09- The Irish Soil Moisture Observation Network - ISMON

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Abstract

Real-time soil moisture measurements are essential to manage climate change adaptation and reduce nutrient losses and greenhouse gas emissions from agriculture and forestry. Soil moisture status influences crop growth, run-off, groundwater recharge and atmospheric dynamics. In this paper we present the Irish Soil Moisture Observation Network (ISMON) as the integrator of several long-term environmental observational networks (AGMET, COSMOS UK - NI, Teagasc, NASCO and Terrain-AI), all of which include several different methodologies for measuring soil moisture at field scale. AGMET is installing novel cosmic ray neutron sensors which can provide landscape averaged soil moisture estimates and NASCO and Terrain AI are using Time Domain Reflectometry probes. Such networks are seen as bridging the scale gap between field-based measurements and satellite-derived soil moisture products and are important in monitoring key biogeochemical processes that vary rapidly in time and space. In the initial phase of the implementation of AGMET network, the current distribution of the stations in relation to the other networks are presented, with the aim being to cover the most relevant soil type, land cover, and climate regimes. It is envisioned that the ISMON will grow further to complete any current shortcomings in the set-up, and feed directly into similar international soil moisture monitoring networks.

Keywords: *Soil Moisture Measurements, Cosmic Ray Neutron Sensors, TDR, TDT, Long-term monitoring network*

1. Introduction

Soil Moisture (SM) is a designated Essential Climate Variable (Global Climate Observing System) as it plays a crucial role in environmental processes such as the water cycle, climate and weather change, vegetation growth and groundwater availability. SM data are required for assessments of agricultural crop and forest production, runoff in response to precipitation events (Robinson *et al.*, 2008), for coupled atmosphere and land surface models for flooding and drought (Seneviratne *et al.*, 2010), and input into Earth System models (Trugman *et al.*, 2018).

Spatial variation in SM are driven by dynamic and static parameters such as redistribution of precipitation inputs responding to elevation, soil type, soil density, underlying geology, local crop growth and nutrition (Qiu *et al.*, 2001). SM can be estimated on the ground using a variety of point/field scale measurements e.g., Babaeian *et al.* (2019). Several satellite-derived global SM data products have been released during the past decades with a resolution of 10's km (the Soil Moisture Active Passive (SMAP) and the European Space Agency's Climate Change Initiative for Soil Moisture (ESA CCI SM). Higher spatial resolutions can be achieved by using satellite observations with higher native resolution (e.g. coherence SAR, thermal infrared) (Das *et al.*, 2019), or by applying appropriate downscaling techniques to the coarse-scale observations (Zappa *et al.*, 2019). The calibration of existing products to ground-based measurements remains a challenge and is the focus of ongoing research.

The recent development of Cosmic Ray Neutron Sensors (CRNS) sensors (Zreda *et al.*, 2012) provides ground-based measurements of SM to an effective depth of ~ 0.1 m to 0.8 m over a footprint of ~ 350 m diameter, depending on the water content of the soil. To improve the monitoring of in-situ SM, CRNS are often deployed in networks at either catchment or national scales. Examples exist in the UK (Cooper *et al.*, 2021), United States (Zreda *et al.*, 2012), Australia (Hawdon *et al.*, 2014), Germany (Baatz *et al.*, 2014; Fersch *et al.*, 2020) and Kenya and India (Montzka *et al.*, 2017; Upadhyaya *et al.*, 2021). This method is increasingly seen as a tool in bridging the gap between scales provided by traditional in-situ measurements (point- and field-scale) and satellite-derived products.

In Ireland, ground-based SM is rarely measured in-situ (systematically) as volumetric water content (EPA 267, 2019), but is frequently expressed as Soil Moisture Deficit (SMD). SMD is driven by patterns of precipitation and actual evapotranspiration ($ET_{a)}$. (Walsh, 2012; O'Sullivan *et al.*, 2018). SMD is estimated on a daily time step for different drainage classes using precipitation and ET_a data. Building on previous models used by Teagasc and Met Éireann, Schulte *et al.* (2015) developed a model (HSMD2.0) for computing SMD to account for differences in drainage regimes and five soil drainage classes. SMD is at the interface between agriculture and the environment and has been used widely with models to predict hydrological time lags in nutrient losses (Fenton *et al.*, 2011; Vero *et al.*, 2014), and as part of the process of estimating groundwater recharge (Hunter Williams *et al.*, 2013) and climate change impacts on groundwater (Schuler et al, 2020). The EPA (2019) emphasises the need for actual SM measurements across the different drainage classes in Ireland and points towards Earth Observation (EO) as a possible solution to produce high-resolution SM maps across the whole country. Thus, Ireland needs to establish a national in-situ SM network and integrate these datasets with EO research in Ireland.

This paper outlines important steps in the ongoing establishment of Irish Soil Moisture Observation Network ISMON. ISMON pulls together several initiatives and stakeholders with interest in the long-term monitoring of SM in Ireland, which will be integrated and coordinated to produce data products for improved climate modelling, land management and monitoring of key biogeochemical processes.

2. Methods

2.1 The ISMON umbrella

The AGMET group (Joint Working Group on Applied Agricultural Meteorology) decided in early 2020 to work towards establishing a SM monitoring network for Ireland. After reviewing the current technology for SM monitoring it was decided to aim for a field level measurement approach, and to complement this with an array of in-situ measurement. Funding was obtained from the Department of Agriculture, Food and the Marine (DAFM) under the national Carbon Tax Fund to establish a network of 10 sites equipped with (CRNS) stations, and five TDR (Time Domain Reflectometry) SM probes at each site.

More recently, in 2021, the National Agricultural Soil Carbon Observatory (NASCO) has been approved and will be funded by the Department of Agriculture, Food and the Marine (DAFM), and is run by Teagasc. The data generated will provide accurate, long-term information on the carbon dynamics of Irish agricultural systems. Establishment is currently underway and will include 18 eddy covariance flux towers, which also include SM TDR probes located on benchmark sites including agricultural grasslands, crop areas, and forestry, covering both mineral soils and peatlands. The data generated will provide accurate, long-term information on the carbon dynamics of Irish agricultural systems.

In parallel, the Terrain-AI project, led by Maynooth University in collaboration with other Irish institutions (Teagasc, TCD, UCD, DCU and UL) is focused on improving our understanding of the impact of human activity on land use and how it relates to climate change. Terrain-AI aims at informing the development of more effective, spatially refined policies around carbon management and mitigation. Data are being captured from satellites, airborne platforms, as well as in-field instruments, from 25+ benchmark sites strategically located across Ireland, including the new NASCO sites. As SM plays a key role in driving carbon and moisture fluxes, a core component of Terrain-AI is the expansion of the soil monitoring network. In addition to the SM measurements obtained at the flux towers locations, Terrain-AI will be installing ~12 TDR probes across different SM regimes.

Established in 2013, COSMOS-UK is a network of 50 sites across the UK, with the primary purpose of delivering SM data in near real-time from a variety of soil and land-use types. There are currently three COSMOS-UK stations in Northern Ireland (installed in 2016 & 2018), with a further 2-3 sites planned. All COSMOS-UK stations are equipped with a CRNS, along with point SM sensors at various depths using the time-domain transmissometry (TDT) technique. All COSMOS-UK sites are managed centrally by the UK Centre for Ecology & Hydrology (CEH) at Wallingford, with data transfer via the mobile phone network. Collaboration has been established with COSMOS-UK and their three stations in Northern Ireland will become part of ISMON.

2.2 Site selection and Co-location

In the first phase of ISMON, the plan is to cover a range of factors influencing SM, i.e. climate, soil type, land cover, and elevation. The AGMET 10 CRNS locations were chosen in consultation with the NASCO, Terrain-AI and HSP. Establishment of the NASCO is currently underway. The 12 Terrain-AI in-situ hydrological measurement sites are mostly collocated with Met Éireann synoptic stations. The Teagasc HSP programme has established a limited in-situ monitoring programme of SM on three of its farms.

The distribution of sites from the first phase of ISMON is shown in Figure 1. It is envisioned that the network will expand.

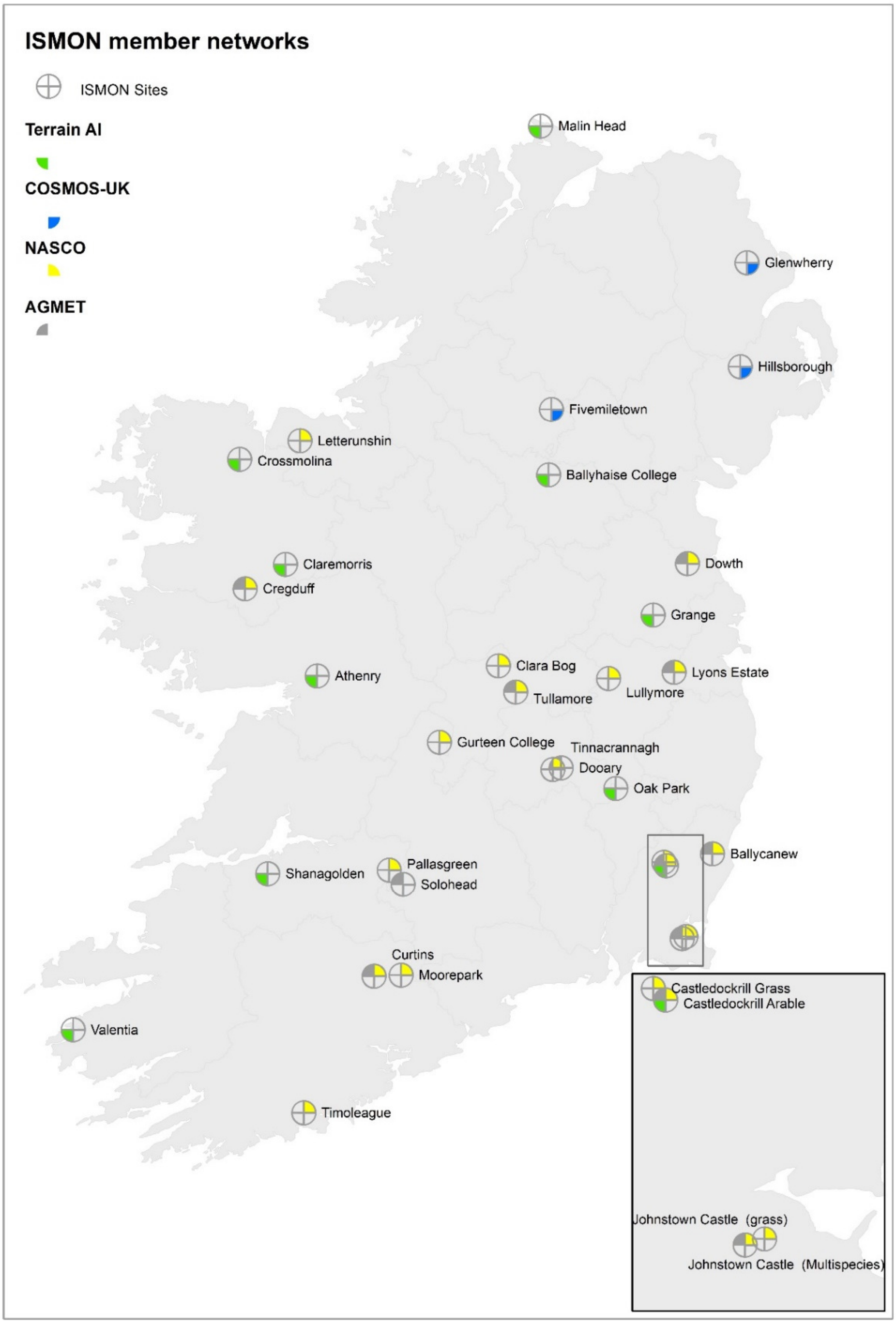

***Figure 1**: Map of the site location of the constituent networks of ISMON. Some sites are part of more than one network. In total there are 32 sites.*

2.1 CRNS sensors and stations

The cosmic ray neutron sensor (CRNS) detects and counts the number of neutrons in the soil and in the air just above the soil (Zerda *et al.*, 2012). The neutrons are produced by incoming cosmic rays (mainly protons) from outside the solar system. By the time the neutrons reach the Earth's surface, they are very fast-moving and are available for absorption by the environment. The number of fast neutrons in and around the soil are counted to determine how much water is present. Drier soil has more fast-moving neutrons, while wetter soil has fewer because more hydrogen from the water is available to absorb the energy. These sensors work in a similar way to neutron probes but use cosmic rays as the source of fast neutrons for displacing slow neutrons for measurement. The CRNS converts fast neutron counts to SM, accounting for variations in atmospheric pressure, humidity and the intensity of incoming cosmic rays. Due to the higher propagation of cosmic rays in thin air, the lateral footprint of the sensor is inversely proportional to the atmospheric (vapour) pressure and is up to 300 m in diameter. The penetration depth strongly depends on the SM content (Franz *et al.*, 2012) and varies from 15 cm in wet soils to approximately 70 cm in dry soils, which decreases exponentially with distance from the sensor (Köhli *et al.*, 2015). Active research is ongoing into the exact footprint sensitivity of the sensors. Research has also focused on how to interpret the measured signals, as it includes responses from the presence of water in vegetation and subsurface biomass as well as clay (Baatz *et al.*, 2015).

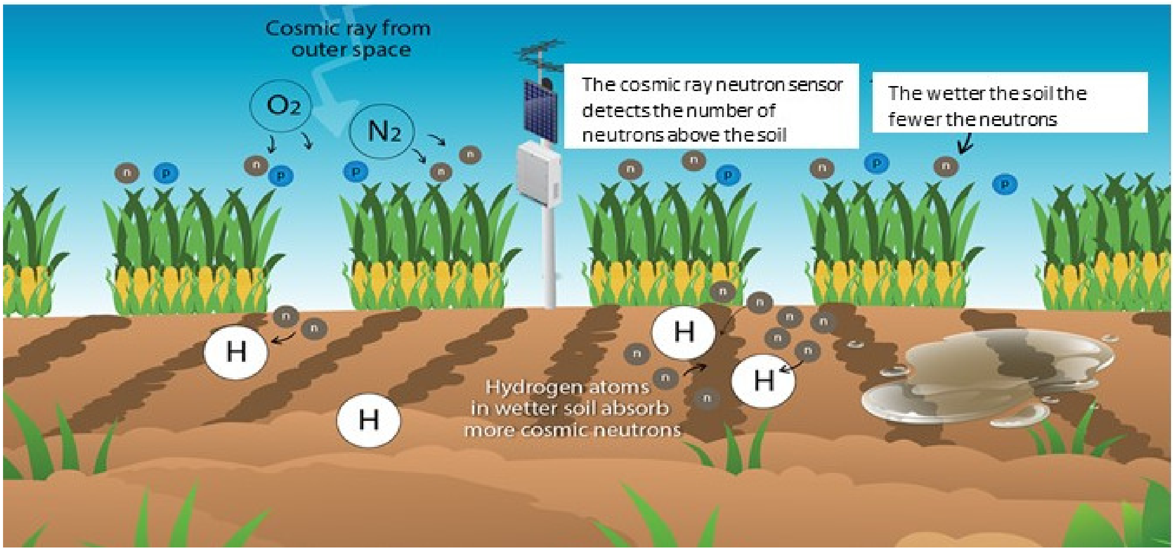

Figure 2*: Illustration of how cosmic rays can be used to measure SM. Taken from https://www.iaea.org/newscenter/news/using-cosmic-rays-to-measure-moisture-levels-in-soil (Infographic: R. Kenn/IAEA)*

At each ISMON station, measurements of barometric pressure, relative humidity, air temperature, wind velocity, precipitation and net solar radiation will be made to provide data for hydro-meteorological modelling. The stations are solar- and battery powered and use a 3G/4G modem to transmit real-time data and allow remote monitoring for efficient maintenance. Figure 3 shows a schematic of a typical AGMET station installation.

Figure 3: *AGMET installation of CRNS at Tullamore Farmer's Journal Farm. Photo by T. Hochstrasser*

3. Calibration and data processing: the next steps

A significant volume of work needs to be carried out to calibrate a CRNS station before it can produce reliable SM information. Example CRNS output data is displayed in Figures 4 and 5 from the COSMOS UK Fivemiletown site in Co. Tyrone. A Walsh Fellow PhD student (Teagasc - Met Éireann co-funded) from UCD will focus on the calibration of the CRNS stations. Spatially-weighted sampling will be carried out at each site to get direct measurements of volumetric water content to characterise the *spatial* variability within the measurement footprint (Schrön *et al.*, 2017). In this method, samples for volumetric water content will be taken in a 'spiderweb' pattern within the footprint of the CRNS. This will allow direct comparison of volumetric water content to the CRNS measurements. Furthermore, soil bulk density, texture (sand, silt and clay), clay structural (lattice) water, soil organic carbon and standing biomass can influence CRNS measurements (IAEA, 2017). Soil samples taken for volumetric water content will thus also be analysed for these parameters and standing biomass within the footprint will be estimated based on point samples/ existing data. If deemed necessary, this calibration field sampling will be repeated over time under different weather conditions. Detailed soil water retention curves will be constructed for the soils at each site to further characterise the soil hydraulic properties.

Five SM probe arrays (TDR probes installed over depth) are installed at each of the AGMET sites within the measurement footprint of the CRNS. Two of these arrays are at 1 m distance from the CRNS, while three are at 20 m distance from the CRNS. Soil-specific calibrations of the SM probes will be carried out for each site. These arrays will capture temporal variability in SM conditions over depth (5 – 100 cm). In combination, the information from SM probes and soil sampling will provide the necessary capture of spatial and temporal variability to calibrate and validate the CRNS measurement.

Soil samples have been taken over depth during the installation of the SM probe arrays at each of the arrays for determination of soil bulk density, texture, organic matter content, and coarse fragment content. This detailed characterisation of the soil at each array location will aid in the process of calibration.

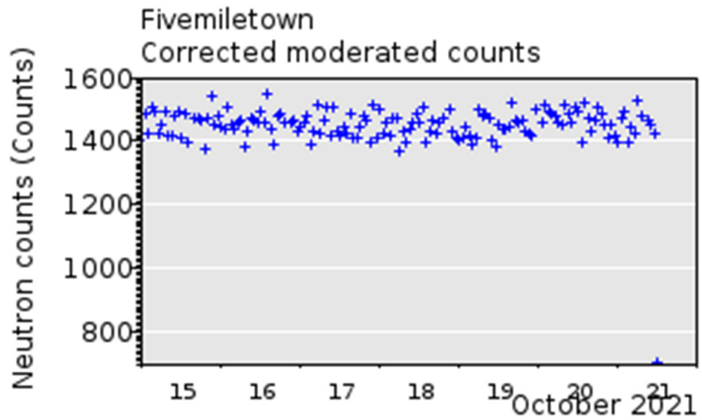

Figure 4: *Live daily neutron counts from the COSMOS UK Fivemiletown site*

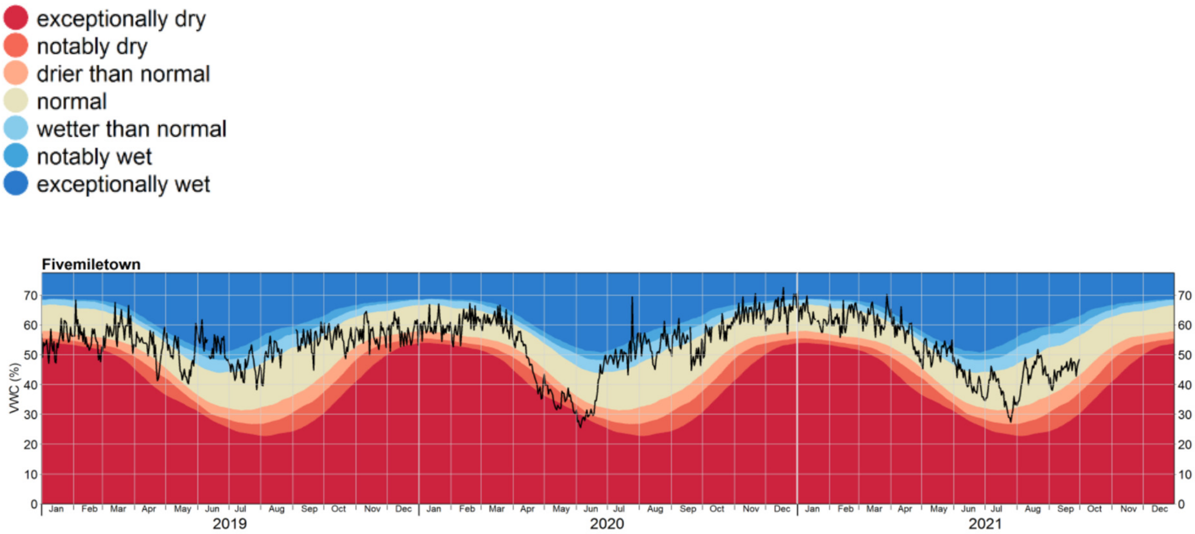

Figure 5: *Mean annual soil Volumetric Water Content (VWC %) at the Fivemiletown COSMOS UK site in 2019, 2020 and 2021, displayed as a black line. The coloured bands indicate historical variability for the site and time of year.*

4. Potential impact of ISMON on Irish hydrology

SM represents a buffer storage between incoming rainfall, and outgoing runoff and percolation to groundwater. Hence it has a key role in understanding catchment hydrology, its modelling, and its influence in moderating water partitioning and water quality. With flood modelling, antecedent conditions are very important and it is known that the same rainfall can produce quite different flood responses depending on whether the catchment is dry or wet. For instance, in 1986 Hurricane Charlie produced two periods of intense rainfall on the Dublin and Wicklow Mountains, the first more severe than the second. Yet it was the second period of rain that produced a much larger flow peak because the catchment was wet after the rain from the first event. Such nonlinear responses, mediated by SM conditions can be seen in most rainfall and flow hydrograph comparisons. Methods have been developed for assimilating SM information into catchment models, whether from remote sensing or in-situ sources (Weisse *et al.*, 2003, Massari *et al.*, 2015, Masseroni *et al.*, 2016, Brocca *et al.*, 2017), with improvements in flood forecasting in many cases. However, each SM data source can have methodological issues (Yang and O'Loughlin, 2020, McCabe *et al.*, 2017), and results can depend on the spatial formulation of the catchment model and whether the catchment is gauged (which facilitates model updating) (Alvarez-Garreton *et al.*, 2015).

SM plays a major role in landslides, soil erosion (Wen *et al.*, 2021) and the failure of steep embankments (think of roads, trains, houses etc.) (Briggs *et al.*, 2017) and river banks. Practical warning systems for these hazards require both precipitation and SM information (Baum and Godt, 2010, Guzzetti *et al.*, 2020).

SM information also has a role in ecohydrological modelling, whether for water fluxes (Hallouin *et al.*, 2020), for vegetation dynamics (Wang *et al.*, 2019) including forestry (Neill *et al.*, 2021), or for disease modelling (Montosi *et al.*, 2012). SM is a key determinant of many soil processes influencing both agronomic and environmental outcomes. Real-time monitoring, quality control and utilisation of SM data is key to enable the creation of decision-support tools (DSTs) in soil management, particularly relating to the temporal and spatial dynamic variation aspects. High resolution SM monitoring could better support assessments of agricultural emissions related to leaching and gaseous losses, (rather than relying on models which are calibrated to test environments and don't necessarily translate to wider environments). SMD is a key SM parameter for guiding management decisions, and in Ireland, a relatively simple model is currently used to estimate SMD for well-, moderate- or poorly-drained soils. The ISMON network described here will further develop our understanding and ability to model SMD and support development of an improved SM model that could be generalised across the range of Irish soil types and climatic conditions. This could allow for the concept of functional land management (O'Sullivan *et al.*, 2015) to come closer to reality.

The prospect of real-time observations of SM with broad national coverage will facilitate a major leap forward for hydrological modelling and can become an important component of our national flood and/or landslide warning system. It would also contribute directly to the national fire index warning system and indicative of forest stability risks during cyclonic activity (Rogo et al., 2021). It will also enable better understanding of extreme flood generation, and a refinement of the analysis of their frequency, leading to better estimation of design flood peaks. The estimation of groundwater and its management will also be improved. However, the structure of hydrological models may need adjustment to make best use of and assimilate the new data source, taking account of whether it is point source data (as here) needing upscaling or more distributed data if it comes from remote sensing. While most hydrological models do have internal components related to SM, in the classical models, they are typically lumped simplistic conceptualisations that are challenging to relate to specific measurements in highly heterogeneous Irish soils, and more work will be required here.

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