Monitoring Relative Surface Soil Moisture Changes Across the Thames Basin using Sentinel-1

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Abstract

Soil moisture is a critical component in many meteorological, hydrological, and agricultural applications, and understanding its spatial and temporal dynamics is vital for the understanding of these processes. Satellite-based remote sensing offers the ability to synoptically capture this spatiotemporal information over large areas, compared to more site-based in-situ field measurements. In this study, we use Sentinel-1 SAR imagery of the River Thames catchment, United Kingdom, over the period 2015 - 2020. A backscatter normalisation process is applied to account for the use of multiple satellite viewing geometries. A change-detection algorithm utilising backscatter power is then applied to the timeseries, to estimate relative surface soil moisture (rSSM) across the study area. To determine information across the large river watershed, smaller sub-catchments, and intra-field scales, the rSSM time series is replicated at multiple spatial scales (1 km, 500m, 250m, and 100m). Although positive biases are present during the growing season of arable farmland, comparison with rainfall data and in-situ soil moisture probes shows there is good agreement with the temporal cycle of soil moisture. These data are being used to evaluate natural flood management by land use and management across a wide area to better understand relationships between surface wetness and water storage in relation to land cover and underlying geology for the Landwise project (Landwise-NFM.org).

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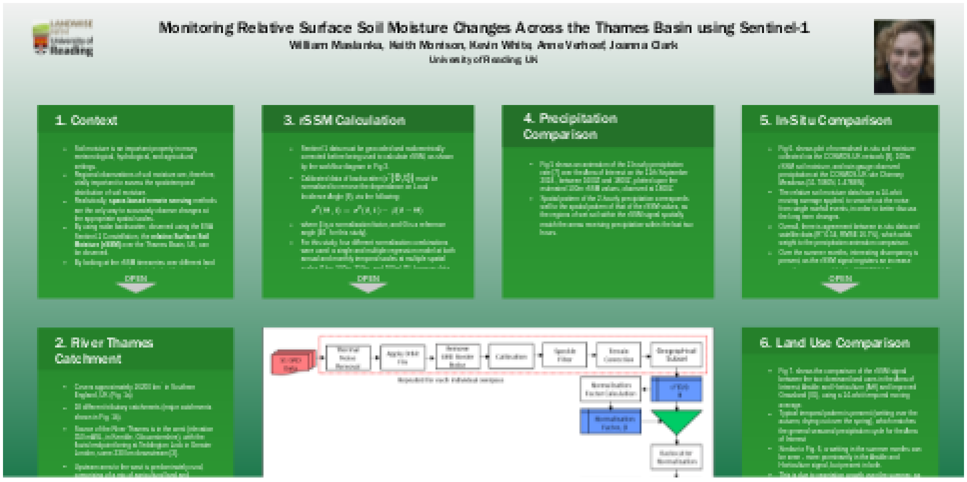

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1. CONTEXT

- Soil moisture is an important property in many meteorological, hydrological, and agricultural settings.
- Regional observations of soil moisture are, therefore, vitally important to assess the spatiotemporal distribution of soil moisture.
- Realistically, **space-based remote sensing** methods are the only way to accurately observe changes at the appropriate spatial scales.
- By using radar backscatter, observed using the ESA Sentinel-1 Constellation, the **relative Surface Soil Moisture (rSSM)** over the Thames Basin, UK, can be observed.
- By looking at the rSSM timeseries over different land cover types, we can begin to look at the impact of land use on soil moisture, to help inform Natural Flood Management (NFM).
- This study uses the TU Wein Change Detection Algorithm (TWCDA [1], Section 3), with a novel monthly multiple-regression normalisation factor, in order to attempt to correct for vegetation growth.

3. RSSM CALCULATION

- Sentinel 1 data must be geocoded and radiometrically corrected before being used to calculate rSSM, as shown by the workflow diagram in Fig 3.
- Calibrated data of backscatter ($\sigma^o(\theta,t)$) must be normalised to remove the dependance on Local Incidence Angle (θ), via the following:

$$\sigma^o(\Theta,t) = \sigma^o(\theta,t) - \beta(\theta - \Theta)$$

- where β is a normalisation factor, and Θ is a reference angle (40^o for this study).
- For this study, four different normalisation combinations were used: a single and multiple regression model at both annual and monthly temporal scales at multiple spatial scales (1km, 500m, 250m, and 100m) [5], however data shown here is from the multiple regression model at the monthly temporal scale at 100m, as detailed below:

$$\beta_r(t) = a(t)\hat{S}(t) + b(t)\overline{\sigma^o}(t) + c(t)$$

- where $\beta_r(t)$ is the monthly multiple regression normalisation factor, $\hat{S}(t)$ is the non-normalised sensitivty, $\overline{\sigma^o}(t)$ is the mean backscatter, and *a*, *b*, and *c*, are constants for month *t*.
- After angle normalisation, the rSSM timeseries can be calculated using the TWCDA, [1]:

$$rSSM(t) = \frac{\sigma^o(\Theta,t) - \sigma^o_d(\Theta)}{S(\Theta)} = \frac{\sigma^o(\Theta,t) - \sigma^o_d(\Theta)}{\sigma^o_w(\Theta) - \sigma^o_d(\Theta)}$$

- where S(Θ) is the normalised Sensitivity between the wet backscatter threshold ($\sigma^o_w(\Theta)$) and the dry backscatter threshold ($\sigma^o_d(\Theta)$) (Fig. 4).

4. PRECIPITATION COMPARISON

- Fig 5 shows an animation of the 2-hourly precipitation rate [7] over the Area of Interest on the 11th September 2018., between 1600Z and 1800Z, plotted upon the estimated 100m rSSM values, observed at 1800Z.
- Spatial pattern of the 2-hourly precipitation corresponds well to the spatial pattern of that of the rSSM values, as the regions of wet soil within the rSSM signal spatially match the areas receiving precipitation within the last two hours.

5. IN-SITU COMPARISON

- Fig 6. shows plot of normalised in-situ soil moisture collected via the COSMOS-UK network [8], 100m rSSM soil moisture, and rain gauge observed precipitaiton at the COSMOS-UK site Chimney Meadows (51.7080N, 1.4788W).
- The relative soil moisture data have a 14-orbit moving average applied, to smooth out the noise from single rainfall events, in order to better discuss the long term changes.
- Overall, there is agreement between in-situ data and satellite data (R^2:0.54, RMSE 16.7%), which adds weight to the precipitation animation comparison.
- Over the summer months, interesting discrepancy is present, as the rSSM signal registers an increase over the summer, whilst the COSMOS-UK VWCI data often decreases.
- This is due to an increase in vegetation growth at the surface, adding an additional contribution to the backscatter signal observed.
- Most obvious over the summer of 2018, where no rain fell between end of May and July.

2. RIVER THAMES CATCHMENT

- Covers approximately 16200 km^2 in Southern England, UK (Fig. 1a)
- 18 different tributary catchments (major catchments shown in Fig. 1b).
- Source of the River Thames is in the west (elevation 350 mASL, in Kemble, Gloucestershire), with the fluvial endpoint being at Teddington Lock in Greater London, some 230 km downstream [3].
- Upsteam area to the west is predominately rural, comprising of a mix of agricultural land and woodland over rolling hills on chalk and limestone geology, with flatter areas being on clays.
- Towards the centre and the east of the catchment, the land becomes increasingly urbanised, as the River Thames flows through Oxford, Reading, and into London.
- Climate of the River Thames Catchment is categorised as Temperate Oceanic (Cfb) by the Koppen climate classification, and received an average of 747 mm (24.9 in) of precipitation annually, over the 1981 - 2010 time period.
- Higher monthly precipitation values generally occur over the autumn and winter months, from cyclonic frontal systems, with flashier, intense thunderstorms producing large rainfall totals in the summer months; both of which have lead to a number of fluvial flooding events in recent years [4,5]

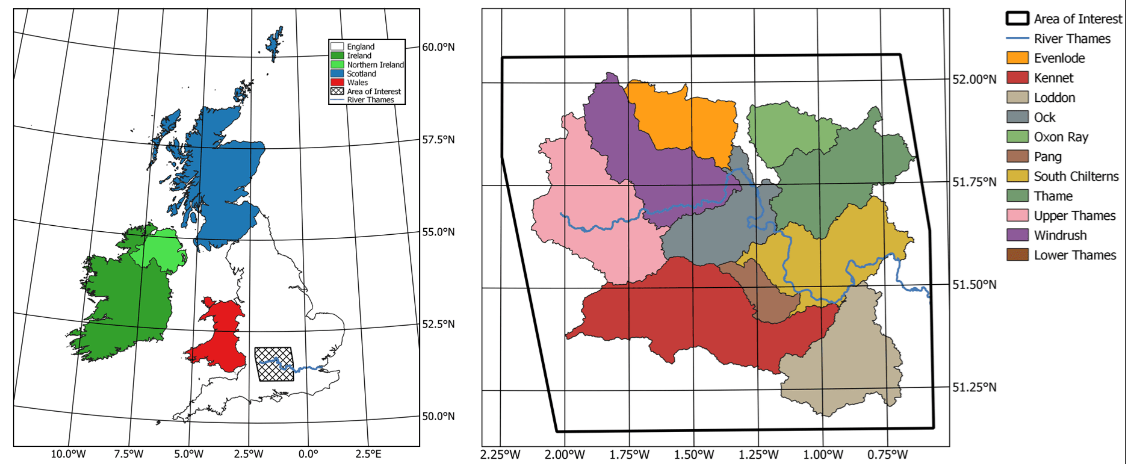


Fig. 1a: Geographical Location of Area of Interest

Fig. 1b: Complete Catchments that fall within the Area of Interest

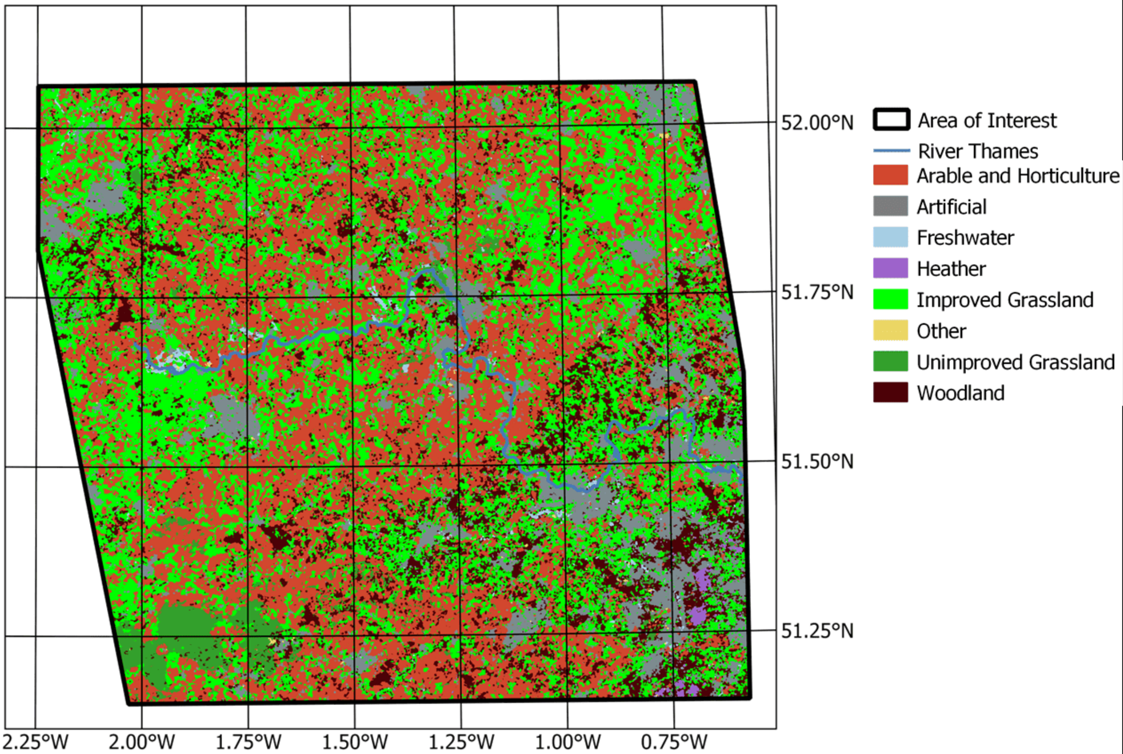


Fig. 2: Land Use of Area of Interest. Taken from [2]

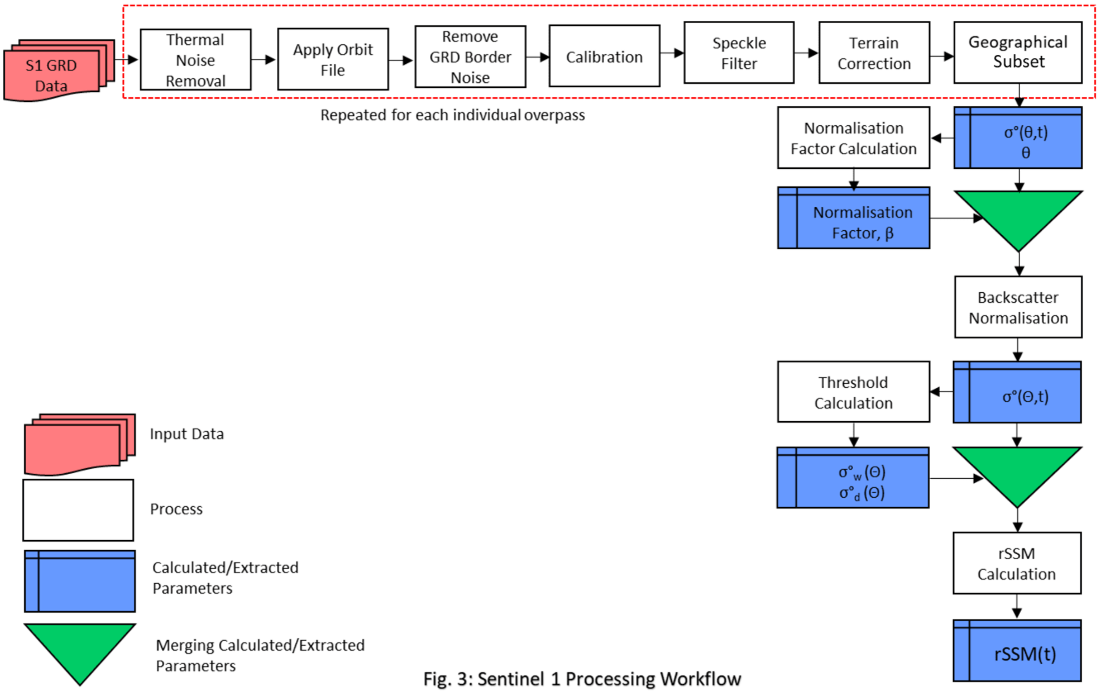


Fig. 3: Sentinel 1 Processing Workflow

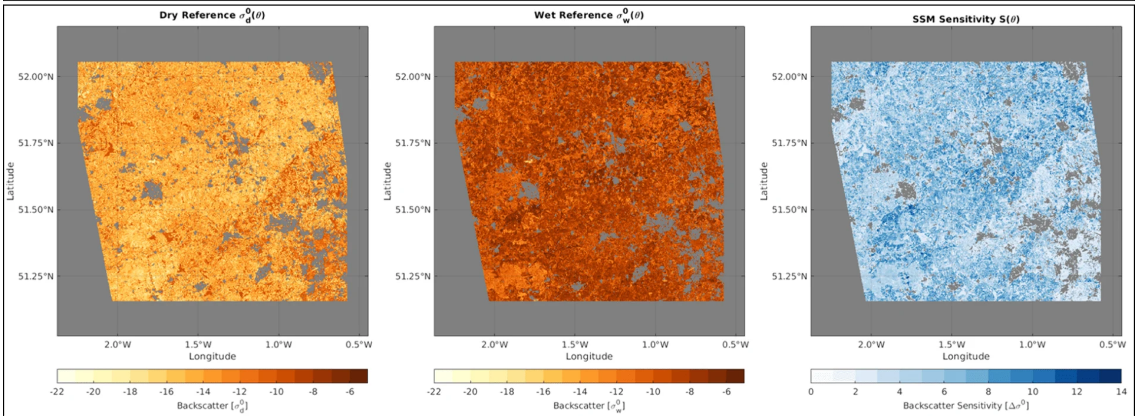
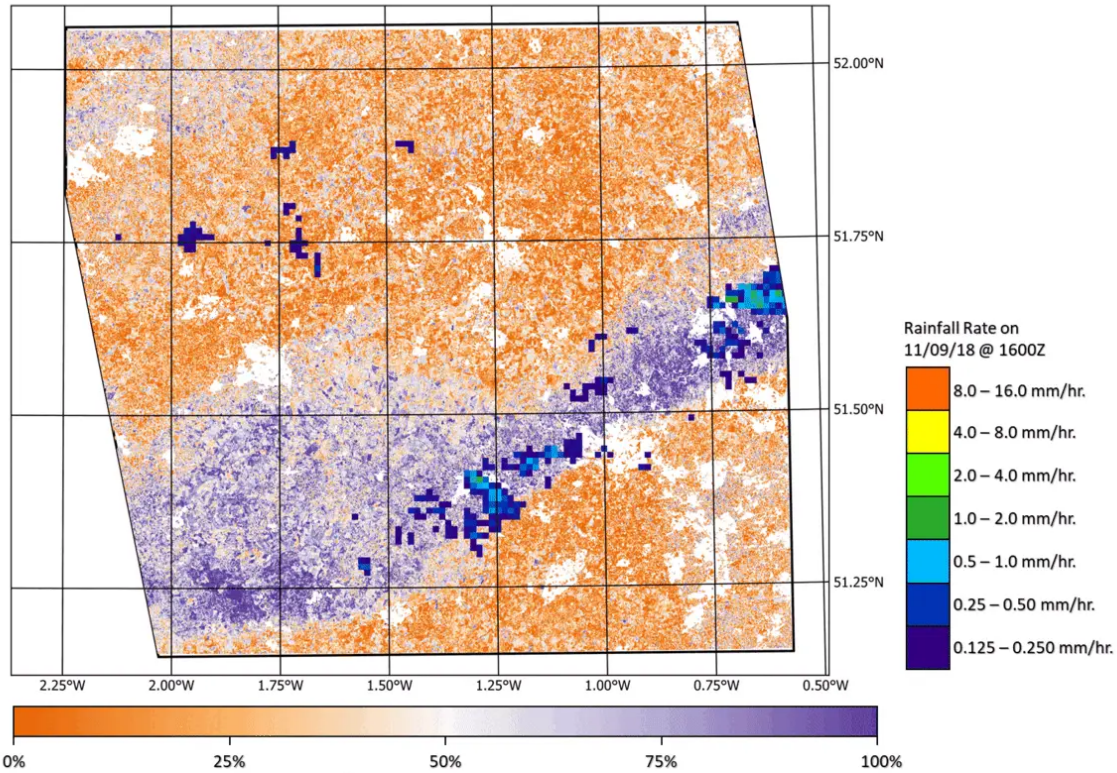


Fig. 4a: Dry Threshold $\sigma^{\circ}_{d}(\Theta)$

Fig. 4b: Wet Threshold $\sigma^{\circ}_{w}(\Theta)$

Fig. 4c: Backscatter Sensitivity $S(\Theta) = \sigma^{\circ}_{w}(\Theta)\ \sigma^{\circ}_{d}(\Theta)$



rSSM for 11th September 2018; calculated at 18:00Z

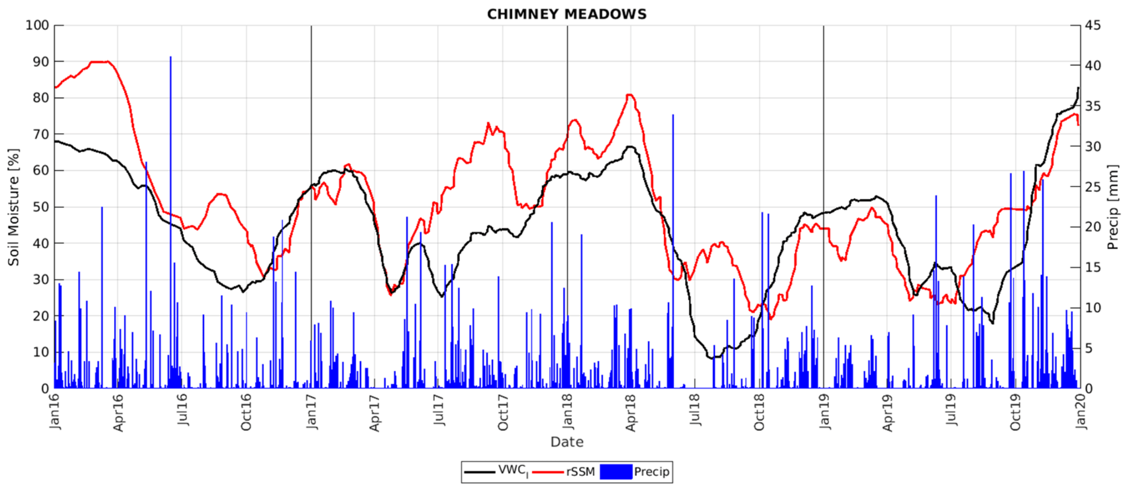


Fig. 6: 14-orbit moving average Volumetric Water Content Index (VWC$_I$), 100m rSSM, and observed precipitation at Chimney Meadows, UK.

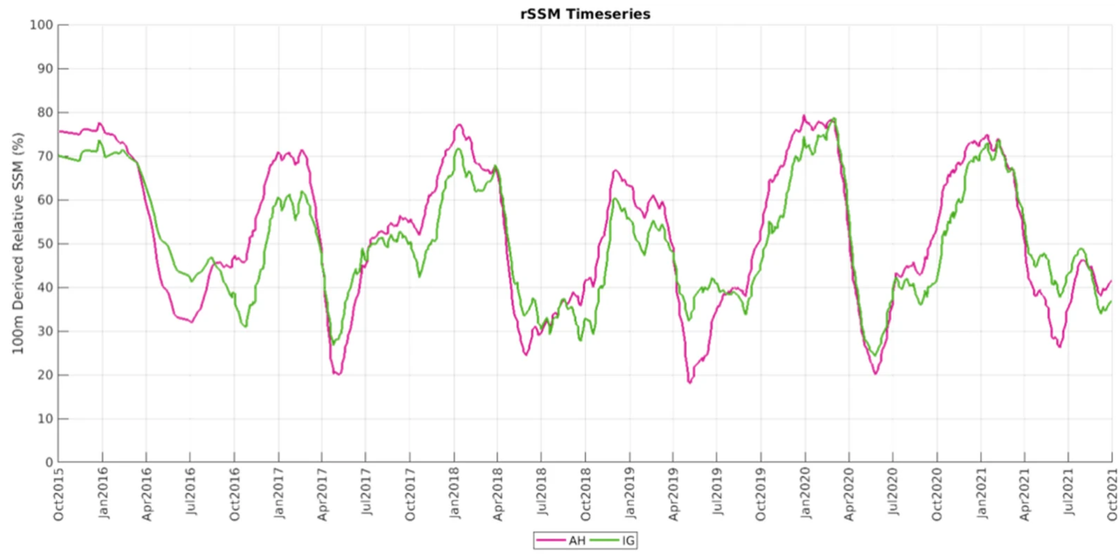


Fig. 7: 14-orbit moving average rSSM value for Arable and Horticulture (AH, pink), and Improved Grassland (IG, green), as detailed by [1].

6. LAND USE COMPARISON

- Fig 7. shows the comparison of the rSSM signal between the two dominant land uses in the Area of Interest; Arable and Horticulture (AH) and Improved Grassland (IG), using a 14-orbit temporal moving average.
- Typical temporal pattern is present (wetting over the autumn, drying out over the spring), which matches the general seasonal precipitation cycle for the Area of Interest
- Similar to Fig. 6, a wetting in the summer months can be seen - more prominantly in the Arable and Horticulture signal, but present in both.
- This is due to vegetation growth over the summer, as there is an increased contribution of backscatter signal from overlying vegetation.

DISCLOSURES

This research was funded by Natural Environment Research Council (NERC) LANDWISE project (NE/R004668/1), part of the NERC Evaluating the Effectiveness of Natural Flood Management Research Programme.

ABSTRACT

Soil moisture is a critical component in many meteorological, hydrological, and agricultural applications, and understanding its spatial and temporal dynamics is vital for the understanding of these processes. Satellite-based remote sensing offers the ability to synoptically capture this spatiotemporal information over large areas, compared to more site-based in-situ field measurements. In this study, we use Sentinel-1 SAR imagery of the River Thames catchment, United Kingdom, over the period 2015 - 2020. A backscatter normalisation process is applied to account for the use of multiple satellite viewing geometries. A change-detection algorithm utilising backscatter power is then applied to the timeseries, to estimate relative surface soil moisture (rSSM) across the study area. To determine information across the large river watershed, smaller sub-catchments, and intra-field scales, the rSSM time series is replicated at multiple spatial scales (1 km, 500m, 250m, and 100m). Although positive biases are present during the growing season of arable farmland, comparison with rainfall data and in-situ soil moisture probes shows there is good agreement with the temporal cycle of soil moisture. These data are being used to evaluate natural flood management by land use and management across a wide area to better understand relationships between surface wetness and water storage in relation to land cover and underlying geology for the Landwise project (Landwise-NFM.org).

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