Use of SI units in soil physics

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ABSTRACT

Descriptions of the state and movement of heat and mass within soil using units conforming to the International System of Units (SI) are discussed. We propose that gas and water flux densities should be expressed in terms of kg m^{-2} s^{-1} and heat flux densities in terms of W m^{-2}. The joule per kilogram (J/kg) is suggested as the preferred unit for describing water potential, and hydraulic conductivity then has units of kg s m^{-3}. Alternative systems are also given.

Additional index words: **Measurement of soil quantities, Flux densities.**

SOIL physicists are generally concerned with heat and mass transport in soil. Subjects they consider most frequently include soil aeration, soil temperature, and soil water. These are described in both static and dynamic terms. When considering adoption of the International System of Units (SI), for teaching or research, one should choose units which (a) are consistent throughout the discipline, (b) give numbers that are easy to manipulate and remember, (c) have physical significance, and (d) where possible, are numerically equal to or are easily obtained from units used in previous systems. These ideas have been discussed by Rose (1979).

STATIC PARAMETERS

Many of the static parameters used in soil physics are dimensionless, and therefore, do not change with adoption of SI. Examples are total and air-filled porosity, degree of saturation, and void ratio. Mass and volume wetness (water content) are also dimensionless, but are normally reported as kg/kg or m^3/m^3 to indicate mass or volume of water per unit mass or volume of soil. These values would not change numerically in SI, but standard SI units would be used.

Densities of solid particles, water, bulk soil, or soil gases all have dimensions M L^{-3} and thus the basic unit is kg m^{-3}. Bulk and particle density, and density of water can be expressed in Mg m^{-3}; this gives numbers which are conveniently remembered and are numerically equal to those in familiar centimeter-gram-second (cgs) units. Soil gas concentrations also can be expressed in terms of mass per unit volume of soil air. Here, since mass per unit volume is lower than for solids and liquids, convenient units are g m^{-3}.

The potential energy of water in soil can be expressed on a mass or volume basis. Energy per unit mass has dimensions of L^2T^{-2}. Units are joules per kilogram (J/kg) in SI. Energy per unit volume is dimensionally equivalent to pressure, and the SI pressure unit, the Pascal (Pa), is used. One J/kg is 1 kPa if the density of water is 1 Mg/m^3; and since 1 bar = 100 kPa, 1 J/kg is equal to 0.01 bar at this same density. The volume basis potential has several disadvantages, the most important of which is that its use in flow equations requires the assumption that the density of water is a constant (Hubbert, 1956).

Adoption of either J/kg or Pascal as the standard water potential unit would require some relearning for most soil physicists since neither is numerically equal to the more familiar units in common use. The mass basis potential has fewer assumptions associated with its use and is more clearly related to the concept of energy status of water in soil. It is preferred, therefore, over the pressure unit.

It also is possible to use the height of a water column in the earth's gravitational field as an index of water potential. Use of this index has some advantages in flow equations, as will be discussed later. The potential in J/kg is just the gravitational constant multiplied by the height of the water column. Since the gravitational constant is close to 10 (9.81 m s^{-2}), hydraulic head in meters of water is approximately 10 times water potential in J/kg or kPa.

Variables related to soil thermal status are temperature and specific heat. Temperature is expressed in Kelvin or Celsius, which is conventional. The SI unit for specific heat is joule per kilogram kelvin (J kg^{-1} K^{-1}).

DYNAMIC PARAMETERS

Mass and energy transport in soil are described using the Darcy law for water, the Fourier law for heat, and the Fick law for gas diffusion. Each of these laws states that a flux density of heat or substance is proportional to a driving force. The driving force for water flow is a water potential gradient (J kg^{-1} m^{-1} or m s^{-2}, since J = N m = kg m^2 s^{-2}). The driving force for heat flow is a temperature gradient (K m^{-1}), and the driving force for gas diffusion is a concentration gradient (kg m^{-4}). The SI unit for heat flux density is watts per square meter (W m^{-2}), which requires that thermal conductivity be in units of W m^{-1} K^{-1}. Flux density for gas is kg m^{-2} s^{-1}, which results in units for diffusivity in the Fick equation of m^2 s^{-1}.

Water flux density can be expressed either as mass of water per unit area per unit time (kg m^{-2} s^{-1}) or volume

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Table 1. SI units for use in soil physics

Quantity	Application	Unit†	Symbol
Density	Particle density Bulk density	megagram per cubic meter	Mg/m^3
Concentration	Gas concentration	gram per cuic meter (P)	g/m^3
		mole per cubic meter (A)	mol/m^3
	Water content	kilogram water per kilogram soil	kg/kg
		cubic meter water per cubic meter soil	m^3/m^3
Potential energy of soil water	Driving force for flow	joule per kilogram (P)	J/kg
		kilopascal (A)	kPa
		meter of water in a gravitational field (A)	m
Specific heat	Heat storage	joule per kilogram kelvin	$J\ kg^{-1}\ K^{-1}$
Flux density	Heat flow	watts per square meter	W/m^2
Flux density	Gas diffusion	gram per square meter second (P)	$g\ m^{-2}\ s^{-1}$
		mole per square meter second (A)	$mol\ m^{-2}\ s^{-1}$
	Water flow	kilogram per square meter second (P)	$kg\ m^{-2}\ s^{-1}$
		cubic meter per square meter second (A)	$m^3\ m^{-2}\ s^{-1}$ or m/s
Thermal conductivity	Heat flow	watt per meter kelvin	$W\ m^{-1}\ K^{-1}$
Gas diffusivity	Gas diffusion	square meter per second	m^2/s
Hydraulic conductivity	Water flow	kilogram second per cubic meter (P)	$kg\ s\ m^{-3}$
		cubic meter second per kilogram (A)	$m^3\ s\ kg^{-1}$
		meter per second (A)	m/s

† (P) = preferred, (A) = alternate.

of water per unit area per unit time ($m^3\ m^{-2}\ s^{-1}$ or $m\ s^{-1}$). The latter has the disadvantage of varying with water density, but results in the familiar depth/time units which are in current use. When the flux density and driving force are expressed on a volume basis, the hydraulic conductivity has units of $m^3\ s\ kg^{-1}$, while for mass-based flux density and driving force the units are $kg\ s\ m^{-3}$. There are advantages to using mass fluxes for water as well as gases, and the (approximate) conversion from mass flux density to depth per unit time is simple ($1\ kg/m^2 = 1$ mm). Consistency is the main advantage to be gained by SI, and this is best accomplished by using mass flux density.

As we previously mentioned, it is common for soil physicists to use depth of water in a gravitational field as an index of water potential. This practice parallels that of engineers who, with Darcy, express the basic flow equation in terms of hydraulic head and hydraulic gradient. It also is formally comparable to the foregoing expression for potential by expressing it in terms of energy per unit of weight of water in a gravitational field. The advantage of this approach is that the driving force in Darcy's law becomes dimensionless and that the flux density and hydraulic conductivity have the same dimensions, namely depth of water per unit time. Furthermore, it relates directly to laboratory and field measurements. A disadvantage is that it represents a departure from the consistent set of units presented above. When the use of potential is expanded to include, for example, osmotic potential, the expression in terms of the height of a column of water is a bit forced.

Table 2. Unit systems for water flow applied to Darcy's law

Flux density	Hydraulic conductivity	Potential gradient
Potential in energy per unit mass $kg\ m^{-2}\ s^{-1}$	$kg\ s\ m^{-3}$	$J\ kg^{-1}\ m^{-1}$
Potential in energy per unit volume $m\ s^{-1}$	$m^3\ s\ kg^{-1}$	$Pa\ m^{-1}$
Potential in energy per unit weight $m\ s^{-1}$	$m\ s^{-1}$	$m\ m^{-1}$

The overriding consideration in adoption of SI is consistency, and in light of this, it seems reasonable to favor reporting potentials in $J\ kg^{-1}$ and conductivities in $kg\ s\ m^{-3}$ so that flux densities are in $kg\ m^{-2}\ s^{-1}$. If the units for conductivity seem unwieldy, perhaps a name could be attached to them such as with other combinations of units. It is not inconsistent with the SI rules, however, to express flux densities and driving forces in volume units, or to express the driving force in terms of a hydraulic gradient. Depending on the intended audience and/or use, these deviations from a rigorously consistent system seem acceptable.

Hydraulic conductivities in m/s are multiplied by water density and divided by the gravitational constant to convert to $kg\ s\ m^{-3}$. For an approximate conversion, multiply m/s by 100 to get $kg\ s\ m^{-3}$. Conductivity in $kg\ s\ m^{-3}$ is converted to $m^3\ s\ kg^{-1}$ by dividing by the square of the water density. Thus $kg\ s\ m^{-3}$ are approximately 10^6 larger than $m^3\ s\ kg^{-1}$.

Table 1 lists our proposed units for soil physics along with acceptable alternatives. Table 2 is intended to clarify the interrelationships among the three sets of conventions for the Darcy equation.

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