Volumetric Calibration of Neutron Moisture Probes

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ABSTRACT

A volumetric method of estimating the slope (b coefficient) of a neutron moisture probe calibration curve is discussed. Coefficients obtained for three probes by this method did not differ significantly between soil series or between horizons within a series. Simply dividing the count rate in water by 100 gave a value virtually identical to the b coefficient determined volumetrically for these probes and soils. Agreement was excellent between measured outflow and outflow predicted from neutron measurements made with a volumetrically calibrated moisture probe.

The neutron method is widely used to study soil moisture changes with time, which are in turn used to determine evapotranspiration and water movement in soils. As used in the field today, moisture changes are determined from curves purporting to relate slow neutron count rate to soil water content (1, 3, 8). For probes having a linear count response over the usual range of water contents experienced, this curve takes the form

\[ w = a + \frac{c}{b} \tag{1} \]

in which water content \( w \) in percent moisture by volume is a function of slow neutron count rate \( c \). The \( a \) and \( b \) coefficients establish the level and slope of the line.

Users ordinarily calibrate probes gravimetrically, expressing results in terms of water content by volume, 105\(^\circ\)C oven-dry basis, but a variable amount of bound water and organic hydrogen remain in different soils dried at this temperature (4). Hydrogen remaining in soil after drying also moderates response of the probe is linear (2), and each determination of \( \Delta c/\Delta w \) is an independent estimate of \( b \) with bound hydrogen effects held constant.

The first objective of this paper is to determine whether different soil materials affect the value of \( b \) (equation [3]) as determined by volumetric calibration of three P-19 moisture probes. If \( b \) proves constant in these soils, a second purpose is to test the hypothesis that there is no significant difference between \( b \) determined experimentally and \( b \) calculated from a straight line connecting the counting rate in 0 and 100% water. The final objective is to compare outflow from an enclosed, draining soil mass with predicted outflow based on moisture changes obtained when a volumetrically calibrated neutron probe is used.

METHODS AND EQUIPMENT

Probe Calibration

Three P-19 moisture probes and Model 2800 sealers, manufactured by Nuclear-Chicago Corporation, were used in the study. The probes, standard equipment supplied by the manufacturer, are 3.81 cm in diameter and consist of a three-transistor preamplifier connected to a BF\(_3\) neutron detector tube. The neutron source is a 5 me (nominal) Ra-Be capsule having a total emission of about \( 6 \times 10^6 \) neutrons/sec. Access tubing was the standard 4.1275 cm outside diameter, 3.9497 cm inside diameter steel tubing recommended by the manufacturer.

![Diagram of equipment](image-url)
The $b$ coefficients were determined in drums of soil prepared from the B or C horizon of four of the most common soils of the Coweeta basin. Two independent measurements of $b$ were made in soil of each horizon. Soil was passed through a 1.27-cm mesh screen, thoroughly mixed, and uniformly packed into a 1,000-liter steel drum. The intention was to pack soil to the approximate field density of these soils (1.3 g/cm$^3$). The drum, 1.02 m in diameter and 1.27 m high, was calibrated so that soil volume could be measured to the nearest 0.1% (Fig. 1). After the drum was filled, 3-min slow neutron counts were taken in a centrally located access tube. Measurements began with the probe on the bottom of the drum and positioned at successive 5.08-cm intervals to the soil surface.

Next, a measured volume of water was metered slowly from a 200-liter container into the base of the drum to saturate the soil with minimum entrapment of air. Water addition ceased when free water was visible at the soil surface, saturation usually occurring within 4 hours. Then, with the soil saturated, the count rate of the soil column was determined as before. Change in water content was obtained by dividing the volume of water required to saturate the soil by the soil volume. Average change in count rate caused by the addition of water was calculated for the midportion of the drum (that portion determined to be virtually unaffected by soil-air interface effects). Assuming that this portion of the drum represented moisture conditions in upper and lower portions of the drum as well, measurements of $\Delta c$ and $\Delta w$ were used to calculate $b$ in equation [3].

**Volumetric Field Check of Calibration**

After $b$ coefficients were obtained for each soil, measured outflow from a large soil model (designed to simulate the action of a watershed) was compared with outflow estimated from neutron measurements.

The soil model was 1.40 m wide, 2.13 m deep, 60.96 m long and inclined 20.6 degrees from the horizontal (Fig. 2). It contained 182 m$^3$ of soil averaging 1.3 g/cm$^3$ in bulk density. Nine access tubes were randomly located with respect to the centerline of the model but no closer than 30 cm to the edge. The first tube was positioned 1.40 m from the lower end of the model; remaining tubes were spaced at 7.60-m intervals to the upper end of the model. Neutron count rate measurements began approximately 28 cm below the soil surface and were made at 30-cm depth intervals thereafter. The lowest measurements were made about 18 cm above the floor of the model.

The model was recharged to near saturation by sprinkling, and then covered with polyethylene to prevent evaporation loss and rainfall increments. Moisture change and outflow were followed for the next 90 days as water drained from the lower end of the model. Average moisture change was converted to water volume for comparison with measured outflow.

**RESULTS AND DISCUSSION**

Successful calibration is contingent upon containing the entire sphere of influence within the soil column (1, 6, 7). Data by Van Bavel et al. (9) guided initial moisture content and drum dimensions. Initial soil moisture ranged from 17 to 32% by volume, and for the drum dimensions used, was sufficient to minimize neutron escape from the center third of the soil column.

During volumetric calibration, moisture must be uniform throughout the soil column before and after addition of water. Density and moisture samples assured that this requirement was met. Density for all drums averaged 1.26 g/cm$^3$ ± a 0.01 g/cm$^3$ standard error within and between soil columns. Count rates taken at 5.08-cm intervals through the midportion of the columns were also uniform. Standard error of these rates varied less than the equivalent of 0.25% moisture by volume for most soil columns, and not over 0.50% for any column.

The 16 $b$ coefficients obtained for each probe were tested by analysis of variance techniques to determine whether they differed between B and C horizon soil or between soil series. Data for Probe 72 and Sealer 89 (Table 1) are representative of data for all three probes, and show that coefficients did not

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>$F^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among horizons</td>
<td>7</td>
<td>79.94</td>
<td></td>
</tr>
<tr>
<td>Series</td>
<td>3</td>
<td>108.10</td>
<td>1.84 NS</td>
</tr>
<tr>
<td>Among horizons within series</td>
<td>4</td>
<td>58.82</td>
<td>1.12 NS</td>
</tr>
<tr>
<td>Among observations within horizons</td>
<td>8</td>
<td>52.34</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*NS = nonsignificant at the 0.05 confidence level.
DOUGLASS: VOLUMETRIC CALIBRATION OF NEUTRON MOISTURE PROBES

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Fig. 4—Comparison of outflow from a large soil model with outflow predicted from neutron measurements. The straight line represents a 1:1 relationship between predicted and measured outflow.

differ between soil horizons within a soil series or between series. Standard errors of \( b \) for Probes 72, 73, and 163 were 2.6, 1.2, and 1.9 counts/min per percent moisture, respectively. Expressed as a percentage of \( b \), these errors average < 1%. Thus, the calibration error of a 25% change in moisture volume is < 0.27% by volume, and the absolute volume error decreases proportionately as the size of the moisture change decreases. This is greater accuracy than has been reported for other calibration methods.

A simpler version of volumetric calibration is to assume that the counting rate at 0 moisture is 0 and that the slope of the calibration curve is linear from 0 to 100% moisture. A comparison of volumetrically derived line segments expressed as water equivalent of thermalized neutrons\(^4\) and the line connecting counting rate at 0 and 100% moisture (corrected for background and coincidence loss) shows that within the range of moisture conditions investigated, there is good agreement between slopes (Fig. 3). The average \( b \) coefficient for each probe determined by volumetric calibration and by dividing the adjusted count rate in water by 100 differed by only 2 counts/min per percent moisture volume (Table 2). The difference in coefficients is not statistically significant. This simple procedure makes possible the recalibration of these probes periodically or after repairs.

Because the simpler calibration technique is not fundamentally sound, it must be pointed out that the agreement of \( b \) coefficients may be only fortuitous. Proof that counting response is linear from 0 to 100% water requires measuring \( b \) without corrections for background.

\(^4\) Water equivalent of thermalized neutrons might be thought of as the "absolute water content" if one assumes that all neutron thermalizers in soil are part of a water molecule.

Table 2—Comparison of \( b \) coefficients determined in water and by volumetric calibration

<table>
<thead>
<tr>
<th>Probe</th>
<th>( b = \text{count rate}^* + 100 )</th>
<th>( b = \Delta V / \Delta W )</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>234</td>
<td>238</td>
<td>2</td>
</tr>
<tr>
<td>73</td>
<td>194</td>
<td>183</td>
<td>1</td>
</tr>
<tr>
<td>163</td>
<td>180</td>
<td>190</td>
<td>1</td>
</tr>
</tbody>
</table>

* Corrected for background count and coincidence loss.

Outflow for the covered soil model and water volume changes were compared for a 90-day drainage period. This comparison provides a rigorous test of calibration accuracy because an error in \( b \) will cause actual and predicted outflow to depart from a 1:1 relationship as outflow becomes larger. Measured outflow agreed closely with outflow estimated from \( b \) derived volumetrically (Fig. 4). The scatter of predicted points around actual outflow is within the measurement error of the method (5) and no diverging trend from a 1:1 relationship is apparent. Thus, accurate estimates of actual moisture change in the model were obtained when the volumetrically calibrated probe was used. Conversely, when the same count rate data was converted to outflow by means of the manufacturer's calibration, predicted outflow was about 20% less than actual outflow.

SUMMARY

In volumetric calibration, the neutron probes are calibrated directly by measuring the count rate change associated with
moisture volume change in a large homogeneous soil mass. The b coefficients determined volumetrically for three standard commercial probes in four soil types did not differ between soils or between horizons within a soil series. Virtually the same b value was obtained by simply dividing the counting rate in water (corrected for background and coincidence loss) by 100. The shorter method has advantages of directness and simplicity, but soundness of assumptions inherent in the method are questionable, and it is not recommended for field use. The average count-rate change in a large, draining soil model converted to outflow on a basis of the volumetrically derived slope agreed closely with measured outflow and gave an accurate estimate of moisture change.

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LITERATURE CITED