COSMIC-RAY HYDROMETROLOGY: MEASURING SOIL MOISTURE WITH COSMIC-RAY NEUTRONS

Definition

*Cosmic-ray hydrometrology***.** The science of measuring hydrologic variables through their effects on secondary cosmic-ray intensity.
Primary cosmic ray. A charged particle, usually a proton, traveling toward Earth with relativistic speed.
Secondary cosmic-ray. An energetic proton, neutron or other subatomic particle generated as a consequence of primary cosmic rays colliding with Earth.

Introduction

Cosmic-rays continually bombard Earth, giving rise to a small but measureable flux of background neutrons at the land surface. These ambient neutrons respond strongly to the presence of land-surface water in the form of soil moisture and snow, or more specifically to the hydrogen which that water contains. The unique ability of hydrogen to influence neutron intensity has been known since the discovery of the neutron itself in the 1930s, when the mysterious non-ionizing radiation was first identified through its ability to scatter hydrogen nuclei from paraffin (Chadwick, 1932), losing substantial fraction of its energy in the process. By the late 1950s, soil scientists began applying neutron scattering principles to the field determination of soil water content by lowering radioisotopic neutron sources and co-located neutron detectors down bore holes and measuring the intensity of back scattered neutrons (Gardner and Kirkham, 1952). It was later demonstrated that water content in the shallow subsurface and snow water equivalent depth could be obtained passively by measuring background cosmic-ray neutrons with detectors buried in the top meter of soil (Kodama et al., 1985), although the method was never widely adopted. More recently, Zreda et al. (2008) showed the feasibility of non-invasively measuring soil water content through aboveground measurements of cosmic-ray neutron intensity. This technique operates at a scale of tens of hectares, which fills an important gap between the scales of invasive point measurements and satellite remote sensing footprint.

Neutron interactions in soil

The transmission of fast neutrons through bulk matter is profoundly influenced by the presence of hydrogen, which at the land surface is present mainly in the form of liquid and solid water and plant carbohydrates. Hydrogen is uniquely effective in moderating (slowing) neutrons by virtue of its low mass and relatively large elastic scattering cross section, which is a measure of the probability of interacting elastically with a neutron. As with any two particles having the same mass, a fast neutron can theoretically be brought to rest through a single head-on collision with hydrogen (Glasstone and Edlund, 1952). The fewer collisions needed to moderate a fast neutron, the lower the fast neutron intensity will be. Elastic collisions with hydrogen and other light nuclei progressively moderate a fast neutron until it is either absorbed by a nucleus or is reduced to a velocity on the order of the thermal motions of surrounding molecules, at which point there is no net change in energy through subsequent collisions. A distinguishing characteristic of thermal neutrons is their strong tendency to be absorbed by nuclei. Common absorbing elements in the soil matrix include major elements such as Fe, Ca, K, and trace elements with unusually high absorption cross sections, such as B, Gd and Sm.

Cosmic-ray neutrons

Cosmic-ray neutrons are an ever-present part of the land-surface radiation environment. They are a by-product of chain reactions initiated at the top of the atmosphere by primary cosmic rays (Simpson, 1951) (A simulated particle cascade created by a 10 GeV primary interacting with nitrogen is shown in Figure 1). The primary radiation is composed of highly energetic particles, mainly protons and helium nuclei, which are believed to have been accelerated in shock waves associated with supernovas occurring throughout the Milky Way (Uchiyama et al., 2007). Energetic primaries collide with atmospheric gas molecules, unleashing cascades of secondary protons, neutrons and other subatomic particles, some of which penetrate to sea level.

The neutrons utilized for passive water content measurements are generated mainly by cascade neutrons interacting with matter. Fast neutrons are produced in two types of interactions. A cascade neutron can transfer kinetic energy to an entire target nucleus, raising it to an excited energy state. The nucleus then cools off by "evaporation", i.e. the emission of fast neutrons in random directions. Cascade neutrons with higher energies will tend to interact at the surface of a nucleus, dislodging the outer most neutrons in a mostly forward direction (Krane, 1987). Regardless of how they are produced, fast neutrons are scattered elastically in random directions until they are eventually absorbed by soil or atmospheric nuclei.

Fast neutron intensity at the land surface reflects the equilibrium between production, moderation and absorption of neutrons in the ground and atmosphere (Figure 2). Neutrons are scattered between the ground, which tends to be the better moderator when wet, and the atmosphere, which is the better thermal neutron absorber. Any change in water content at the land surface disturbs this equilibrium. An increase in the amount of soil water or snow decreases the intensity in the fast to epithermal region because neutrons are more efficiently reduced to lower energies through collisions with hydrogen. Conversely, thermal neutron intensity first increases with increasing water content, and then decreases monotonically. This behavior is explained by the competing roles of hydrogen as an absorber and moderator. Initially, a small increase in water content rapidly increases the rate of thermalization, which increases the thermal neutron flux. But above a few percent gravimetric soil moisture content, the role of hydrogen as a moderator is challenged by its tendency to absorb neutrons.

Retrieval of soil moisture

For a wide range of soil compositions, a "universal" shape-defining function can be used to convert neutron counting rates to soil water content (Figure 3). This function is valid for neutrons in the epithermal to fast part of the spectrum (10^0-10^6 eV), where neutron absorption is minor. A calibration curve for soil water content has been obtained by fitting simulated gound-level neutron fluxes to the semiempirical shape-defining equation:

$$\theta(\phi/\phi_r) = \frac{1}{B}\left(\frac{A}{(\phi/\phi_r) - D} - C\right) \tag{1}$$

where (ϕ/ϕ_r) is the neutron intensity normalized to a reference soil moisture state. The dependence of land surface neutron intensity in the epithermal to fast energy range on gravimetric soil water content is represented in silica-dominated soils by A=0.562, B=0.060, C=0.942, D=0.449, with the reference state dry soil. The shape of the function is not significantly altered by differences in soil texture, salinity, bulk density or moderate amounts carbonates or organic matter in soil.

Although the shape of the calibration function is largely invariant, the absolute "source" neutron intensity is highly variable across the surface of the Earth. In other words, the calibration function can translate on the intensity axis depending on location. Elevation differences are responsible for the biggest differences in source intensity. The elevation effect is more accurately described as a function of the mass shielding depth at a site, which is the product of atmospheric depth and air density and is expressed in units of g cm^{-2}. Local barometric pressure readings are usually an acceptable proxy for mass shielding depth. Neutron-generating cascades are attenuated exponentially as a function of mass shielding according to

$$\phi_2 = \phi_1 \exp[(x_1 - x_2)/\Lambda] \tag{2}$$

where ϕ_1 and ϕ_2 are the neutron intensities at depths x_1 and x_2 [g cm^{-2}] and the attenuation length Λ is ~130 g cm^{-2} at high to mid latitudes (Desilets et al., 2006). According to this relationship, the neutron intensity at an elevation of 3000 m (750 g cm^{-2}) meters is almost

9 times greater than at sea level (1033 g cm^{-2}). Neutron intensity decreases by about half from high and mid latitudes to the equator due to stronger magnetic shielding of primary cosmic rays at lower geomagnetic latitude. The elemental composition of soil may also have some effect on neutron source intensity because of differences between elements in the number of neutrons emitted following excitation.

The spatial variability in cosmic-ray intensity means that the calibration function must be normalized to the local neutron source strength. This can be accomplished by obtaining at least one field calibration point. Because the radius of influence is large, many field samples are usually needed in order to obtain an areally representative average moisture (e.g. Western and Blöschl, 1999; Famiglietti et al., 2008). Different strategies to obtaining this point may be employed. One consideration is that average soil water content is ideally in the middle of the anticipated moisture range. Another consideration is that samples should be collected when the distribution of soil moisture is expected to be fairly uniform, in order to reduce the number of samples required for representativeness. A calibration is transferrable to another site if the topography, biomass concentration and soil composition are similar between the two sites and elevations and latitudes are similar. Differences in source neutron intensity related to elevation and latitude can be compensated for by applying published scaling factors for neutron intensity (e.g. Desilets et al., 2006).

Counting rates should also be corrected for fluctuations in neutron source intensity over time. These are related mainly to variations in barometric pressure and solar activity. Corrections for barometric pressure can be made with Eq. 2 using local pressure data and the local attenuation length for neutron generating cosmic rays. Changes related to solar activity can be corrected using publicly available data from the global network of neutron monitors (Kuwabara et al., 2006).

Measuring neutron intensity

Neutron detectors tend to be most sensitive over a limited range of energies. The optimal sensitivity for soil moisture measurements is in the epithermal (10^0-10^1 eV) range because a reasonably high count rate can be achieved while sensitivity to neutron absorbers is minimized. Although the shape of the calibration function is nearly constant up to 10^6 eV, neutron intensity drops off rapidly with energy according to a $1/E$ law (Glasstone and Edlund, 1952). Measurements at higher energies therefore require larger or more efficient detectors or longer averaging times in order to compensate for lower neutron intensity.

The analytical precision of soil moisture determinations is governed by Poissonian statistics, which assumes that neutron counts are uncorrelated. The coefficient of variation is given by $N^{-0.5}$, where N is the counting rate. A precision of better than 2-3% for one hour of counting is easily achieved at sea level using portable equipment.

Sample Volume

A major advantage of subaerial cosmic-ray measurements is that a large area can be sampled non-invasively from the ground or a low-flying aircraft. The radius of influence for 86% (two e-fold drops) of the counts is 350 meters at sea level for a ground based, omnidirectionally sensitive neutron detector. Several factors are responsible for the large radius of influence: the neutron source is distributed across the land surface, the mean free path for atmospheric collisions is on the order of 30 m, and trajectories are randomized through collisions in the atmosphere. The footprint increases with elevation in proportion to the atmospheric collision mean free path length, which is inversely proportional to atmospheric pressure. The measurement depth depends strongly on soil moisture, ranging from 0.6 m in dry soil to 0.2 m in saturated soil for 86% of the response.

Summary

Soil water content can be inferred from subaerial measurements of cosmic-ray neutron intensity. The hydrogen in soil water and dominates the moderating power in the land-surface environment. Through its ability to moderate and absorb neutrons, hydrogen exerts a strong control on neutron fluxes in the fast to thermal energy range. Cosmic ray measurements are passive, non-invasive, non-contact and represent a sample area of tens of hectares and a depth of tens of centimeters. The method has moderate power demands and data processing and transmission requirements, which makes it particularly well suited for long term monitoring and field campaigns. A promising direction for future research is coupling neutron observations to land-surface models and possibly even inverting neutron data to obtain soil properties and evapotranspiration. Furthermore, advances in neutron detection technology, for example in the area of directionally sensitive neutron detectors (Mascarenhas et al., 2006), have the potential to open new applications and spatial scales for hydrologic measurements.

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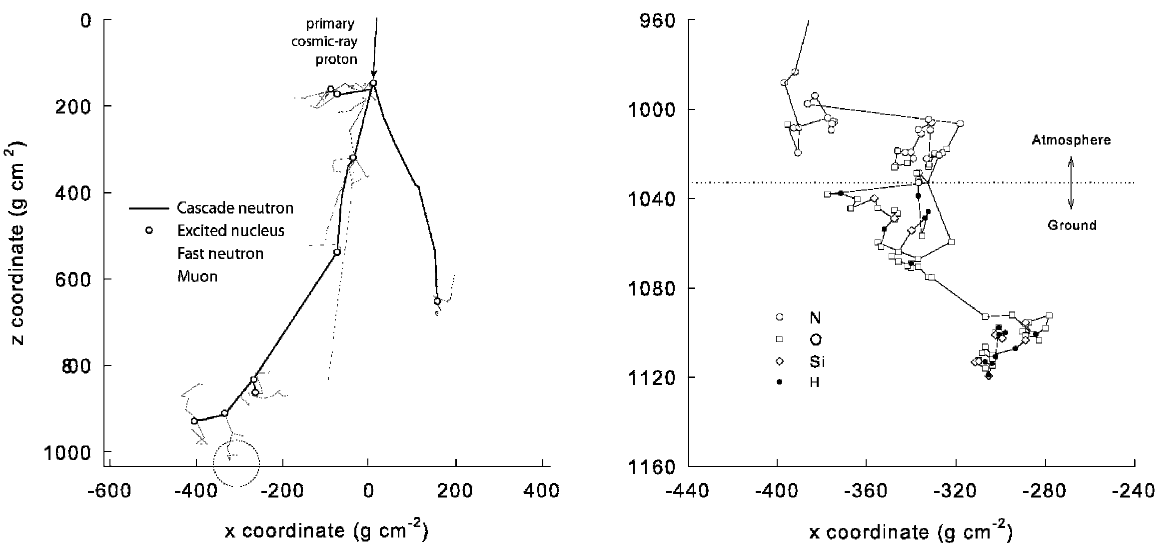

Figure 1. Atmospheric particle cascade simulated with the radiation transport code Monte Carlo N-Particle eXtended (MCNPX -- Pelowitz, 2005). A 10 GeV primary cosmic-ray proton collides with atmospheric nitrogen, triggering a particle cascade that reaches sea level. Fast neutrons are generated at each collision marked by a circle. The

fast neutrons are scattered in random directions as they are moderated and eventually become captured.

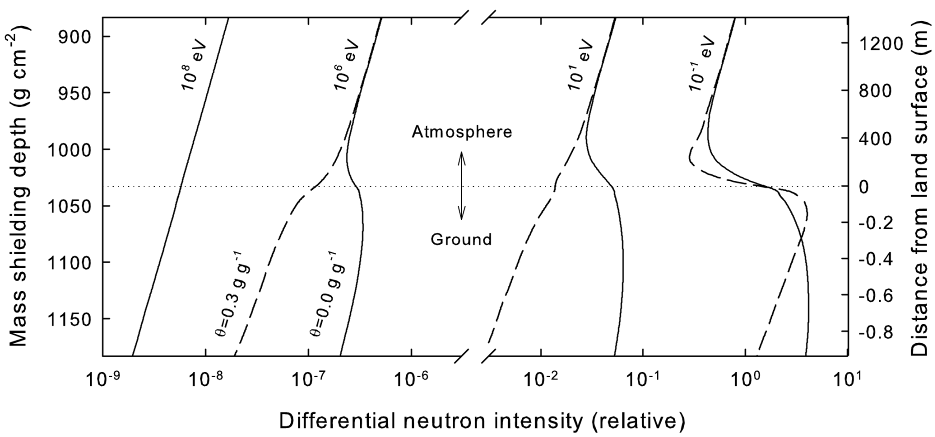

Figure 2. Depth profiles of neutron intensity near the land surface for different energies simulated with MCNPX. Between 10^1-10^6 eV, where elastic scattering interactions dominate, the shape of the profile and its sensitivity to soil moisture are remarkably constant. At lower energies (<10^{-1} eV), thermal neutron absorption becomes important and the shape of the profile reflects the strong contrast between the absorbing properties of the ground and atmosphere. At higher energies (>10^8 eV) the profile reflects exponential attenuation expected for cascade neutrons.

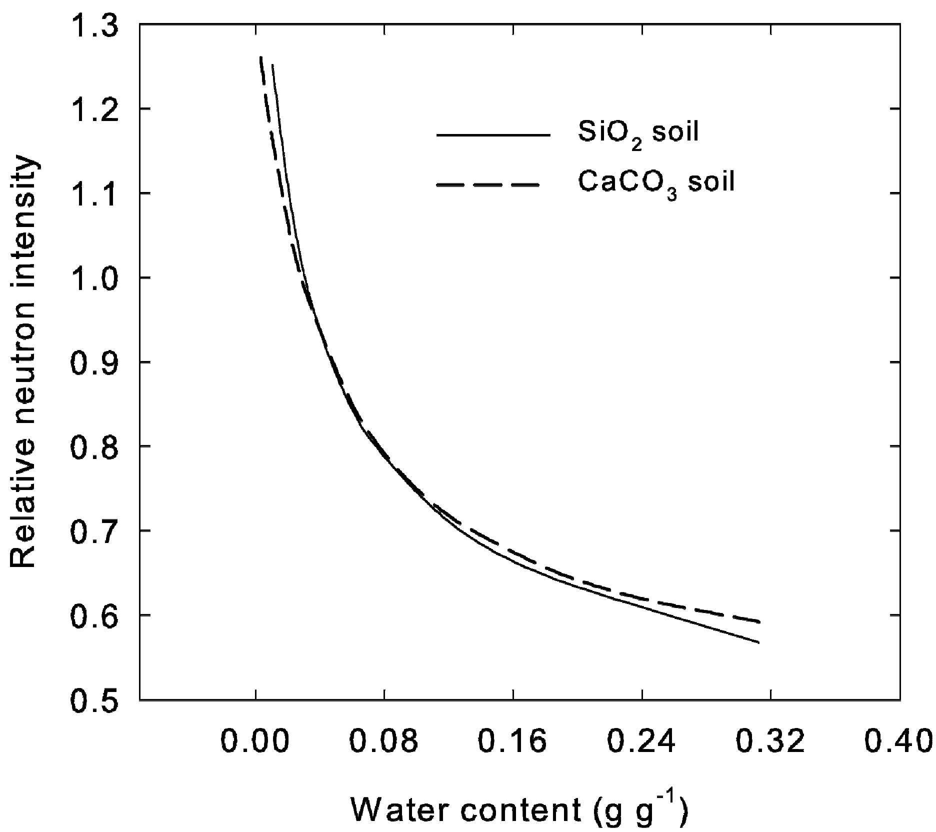

Figure 3. The dependence of neutron intensity on soil water content at 0-2 meters above the ground. The profiles were calculated with MCNPX for a soil matrix with pure SiO_2.

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