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REMARKS ON THE EFFECT OF TEMPERATURE ON WATER POTENTIAL AND WATER TRANSPORT IN SOIL

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Remarks on the effect of temperature on water potential and water trasport in soil

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A definition for the total differential of the specific partial potential of the Gibb's free energy for the water component in the soil system in the gravitational field (μ') may be thermodynamically expressed as:

$$d\mu'_w = -\bar{S}_w dT + \bar{V}_w dP + \left(\frac{\partial \mu_w}{\partial m_w}\right) dm_w + \bar{V}_w d\pi_z + \sum \left(\frac{\partial \mu_w}{\partial m_{js}}\right) dm_{js} + \left(\frac{\partial \mu_w}{\partial \sigma_e}\right) d\sigma_e + g dz \qquad (1)$$

wherein: $\bar{S}_w$ = specific (=massic) partial entropy of the water in soil; T= Temperature; $\bar{V}_w$ = specific (=massic) partial volume of the water in soil; P= overall pressure; μ_w = matric free energy of the water; m_w = mass of water; π_z = osmotic pressure built up by all solutes in the liquid phase; m_{js} = mass of any other solid phase component; σ_e = effective strenght in the solids, originating envelope pressure; g= gravity acceleration; z= vertical distance.

All coefficients in the r.s.m. are functions of all other indipendent variables in the other terms in the same r.s.m., excepting the concentration of soluble substance, which is taken as zero for the coefficient of dm_w.

This equation cannot be integrated. The more important obstacle to this in the fact that $\bar{S}_w$ is greately affected by pratically all other variables except the gravitational component. With some aproximations and assuntions, all terms, other than the first one, can be considered indipendent for practical purposes and the equation, for any given T, can be integrated to give the well known additive components of the total water potential in the soil. Under this point of view, what we would like to call the "thermal component" of the water potential in the soil is irremediably confused with the other components and the set of these can be determined only for given T. Our knowledges are still poor on many aspects of this point (e.g. on the effects of T on the water potential in swelling soils).

The temperature affects the matric potential (ψ_{pm}) of the liquid water in many ways:

(a) the water surface tension is approximately given by: γ = 76.08 - 0.168 T, therefore an increase in T corresponds to an increase in ψ_{pm} (decrease in absolute value of ψ_{pm}), for any given moisture content (θ).

(b) According to the equations: $\psi_{pm(v)} = -2\gamma/r$, or $\psi_{pm(m)} = -2\gamma/\rho_l r$ and $\psi_{pm(w)} = -2\gamma/\rho_l g r$ the thermal expansion of the water (at T > 4°C) for any given θ does not affect the water potential expressed by volume (in pressure units), but it affects inversely when the potential is referred to mass or wheight units. This is true only when the reference free water out of the soil has the same temperature of the soil water and not when the standard free water is kept at a standard temperature (e.g. 20°C); in the latter case the volume of water extracted from the soil has to be corrected for temperature and then $\psi_{pm(v)}$ is corrected too.

(c) Difference in thermal expansion of water and solids make the menisci to protude in the pores and to increase ψ_{pm} as T increases (coeff. ther. exp.: 15×10^{-5} for water; 2.5×10^{-5} for glass).

(d) Thermal expansion of trapped air has a still greater effect in the same direction (coeff. therm. exp. of air: 366×10^{-5}); this effect is expected to be larger at rather high θ, but not near saturation.

(e) Increase in T decreases water adsorption bonds on the solid surface, changes the double layer thickness and affects the swelling pressure in swelling soils; in so doing it changes ψ_{pm} at given θ.

In the vapor phase the temperature inversely affects the water (pressure) potential in two ways. According to equation:

$\psi_{pm} = (RT/M) \ln (P/Po) < 1$, T enters directly and indirectly, through P_o, being $\ln P_o \approx 14.2 - 5265.7/T$

Many of these aspects need deeper insight.

The temperature affects the water movement in the soil by changing its potential and its diffusivity. For any given uniform soil temperature, both ψ_{pm} and $K(\psi_{pm})$ are somewhat different, or $D(\theta)$ when the diffusivity form is taken; these effects are usually neglected. Much more important is the effect of a temperature gradient. This affects the liquid as well as the vapor phase flow of water, both interacting among them.

The interaction between the water flows in liquid, vapor and adsorbed phases at isothermal conditions can be summarized by the following equations of Philip and De Wries:

$$q_l = - D \frac{d\theta}{ds} \tag{2}$$

$$q_{vap(l)} = -\left\{ \frac{Da \cdot \alpha (\varphi - \theta) \nu}{\rho_l} \cdot \frac{MC_o}{RT} \cdot e^{(\psi_{pm} M/RT)} \cdot \frac{d\psi_{pm}}{d\theta} \right\} \cdot \frac{d\theta}{ds} \tag{3}$$

$$q_{ad(l)} = - \frac{A_m \cdot \alpha' \cdot \pi \phi s_p \cdot v_m}{16 \rho_{ad}} \cdot \frac{d\theta}{ds} \tag{4}$$

wherein: q_l, $q_{vap(l)}$ and $q_{ad(l)}$ are water fluxes in liquid, vapour and adsorbed phase all expressed as equivalent volume of liquid water per unit cross area per unit time; Da = coefficient of vapor diffusion in air; α, α' = tortuosity factors; φ = porosity; θ = volumic moisture; ν = mass-flow factor; ρ_l = volumic mass of liquid water; ρ_{ad} = density of water adsorption; M = molecular weight of water; C_o = saturated vapor concentration in the air; R = gas constant (per mole); ψ_{pm} = matric potential; s = distance in the flow direction; A_m = massic (= specific) surface area; ϕ = diameter of water molecules; s_p = thickness of adsorbed monolayer; v_m = mean velocity of adsorbed water molecules. After summation member to member, these equations yield a unic phenomenological equation of Darcy's type: $q_{\Sigma(l)} = -D_\Sigma \, d\theta/ds$. The function $D_\Sigma(\theta)$ can be non monotonic as is shown by an example taken from Philip (fig. 1).

When a temperature gradient is superimposed, Philip and De Wries have found for liquid and vapor flows the following equations, based on some assumptions ($\psi_{pm} > -600$ bars, to neglect adsorption; temperature effects on liquid phase limited to γ variations):

$$q_l = - K \cdot \frac{d \ln \gamma}{dT} \cdot \frac{dT}{dz} - K \left(\frac{\partial \psi_m}{\partial \theta}\right)_T \cdot \frac{d\theta}{dz} - K \frac{d\psi_g}{dz} \tag{5}$$

$$q_{vap(l)} = - \frac{1}{\rho_l} \left\{ \left[D_a \cdot \alpha \cdot (\varphi - \theta) \cdot \nu \cdot U_{rf} \cdot \frac{dC_o}{dT} \right] \cdot \frac{dT}{ds} - \left[D_a \alpha (\varphi - \theta) \cdot \nu \cdot \frac{MC}{RT} \frac{\partial \psi_{pm}}{\partial \theta} \right] \frac{d\theta}{ds} \right\} \tag{6}$$

wherein: K = hydraulic conductivity; γ = water surface tension; T = absolute temperature; ψ_g = gravitational potential; U_{rf} = relative humidity (as a fraction); C = effective water vapor concentration in the air. The space coordinate is chosen as vertical (z) in the first of these equations; for the other coordinates (x or y) the last term of the r.s.m. must be suppressed.

Equation 5 gives the liquid flux as the result of three components, one for the contribution of the moisture gradient (matric forces), one for gravity forces, and one as an effect of the thermal gradient. Equation 6 gives the two components (gravity is neglected) for the vapor flow: one for the vapor diffusion as such (here expressed as a function of moisture gradient according to eq. 3) and the other in response to thermal gradient.

The effects on the heat flow is shown by the equation:

$$C_{P(v)} \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial s}\left(K_c \frac{\partial T}{\partial s}\right) - L_c \frac{\partial}{\partial s}\left(D_{\theta_{vap}} \cdot \frac{\partial \theta}{\partial s}\right) \qquad (7)$$

wherein: $C_{P(v)}$ = volumic thermal capacity at constant pressure (specific heat); t = time; K_c = thermal conductivity; $D_{\theta_{vap}}$ = coefficient in square brakets of the last term in eq. (6), L_c = latent heat of evaporation of water.

The examination of all these equations leads to considerations of practical interest as shown in the examples of fig. 2. Very seldom these processes are taken in consideration for measurements in field experiments.

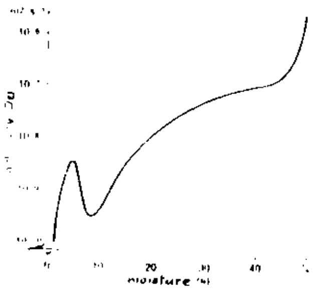

fig 1. Total diffusivity (ex. from Philip)

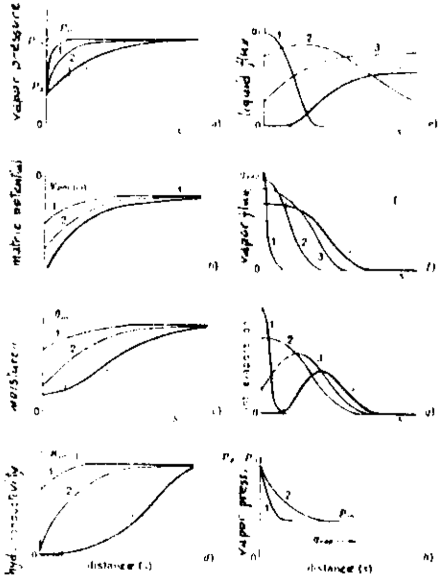

fig 2. Isothermal vapor and liquid flow of water crossing the soil surface.
a to g: flux directed outward;
h: flux directed inward.

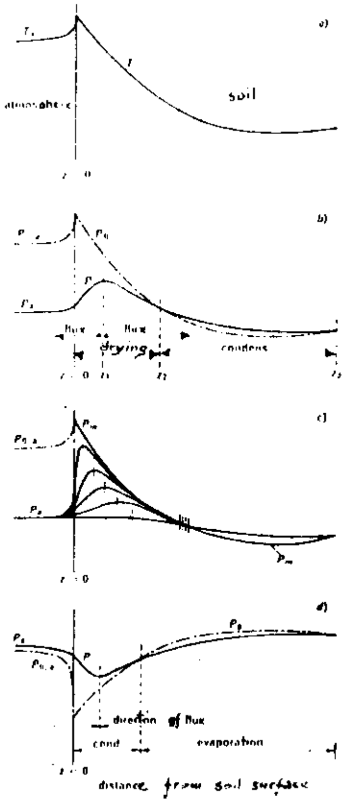

fig 3.

Interactions between heat- vapor- and liquid flows crossing the soil surface.
a,b,c: Highest temperature at the soil surface;
d: Lowest temperature at the soil surface.