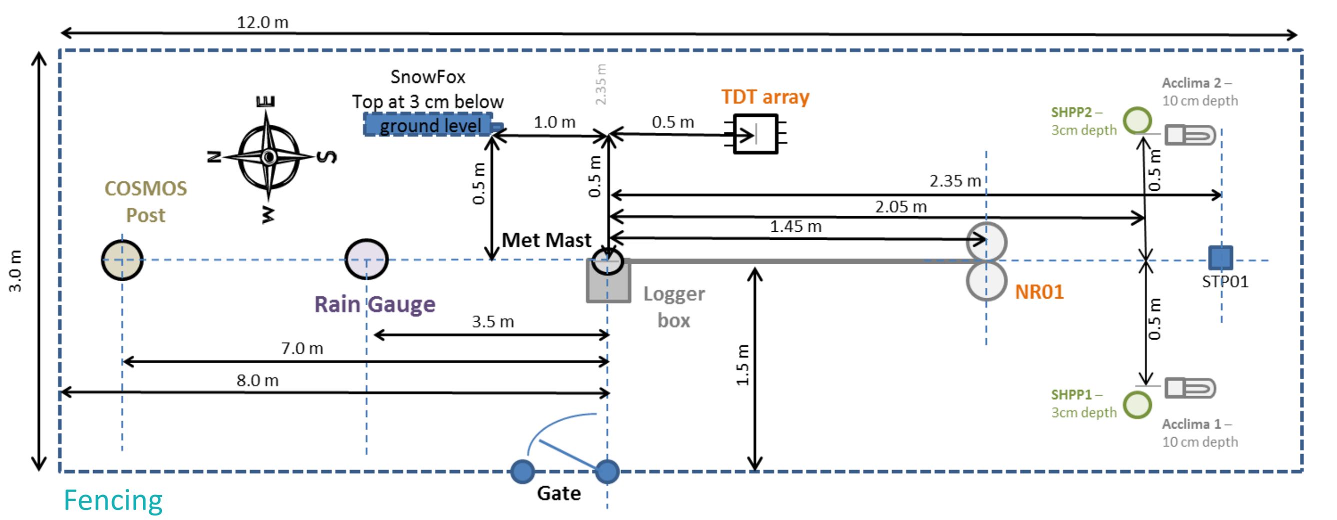
The html can be previewed by pasting the text into one of the many available online html editors, e.g. http://www.onlinehtmleditor.net or http://scratchpad.io .

Appendix F Site Layout

Original Layout - note SnowFox not at all sites



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
STP_TSOIL5		x	x	x		x			x
STP_TSOIL50		x	x	x		x			x

PARAMETER_ID	ZERO	SAMPLES	POWER	SENSOR_FAULT	DIAGNOSTIC	RANGE	SECONDARY_VAR	SPIKE	ERROR_CODE
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

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