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Standard Guide for Comparison of Techniques to Quantify the Soil-Water (Moisture) Flux[1]

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1. Scope

1.1 This guide describes techniques that may be used to quantify the soil-water (or soil-moisture) flux, the soil-water movement rate, and/or the recharge rate within the vadose zone. This guide is not intended to be all-inclusive with regard to available methods. However, the techniques described do represent the most widely used methods currently available.

1.2 This guide was written to detail the techniques available for quantifying soil-moisture flux in the vadose zone. These data are commonly required in studies of contaminant movement and in estimating the amount of water replenishing a renewable groundwater resource, that is, an aquifer. State and federal regulatory guidelines typically require this information in defining contaminant travel times, in performance assessment, and in risk assessment. Both unsaturated and saturated flow modelers benefit from these data in establishing boundary conditions and for use in calibrations of their computer simulations.

1.3 This guide is one of a series of standards on vadose zone characterization methods. Other standards have been prepared on vadose zone characterization techniques.

1.4 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

- D653 Terminology Relating to Soil, Rock, and Contained Fluids
- D1452 Practice for Soil Exploration and Sampling by Auger Borings
- D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
- D3404 Guide for Measuring Matric Potential in Vadose Zone Using Tensiometers
- D4643 Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating
- D4696 Guide for Pore-Liquid Sampling from the Vadose Zone
- D4700 Guide for Soil Sampling from the Vadose Zone
- D4944 Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester
- D5126 Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in Vadose Zone
- D5220 Test Method for Water Mass per Unit Volume of Soil and Rock In-Place by the Neutron Depth Probe Method

3. Terminology

3.1 *Definitions:*

3.1.1 *chlorine-36, ^{36}Cl*—a radioactive isotope of chlorine, containing one extra neutron in the nucleus, and a decay half-life of 300,000 years.

3.1.2 *deuterium, ^{2}H*—a stable isotope of hydrogen, containing one extra neutron in the nucleus.

3.1.3 *oxygen-18, ^{18}O*—a stable isotope of oxygen, containing two extra neutrons in the nucleus.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.4 *recharge flux, (LT^{-1})*—the soil-moisture flux of water moving through the vadose zone, beneath the zone of evapotranspirative uptake, which eventually replenishes water to an underlying aquifer.

3.1.5 *soil-moisture flux, (LT^{-1})*—synonymous with specific discharge.

3.1.6 *specific discharge, (LT^{-1})*—the rate of flow of water through a porous medium per unit area measured at a right angle to the direction of flow. **(D653)**

3.1.7 *specific flux, (LT^{-1})*—synonymous with specific discharge.

3.1.8 *tritium, ^3H*—a radioactive isotope of hydrogen, containing two extra neutrons in the nucleus, and a decay half-life of 12.3 years.

3.2 Definitions of other terminology used in this guide may be found in Standard D653.

4. Summary of the Guide

4.1 The quantitative techniques described for assessing soil-moisture flux are:

4.2 *Water Balance Methods*—The water balance method is based on the mass balance of input/output parameters in the hydrologic budget. The hydrologic budget for any given locale may be summarized in terms of the influence of the following factors/phenomena: precipitation, runoff, infiltration, evapotranspiration, interflow, sources/sinks, and recharge rate. Soil-moisture flux may be estimated by determining all parameters in the hydrologic budget (for example, precipitation rate) except the desired flux term, which is solved by differencing the water balance equation. One or more of the parameters needed in the water balance method are typically difficult to estimate, and therefore cause significant uncertainties when estimating soil-moisture flux with this method.

4.3 *Chloride Mass-balance Method*—The chloride mass-balance method is similar to the water balance method in that mass balance concepts are employed. However, the chloride mass-balance approach relies upon the transport of chloride in soils to predict soil-moisture flux based on a knowledge of chloride deposition at the land surface. The uncertainties associated with chloride deposition and transport are much less than the uncertainties associated with estimating components of the hydrologic budget.

4.4 *Soil-Physics Based Approaches*—A multitude of soil-physics based approaches exist to quantify the soil-moisture flux. These techniques rely upon indirect measures of soil-water movement, for example, physical data such as moisture content and pressure head, as input to mathematical equations to solve for the flux. The Darcy's Law approach is most commonly used, with variants on this method employed in infiltration quantification, for example, Green and Ampt equation. A more rigorous approach to estimating the soil-moisture flux is to employ Richard's equation, a transient, non-linear formulation describing flow through unsaturated porous media. Unsaturated hydraulic characteristic data required as input to these soil-physics based methods can be very uncertain with regard to spatial variability and/or measurement error.

4.5 *Bomb-pulse Tritium and Chlorine-36 Methods*—Environmental tracers may also be used to estimate the soil-moisture flux. Tritium (a radioactive isotope of hydrogen) and chlorine-36 (a radioactive isotope of chlorine) exist today in the environment because of natural processes in the earth's atmosphere. However, the atmospheric nuclear testing which occurred in the late 1950s and early 1960s created much higher concentrations of these radioisotopes in atmospheric fallout than normal. By sampling the concentrations of these radioisotopes in subsurface soils one can determine the extent of infiltration over the past 30 to 40 years, and therefore quantify the soil-moisture flux.

4.6 *Stable Isotope Methods*—Another environmental tracer technique employs knowledge of naturally occurring deuterium (a stable isotope of hydrogen) and oxygen-18 (a stable isotope of oxygen) in the water molecule and how transport processes occur in subsurface soils. Because deuterium and oxygen-18 are natural components of the water molecule, and their behavior during evaporation and transient temperature phenomena are understood, the soil-moisture flux may be quantified based on this knowledge.

4.7 *Other Tracer Techniques*—Other tracer techniques exist to quantify the soil-moisture flux. In this category, techniques are discussed which physically introduce a tracer, or chemical constituent, into infiltration water or directly into the subsurface to monitor soil-water movement over a specified time frame. Tracers such as bromide, chloride, certain organic compounds, certain short-lived radionuclides, and tritium may be used in these types of tests. Obviously, the application of tracers in a man-made experiment has limitations on the length of analysis time. These techniques are best used to investigate shorter time-frame infiltration and soil-water movement rates, as well as adsorption phenomena.

5. Significance and Use

5.1 The determination of the soil-moisture flux is one of the fundamental needs in the soil physics and hydrology disciplines. The need arises from requirements for defining recharge rates to groundwater for water supply predictions, for contaminant transport estimates, for performance/risk assessment studies, and for infiltration testing purposes. The techniques outlined in this guide provide a number of alternatives for quantifying soil-moisture flux and/or the recharge rate for various purposes and conditions. This guide is not intended to be a comprehensive guide to techniques available for quantifying soil-moisture flux, but rather a "state-of-the-practice" summary. Likewise, this guide is not intended to be used as a comprehensive guide to performance of these methods, those detailed methods may come at a later time. Techniques that might be useful for the implementation of these methods, for example, sampling network design, are not part of this guide, but may come at a later time.

5.2 All of the techniques discussed in this guide have merit when it comes to quantification of the soil-moisture flux. Factors influencing the choice of methods include: need/objectives; cost; time scale of test; and defensibility/reproducibility/reduction in uncertainty. If the need for soil-moisture flux information is crucial in the decision making process for a give site or study, the application of multiple techniques is recommended. Most of the techniques identified above have independent assumptions associated with their use/application. Therefore, the application of two or more techniques at a given site may help to bound the results, or corroborate data distributions. The uncertainties involved in these analyses are sometimes quite large, and therefore the prospect of acquiring independent data sets is quite attractive.

5.3 As stated above, each of these techniques for quantification of soil-moisture flux has assumptions and limitations associated with it. The user is cautioned to be cognizant of those limitations/assumptions in applying these techniques at a given site so as not to violate any conditions and thereby invalidate the data.

5.4 In general, the tracer techniques for quantifying soil-moisture flux will have less uncertainty associated with them than do the soil-physics based modeling approaches because they are based on direct measures of transport phenomena, rather than indirect measures of soil characteristic data/parameters. However, the forward problem of predicting future soil-water movement rates or transient behavior is best served by the modeling applications. The tracer methods may be used to calibrate, or supply boundary condition data to, the modeling techniques.

5.5 Published reviews of these methods are also available in the literature (**1**, **2**, **3**).[3]

6. Quantitative Techniques

6.1 This standard is not intended for use as a specific guide to field operations, but as a guide to choosing one or more appropriate methods for quantifying the soil-moisture flux, soil-water movement rate, and/or the recharge rate. Therefore, issues regarding the selection of sampling locations and the adequacy of sampling, for example, sampling network design, are outside the scope of this guide.

6.2 *Water Balance Methods*

6.2.1 *Theory*

6.2.1.1 The technique that was typically employed in water resources planning to estimate the rate and amount of recharge to an aquifer was the water balance approach. In this method, all inputs and outputs to the aquifer are estimated, for example, precipitation, evapotranspiration, surface runoff, pumping, discharge, and interflow, and the interrelationship between the parameters derived from simple mass-balance concepts. The water balance equation for a given watershed may be represented as follows:

$$R = P + I - ET + Sr_{on} - SR_{off} + L_{on} - L_{off} - \Delta S \quad (1)$$

where:

R = recharge rate or soil-moisture flux below the root zone [L/T],
P = precipitation rate [L/T],
I = irrigation water application [L/T],
ET = evapotranspiration rate [L/T],
SR_{on} = surface water runon [L/T],
SR_{off} = surface water runoff [L/T],
L_{on} = interflow (water laterally entering the zone of interest) [L/T],
L_{off} = interflow (water laterally leaving the zone of interest) [L/T], and
ΔS = change in soil moisture storage [L/T]. The water balance equation is then solved for the recharge rate.

6.2.1.2 The main drawback to this approach is that parameters such as evapotranspiration are very difficult to measure or estimate. There is a large amount of uncertainty in evapotranspiration estimates. This uncertainty in the input parameters then translates into a large uncertainty in the recharge estimate. Therefore, independent methods for estimating the recharge rate have been developed. The water balance method may be used to solve for any of the parameters shown in Eq 1, given estimates for the other parameters. There may be some applications (discussed below) which may employ other methods to estimate the recharge rate and then to solve for evapotranspiration, for instance. The water balance approach is basically a mass balance method. Eq 1 has also been used in more simplified form for smaller scale, test-specific applications to define soil-moisture flux. Infiltration techniques, such as the instantaneous profile (IP) method (**4**) , rely on water balance methods to estimate soil-moisture flux. The IP method, and its variants, are generally used to quantify hydraulic characteristic data, such as the unsaturated hydraulic conductivity as a function of moisture content. In so doing, the soil-moisture flux is quantified by a mass balance method and used as input to a mathematical/graphical procedure to determine the hydraulic characteristic data. Data requirements generally include the determination of moisture content and pressure head in situ. Neutron logging, Time Domain Reflectometry, Resonant Frequency Capacitance, and cross-hole gamma methods may be used to quantify changes in soil moisture with time (ASTM D18.21.89.16 and D18.21.89.17). Tensiometers are used for the determination of the pressure head changes during the IP test (Guide D3404). In the IP method, the drainage portion of the infiltration test is the most important data gathering sequence, when inflow, surface runoff, interflow, discharge, and evapotranspiration are essentially zero. Therefore, changes in soil-moisture storage with time can be equated to soil-moisture flux.

6.2.1.3 Another application of the water balance method is in the use of weighing lysimeters (**5**). The concept of a weighing lysimeter is relatively simple. Typically, a cylinder is emplaced in the ground filled with soil approximating the stratigraphy of the surrounding soil. The cylinder may be set on a weighing pan to quantify changes in weight/mass due to precipitation, evapotranspiration, and recharge/outflow. The lower boundary flux condition must be maintained equivalent to the surrounding media if natural conditions are to be approximated. Care must be taken in the construction of lysimeters to ensure that the potential for preferential flow along sidewalls is minimized. Weighing lysimeters are typically used to define evapotranspiration components.

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.