Theory and application of measuring mesoscale soil moisture by cosmic-ray fast neutron probe

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Abstract. In recent years, measurement of surface soil moisture by the cosmic-ray fast neutron probe has gradually attracted more attention. The intensity of the fast neutrons above the ground is sensitive to water content changes, largely insensitive to soil chemistry and inversely correlated with hydrogen content of the soil. Measurement of this intensity with a portable neutron detector placed above the ground permits the possibility of monitoring soil moisture. By this passive, non-invasive and intermediate scale measurement, soil moisture at a horizontal scale of around 660 m and depths of 12 to 76 cm can be inferred. And the large footprint makes this method suitable for weather and short-term climate forecast initialization and for validation of soil moisture inverted from satellite sensors. In this paper, the results of the cosmic-ray instruments well reflected the variation trend of soil moisture at the field scale. We found that irrigation and infiltration were two most important factors that affected the variation of soil moisture during a growing season of maize in Zhangye and the soil moisture of different period in the growing season of maize was very different. At last, Wireless Sensor Network data were used to validate this result and we found their correlation was very well with a RMSE of 0.0275 m$^3$ m$^{-3}$ in the non-irrigation time.

1. Introduction

Soil water plays an important role in the process of water movement in a variety of scales as an important part of the water resources[1]. For a long time, how to accurately measure soil moisture has been the focus of the study of related disciplines. So far, domestic and foreign researchers have put forward dozens of methods to measure soil water content from different avenues[2]. The traditional measurement methods include weighing method (oven-drying method), neutron probe, capacitance method, tonometry method, time domain reflectometry[3], frequency domain reflectometry, however, these measurements are detrimental and point measurement method which only can provide small-scale or on a very small scale soil water content. It is difficult to get the soil moisture content on the regional distribution[4]. The feasibility study of remote sensing to monitor soil moisture has already begun in the 1960s, and the application of research also carried out in the mid of 1970s. The use of remote sensing technology can achieve real-time, fast, long time series, a large area of soil moisture[5], but soil moisture remote sensing obtains is the pixel average[6], which spatial resolution varies between meters (aerial remote sensing) to tens of kilometers (aerospace remote sensing). And the traditional point methods or interpolation methods cannot guarantee the accuracy of ground real-value to verify this data, limiting the application of remote sensing large-scale measurements in soil moisture monitoring.
There is a gap between the traditional point measurements (point scale) and remote sensing (large scale), that is, soil moisture information in farmland scale or in small watershed scale cannot be obtained, and validation data for remote sensing inversion planar soil moisture are not available[7]. In recent years, the use of the cosmic-ray fast neutron to measure surface soil moisture gradually attracted attention. Cosmic-ray fast neutron method is a passive, non-intrusive, mesoscale soil moisture measurement method, which measurement radius is about 330 meters and effective measurement depth varies from 12 cm to 76 cm. The large footprint makes this method suitable for weather and short-term climate forecast initialization and for validation of soil moisture inversed from satellite sensors[8-9]. In this paper, this new method was used in the Heihe Watershed Allied Telemetry Experimental Research (HiWATER)[10] for long sequence soil moisture monitoring and the observation was validated by the wireless sensor network (WSN)[11] data.

2. Theory of cosmic-ray fast neutron method

2.1. Production of cosmic-ray fast neutrons
There are a lot of high-energy particles flows in the space and affected by the Earth's magnetic field, these high-energy particles are captured into the atmosphere and collide with nuclei in the atmosphere to produce secondary cosmic rays. Secondary cosmic rays can pass through the atmosphere into the soil and then collide with the nuclei in the soil to produce 1-2MeV fast neutron. These fast neutrons undergo elastic collisions with nuclei, lose energy and transfer to thermal neutrons (energy 0.025 eV) or epithermal neutrons (energy 1-10 eV). Some fast neutrons are absorbed by soil with collision, while the other part will be scattered into the air.

The process of moderation of neutrons depends on three factors that together define the neutron stopping power of a material: (1) the elemental scattering cross section or probability of scattering (hydrogen has a high probability of scattering a neutron); (2) the logarithmic decrement of energy per collision, which characterizes how efficient each collision is (hydrogen is by far the most efficient element); and (3) the number of atoms of an element per unit mass of material, which is proportional to the concentration of the element and to the inverse of its mass number (hydrogen makes up a high fraction of all atoms in most soils). Hydrogen has by far the highest stopping power[12]. For example, it takes only 18 collisions with hydrogen to moderate a fast neutron (energy 2 MeV) to thermal neutron (0.025 eV), while the next most efficient element, carbon atom, needs 113 collisions.

Generally, the fast neutron intensity in the air shows an inversely proportional relationship to the amount of soil water content in the surface. Because more soil water content provides more hydrogen atoms and more neutrons are moderated and absorbed, and thereby the ground probe detects less of fast neutrons. The number of fast neutrons above the dry soil will be greater than that above the wet soil. With respect to the content of water in the soil, the air vapor content [13] and soil lattice water content [14] will be relatively smaller. Though recent scholars study these impacts on the fast neutron, studies have yet to be in-depth. This paper investigates to ignore its impact, and thus the change of fast neutron intensity is mainly influenced by the water content in the soil. The inverse relationship between the fast neutron intensity and soil moisture is the physical basis of the cosmic-ray fast neutron method, and we can measure fast neutron intensity to monitor surface soil moisture in a large scale. [15].

2.2. Footprint and depth of cosmic-ray fast neutron method
The footprint of the cosmic-ray fast neutron method is defined as the area around the probe from which 86% of counted neutrons arise. According to the neutron transport code MCNPX[16] (Monte Carlo N-Particle eXtended) simulation results, the diameter of the footprint is about 660 meters[9] at sea level, which is consistent with knowledge of early neutron transport theory[17-18]. The footprint is mainly associated with the physical and chemical properties of air and is inversely proportional to the air density, regardless of the surface soil moisture. Because the scattering mean free path of neutron is inversely proportional to the number of molecules per unit volume of air. If there are more molecules
in the air, they will provide more chances to collide with neutrons and slow down the distance of neutron transmission. Therefore the footprint will be smaller in higher density area. At high altitude, air pressure will be lower and footprint will be larger than the low altitude areas, for example, the increase of footprint between sea level and 3000 meters of altitude is approximately 25%[19]. The study area is 1550 meters above sea level and the by the detection radius can be estimated about 350 meters.

The effective depth of measurement, \(z\), is defined as the thickness of soil from which 86% of counted neutrons arise, depending inversely on soil moisture. As discussed above, fast neutrons are inversely proportional to soil water content and higher soil moisture provides more hydrogen atoms. More fast neutrons are rapidly moderated and absorbed and cannot continue to propagate downward. So \(z\) depends inversely on the soil moisture. According to the the MCNPX simulated results, the effective depth varies non-linearly from 12 cm (wet soil, water content 0.40 m\(^3\)m\(^{-3}\)) to 76 cm (dry soil, the water content of 0)[9]. Recently, a specific formula is given to calculate this parameter according to MCNPX simulation results, see equation (1)[20].

\[
z = \frac{5.8}{\rho_{bd} \times \tau + \theta + 0.0829}
\]

Where \(\rho_{bd}\) is the dry bulk density of soil (g cm\(^{-3}\)), \(\tau\) is the weight fraction of lattice water in the mineral grains and bound water (very small, ignored in this paper), \(\theta\) is volume soil moisture and \(z\) is effective depth (cm).

2.3. Calculation of soil moisture with fast neutrons

Because the fast neutron propagation is affected strongly by the air pressure, it has to be corrected according to instrument manual to remove this variance. Then soil water content can be calculated. Correction formula is equation (2).

\[
N = N_{\text{raw}} \times \text{Exp}(\beta \times (P - P_0))
\]

Where \(N_{\text{raw}}\) is raw fast neutrons, \(\beta\) is a constant, 0.0077, \(P\) is the actual measurement of air pressure and \(P_0\) is the theoretical value of local air pressure.

After air pressure correction, there is a non-linear relationship between fast neutrons and soil water content. The formula in the instrument manual is used here to calculate soil moisture, see equation (3).

\[
\theta_m = \frac{1}{a_1 \left( \frac{a_2}{(N / N_0) - a_3} - a_4 \right)}
\]

Where \(\theta_m\) is gravimetric water content (kg kg\(^{-1}\)), \(N_0\) is fast neutron count rate over dry soil, and \(a_1\),\(a_2\),\(a_3\) and \(a_4\) are constants.(\(a_1=0.079\), \(a_2=0.640\), \(a_3=0.370\) and \(a_4=0.910\))

3. Application in Zhangye Oasis

The study area is located in the middle reaches of Heihe River Basin[10], Gansu Province in China. One typical irrigation district, Daman Irrigation District (DID), is selected to perform this experiment in Zhangye. The instrument was located on 100.372 E 38.856 N. This region belongs to arid desert climate zone and the average annual precipitation is about 121.5 mm. The main crop was maize during the experiment carried out from May 2012 to September 2012.

The cosmic-ray soil moisture detection instrument (named crs_b) was installed west side of Daman Super Station[21]. The instrument is equipped with a fast neutron detector, which is about 50 cm above the ground, a built-in barometric pressure sensor and a data logger. The sampling frequency is set 1 hour. Figure 1 shows the study area.
4. Calibration of cosmic-ray fast neutron probe

To calculate soil water content, the cosmic-ray instrument must be calibrated in order to determine a necessary parameter $N_0$ in equation (3). 64 soil samples were collected each time on the afternoon of July 11 and the afternoon of September 16. These samples were distributed on four radial distances from the instrument: 50m, 100m, 200m and 300m and each circle had four point samples which located at east, south, west and north of the instrument. Each point was collected two depths: 0-10cm and 10-20cm soil by using soil borer. Because the farmers used plastic film to protect their crops, we also collected two samples under this film for the soil usually contained more water than the soil without film. Four soil bulk density samples were also collected in order to covert gravimetric soil moisture to volumetric water content.

| Table 1. Data of soil samples |
|-------------------------------|
| depth (cm) | 2012-7-11 | 2012-9-16 |
| wt(%)     | vwc(%)    | wt(%)     | vwc(%)    |
| 0-10      | 17.87     | 26.63     | 16.04     | 23.90     |
| 10-20     | 17.30     | 25.78     | 16.46     | 24.53     |

The average water content of 0-10cm and 10-20cm soil in each point was calculated. We found that there was little difference between the point under plastic film and the point without this film. Considering the crop and irrigation order were same in the whole footprint, all soil samples were set the same weight and the arithmetic average of all collected soil samples was calculated as the footprint average soil water content. The average bulk density was 1.49 by analyzing four soil bulk density samples. All measurement data are shown in Table 1.

As discussed above, the effective depth is inversely proportional to the soil water content of footprint region. And the depths on July 11 and September 16 were between 10-20cm according to our soil samples data and equation (1). However, we did not collect these data directly. So we made a hypothesis that the soil water was uniform distribution between 0-10cm and 10-20cm. Then we calculated soil water content in each depth from 10 to 20cm. For example, soil moisture at 0-15cm...
depth was calculated according to this formula: 
\[
\frac{(0-10\text{ cm average} + 10-20\text{ cm moisture content} \times 0.5)}{(1 + 0.5)}\text{ and soil moisture at 0-16cm depth was: } \frac{(0-10\text{ cm average} + 10-20\text{ cm moisture content} \times 0.6)}{(1 + 0.6)}. \]
At last the effective depth every 1cm between 10 to 20cm was calculated by using equation (1). The calculation results are shown in Table 2.

### Table 2. Measurement depth of the calibration data

| Depth (cm) | 7-11 (wt\%) | 7-11 Depth\(^a\) (cm) | 9-16 (wt\%) | 9-16 Depth\(^a\) (cm) |
|-----------|-------------|------------------------|-------------|------------------------|
| 10        | 17.87       | 16.6                   | 16.04       | 18.0                   |
| 15        | 17.68       | 16.7                   | 16.18       | 17.9                   |
| 16        | 17.66       | 16.8                   | 16.20       | 17.9                   |
| 17        | 17.64       | 16.8                   | 16.21       | 17.9                   |
| 18        | 17.64       | 16.8                   | 16.23       | 17.9                   |
| 19        | 17.60       | 16.8                   | 16.24       | 17.9                   |
| 20        | 17.59       | 16.8                   | 16.25       | 17.8                   |

\(^a\) depth of equation (2)

According to Table 2, 17cm was the closest value on July 11 and 18cm on September 16 because they corresponded nearest to the depth which was calculated according to equation (1). So the soil moisture at 17cm and 18cm were set as 0m of equation (3) respectively. After pressure corrected, fast neutrons during soil sample collection time (15 pm-20 pm) were averaged as N of equation (3). Then \(N_0\) was calculated according to equation (3), 3195 on July 11 and 3364 on September 16. We used their average 3280 as the final \(N_0\) to calculate soil moisture during experiment time.

### 5. Results and discussion

After \(N_0\) was given, soil moisture can be calculated by using equation (2). The changes of regional soil moisture in the maize growing season from June 1 to September 30 were shown in Figure 2. The green line indicated that raw soil moisture calculated from 1 hour fast neutrons, which showed some volatility for cosmic ray was passive. We used 12 hours smoothed data to analyze which was shown in blue line.

#### 5.1. Validation of soil moisture

There were 19 soil moisture/temperature probes (named SoilNET) installed in the footprint of the cosmic-ray fast neutron probe. SoilNET could monitor 4cm, 10cm, 20cm and 40cm soil moisture and temperature data and were installed completely on June 22. According to soil moisture observed by cosmic-ray fast neutron probe was relative high and the effective depth was about 15cm by equation (1). So we chose the average of 4cm and 10cm soil moisture of SoilNET as the validation data in accordance with the depth of 15cm (Figure 3).
Figure 3. Comparison of the crs_b and Soilnet data (a for entire time period and b for non-irrigation period)

From Figure 3(a), cosmic-ray soil moisture and SoilNET soil moisture had the same trend in the whole sequence of June 22-August 18. The correlation coefficient was 0.79 and root mean square error (RMSE) was 0.037. However there was significant difference in irrigation time, in which the cosmic-ray soil moisture was much higher than that of SoilNET. This was because flood irrigation was used by local farmers and there was much surface water existed after irrigation. While surface water could significantly reduce the number of cosmic-ray fast neutrons for they held more hydrogen atoms and as a result that cosmic-ray fast neutron probe would detect much less. So soil moisture from cosmic-ray fast neutron probe was very high during irrigation. Because the SoilNET probes were all buried in the soil and not affected by the surface water, their measurement value was closer to the actual situation. So Figure 3(b) gave the comparison of two soil moisture change without irrigation time (July 1-July 5, July 27-August 1). Compared with Figure 3 the correlation coefficient was significantly higher, reaching 0.86 and RMSE reduced to 0.0275. It was also proved that soil moisture from cosmic-ray fast neutron probe was a regional data by the good consistency with SoilNET in its footprint and could be used to monitor soil moisture changes in farmland.

5.2. The bimodal change of soil moisture in irrigation period

Soil moisture calculated from cosmic-ray fast neutrons was mainly affected by the irrigation and precipitation and showed a bimodal change during irrigation time according to Figure 2. The main reason was that the footprint consisted of three different communities which were named fourth community (4C), fifth community (5C) and sixth community (6C) and had different irrigation time.
The fourth community farmland (accounting for 51.6% of the footprint) was firstly irrigated during which the first peak appeared. Then the sixth community farmland (accounting for 0.4% of the footprint) was irrigated and finally the fifth community farmland (accounting for 42.6% of the footprint) was irrigated. Soil moisture decreased during the sixth community irrigation because it accounted for a very small part of the source area and the whole water amount reduced, leaving the fast neutrons increased. When the fifth community farmland begun to irrigate and about 42.6% of crs_b footprint was affected, so the whole water amount in the footprint became to increase and the second peak appeared. This bimodal change was very clear in the first three irrigations, however, the fourth irrigation was very small and the fifth and sixth communities were irrigated at the same time, this change was not obvious in the fourth irrigation.

5.3. Variance of soil moisture in growing season
There were three different periods of variance of soil moisture in whole growing season. The first period began from June 1 and end about on June 26, during which average soil moisture was 25%. Though the first round of irrigation happened on June 4, the maize plants were very low and surface evaporation was very strong under local strong sunlight conditions. So the soil moisture was relative low. Then average soil moisture increased after the second irrigation and held at 35% during the second period from June 27 to September 1. The second period was the main growth time of maize and three irrigations and many relative strong rains happened in this time. High maize plants could also block the strong sunlight to weaken the evaporation of soil moisture. So the soil moisture from the cosmic-ray fast neutron probe was at a relative higher level and consistent with the real fact. In the third period from September 1 to September 30, the soil moisture continued to decline and maintained at 25%. There was no irrigation and only a little of rain in the third period and the maize plants were close to mature by absorbing soil water, so the overall soil moisture decreased rapidly and was relative low.

6. Conclusion
Currently, traditional soil moisture measurements are always detrimental and small-scale measurements, which is time-consuming, laborious to obtain regional or large-scale soil moisture. Especially in the case of the rapid development of remote sensing technology, it is hard to achieve scale match in the validation of remote sensing soil moisture though interpolation. How to obtain pixel soil water content information of remote sensing in order to validate or evaluate the precision is an urgent problem. Luckily, cosmic-ray fast neutron method provides a new regional soil moisture measurement way, which detection radius can be 350 meters and supports to monitor soil moisture at long time series. Soil moisture from cosmic-ray fast neutron method could monitor the changes in the growing season of maize and was really a surface average data by comparing with SoilNET data. However, there are also many problems to be solved in cosmic-ray fast neutron method, such as surface water effect during irrigation when cosmic-ray soil moisture was much higher and not consistent with the real situation. Also how to deal with the external factors (such as the air humidity, magnetic field changes, other water sources, etc.) impact on the fast neutrons will be the following study focus.

References
[1] Zhang B Y 2007 Review of the research on the basic theoretics and its application of soil water Science of Soil and Water Conservation 5(2) 122-129.
[2] Deng Y C and Xu Y H 2007 Introduction to the Methods of Soil Moisture Content Measuring Journal of China Hydrology 27(4) 20-24
[3] Topp G C, Davis J L and Annan A P 1980 Electromagnetic determination of soil water content:measurements in coaxial transmission lines Water Resources Research 16(3) 574-582.
[4] Robinson D A, Campbell C S, Hopmans J W, Hornbuckle B K, Jones S B, Knight R, Ogden F,
Selker J and Wendroth O 2008 Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review Vadose Zone Journal 7(1) 358-389.

[5] Vinnikov K Y, Robock A, Qiu S, Entin J K, Owe M, Choudhury B J, Hollinger S E and Njoku E G 1999 Satellite remote sensing of soil moisture in Illinois, United States Journal of Geophysical Research-Atmospheres 104(D4) 4145-4168.

[6] Famiglietti J S, Devereaux J A, Laymon C A, Tseggaye T, Houser P R, Jackson T J, Graham S T, Rodell M and van Oevelen P J 1999 Ground-based investigation of soil moisture variability within remote sensing footprints During the Southern Great Plains 1997 (SGP97) Hydrology Experiment Water Resources Research 35(6) 1839-1851.

[7] Weihermuller L, Huisman J A, Lambot S, Herbst M and Vereecken H 2007 Mapping the spatial variation of soil water content at the field scale with different ground penetrating radar techniques Journal of Hydrology 340(3-4) 205-216.

[8] Shuttleworth W J, Zreda M, Zeng X, Zweck C and Ferre T P A 2010 The COSmic-ray Soil Moisture Observing System(COSMOS): a non-invasive, intermediate scale soil moisture measurement network. Proceedings of the British Hydrological Society's Third International Symposium (Newcastle University, UK).

[9] Zreda M, Desilets D, Ferré T P A and Scott R L 2008 Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons Geophysical Research Letters 35(21) L21402.

[10] Li X, Cheng G, Liu S, Xiao Q, Ma M, Jin R, Che T, Liu Q, Wang W and Qi Y 2013 Heihe Watershed Allied Telemetry Experimental Research (HiWATER): Scientific Objectives and Experimental Design Bulletin of the American Meteorological Society.

[11] Jin R, Li X, Yan B P, Luo W M, Li X H, Guo J W, Ma M G, Kang J and Zhang Y L 2012 Introduction of eco-hydrological wireless sensor network in the Heihe River Basin[J]. Advances in Earth Science 27(9) 993-1005

[12] Zreda M, Zeng X, Shuttleworth W J, Zweck C, Ferre T, Rosolem R, Franz T, Desilets D, Desilets S and GWomack G 2011 Cosmic-Ray Neutrons, An Innovative Method for Measuring Area-Average Soil Moisture GEWEX News 21(3) 6-10.

[13] Rosolem R, Shuttleworth W, Zreda M, Zweck C, Franz T and Zeng X 2012 The Effect of Atmospheric Water Vapor on the Cosmic-ray Soil Moisture Signal Hydrol Earth Syst Sci in preparation.

[14] Franz T E, Zreda M, Rosolem R and Ferre T P A 2012 A universal calibration function for determination of soil moisture with cosmic-ray neutrons Hydrol Earth Syst Sci Discuss 9(9) 10303-10322.

[15] Desilets D, Zreda M and Ferré T P A 2010 Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays Water Resources Research 46(11).

[16] Pelowitz D 2005 MCNPX User's Manual Version 2.5.0. LA-CP-05-0369 Los Alamos National Labs Los Alamos

[17] Glasstone S and Edlund M C 1952 The elements of nuclear reactor theory 5th ed (New York van Nostrand) 416pp.

[18] Hess W N, Patterson H W, Wallace R and Chupp E L 1959 Cosmic-Ray Neutron Energy Spectrum Physical Review 116(2) 445-457.

[19] Zreda M, Shuttleworth W J, Zeng X, Zweck C, Desilets D, Franz T, Rosolem R and Ferre T P A 2012 COSMOS: the COSmic-ray Soil Moisture Observing System Hydrology and Earth System Sciences 16(11) 4079-4099.

[20] Franz T E, Zreda M, Ferre T P A, Rosolem R, Zweck C, Stillman S, Zeng X and Shuttleworth W J 2012 Measurement depth of the cosmic ray soil moisture probe affected by hydrogen from various sources Water Resour Res 48(8) W08515.

[21] Liu S 2013 Multi-scale observation experiment on evapotranspiration over heterogeneous land surface: Flux observation matrix Manuscript in preparation.