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Soil Moisture Measurement FOR AGRICULTURE

Wheat, canal irrigation, India. Photo Credit HK Singh, Shutterstock

WHILST INFRASTRUCTURE projects have often focused on improving the supply of water for agriculture, there has been much less focus on managing or reducing the agricultural water demand. The net effect of increasing supply, without managing demand, is that agricultural water (and energy) consumption increases, without necessarily increasing food production. Improved agricultural Water Use Efficiency (WUE) can help address this issue, as well as contributing to reducing the pressures on water resources (NITI Aayog 2019). This chapter outlines how recent improvements in large area measurement of soil moisture and the availability of high-resolution Soil Moisture Deficit information at a fine scale can provide actionable guidance to farmers. Practical methods, demonstrated in farm pilot studies, to manage irrigation demand are discussed, along with considerations of efficient irrigation methods, with the objective of improving WUE.

2.1 Agricultural water use challenges

Crop production is often water-limited in many regions, such as in tropical sub-humid and hot semi-arid climates. Irrigation, where available, is often applied to increase agricultural production, or to grow crops with a higher water requirement. In India, in particular, farmers are supported by low, or no cost, electricity supplies to pump water for agricultural use, and there is often no metering required. Some Indian States are beginning to change this by encouraging sustainable, on-farm water-use practices to support better **demand-side management of water resources**. Indicator 17, of the Composite Water Resources Management Index (NITI Aayog 2019), surveys the segregation of agricultural electricity supplies (feeders) from other non-agricultural users. Segregated feeders allow households to receive a continuous supply, whilst farmers receive electricity for certain planned periods to irrigate 'in a targeted and effective manner.' Progressive States such as

Agricultural water demand can be managed through improved Soil Moisture Deficit information.

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Andhra Pradesh, Gujarat and Punjab have large areas of segregated power feeders, whereas Karnataka is one of the worst performing States in this regard. Punjab is currently trialling an innovative programme to provide farmers with a fixed electricity quota, and a payment of INR 4 per kilowatt-hour of electricity saved. Without incentives, farmers may otherwise seek to maximise the water applied to their crops when electricity is available.

In general, applied irrigation is not matched to the actual crop water demand, usually resulting in over-irrigation, wasted water and power, as well as over-exploitation of water supplies e.g. unsustainable groundwater depletion (FAO 2015). Some farmers may not appreciate that there is an optimum soil moisture (SM) requirement for a particular crop; they may not feel confident to reduce irrigation, for fear of under-watering leading to a poor crop outcome; and there may be a genuine concern that electricity will not be available when irrigation is actually required. This is further compounded by inefficient irrigation methods, for instance, water is often applied during the heat of the day, when evaporation losses are highest, and using gun irrigation which results in water losses both from spray and canopy evaporation.

Inappropriate use of stored water, groundwater, ponds and reservoirs due to excessive irrigation, reduces resilience to drought, possibly preventing cropping for a particular season, reducing income and food security. In contrast to the current continual depletion of groundwater observed in many regions, extensive groundwater stores should be conserved as a buffer for inter-annual variability of precipitation, such that they are recharged during high rainfall years and drawn down during drought years. This is likely to become even more important in the context of climate change, which is predicted to increase inter-annual variability of precipitation. It should be noted, that as groundwater is depleted, more power is consumed to pump the same amount of water from deeper reserves. With rapid population growth increasing the demand for food and thus agricultural intensification, infrastructure-heavy approaches may not be sufficient to support water supply for irrigation. Transformation of agricultural water management practices, i.e. demand-side, is essential to enable sustainable intensification.

2.2. Saving water using soil moisture information

There needs to be a paradigm shift from supply-driven irrigation to demand-driven irrigation, i.e. based on crop water requirement, after first taking account of current Soil Moisture Deficit. **Soil moisture deficit (SMD)** is simply the amount of water (expressed in mm) required to bring SM content back to field capacity. Using SMD information to determine crop water requirement is the well-established technique of **deficit irrigation**, which is applied by many larger growers globally, and in small scale research projects (Moene 2014). It requires up to date information on the actual SMD in a particular field for a particular crop, usually combined with crop models and decision support systems (**Figure 2.1**), which makes it less accessible to smaller farmers. Recent work has focused on delivering readily actionable SMD-based irrigation advisories to farmers and water resource managers in a few pilot areas (see **Box 2.1**).

The concept is to provide simple 'yes, no, maybe' irrigation guidance for a particular location, soil type, and crop type or crop class, which can

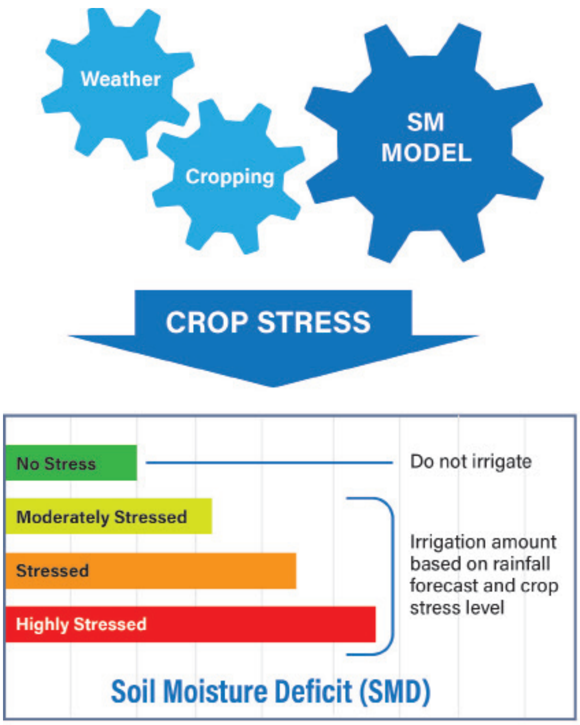
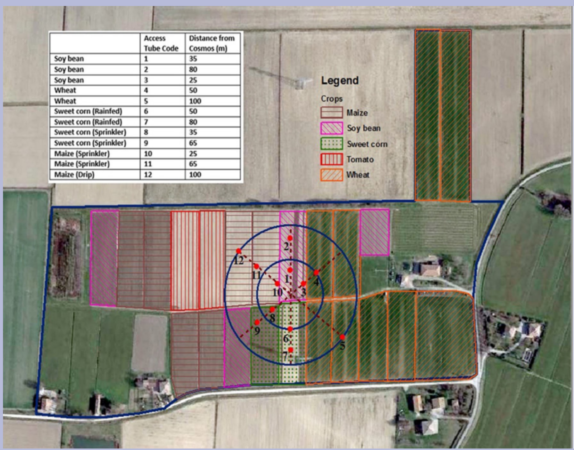


Figure 2.1 Schematic for decision support system for crop irrigation. The crop stress level is determined using the specific crop wilting point, soil field capacity and soil moisture.

BOX 2.1 Deficit Irrigation Farm Pilots

Two pilot studies are presented here that show the potential to provide better SMD-based crop water stress guidance for irrigation decision making.

The first study was undertaken in a mixed crop farm in Bologna, Italy during the cropping season of 2014 and 2015. The study was part of the Government of India and European Commission co-funded programme Water4Crops (Integrating bio-treated wastewater reuse and valorization with enhanced water use efficiency to support the Green Economy in Europe and India).

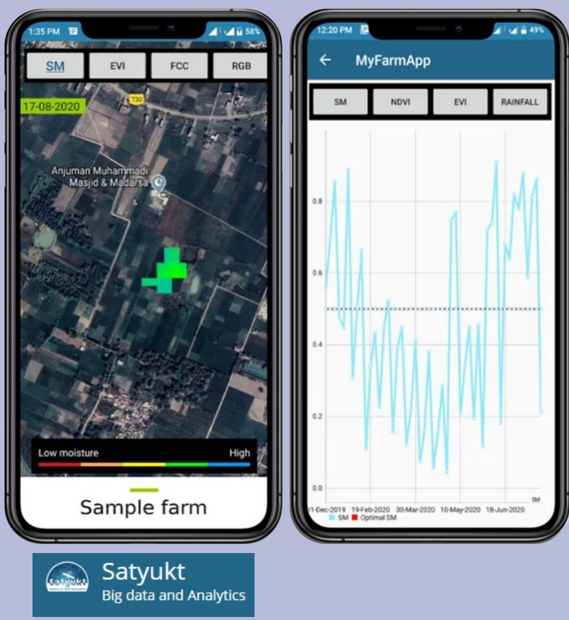


CRNS comparison with *in situ* point sensors located at different distances from the CRNS, as indicated by the red dots. (Image from Ragab et al 2017).

In this study, very high spatial resolution SMD was derived from in situ sensors (including a CRNS), whilst also comparing estimates of evapotranspiration based on meteorological data (i.e. the Penman-Monteith equation) to direct eddy covariance evaporation measurements. The study showed that the area-average CRNS produced similar soil moisture deficit values to the weighted area-average of the *in situ* point sensors used, and represented the majority of the root mass between 0 and 50 cm (Ragab et al 2017). Furthermore, the research identified that evapotranspiration estimates based on calculated potential evaporation, even with crop factors included, were significantly over-estimated. This was especially true in hot, drier periods, where water is limited, thus leading to over-estimates of water-use by the crop and in turn, irrigation demand when compared to the in situ actual evaporation measurements. Overall, for one growing season, the research showed that at least 40% of irrigation water could be saved if the new technologies were used to determine soil and crop water requirements.

The second study shows how the modelling and interpretation needed to go from SM data to SMD (requiring knowledge of local soil hydrological properties) and crop water stress assessment (requiring information on typical crop type water demand for the expected growth stage, and crop wilting point, to determine the available water for the crop), can be done centrally, as a service to end-users. To provide such high spatial resolution SM information on demand, where there is little or no in situ monitoring of SM, satellite remote sensing data may be specially processed for smaller spatial extents.

Satyukt Analytics[1], an agritech start-up in India, are collaborating in a trial with more than one hundred farmers, to provide them directly, via their smart phone using the MY FARM app or SMS, with field scale SM for their selected field. The farmer provides information about the farm, as well as crop type and age. They are then provided with information on SM, vegetation cover, and weather for the specified date or over a time-period, including irrigation advice. To further enhance the SM products, this two-way information exchange can be further improved. Farmers can assist with field surveys, using low-cost field probes, for example the SHOOL probe, as well as providing improved soil type information. This information can then be used to improve the accuracy of the irrigation advice based on SMD.



The MY FARM App (Image accessed from: www.satyukt.com/significance-of-my-farm-app-in-agricultural-monitoring; on 2/08/2021)

1 https://satyukt.com/web

assist farmers to use water more efficiently. With the right incentives in place to save water (such as payments for water saved or electricity saved, as mentioned above), real improvements in sustainable water management can be achieved. Appropriate support and training will be required, particularly to alleviate fear, or mitigate the risk, of crop failure. Together, this could result in irrigation being applied at the optimal time and quantity, with a large reduction in over-watering, whilst at least maintaining, if not improving, crop yield. One of the key data inputs required to deliver deficit irrigation guidance is high-resolution data on the current (near real-time) SM of a field, and sources of this data are described next.

2.3. Accessing appropriate soil moisture information

To have any decision support system for crop irrigation, we need information about SM. It can be obtained from measurements taken in the field and from publicly available spatiotemporal SM data products. For this information to be relevant, the corresponding SM depth should be that of root zones and the horizontal scale should be representative of the field in which crop irrigation decisions are being made. The data should also be near real-time since delayed information, of for instance one month, is not useful anymore. Different SM measurement techniques and data sources pose different challenges with respect to the above three criteria and they are explained in the remainder of this subsection.

The most accessible way of taking field SM measurements is via **electromagnetic point sensors** (Hardie 2020; Lekshmi S. U. et al 2014; Robinson et al 2008). They can be used as hand-held devices for easy and quick surveying of a plot, or as an array of sensors for continuous monitoring of a selected area. **Figure 2.2** lists point sensor types, classified in terms of how they can be installed to measure SM.

Portable surface sensors are especially useful for rapidly assessing spatial variability of SM over fields. Some models, such as Field Scout TDR350 and the Indian sensor NEERx Technovation SHOOL, have the option of replaceable rods of length up to 20 cm and 30 cm respectively, for probing beyond the soil surface layer. If SM at larger depths is of interest then the other sensor types shown in **Figure 2.2** are more suitable. Some sensors, such as the SHOOL, can provide a compromise between portable surface and buried sensors, by allowing it to be used as a portable device but also to be buried for continuous monitoring at desired soil depths (Agrawal et al 2019). Profiling probes can also be used for continuous SM measurements at multiple fixed depths along the sensor probe from the surface. However, the possible effect of topsoil shrinkage on data quality should be taken into consideration with this type of sensor. Any buried sensor and profiling probe may suffer from soil shrinkage, but this effect is more noticeable close to the soil surface where the soil will dry out and shrink more.

An alternative approach to field measurements for obtaining SM information is to use the available **near real-time data products**. These products are typically based on processed satellite data (PSD) or land surface model data (LSMD), which includes a SM model. LSMD have the potential to be high quality, as observed precipitation and other meteorological variables drive the hydrological SM model. However, there is usually no attempt to include irrigation inputs, which often occur at a very fine scale. PSD, in comparison, uses satellite sensors directly sensitive to SM, and therefore can capture irrigation inputs. The potential downside of PSDs is that the measurement depths are rather shallow, and there are many confounding factors, such as vegetation, soil roughness, tillage etc., which must be accounted for to retrieve accurate SM. For both LSMD and PSD, the accuracy of absolute SM will be limited by the knowledge of the local soil hydrological properties. **Table 2.1** lists some of the freely accessible products that should be considered for use in water resources management.

As shown in **Table 2.1**, AMSR2 LPRM, ScatSat-1, SAC-ISRO and SMAP L4 EASE-Grid data products are available daily, with SMAP L4 EASE-Grid providing surface and root zone SM (modelled from surface observations). Shallower products can provide useful information, but they require further modelling to represent root zones. While ERA5-Land and GLDAS Noah-LSM can supply SM information at root zone depths, their long latency makes them less suitable for crop irrigation management. It is also worth emphasising that, when available, ScatSat-1 will have a

PORTABLE SURFACE SENSORS

Image: courtesy of NeerX Technovation

Probe is inserted vertically into ground surface without the need for additional tools.

PROS
- Easy field surveying (farmer-friendly).
- Rapid assessment of spatial variability.
- Some may be operated while standing.
- Data is displayed on a monitor and/or smart phone.
- Can be multifunctional.

CONS
- May not be as suitable for long-term continuous monitoring as other sensor types.
- Typical probe length does not exceed 20 - 30 cm.

EXAMPLES SHOOL sensor (NEERx Technovation, India); Field Scout TDR350 (Spectrum Technologies, USA); Stevens HydraGO (Stevens Water Monitoring Systems Inc, USA).

PROFILING PROBE WITH ACCESS TUBE

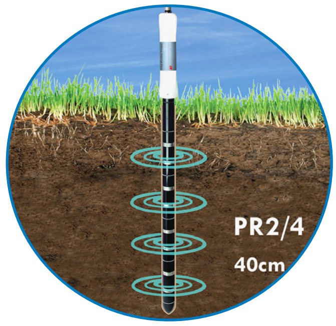


Image: courtesy of Delta-T Devices Ltd

Profiling probe is inserted into already installed vertical access tube.

PROS
- Single probe can be easily inserted and removed between many access tubes.
- Gives depth profile up to ~ 100 cm.

CONS
- Access tubes reduce accuracy of readings.
- An auger-type tool is needed to install access tubes.
- Soil shrinkage in topsoil during dry seasons may reduce probe contact with soil.

EXAMPLES Delta-T PR2 probe (Delta-T Devices Ltd, UK).

All require good contact with soil. Care should be taken to ensure no air gaps between probe and soil.

PROFILING PROBE, WITHOUT ACCESS TUBE

Image: courtesy of Campbell Scientific

Profiling probe is installed directly into ground in a vertical position.

PROS
- Potentially higher accuracy due to closer contact with the soil.
- Gives depth profile up to ~ 100 cm.
- Good for continuous monitoring.

CONS
- Not portable; auger-type tool is needed for installation.
- Soil shrinkage in topsoil during dry seasons may reduce probe contact with soil.
- More complex installation with a data logger.

EXAMPLES SoilVUE 10 (Campbell Scientific, UK); Stevens GroPoint Profile (Stevens Water Monitoring Systems Inc, USA).

BURIED SENSORS

Image: courtesy of NeerX Technovation

Sensors are buried in the ground.

PROS
- Very good for continuous monitoring at various soil depths as part of a sensor array.
- High accuracy if correctly installed.
- Good for depths greater than 30cm.

CONS
- Not portable, soil excavation is required.
- More complex installation with a data logger.
- Soil shrinkage may reduce accuracy of measurements.

EXAMPLES SHOOL sensor with Micro-Climatic Station (NEERx Technovation, India); Stevens HydraProbe (Stevens Water Monitoring Systems Inc, USA).

Figure 2.2 Electromagnetic soil moisture point sensor types.

SM data product	Temporal/ spatial resolution	Representative Soil Depth	Units	Availability
ERA5-Land	Hourly/ 11 km	0–7 cm, 7–28 cm, 28–100 cm, 100–289 cm	$m^3 m^{-3}$	From 01/01/1981 with 2-3 months latency
LSMD, file format: netCDF, source: https://cds.climate.copernicus.eu				
GLDAS Noah-LSM v2.1	3-hourly or daily/ 25km	0–10 cm, 10–40 cm, 40–100 cm, 100–200 cm	$kg m^{-2}$	From 01/01/2000 with 1.5 months latency
LSMD, file format: netCDF, source: https://ldas.gsfc.nasa.gov/gldas				
AMSR2 LPRM downscaled	Daily/10 km	0–2 cm	%	From 02/07/2012 Daily
PSD (passive), file format: netCDF, source: https://disc.sci.gsfc.nasa.gov				
ScatSat-1*	Daily/2 km	0–5 cm	$m^3 m^{-3}$	Daily*
PSD (active), file format: GeoTIFF, source: https://www.mosdac.gov.in *Under development as research product				
SAC-ISRO	Daily/12.5 km	5–10 cm	$m^3 m^{-3}$	From 04/04/2015 Daily
PSD (passive), file format: GeoTIFF, source: https://www.mosdac.gov.in/				
SMAP L4 EASE-Grid	3-hourly/ 9 km	0–5 cm, 0–100 cm	$m^3 m^{-3}$	From 31/03/2015 Daily
PSD (passive), file format: HDF5, source: https://nsidc.org				

Table 2.1 Remote sensing soil moisture data products. LSMD – Land Surface Model Data; PSD – Processed Satellite Data.

very fine spatial resolution of 2 km, which is very encouraging for agricultural applications. A potential issue with all the data products is that they are downloadable as different file formats, which are not always accessible to all end-users. In future, users of various computer literacy levels should be given easy access to this SM information.

While the remote sensing data gives a wide spatiotemporal coverage, it needs to be validated with ground-based observations (Upadhyaya et al 2021; Pandey et al 2020). This can be done by an array of point sensors to obtain spatial average SM, or by sensors that intrinsically measure average SM over a specific area. An example of such sensors is the **Cosmic Ray Neutron Sensor (CRNS),** which measures naturally occurring neutrons originating from cosmic rays. Changes in neutron count rates are primarily caused by changes in SM. The count rate is inversely related to the SM content and prior to being used to infer SM, it must be corrected for time variations in atmospheric pressure, humidity and incoming cosmic ray neutron fluxes using an appropriate neutron monitor[1].

The CRNS can be used to sense highly accurate daily SM of an area of around 12 ha, with radius of approximately 200 m (Evans et al 2016; Andreasen et al 2017). The technique is non-invasive with a CRNS positioned just above the ground in the middle of the footprint (see **Box 2.2** for an example). Aside from having great potential for validating satellite soil moisture products, it can be applied as an accurate area-average soil moisture continuous monitoring system. The technique is under continuous development to improve

1 https://www.nmdb.eu

BOX 2.2 Deficit Irrigation Farm Pilots

The Indian COSMOS Network[1] was established by the SUNRISE programme in partnership with Indian institutions across India. It currently consists of eight stations (Right).

The aim of establishing the network was to:

- Improve soil moisture mapping of current status at district, State and national scales.
- Provide agricultural advisory information to improve crop outcomes and income for farmers.
- To contribute to water resource information and outlooks for sustainable water use.

The data from the network are available as daily volumetric water content (VWC) or as daily soil moisture deficit (SMD) at 50 cm soil depth. In addition to CRNS SM data, Indian COSMOS Network sites also provide measurements of relative humidity, precipitation, temperature, pressure and VWC from SM point sensors.

The original Indian COSMOS network Partnership consisted of the following, including their roles:

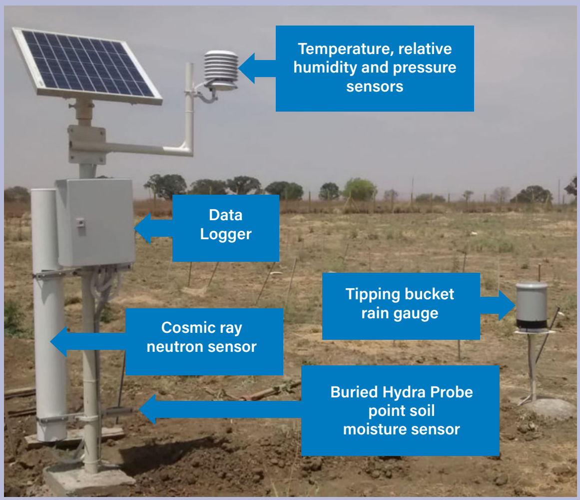
- National Institute of Hydrology – Management and operation of Henval & Bhopal sites; plus data management
- Indian Institute of Science, Bangalore - Management and operation of Berambadi, Madahalli & Singanallur sites
- Indian Institute of Tropical Meteorology - Management and operation of Pune site
- University of Agricultural Sciences, Dharwad - Management and operation of Dharwad site
- Indian Institute of Technology, Kanpur - Management and operation of Kanpur site
- UK Centre for Ecology & Hydrology - Technical expertise, training and capacity building for application of the CRNS, site installation, calibration, SM retrieval, and data management.

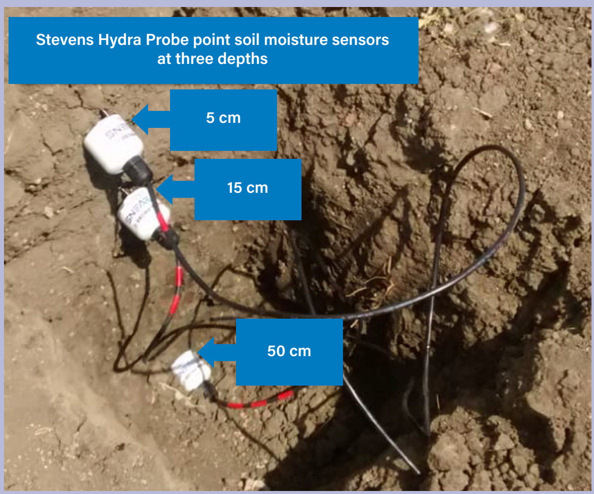
Indian COSMOS Network sites across India.

The network site data is currently available via the respective organisations for their sites.

A station has also been established and is being operated by the Space Application Centre (a centre of the Indian Space Research Organisation) at Anand, Gujarat.

These data have the potential to strengthen SM data provision for decision-making in India.





COSMOS site in Bhopal with main components indicated by arrows. The site is a part of the Indian COSMOS network and provides continuous measurements of soil moisture and associated meteorological data. Photo courtesy of PHAME Enterprises[2].

1 https://cosmos-india.org/ 2 https://www.phametechnology.com

the quality of the derived SM data; for example correctly accounting for the water stored in biomass (Baatz et al 2015).

2.4 Sharing information in a timely manner

There are SM products soon to be available at a useful spatial scale of 2 km. These can be combined with knowledge of local soil water field capacity, to calculate SMD, with a latency of only one or two days. At this scale, there would be opportunities for further refinement and to increase relevance of the guidance, by selecting a soil-type option, and the crop-type of interest. This development would be a step-change in disseminating timely irrigation guidance based on SMD. The very fine spatial resolution products typically originate from satellite measurements and as such are only able to penetrate the top 0–5 cm of soil. SM models are able to provide information about root zone layers, but require a better access to near real-time driving data. Current latencies in national precipitation and other meteorological data prevent application of SM models for near real-time irrigation guidance. In order for irrigation guidance to be of use, these challenges would need to be overcome. Secondly, the guidance would need to be shared in a timely manner, through trusted routes. Dissemination routes can be via water resource outreach officers and practitioners, agronomists, or through farm co-operatives and other trusted NGOs that support farmers. Web or mobile apps are a potential means of disseminating this information at this level. The refined guidance would then be sent by SMS to farmers, along with other agricultural advisory information.

Using field officers would give the added benefit of understanding local context and issues. With practice, these officers would become quite experienced in understanding the value, as well as the limitations of the irrigation guidance provided for their district. They can add their own insights and thus help bridge the gap between the information service and uptake by end users, by increasing user confidence in the guidance. A pilot study is currently underway in India, where high resolution (field-scale) guidance is being developed (see **Box 2.1**).

It is important to note, however, that 'field-scale' is usually much smaller (typically 1 ha or less) in regions with large numbers of marginal small-holder farmers, such as in India, compared with 'field-scale' for regions with big commercial growers, where fields are typically at least an order of magnitude larger (greater than 10 ha). The extremely fine spatial resolution needed for small-holder fields, increases the challenge of providing relevant SM information because of the diversity in crops and cropping practice (including irrigation) over tens of metres. Therefore, robust integration of all SM information sources, from satellites, models and *in situ* measurements, is warranted to address this requirement for hyper-resolution SM or SMD information.

2.5 Towards increased agricultural soil moisture monitoring

It is becoming increasingly practical to provide near real-time SMD based irrigation guidance to farmers, water resource practitioners and agronomists, albeit for limited spatial extents at the field scale. New high-resolution SM products at national scale offer the possibility to provide advice extensively. There will need to be a trade-off of increased uncertainty at the field scale, due to spatial averaging of many fields with different crops and water management, as well as an increasing probability that soil type may vary. However, via an interactive web app (or smart phone app), the guidance can be adjusted for crop type, any known variation in local soil properties, and the timing of the last irrigation for a particular field.

The growing number of programmes to incentivise reduced power and water use across India provide a unique path to embracing these new technologies. For example, under the power sector reform programmes, solar power is being promoted for use in pumping water, with excess power being sold to the grid. If farmers were better informed on the soil moisture needs for their crop, they could use less water towards irrigation, and hence less power to pump this water, subsequently gaining income from selling the excess power. Moving forward, the developments in providing actionable irrigation guidance to famers, through new improved SM products, combined with incentives to save water and power, should be leveraged to increase agricultural water use efficiency, extensively, across large regions.

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