Soil Volumetric Moisture Content Observation and Data Validation Based on Cosmic-ray Neutron Method

Xueqin LV*, Hongzhi HUANG, Jincan HUANG
Guangdong Atmospheric Data Center, Guangzhou 510080, China

Abstract To investigate the accuracy and applicability of the cosmic-ray neutron method for long-term observation of soil water content, this study took the national meteorological observatories in Shouxian, Anhui Province and Dali, Yunnan Province as test sites and carried out fixed-point synchronous observation experiments lasting 2 – 3 months. Automatic observation data from cosmic-ray neutron soil moisture sensors and measured data from manual soil sampling were collected simultaneously. Correlation analysis, deviation analysis and root mean square error (RMSE) calculation were adopted to verify the reliability and stability of the automatic observation instruments, analyze the characteristics of observation deviations, and test the performance consistency of different devices deployed at the same site. The results show that the root mean square errors (RMSE) between cosmic-ray neutron observation values and manual measurement values at the three sampling sites are 0.015, 0.018 and 0.013, respectively. The correlation coefficient ρ reaches 0.80 at the undisturbed Dali observation site, while the correlation coefficients are 0.54 and 0.61 at the Shouxian observation sites affected by soil tillage. All instruments present favorable performance consistency. The research findings can provide technical support for long-term continuous regional soil moisture monitoring, and offer references for the optimized deployment of cosmic-ray neutron soil moisture measuring instruments.

Key words Soil water content; Cosmic-ray neutron method; Automatic observation; Manual measurement; Data validation
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Soil moisture is a key parameter in the hydrological cycle and energy exchange of terrestrial ecosystems, and its spatiotemporal distribution characteristics directly affect crop growth, soil erosion, and regional climate regulation[1]. The traditional soil moisture observation method, which uses manual sampling and drying as the standard, has the advantage of high measurement accuracy. However, it has limitations such as time-consuming, labor-intensive, destructive sampling, and inability to achieve continuous observation[2]. With the development of sensor technology, automatic observation devices such as time domain reflectometer (TDR) and frequency domain reflectometer (FDR) have been widely used. However, their observation range is limited to single points or very small scale areas, making it difficult to reflect the spatial heterogeneity of soil moisture at the field scale[3]. With the rapid development of science and technology in China, especially the emergence of soil moisture sensors based on cosmic-ray neutron method in recent years, it is expected to fill the gap in soil moisture monitoring mentioned above. The cosmic-ray neutron method is a mesoscale soil moisture observation technique based on the interaction between fast neutrons and hydrogen atoms. Its effective observation radius can reach 15 – 300 m, and the observation depth is 0 – 40 cm. It can achieve non-destructive and continuous automatic observation of soil moisture at the field scale[4]. Since its proposal in the 1990s, this technology has been applied in the observation of various underlying surfaces such as farmlands, grasslands, and forests. However, the observation accuracy varies in different regions due to factors such as soil texture, organic matter content, and soil salinity[5-9].

At present, research on the validation of cosmic-ray neutron method is mostly focused on single point and station, and there is a relative lack of data validation for multiple points and stations of the same type of observation instrument. Based on this, this study selected Shouxian in Anhui Province and Dali in Yunnan Province as experimental areas to conduct a 2-month automatic observation of regional soil moisture measurement instruments (cosmic-ray method) and manual synchronous observation. Through data comparison and analysis, the applicability of this method in this region was verified, in order to provide scientific basis for the construction of regional soil moisture observation networks.

1 Materials and methods

1.1 Overview of the study area The study area is located at the Shouxian National Meteorological Observatory of Huainan City, Anhui Province and the Dali National Meteorological Observatory of Yunnan Province. Shouxian belongs to the subtropical northern edge monsoon humid climate, with obvious transitional characteristics between the north and south climates, distinct four seasons, cold winters and hot summers, and rainy and hot seasons. The annual average temperature is about 15.1 – 15.2 ℃, and the average annual precipitation is between 905 and 931 mm, concentrated during the rainy season from June to August. The soil type is mainly paddy soil, with an average soil bulk density of 1.48 g/cm^3. The annual average temperature in Dali, Yunnan is 12 – 19 ℃, and the average annual precipitation is about 836

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* Corresponding author.

mm, concentrated from May to October. The main soil type is paddy soil, with a typical soil bulk density of 1.28 g/cm^3.

1.2 Observation instruments and deployment

(1) The automatic soil moisture observation instrument adopted HZJF-SM1 regional soil moisture measuring instrument (cosmic-ray method), with 2 sets and 1 set of experimental equipment respectively installed in Shouxian, Anhui Province and Dali, Yunnan Province. Among them, two stations in Shouxian were numbered ZZ01 and ZZ02, with a distance of more than 5 m between them, both located at the center of the Shouxian ground meteorological observation site. The Dali station, numbered ZZ03, was also basically located at the center of the Dali ground meteorological observation site. The observation objects of the above stations were representative native soils in the local area. The fast neutron sensor was mounted on a column through a bracket, parallel to the column in the vertical direction, with the sensor's lower edge 1.2 m above the ground. The instrument detects the slowing effect of hydrogen atoms (mainly from soil moisture) and fast neutrons in the soil to invert the soil moisture content. The observation range was centered on the site, with a radius of 100 m and a depth of 0 – 40 cm in the soil area.

(2) The artificial observation sampling points were arranged with the regional soil moisture measuring instrument as the center. 20 artificial soil sampling points were set up according to the principle of uniform distribution, with 5 layers taken from each sampling point. The location and depth of manual sampling points are shown in Fig. 1.

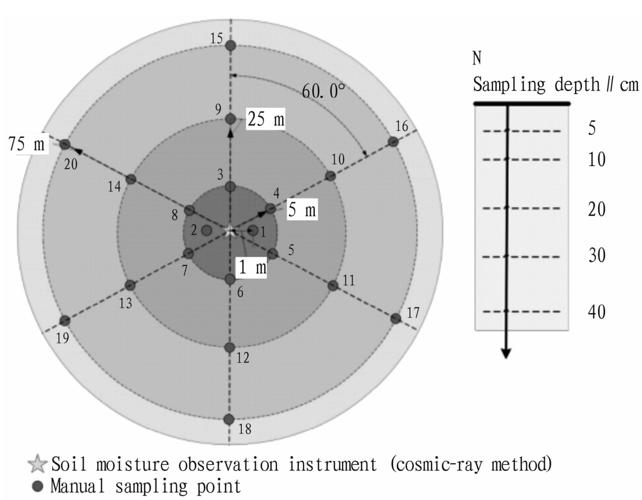

Fig. 1 Sampling point location and sampling depth

1.3 Observation methods and periods

(1) Dual link storage of observation experiment data. Dali station was operated in conjunction with manual observation for over three months starting from September 1, 2025, while Shouxian dual station was put into operation in conjunction with manual observation for over a month starting from November 20, 2025. The instrument automatically recorded soil volumetric moisture content data, which were loaded into the instrument's built-in memory card, and were uploaded to the data receiving server to ensure data security.

(2) Manual and automatic observations were synchronized. According to business regulations, the observation is conducted on 3rd, 13th, 23rd, 8th, 18th and 28th, and soil sampling work is required to be completed within 2 h. A total of 6 manual observation data can be obtained per month. If soil sampling is affected by precipitation or irrigation, it can be postponed until 2 days after the precipitation or irrigation stops. When the postponed date exceeds the next manual observation time, no retesting will be conducted. During observation, soil samples were collected in layers using soil drilling method at each sampling point, with sampling depths of 5, 10, 20, 30, and 40 cm soil layers. The soil sample was loaded into an aluminum box and weighed. After bringing it back to the laboratory, it was dried in a 105 ℃ oven for at least 12 h until the weight remained unchanged. Then, it was weighed again, and the soil volumetric moisture content was calculated using the formula (1):

$$\theta v = \frac{mf - md}{md} \times \rho b \tag{1}$$

where θv is soil volumetric moisture content (%); mf is wet soil mass (g); md is dry soil mass (g); ρb is soil bulk density (g/cm^3).

1.4 Analysis methods and data processing

(1) Analysis method: firstly, Excel was used to clean all automatically observed data. The data affected by equipment failures, rain, and obvious human factors were removed, and correlation and error analysis were conducted. The main evaluation indicators are correlation coefficient (ρ), mean absolute error (MAE), and root mean square error (RMSE). The calculation formulas (2) and (3) are as follows:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} | Oi - Pi | \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (Oi - Pi)^2} \tag{3}$$

where Oi is manually measured value; Pi is automatic observation value; n is observation frequency.

(2) Data processing: for the dataset in the entire comparison period, the obviously unreasonable data were cleared out, and manually observed soil volumetric moisture content and corresponding automatic observation data were extracted, as shown in Table 1 – 3.

Table 1 Comparison between manual and automatic observation at station ZZ01 %

Station No.	Time	Manual observation	Instrument measurement	Absolute error
Z2001	2025 – 11 – 23 09:00	43.25	44.58	1.33
ZZ001	2025 – 11 – 28 09:00	44.32	45.20	0.88
ZZ001	2025 – 12 – 03 10:00	44.10	44.38	0.28
ZZ001	2025 – 12 – 08 10:00	43.36	41.92	–1.44
ZZ001	2025 – 12 – 13 09:00	42.90	41.91	–0.99
ZZ001	2025 – 12 – 18 10:00	43.43	41.21	–2.22
ZZ001	2025 – 12 – 24 10:00	44.18	41.88	–2.30
ZZ001	2025 – 12 – 28 10:00	42.52	41.52	–1.00

Table 2 Comparison between manual and automatic observation at station ZZ02 %

Station No.	Time	Manual observation	Instrument measurement	Absolute error
ZZ002	2025-11-23 09:00	43.25	45.12	1.87
ZZ002	2025-11-28 09:00	44.32	45.17	0.85
ZZ002	2025-12-03 10:00	44.10	44.00	-0.10
ZZ002	2025-12-08 10:00	43.30	41.26	-2.10
ZZ002	2025-12-13 09:00	42.90	40.71	-2.19
ZZ002	2025-12-18 10:00	43.43	42.58	-0.85
ZZ002	2025-12-24 10:00	44.18	41.69	-2.49
ZZ002	2025-12-28 10:00	42.52	40.22	-2.30

Table 3 Comparison between manual and automatic observation at station ZZ03 %

Station No.	Time	Manual observation	Instrument measurement	Absolute error
ZZ003	2025-09-03 19:00	40.70	41.51	0.81
ZZ003	2025-09-05 09:00	40.32	41.42	1.10
ZZ003	2025-09-16 09:00	45.08	44.42	-0.66
ZZ003	2025-10-10 09:00	46.11	45.51	-0.60
ZZ003	2025-10-29 14:00	41.83	43.27	1.44
ZZ003	2025-11-6 18:00	46.29	45.11	-1.18
ZZ003	2025-11-3 14:00	41.80	41.91	0.11
ZZ003	2025-12-13 10:00	44.87	43.65	-1.22
ZZ003	2025-12-18 10:00	43.50	41.36	-2.14
ZZ003	2025-12-23 11:00	43.35	41.39	-1.96
ZZ003	2025-12-28 10:00	43.89	42.36	-1.53

Correlation and error analysis were conducted on the manual and automatic observation data of three stations. The results were as follows: the correlation coefficient ρ of station ZZ01 was 0.54, with a MAE of -0.68% and a RMSE of 0.015; the correlation coefficient ρ of station ZZ02 was 0.61, the MAE was -0.91%, and the RMSE was 0.018; the correlation coefficient ρ of station ZZ03 was 0.80, the MAE was -0.53%, and the RMSE was 0.013.

2 Results and analysis

2.1 Temporal variation characteristics of soil volumetric moisture content Seen from Table 1-3, there were regular fluctuations in the automatically observed soil volumetric moisture content in both Shouxian and Dali. By carefully examining the precipitation situation in two places, it was found that during the entire comparative verification period, the number of rainfall events in Shouxian was relatively low and the changes were relatively mild, as shown in Fig. 2. However, the rainfall in Dali was repetitive and frequent, so the fluctuation of soil volumetric moisture content was relatively severe, as shown in Fig. 3. Overall, the temporal variation characteristics of soil volumetric moisture content were basically consistent with the local rainfall start time, end time, and intensity, demonstrating good followability.

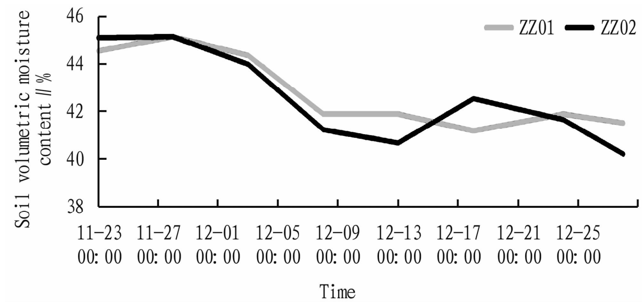

Fig. 2 Trend of soil volumetric moisture content changes at Shouxian station, Anhui Province

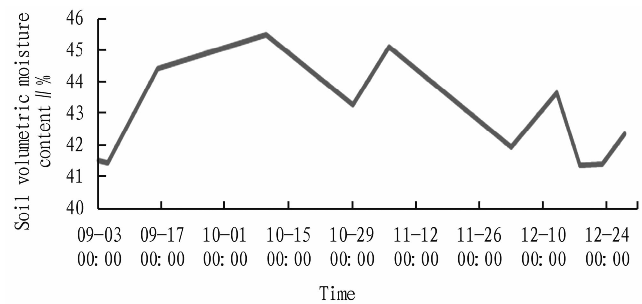

Fig. 3 Trend of soil volumetric moisture content changes at Dali station, Yunnan Province

During the comparative observation period, there was very little rainfall at Shouxian station, so the soil volumetric moisture content in the area showed a downward trend over time, which is in line with objective facts. The equipment observation data of stations ZZ01 and ZZ02 showed similar trends, with the maximum absolute relative error of 1.37%. This fully demonstrated the good consistency of the performance of automatic observation equipment, as shown in Fig. 2.

During the observation period, the soil volumetric moisture content in the Dali observation station increased significantly to over 46% on October 10, 2025 and November 6, 2025. This was due to the influence of rainfall events (both occurring two days before that date, with rainfall of 18 and 62 mm), which resulted in a significant peak in soil volumetric moisture content. The trend of changes in manual and automatic observation values remained consistent, fully demonstrating that the regional soil moisture measurement instrument (cosmic-ray method) can sensitively capture the dynamic changes in soil moisture.

2.2 Correlation analysis between automatic and manual observation data The correlation between the observed values of the automatic observation equipment and the manually measured values was calculated. The data correlation between the two stations in Shouxian was relatively small, with correlation coefficients of $\rho=0.54$ and $\rho=0.61$, respectively. The reasons were as follows: firstly, during the comparison process, the paddy fields were overturned, and the surface of the paddy fields was uneven, which affected the accuracy of manual soil extraction to a certain extent. Secondly, the equipment had a short operating time and there were relatively few observation data samples, resulting in certain deviations in data fitting. The data correlation of the Dali station was relatively high, with a correlation coefficient of $\rho = 0.80$. This may be because the soil at the observation site has not been overturned, and the surface was relatively flat and stable. Although there was frequent rainfall, the accuracy of manual soil sampling was relatively high.

The RMSE of three stations, ZZ01, ZZ02, and ZZ03, were 0.015, 0.018, and 0.013, respectively, which were relatively small overall. This indicated that the following performance between automatic and manual observation was consistent, and the accuracy of the observation data from the regional soil moisture measuring instrument (cosmic-ray method) was high. Moreover, the error between the automatic and manual observation values was positive or negative, which was in line with objective facts, and there was no obvious systematic error.

3 Discussion

This study conducted 2 – 3 months of automatic and manual comparative observations. According to statistics, the overall deviation of the observation data between the two was relatively small. It preliminarily verified the accuracy, reliability, and stability of the regional soil moisture measurement instrument (cosmic-ray method) in soil moisture observation in northern and southern regions of China, which can better meet the observation needs of soil moisture at the field scale.

The sources of observation data bias mainly included two aspects: first, soil turning affected the accuracy of manual soil sampling, resulting in certain deviations in manual observation values; the second was the interference of environmental factors. The differences in rainfall intensity and changes in surface vegetation coverage during the synchronous observation period may affect the detection environment of the neutron instrument, thereby affecting the observation accuracy.

Overall, compared to traditional manual observation and single point observation using TDR method, the regional soil moisture measurement instrument (cosmic-ray method) has the advantages of non destructiveness, large observation range, and all-weather automatic observation. It is more suitable for soil moisture observation business at the field scale and will become the future development direction of soil moisture observation.

4 Conclusions

(1) The automatic observation values of the regional soil moisture measuring instrument (cosmic-ray method) had a high correlation with the manually measured values, with small observation errors. The trend of the two changes was consistent during the 2 – 3-month observation period, indicating that the instrument can accurately reflect the dynamic changes in soil moisture in the study area.

(2) This study verified that the regional soil moisture measurement instrument (cosmic-ray method) is generally suitable for use in both the northern and southern regions of China, providing technical support for long-term observation of regional soil moisture and reference for the deployment and application of the instrument in similar areas.

(3) Due to the short time period for comparison and verification, the long-term stability and accuracy of the automatic observation instrument need further validation.

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