Soil Moisture Estimation Using Cosmic-Ray Soil Moisture Sensing at Heterogeneous Farmland

Xujun Han, Rui Jin, Xin Li, *Senior Member, IEEE*, and Shuguo Wang

***Abstract*—The Cosmic-ray Soil Moisture Observing System is a promising soil moisture measurement network. It can measure soil moisture at an intermediate spatial scale with a single sensor. In this letter, the measured cosmic-ray neutron counts during the Heihe Watershed Allied Telemetry Experimental Research were used to evaluate the capabilities of the cosmic-ray probe in soil moisture retrieval at a heterogeneous farmland. The Cosmic-ray Soil Moisture Interaction Code model was utilized to model the interaction between the measured neutron counts and the soil water content. Soil moisture at the footprint scale of the cosmic-ray probe obtained using a wireless sensor network (SoilNET) was used as the calibration and validation data. The results show that the cosmic-ray probe is capable of monitoring the hourly heterogeneous soil moisture dynamics at the intermediate spatial scale in a noninvasive way. Moreover, the informative measurement depth of the cosmic-ray probe can also be derived and is consistent with the soil moisture results.**

***Index Terms*—Inverse problems, neutrons, soil moisture, wireless sensor networks.**

I. Introduction

THE land-surface–atmosphere interaction is sensitive to the soil moisture condition [1], [2]. Various methods have been developed to measure the soil moisture: 1) the point-scale methods like the time-domain reflectometry [3]; 2) the small-catchment or larger field-scale soil moisture measurement using a wireless sensor network by deploying many local sensors at separated locations [4]; and 3) the regional-/global-scale soil moisture retrieval by remote sensing [5], [6]. Recently, the COsmic-ray Soil Moisture Observing System (COSMOS) has been established [7], enabling the noninvasive measurement of soil moisture at an intermediate spatial scale with a single sensor. The investment and maintenance costs of a cosmic-ray soil moisture probe are lower than other ground-based facilities such as the wireless sensor network. The cosmic-ray soil moisture probe has been deployed during the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) [8]. The objective of this study is to investigate the applicability of cosmic-ray soil moisture sensing in retrieving intermediate spatial-scale soil moisture at a heterogeneous farmland.

The cosmic rays consist primarily of primary protons, which have a galactic origin. Victor Hess first discovered the cosmic rays in 1912. These primary cosmic rays collide with atmospheric nuclei, generating secondary cosmic rays mainly consisting of neutrons [9]. These high-energy neutrons undergo collisions and lose energy, eventually leading to the production of fast neutrons; these fast neutrons are then moderated, lose energy, and eventually become thermal neutrons and disappear either by being absorbed or by decaying. The fast neutrons are generated within the soil and near the land surface after the high-energy neutrons reach the soil. Some fast neutrons are scattered back to the near land surface atmosphere by diffusion [10], [11], which can be measured by a cosmic-ray probe.

Because hydrogen is the best neutron moderator, in wet soils, fewer neutrons are able to escape back to the atmosphere than in dry soil. Therefore, the measured intensity of fast neutron counts above the ground depends on the soil water content of the ground [7], [12]. The surface hydrogen plays an important role in moderation or removal of fast neutrons, and its amount is related to the soil moisture content. Hydrogen atoms are present as water in the soil, lattice water of soil, below-ground biomass, atmospheric water vapor, snow water, above-ground biomass, intercepted water by vegetation, and water on the ground. These additional hydrogen sources contribute to the measured neutron intensity. The role of these additional hydrogen sources should be included in the analysis of the cosmic-ray measurements. Formulations for handling the water vapor [10], the lattice water and organic carbon [13], and a litter layer present on the land surface [14] have been developed. The studies demonstrate that the measured neutron density is inversely correlated to the soil moisture content and the cosmic-ray probes respond to soil moisture [15], [16]. The neutrons are mainly impacted by the hydrogen atoms included in the soil water and emitted to the atmosphere where the neutrons mix instantaneously at a scale of hundreds of meters. The increase in soil moisture from 0% to 40% can decrease the cosmic-ray neutron intensity to 60% of the surface cosmic-ray neutron intensity [16]. The footprint of a cosmic-ray probe measurement represents a circle with a diameter of $\sim$600 m at sea level [17], and the measurement depth decreases nonlinearly from $\sim$76 cm (dry soils) to $\sim$12 cm (saturated soils) [16]. Since 2008, more and more cosmic-ray probes have been deployed to monitor the soil moisture content over a horizontal footprint of hectometers and to a depth of decimeters at regional scale [7], [15], [16], [18].

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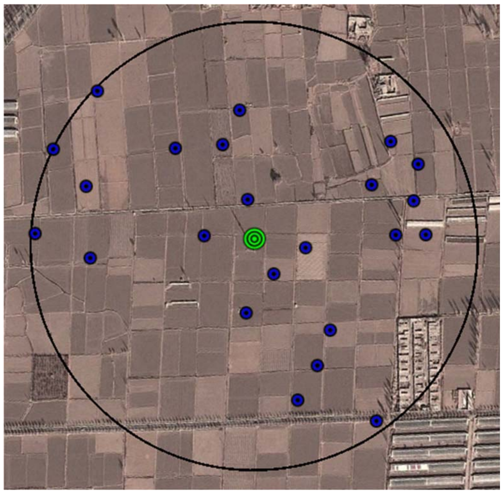

Fig. 1. Footprint of the cosmic-ray soil moisture probe (green cycle) and SoilNET nodes (blue cycle).

II. STUDY AREA

In 2012, various field campaigns in the context of the Hi-WATER [8] were carried out to perform simultaneous airborne, satelliteborne, and ground-based remote-sensing experiments at various scales of the Heihe River Basin (HRB). This study was carried out in the central part of HRB, which is the second largest in-land river basin of China located between 97.1° E–102.0° E and 37.7° N–42.7° N. A multiscale observation experiment on evapotranspiration [19] was performed in the central artificial oasis experimental area from June to September. In order to capture the heterogeneity of soil moisture and soil temperature, the SoilNET nodes [4] were used to measure soil moisture and soil temperature at four layers [20]. One cosmic-ray probe (CRS-1000B; Fig. 1, green cycle) was implemented in this area, and there are 23 SoilNET nodes [21] in the footprint (Fig. 1, blue cycle). The principal crop types within the footprint of the cosmic-ray soil moisture probe are seed corn. Irrigation is implemented through channels on the basis of the flooding irrigation method. The measured soil moisture from 23 SoilNET nodes at the footprint of the cosmic-ray probe was used for calibration and validation. The elevation is 1519 m, and the site is continental drought climate with silt loam soil.

III. COSMIC

The interaction between the measured neutron counts and the soil water content can be derived by a simple physical analytic model: COsmic-ray Soil Moisture Interaction Code (COSMIC) model [22]. COSMIC was used as the cosmic-ray forward model to simulate the neutron count rate response to the soil moisture profile in this study. COSMIC represents the number of fast neutrons reaching the COSMOS probe N_{COSMOS} at a near-surface measurement point as

$$N_{\mathrm{COSMOS}} = N \int_0^\infty \left\{ A(z) \left[\alpha \rho_s(z) + \rho_w(z)\right] \times \exp\left(-\left[\frac{m_s(z)}{L_1} + \frac{m_w(z)}{L_2}\right]\right)\right\} dz \quad (1)$$

$$A(z) = \left(\frac{2}{\pi}\right) \int_0^{\pi/2} \exp\left(\frac{-1}{\cos(\varphi)}\left[\frac{m_s(z)}{L_3} + \frac{m_w(z)}{L_4}\right]\right) d\varphi \quad (2)$$

$$\alpha = 0.405 - 0.102 \times \rho_s \quad (3)$$

$$L_3 = -31.76 + 99.38 \times \rho_s \quad (4)$$

where N is the high-energy neutron intensity (in counts per hour), z is the soil-layer depth (in meters), ρ_s is the dry soil bulk density (in grams per cubic centimeter), ρ_w is the total soil profile water content, including the lattice water, $m_s(z)$ and $m_w(z)$ are the integrated mass per unit area of dry soil and water (in grams per square centimeter), α is the relative efficiency of creation of fast neutrons by soil, φ is the angle between the vertical line below the detector and the line between the detector and each point in the plane [22], L_1 is the high-energy soil attenuation length with a value of 162.0 g cm^{-2}, L_2 is the high-energy water attenuation length of 129.1 g cm^{-2}, L_3 is the fast neutron soil attenuation length (in grams per square centimeter), and L_4 is the fast neutron water attenuation length with a value of 3.16 g cm^{-2}.

COSMIC discretizes the soil profile into 300 layers with a soil profile depth of 3 m. The layered soil water content is used and interpolated by COSMIC. The fast neutron count rate and the layered contribution are calculated by COSMIC. Finally, the depth-averaged soil moisture and the effective sensing depth of the cosmic-ray soil moisture probe are also calculated by COSMIC.

IV. COSMOS MEASUREMENT CORRECTION

The measured neutron counts contain the contribution from different sources: water in the soil, lattice water of soil, below-ground biomass, atmospheric water vapor, snow water, above-ground biomass, intercepted water by vegetation, and water on the ground, which blurs the relation between the measured neutron counts and the soil moisture content. The influences of additional sources have to be reduced before soil moisture retrieval. Different corrections have been proposed for these additional hydrogen sources like atmospheric vapor [10], lattice water and organic carbon in the soil [13], litter layer [14], and above-ground biomass [13]. In this letter, the cosmic-ray neutron intensity reaching the land surface is influenced by air pressure, atmospheric water vapor content, and incoming neutron flux.

The correction factor f_P for pressure is defined as [7]

$$f_P = \exp\left(\frac{P - P_0}{L}\right) \quad (5)$$

where L (in grams per square centimeter) is the mass attenuation length for high-energy neutrons and a value of 128 g cm^{-2} was used in this study [7], P (in millibar) is the local air pressure, and P_0 (in millibar) is the average air pressure during the measurement period.

The correction factor for atmospheric water vapor f_{wv} is defined as [10]

$$f_{wv} = 1 + 0.0054 \times \left(\rho_{v0} - \rho_{v0}^{\mathrm{ref}}\right) \quad (6)$$

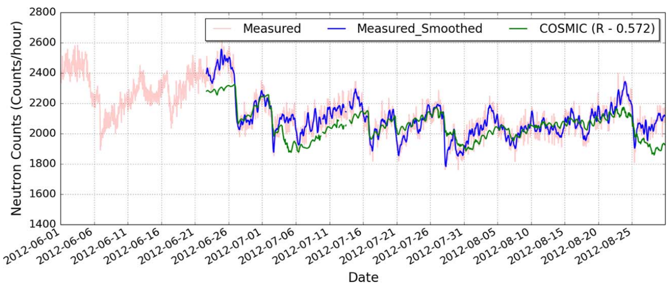

Fig. 2. Measured neutron counts from the cosmic-ray soil moisture probe (red line), smoothed neutron count measurement (blue line), and simulated neutron counts from COSMIC (green line).

where ρ_{v0} (in kilograms per cubic meter) is the absolute humidity at the measurement time and ρ_{v0}^{ref} (in kilograms per cubic meter) is the average absolute humidity during the measurement period.

Because the cosmic-ray probe aims to measure the neutron flux based on the incoming background neutron flux, fluctuations in the incoming neutron flux should be removed. The correcting factor for the incoming neutron flux f_i is defined as

$$f_i = \frac{N_m}{N_{\mathrm{avg}}} \tag{7}$$

where N_m is the measured incoming neutron flux and N_{avg} is the average incoming neutron flux during the measurement period. The measured neutron count rate at the Jungfraujoch station in Switzerland at 3560 m (http://cosray.unibe.ch) was used to calculate N_m and N_{avg}.

Finally, the calibrated neutron count is given as follows:

$$N_{\mathrm{Corr}} = N_{\mathrm{Obs}} \times f_P \times f_{wv} \times f_i \tag{8}$$

where N_{Corr} represents the corrected neutron counts and N_{Obs} represents the measured neutron counts by the cosmic-ray probe.

The cosmic-ray soil moisture probe measured soil moisture in the hourly frequency. In addition, the high-frequency noise in soil moisture is not relevant to the temporal variation of soil moisture which will not change so frequently in the hourly step, so the temporal Savitzky–Golay filter [23] with moving average window size of 31 and polynomial of order 4 was applied on N_{Corr} to remove the high-frequency noise from the measured cosmic-ray neutron counts after finishing the aforementioned corrections. This smoothing filtered out the temporal noise contained in the original cosmic-ray neutron count measurement. The smoothed cosmic-ray neutron counts are showed in Fig. 2 (blue line), and they will be used for the soil moisture estimation next.

V. COSMIC Calibration

The high-energy neutron intensity parameter N of the forward COSMIC model needs to be calibrated first by using the measured cosmic-ray fast neutron count rate and the soil moisture content before soil moisture estimation. The optimal parameter N should result in the best-fitted neutron count simulation from COSMIC compared with the measured neutron counts, and then, it was used for soil moisture retrieval.

The cosmic-ray soil moisture probe footprint is composed of many small irrigated farmland patches, each belonging to a different farmer. Moreover, the amount of applied irrigation is spatially variable, which is related to the different crop managements of the diverse farmland patches. Soil moisture content is also affected by these diverse irrigation practices and is highly heterogeneous spatially. In order to catch the representative spatial soil moisture, the arithmetic mean of the soil moisture profile obtained by 23 SoilNET wireless nodes, which were located within the footprint of the cosmic-ray soil moisture probe, was used to optimize the parameter N that could minimize the discrepancy between the measured fast neutron count rate and the simulated one. The spatially averaged soil moisture content was assumed to be a representative of the soil moisture measured at the cosmic-ray soil moisture probe footprint scale. Two and a half months' soil moisture measurements are available during the study period from the HiWATER database. The SoilNET soil moisture at the first one and a half months' period was used for the COSMIC model calibration. Measurement depths of SoilNET are 4, 10, 20, and 40 cm, respectively. The gradient search algorithm L-BFGS-B, which is a variant of the limited-memory Broyden Fletcher Goldfarb Shanno (BFGS) algorithm [24], was used to minimize the cost function, which was defined as the root-mean-square error (rmse) of simulated neutron counts calculated using the corrected neutron counts N_{Corr}. The optimal value of N was obtained as 615.96 counts h^{-1}.

After the calibration, the optimal N and the spatially averaged soil moisture were used in COSMIC to model the neutron counts. In Fig. 2, the measured neutron counts from the cosmic-ray soil moisture probe (red line) and the simulated neutron counts from COSMIC (green line) are plotted. The simulated results show that the COSMIC could catch the cosmic-ray responses to the soil moisture dynamics with the correlation coefficient of 0.572. It should be noted that the measured neutron counts were not instantaneous measurements taken every hour but were integrated hour-long measurements.

VI. Soil Moisture Retrieval and Validation

The homogeneous layered soil moisture was assumed in COSMIC before the soil moisture retrieval. The cost function was defined as the absolute value of the difference between the measured neutron counts and the neutron counts simulated by COSMIC and was minimized with the same algorithm BFGS used in the COSMIC calibration. Finally, the hourly soil moisture was retrieved step by step.

The derived soil moisture using the cosmic-ray soil moisture probe (red line) is showed in Fig. 3, with comparison of 10-cm average SoilNET soil moisture (blue line) and 20-cm average SoilNET soil moisture (green line). The correlation coefficients and rmse between the retrieved soil moisture and the SoilNET measurement are summarized in Table I. The results show that the retrieved soil moisture is closer to the 10-cm SoilNET measurement. The biases between the retrieved soil moisture and the SoilNET measurement for 10 and 20 cm are 0.004 and 0.044 m^{3}m^{-3}, respectively. The soil moisture inversion is almost unbiased compared with the 10-cm

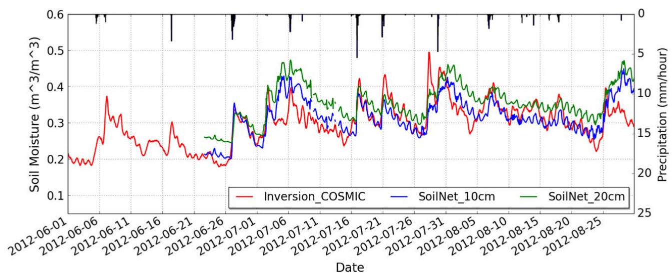

Fig. 3. Soil moisture time series of retrieval using the cosmic-ray soil moisture probe (red line), 10-cm average SoilNET soil moisture (blue line), and 20-cm average SoilNET soil moisture (green line).

TABLE I
CORRELATION COEFFICIENTS (R) AND RMSE BETWEEN THE RETRIEVED SOIL MOISTURE AND THE SOILNET MEASUREMENT (10 cm DEPTH AND 20 cm DEPTH)

Depth	R	RMSE (m^3m^{-3})
10 cm	0.66	0.04
20 cm	0.65	0.06

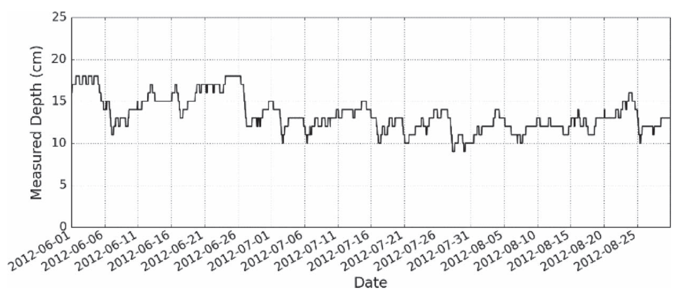

Fig. 4. Derived measurement depth of the cosmic-ray probe.

measurement. We should mention that SoilNET measures soil moisture at 10 cm or at 20 cm, while COSMOS is an integrated value between 0 cm and the effective measurement depth.

In this letter, the COSMIC model delineates the soil profile as 300 layers with 3 m depth and allows us to derive the signal contribution of different soil layers. The measurement depth of the cosmic-ray soil moisture probe changes according to the soil moisture content (i.e., lower soil moisture results in deeper measurement depth). Hourly measurement depth can be derived based on the contribution of separate soil layers. The measurement depth can be calculated by multiplying the contribution of each soil layer to the fast neutron counts and the soil layer thickness. The derived measurement depth of the cosmic-ray soil moisture probe is shown in Fig. 4. In June, the measurement depth of the cosmic-ray probe was around 15 cm depth. When the soil moisture goes up from July, the measurement depth decreased to the range of 10 and 15 cm depth. The measurement depth results are consistent with the soil moisture results, in which the retrieved soil moisture is close to the 10-cm-depth SoilNET measurement.

The soil moisture in June is lower (around 0.25 m^3m^{-3}) than the following soil moisture that is always above 0.25 m^3m^{-3}. The high soil moisture corresponds to the irrigation events that begin from May to October each year. When soil moisture values are between 0.2 and 0.45 m^3m^{-3}, the COSMOS measurement depth (thickness) is between 10 and 20 cm.

VII. SUMMARY AND DISCUSSION

The cosmic-ray soil moisture probe was assessed to retrieve soil moisture dynamics at the heterogeneous irrigated farmland field. The physical COSMIC model was first calibrated using field soil moisture measurement and then utilized for the soil moisture estimation. Before the soil moisture estimation, measured neuron counts were corrected to remove the effects of atmospheric pressure, atmospheric water vapor, and fluctuations in the incoming neutron flux separately. The high-frequency noise was also removed by a temporal filter.

The results show that the heterogeneous soil moisture at an intermediate spatial scale can be obtained from using the cosmic-ray neuron count measurement in a noninvasive way. The measurement depth derived in COSMIC based on the layered contribution of fast neutron counts in the soil is consistent with the soil moisture retrieval results. The accuracy of the soil moisture determination is within 0.04 m^3m^{-3} of the soil moisture measurements using SoilNET wireless network (Table I).

The newly developed physical model COSMIC is proved to be successful in the soil moisture estimation. Moreover, there is only one parameter (N: the high-energy neutron intensity) of COSMOS that needs to be calibrated before inversion. However, the calibrated parameter value is not a universal solution and should be calibrated for each location.

The heterogeneous soil moisture at the cosmic-ray probe footprint was characterized by the spatially averaged soil moisture from the wireless sensor network (SoilNET). The small farmland patches at the cosmic-ray probe footprint were irrigated separately at different time periods. The 23 SoilNET nodes may not catch the full spatial variability of the soil moisture at the cosmic-ray soil moisture probe footprint scale. Moreover, the horizontal contribution of soil moisture [25] to the neutron count measurement was not considered because of limited available SoilNET nodes at the same time. We only used the simple average of SoilNET measurement in the calibration and validation. During the crop-growing season, the vegetation water content will contribute to the measured fast neutron counts; this impact needs to be investigated further and is not taken into account during this study. In summary, the soil moisture retrieval results prove the promising feasibility of the cosmic-ray soil moisture probe in measuring small-scale soil moisture. More work is required to reduce the uncertainties (the impacts of biomass, incoming neutron flux and air pressure, and temporal noise) associated with the measured cosmic-ray fast neutron counts and to improve the COSMIC model (the calibration of parameter values).

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REFERENCES

[1] A. C. M. Beljaars, P. Viterbo, M. J. Miller, and A. K. Betts, "The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies," *Mon. Weather Rev.*, vol. 124, no. 3, pp. 362–383, Mar. 1996.

[2] A. K. Betts, J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo, "The land surface–atmosphere interaction: A review based on observational and global modeling perspectives," *J. Geophys. Res., Atmos.*, vol. 101, no. D3, pp. 7209–7225, Mar. 1996.

[3] D. A. Robinson, S. B. Jones, J. M. Wraith, D. Or, and S. P. Friedman, "A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry," *Vadose Zone J.*, vol. 2, no. 4, pp. 444–475, Nov. 2003.

[4] H. R. Bogena *et al.*, "Potential of wireless sensor networks for measuring soil water content variability," *Vadose Zone J.*, vol. 9, no. 4, pp. 1002–1013, Nov. 2010.

[5] D. Entekhabi *et al.*, "The Soil Moisture Active Passive (SMAP) mission," *Proc. IEEE*, vol. 98, no. 5, pp. 704–716, May 2010.

[6] Y. H. Kerr *et al.*, "The SMOS mission: New tool for monitoring key elements of the global water cycle," *Proc. IEEE*, vol. 98, no. 5, pp. 666–687, May 2010.

[7] M. Zreda *et al.*, "COSMOS: The COsmic-ray Soil Moisture Observing System," *Hydrol. Earth Syst. Sci.*, vol. 9, no. 4, pp. 4505–4551, Apr. 2012.

[8] X. Li *et al.*, "Heihe Watershed Allied Telemetry Experimental Research (HiWATER): Scientific objectives and experimental design," *Bull. Amer. Meteorol. Soc.*, vol. 94, no. 8, pp. 1145–1160, Aug. 2013.

[9] D. Lal and B. Peters, "Cosmic Ray Produced Radioactivity on the Earth," in *Kosmische Strahlung II / Cosmic Rays II.*, K. Sitte, Ed. Berlin, Germany: Springer-Verlag, 1967, pp. 551–612.

[10] R. Rosolem *et al.*, "The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system," *J. Hydrometeorol.*, vol. 14, no. 5, pp. 1659–1671, Oct. 2013.

[11] W. N. Hess, H. W. Patterson, R. Wallace, and E. L. Chupp, "Cosmic-ray neutron energy spectrum," *Phys. Rev.*, vol. 116, no. 2, pp. 445–457, Oct. 1959.

[12] L. D. Hendrick and R. D. Edge, "Cosmic-ray neutrons near the earth," *Phys. Rev.*, vol. 145, no. 4, pp. 1023–1025, May 1966.

[13] T. E. Franz, M. Zreda, R. Rosolem, and T. P. A. Ferre, "A universal calibration function for determination of soil moisture with cosmic-ray neutrons," *Hydrol. Earth Syst. Sci.*, vol. 17, no. 2, pp. 453–460, Feb. 2013.

[14] H. R. Bogena, J. A. Huisman, R. Baatz, H. J. Hendricks Franssen, and H. Vereecken, "Accuracy of the cosmic-ray soil water content probe in humid forest ecosystems: The worst case scenario," *Water Resourc. Res.*, vol. 49, no. 9, pp. 5778–5791, Sep. 2013.

[15] D. Desilets, M. Zreda, and T. P. A. Ferré, "Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays," *Water Resourc. Res.*, vol. 46, no. 11, pp. W11505-1–W11505-7, Nov. 2010.

[16] M. Zreda, D. Desilets, T. P. A. Ferre, and R. L. Scott, "Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons," *Geophys. Res. Lett.*, vol. 35, no. 21, pp. L21402-1–L21402-5, Nov. 1, 2008.

[17] D. Desilets and M. Zreda, "Footprint diameter for a cosmic-ray soil moisture probe: Theory and Monte Carlo simulations," *Water Resourc. Res.*, vol. 49, no. 6, pp. 3566–3575, Jun. 2013.

[18] B. Chrisman and M. Zreda, "Quantifying mesoscale soil moisture with the cosmic-ray rover," *Hydrol. Earth Syst. Sci.*, vol. 17, no. 6, pp. 7127–7160, Jun. 2013.

[19] Z. W. Xu *et al.*, "Intercomparison of surface energy flux measurement systems used during the HiWATER-MUSOEXE," *J. Geophys. Res., Atmos.*, vol. 118, no. 23, pp. 13 140–13 157, Dec. 16, 2013.

[20] R. Jin *et al.*, "A nested eco-hydrological wireless sensor network for capturing the surface heterogeneity in the midstream area of the Heihe River Basin, China," *IEEE Geosci. Remote Sens. Lett.*, vol. 11, no. 11, pp. 2015–2019, Nov. 2014.

[21] R. Jin *et al.*, "HiWATER SoilNET observation dataset in the middle reaches of the Heihe River Basin," Heihe Plan Science Data Center 2013.

[22] J. Shuttleworth, R. Rosolem, M. Zreda, and T. E. Franz, "The COsmic-ray Soil Moisture Interaction Code (COSMIC) for use in data assimilation," *Hydrol. Earth Syst. Sci.*, vol. 10, no. 1, pp. 1097–1125, Jan. 2013.

[23] A. Savitzky and M. J. E. Golay, "Smoothing and differentiation of data by simplified least squares procedures," *Anal. Chem.*, vol. 36, no. 8, pp. 1627–1639, Jul. 1964.

[24] C. Y. Zhu, R. H. Byrd, P. H. Lu, and J. Nocedal, "Algorithm 778: L-BFGS-B: Fortran subroutines for large-scale bound-constrained optimization," *ACM Trans. Math. Softw.*, vol. 23, no. 4, pp. 550–560, Dec. 1997.

[25] T. E. Franz, M. Zreda, T. P. A. Ferre, and R. Rosolem, "An assessment of the effect of horizontal soil moisture heterogeneity on the area-average measurement of cosmic-ray neutrons," *Water Resourc. Res.*, vol. 49, no. 10, pp. 6450–6458, Oct. 2013.