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Cyclic Water Transfer in the Top Soil of a Landfill

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Abstract

This paper describes the changes of water content and the kinetics of water flow under infiltration, redistribution, evaporation, transpiration and freeze and thaw of water in top soils of a landfill, which are needed for the assessment of contaminant transfer. The discussion focuses on (a) infiltration in layered soil and sloping layered soil, and one caused by water flow through channels in soils, (b) the changes of water content under evaporation, which occur in different water flow modes under different evaporation conditions, and (c) water depression due to transpiration, in which water flow originates from a deeper layer below the root zone of vegetation. It is concluded that the theoretical prediction of the changes of water content profiles requires (a) a full understanding of the characteristics of individual water flow in cyclic water transfer and (b) a careful setting of the boundary conditions specified at the soil surface since soil properties such as soil structure and especially unsaturated hydraulic conductivity at surface will easily change over the course of time.

Keywords: soil water, Infiltration, Redistribution, Evaporation, Transpiration, Freeze and thaw

1 Introduction

Cyclic water transfer in top-layer soils (commonly known as “top soils”) refers to the repetition of water transfer due to infiltration, redistribution, evaporation of water, transpiration by vegetation (Figure 1), and freeze-thaw in regions where air temperature falls below the freezing point of soil-water. Firstly, since water transfer in top soils is generally accompanied by changes of water content in the underlying subsoil, it is important to study water transfer in the underlying soil layers together water transfer in top soil layers in order to understand cyclic water transfer in a top soil in landfills. In cases where the top soil is sloped, one needs to pay special attentions to water transfer in the slope. Secondly, cyclic water transfer is accompanied by cyclic chemical substance

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transfer, resulting in changes of soil properties such as soil structure and soil texture – i.e. properties that govern the thermal-hydraulic properties of a soil. A proper knowledge of cyclic water transfer is critical to the understanding of mass transport, such as salts and contaminants, in soils. To aid in the prediction and management of the functionality of top soil in landfills, this paper presents a general picture of the kinetics of water flow and changes in water content in a top soil relative to several important events of cyclic water transfer.

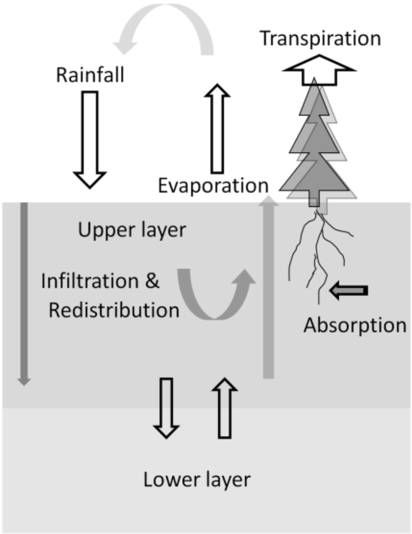


Figure 1: Cyclic water transfer system in top soils. Arrows show the direction of typical water flow

2 Kinetics of Water Movement

Assuming that the driving force of soil water is given by the gradient of potentials of water, which is the energy per unit weight of soil-water, i.e. hydraulic head, the water flux in soils is commonly expresses by a Darcy-type equation as follows [1]:

$$\mathbf{v} = -\mathbf{k} \cdot grad\ \psi \tag{1}$$

where **v** is the water flux through a unit area of soil mass per unit time, **k** is the unsaturated hydraulic conductivity that is commonly expressed as a function of the matric potential or the volumetric water content, ψ is the potential of soil water, i.e. $\psi = \psi_m + \psi_\pi + \psi_g$, where ψ_m is the matric potential attributable to pore structure, ψ_π is the osmotic potential attributable to concentration of solutes and ψ_g is the gravitational potential.

The equation of continuity which states that the flow of water into and out of a unit volume of soil is equal to the change in volumetric water content is given as:

$$\frac{\partial(\rho n S)}{\partial t} + div\ \rho \mathbf{v} = \rho q_0 \tag{2}$$

where n is the porosity, S is the degree of saturation, ρ is the density of water, q_0 is the source or sink of water, i.e. evaporation or condensation rate of water in pore space, and t is time. The source or sink term q_0 of water can be ignored in the case of infiltration of water from soil surface, but needs to be taken into account in considerations of water transfer due to evaporation of water from soil surface and freezing or frost of water in soils.

Substitution of Equation (1) into Equation (2) leads to the commonly cited equation for unsaturated incompressible water flow in the Cartesian coordinate system, with z axis in vertical direction, as follows:

$$\frac{\partial(\rho n S)}{\partial t} = \frac{\partial}{\partial x}\left(\rho k_x \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho k_y \frac{\partial \psi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\rho k_z \frac{\partial \psi}{\partial z}\right) + \rho q_0 \tag{3}$$

2.1 Unsaturated Hydraulic Conductivity and Water Retention Curve

One needs to have knowledge of the unsaturated hydraulic conductivity and water retention characteristics of the soils under consideration in order to apply Equation (3) for analysis of water transfer. The unsaturated hydraulic conductivity is commonly considered to be a function of volumetric water content for the case of no change in soil volume and soil fabric, i.e. no change in pore geometry of soils and in their physicochemical properties. In the case of physicochemical properties, this means that there is no change in concentration of solutes in the pore water, and in the surface functional groups of the constituents of the soil such as clay minerals, organic matter and adsorbed or precipitated chemical compounds. When changes in pore geometry and physicochemical properties of soil constituents occur during water transfer or as time progresses, the unsaturated hydraulic conductivity will be a function of both volumetric water content and several factors that take into account pore geometry and physicochemical properties of soil constituents. The water retention characteristics will correspondingly change with changes in pore geometry and physicochemical properties of the soil. Consequently, in addition to water content, water capacity and diffusivity coefficient, which are discussed in a later section, are similarly affected by the changes in pore geometry and physicochemical properties of the soil.

3 Infiltration

There are two modes of water infiltration from the surface of a bare soil. One is migration of the pond water on the soil surface, and the other is migration of raindrops. They result in dissolving various salts near soil surface and in the break-up of soil aggregates, and formation of a thin soil layer whose properties differ from the soil under consideration. Water applied onto a soil surface migrates into soils mainly due to the actions of capillary and gravitational forces.

In the case of no soil volume change, no pore geometry change and no overburden forces, the commonly used one-dimensional water flow in the vertical direction is obtained from Equation (3) – provided that $\psi = \psi_m + \psi_g$. Using the potential per unit weight of water

(water head), one obtains the following [2]:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(k_z\frac{\partial\psi_m}{\partial z}\right)+\frac{\partial k_z}{\partial z} \tag{4}$$

where z is the space coordinate in vertical direction, and subscript z denotes the vertical component. The second term on the right-hand side of the equation represents the gradient of the gravitational potential. Introducing the water capacity of soils, i.e. $C(\psi_m) = d\theta/d\psi_m$ into Equation (4), and recognizing the influence of ψ_m on k_z, one obtains the following equation:

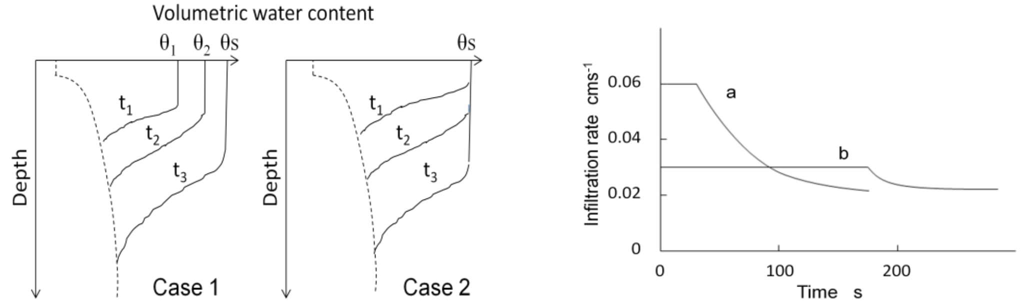
$$C(\psi_m)\frac{\partial\psi_m}{\partial t}=\frac{\partial}{\partial z}\left(k_z(\psi_m)\frac{\partial\psi_m}{\partial z}\right)+\frac{\partial k_z(\psi_m)}{\partial z} \tag{5}$$

Introducing the water diffusivity coefficient $D_z(\theta) = k_z(\theta)(d\psi_m/d\theta)$, one obtains the commonly cited equation for unsaturated water flow as follows [3]:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(D_z(\theta)\frac{\partial\theta}{\partial z}\right)+\frac{\partial k_z(\theta)}{\partial z} \tag{6}$$

The application of Equation (6) for computation of water content profiles is limited to mono-layer soils. Application of governing equations for analysis of cyclic water transfer in soils requires special attention to specification of initial and boundary conditions at the soil surface. The initial condition should specify a water content profile that takes into consideration soil-water depression processes due to evaporation, and which will never be homogeneous in the vertical direction, as shown in Figure 2. The boundary condition at the soil surface must take into account the no-rain (dry) period after the antecedent precipitation, which, in actual fact, will be set in range that goes from the dried to a certain wetted state.

Determination of infiltration uses the relationship between rainfall intensity i and infiltration ability of the soil at the surface – expressed in terms of the unsaturated hydraulic conductivity k_{srf} at the surface. When $i \leq k_{srf}$, the water content profiles will be ones shown as case 1 in Figure 2(A). The profiles shown in the figure are due to the fact that rainwater will promptly infiltrate into soils and pond on the soil surface as time progresses. The infiltration rate will run its course as shown by “b” in Figure 2(B). On the contrary, when $i \geq k_{srf}$, water content profiles will change as shown in case 2, in Figure 2(A), whereupon the infiltration rate will change as shown by “a” in Figure 2(B) because rainwater will promptly pond on the soil surface.



A Schematic water content profile B Infiltration rate for sand

Figure 2: Water content profiles and infiltration rates in water migration process under rainfall. Water content profile for case 2 shows one in migration of the ponded water. θs is the fully saturated volumetric water content. (Data for B adopted from [4])

3.1 Layered Soils

For layered soils consisting a succession of soil strata with different soil properties – especially water retention characteristics and unsaturated hydraulic conductivity -- it is useful to obtain potential profiles of soil water using Equation (5), and to convert the results to volumetric water content profiles in an individual layer, using a relevant water retention curve, since continuity of water content is not kept at the boundary of the soil layers as shown in Figure 3.

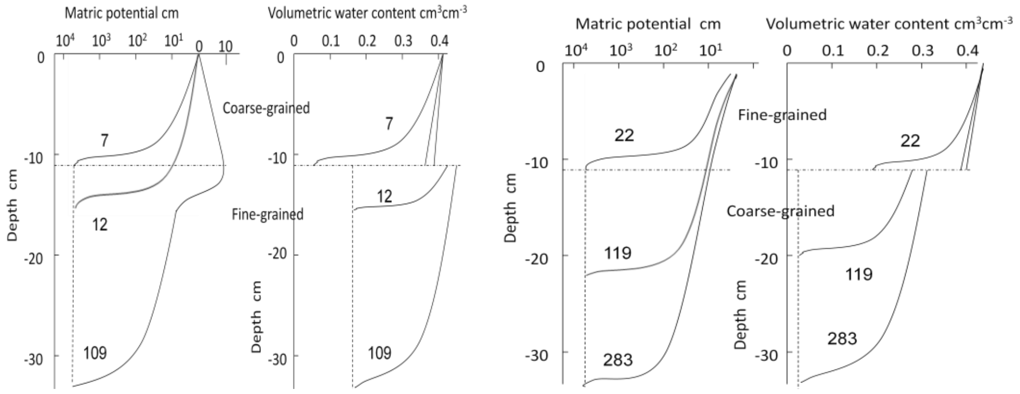
In the case of C-F layers where the upper layer is a coarse-grained soil (C-soil) and the underlying layer is a fine-grained soil (F-soil), infiltration of water into an upper C-soil is very quickly achieved, resulting in migration of the water into the underlying F-soil as soon as the water front reaches the boundary between both layers. On the other hand, for the F-C layer condition where an upper layer F-soil overlies the C-soil layer, water slowly migrates into the upper F-soil, and is stored at the bottom of the layer because of the difference of pore radii between both layers – indicating a likely formation of a capillary barrier at the lower boundary of F-soil.

In the F-C layer case, water stored in the upper F-soil is in a quasi-saturated state, showing negative pressure, and migration of the stored water into the underlying C-soil will be unstable because of the differences in distribution of pore radii in both the upper and lower soil layers. This is especially true for the case where the unsaturated hydraulic conductivity of the underlying C-soil is extremely small, i.e. C-soils are extremely dry. In this case, water migration into the underlying C-soil tends to occur as a finger flow (Figure 4(a)), as a result of the gravitational action when the following requirement is met:

$$\gamma_w g H_U \geq \frac{2T\cos\alpha_U}{r_U} - \frac{2T\cos\alpha_L}{r_L} \tag{7}$$

where H_U is the height of water held by capillary action in the upper F-soil, r_U and r_L are the mean pore radii of the upper and lower soil, respectively, α_U and α_L are the contact angles of the upper and lower soil solids, respectively, T is the surface tension of water, γ_w

is the density of water and g is the acceleration of gravity. The term on the left hand side expresses the action of gravity on soil-water in the upper F-soil and the first and second terms on the right hand side refer to the actions of capillary forces in the upper and lower soil, respectively.



(a) C-F layer

(b) F-C layer

Figure 3: The continuity of matric potential and discontinuity of volumetric water content profiles under infiltration into layered soil [5].

3.2 Sloping Layered Soil

In the case of the sloping layered soil, water stored at the bottom of the upper F-soil moves toward the lower location along slope of the boundary by gravitational action. Associated with this lateral flow, finger flow occurs and grows at a location where the condition expressed by the following condition is satisfied – in the context of funnelled flow (Figure 4(b)). Steenhuis et al. [6] have reported that the interval between fingers could be determined experimentally as follows.

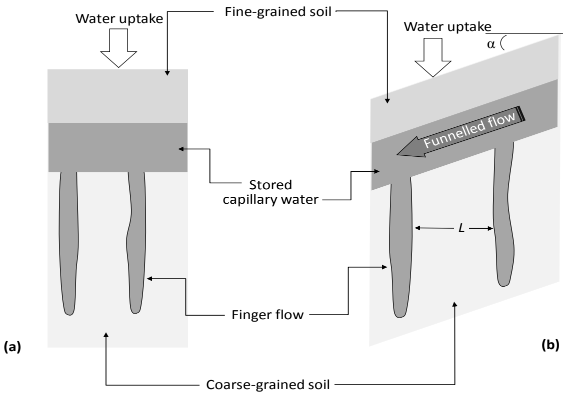


Figure 4: Schematic illustration of finger flow in a layered soil consisting of a F-soil overlying a C-soil. Left-hand sketch (a) shows flow pattern in a level (horizontal) surface situation, and right-hand sketch (b) shows the finger flow pattern in a sloped surface situation.

$$L \le \frac{k_S}{q_{suf}} \tan\alpha \cdot \left[\frac{1}{b} + \left(h_U - h_L \right) \right] \tag{8}$$

where L is the distance between fingers, referred to as the *diversion length*, k_S is the fully saturated hydraulic conductivity of the overlying fine-grained soil, α is the angle of the slope, h_U and h_L are the air-entry head of the upper and lower soil layers, respectively. The coefficient b is a coefficient b in $k = k_S \cdot \exp(b\psi_m)$, where k is the unsaturated hydraulic conductivity of the overlying F-soil, k_s is the saturated hydraulic conductivity and ψ_m is the matric potential. The maximum diversion length is considered to be in range of 5 to 50 m.

Locally, finger flow transfers chemicals into the underlying coarse-grained soil from the upper soils. Because of the rapidity of transport of chemical substances in finger flow, the surrounding soil of finger flow will remain uncontaminated in the underlying coarse-grained soil.

3.3 Flow through Channels

The top layer includes channels formed by plant roots, edaphon, drying, freeze and thaw, and various external forces. Water migration into soils from the soil surface is considerably affected by flow through these channels due to the gravitational force. The flux of water flowing in channels is assumed to be a function of the volumetric water content in the channels because water is considered to flow in channels which are both partially and fully occupied by water. According to German and Beven [7], water flux and the conservation law in channels are given by:

$$q_{ch} = b\vartheta_{ch}^{a} \tag{9}$$

$$\frac{\partial \vartheta_{ch}}{\partial t} = -\frac{\partial q_{ch}}{\partial z} - S \tag{10}$$

where q_{ch} and ϑ_{ch} are the flux and volumetric water content in channels, respectively, a and b are constants, z is the spatial coordinate in a vertical direction, and t is time. S refers to a sink term which represents water uptake into the surrounding soil matrix from channel walls. Combining Eqs. (9) and (10), one obtain:

$$\frac{\partial q_{ch}}{\partial t} = -C_{ch} \frac{\partial q_{ch}}{\partial z} - C_{ch} S \tag{11}$$

where C_{ch} is the *kinematic wave velocity* that is given by $C_{ch} = \frac{\partial q_{ch}}{\partial \theta_{ch}} = ab\theta_{ch}^{a-1}$. The sink term S is given by changes of ϑ_{ch} per unit time as follows:

$$S = \frac{d\vartheta_{ch}}{dt} = \left(\frac{\vartheta_{ch}}{aq_{ch}} \right) \cdot \left(\frac{dq_{ch}}{dt} \right) \tag{12}$$

Equation (11) would give a flux profile that is observed in channels opening on the soil surface after a rainfall. This water flow quickly transports chemical substances to the underlying coarse-grained soil from surface of soils. Because of the rapidity of water flow in channels, the upper soils will remains uncontaminated.

4 Redistribution

After rain ceases to fall, water in top soils will still flow down and water content will decrease. This water flow is called the redistribution of water in soils. Let us consider the redistribution of water when heavy rain water migrates, i.e. when the wetting front reaches deep locations in soils. The gradient of matric potential is close to one during redistribution as shown in Figure 5(a), while the volumetric water content profile shows that their peaks gradually descend downward as their value decrease with time – much like the propagation of the attenuating wave (Figure 5(b)), resulting in the formation of the equilibrium state. Hence, water flow can be assumed to be predominantly controlled by gravitational forces. The flux will be given by the unsaturated hydraulic conductivity in vertical direction. Assuming that unsaturated hydraulic conductivity is a function of volumetric water content, i.e. $q_z = -k_z(\theta)$, we obtain the following relationship from the conservation law:

$$\frac{\partial\theta}{\partial t} = \frac{dk_z}{d\theta}\frac{\partial\theta}{\partial z} \tag{13}$$

Accordingly, we obtain the following characteristic differential equation of Equation (13), called the kinematic wave velocity:

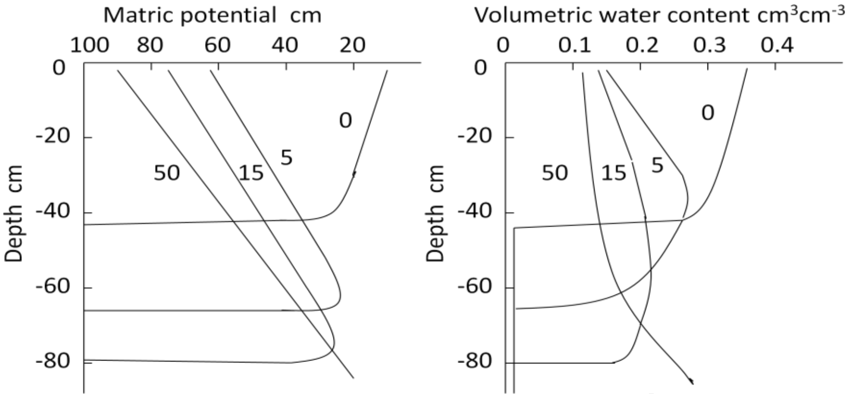
$$\frac{dz}{dt} = -\frac{dk_z}{d\theta} \tag{14}$$

Considering dz/dt at the location of wetting front, Equation (14) expresses the progressing velocity of wetting front in the soil matrix during redistribution. In a special case where the unsaturated hydraulic conductivity is, for example, expressed by $k_z = a(\theta - \theta_m)^N$, where a, N and θ_m are constants, Equation (14) leads to a simple analytical solution for volumetric water content θ in the redistribution processes of soil-water, expressed in terms of $(-z/t)$, where z is negative in the upward-positive vertical axis.

In the event where rain ceases to fall in a short time period, an obvious draining front and a trailing zone will be formed at the back of the migrating water which progresses downward as the propagation of wave; water content decreases, and the equilibrium water content profile is established as time progresses.

5 Evaporation

After infiltration and redistribution of water in soils, water will begin to move upward because of evaporation of water at the soil surface. Evaporation of water at the soil surface is caused by solar heat (radiation), humidity of atmosphere and wind velocity acting on the surface thereby inducing a depression of soil water and a rise in temperature at the soil surface. The resulting formation of gradients of both water content and temperature in soils and water transfer in soils is seen to be due to the movement of the both liquid water and vapor in response to the gradients of volumetric water content and temperature.



(a) (b)

Figure 5: Redistribution of water in sand after infiltration. Numbers shows the elapsed time (hours) after the start of redistribution. Data adopted from [8]

Liquid water movement is expressed by Darcy' law, and vapor movement as gaseous phase transport in soil pores obeys Fick's law: $\mathbf{V}_v = -\mathbf{D}_v \cdot grad\ C_v$. The partial pressure of vapor, which is in equilibrium with the potential of liquid water, is expressed by the relationship: $p_v = p_s \exp\left(g\psi_w / RT\right)$, and the vapor concentration gradient can be represented by the gradient of volumetric water content through the state equation of ideal gases: $C_v = p_v/RT$ [9], where $\mathbf{V}_v$ is the vapor flux, $\mathbf{D}_v$ is the vapor diffusion coefficient, C_v is the concentration of vapor in the pore space, p_v and p_s are the partial pressure of vapor and saturated vapor pressure, respectively, ψ_w is the water potential defined by $\psi_w = \psi_m + \psi_\pi$, g is the acceleration of gravity, R is the universal gas constant and T is temperature.

Considering water movement in bare soils, soil water transfer is expressed by the following equation – taking into account that both liquid water and vapor movement will be determined by the gradients of water potential and temperature:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D_{W\theta}\frac{\partial\theta}{\partial z} + D_{WT}\frac{\partial T}{\partial z} \right) + \frac{\partial k_{L\theta}}{\partial z} \tag{15}$$

where $D_{W\theta} = D_{L\theta} + D_{V\theta}$ and $D_{WT} = D_{LT} + D_{VT}$, subscripts θ and T denote the diffusive coefficients in water transfer due to water potential gradient and temperature gradient, respectively, and subscripts L and V refer to the coefficients of liquid water and vapor transfer, respectively. $k_{L\theta}$ refers to the unsaturated hydraulic conductivity in liquid water transfer due to water potential gradients.

The profiles of volumetric water content will appear in three modes in accord with the magnitude of the potential evaporation capacity *w* in atmosphere, and in contrast with the water flux q_0 at the soil surface as shown in Figure 6.

Case 1 (Figure 6(a)) where $w \ll q_0$, meaning that $w \ll k_{srf}$ t, where k_{srf} is the unsaturated hydraulic conductivity at the soil surface, i.e. water content at the surface is high: Volumetric water content decreases through all the soil sections, forming the equilibrium profiles at any time – since water flow quickly occurs in soils and the gradient of water potential is easily in equilibrium with that of the gravitational potential [10]. Water flow will mainly be caused by the flow of liquid water. This event will appear in the areas where it is humid with a cool atmosphere on the soil surface.

Case 2 (Figure 6(b)) where $w > q_0$, meaning that $w > k_{srf}$, i.e. water content at the surface is medium: The depression of soil water will be considerably higher at the upper portion of the soils and a thin dried layer, which is called dry crust, will be formed at the surface. In the meantime, water content will decrease at all the lower sections in the soil. Water transfer will occur as flow of liquid water and vapor under the gradients of both water potential and temperature. Vapor flow is dominant in the soil layer close to the surface, especially in the dried layer. The dried layer gradually thickens as time progresses. Salt accumulation at the surface is significant – resulting in the formation of a salt crust at the soil surface. After a dried layer is formed, salt accumulation of salts occurs behind the dried layer.

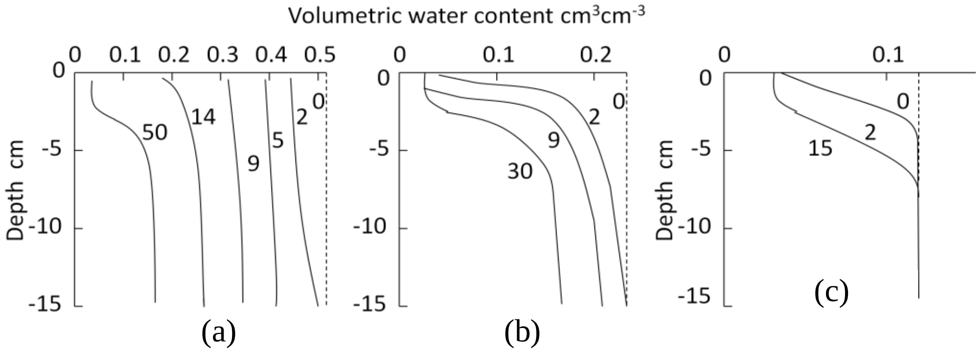


Figure 6: Changes of volumetric water content in sandy loam under evaporation of water in a bare soil. Numbers in graphs show the elapsed time (day).

Case 3 (Figure 6(c)) where $w \gg q_0$, meaning that $w \gg k_{srf}$, i.e. water content at surface is very low: The bulk of the decrease in water content occurs mainly in the upper portion of the soils – to the extent that decreases in water content in the lower portions of the soils are almost negligible. Water flow is mainly due to vapor flow. The decrease in water content in soils results in the growth of the dried layer at surface. This mode of water content decrement is observed in very dry regions where air temperature is very high and the atmosphere is dry – e.g. in a desert setting.

To compute the profiles of volumetric water content using Equation (15), one requires both the initial condition which is given as a profile of water content established by redistribution process of water, and the boundary condition at the soil surface expressed as a function of time and location of the drying front in soils – in relation to potential evaporation rates.

6 Transpiration

In the case where vegetation covers the surface of the top soil, roots absorb water from the surrounding soil matrix around roots, and the absorbed water evaporates through the stomata of leaves. In addition, roots draw up soil-water from the underlying soil layer to the root zone as a result of the depression of water in the root zone. This event is called transpiration of soil-water due to plants. Water flow and water depression in the top soil which is covered by vegetation occur through transpiration by plants and by evaporation at the soil surface.

According to an idea by Professor Ishida, T., Utsunomiya University, Japan, the equation which governs the water flow in soils under transpiration may be expressed as follows:

$$C(\psi_w)\frac{\partial\psi_w}{\partial t}=\frac{\partial}{\partial z}\left(k_z(\psi_w)\frac{\partial\psi_w}{\partial z}\right)+\frac{\partial k_z(\psi_w)}{\partial z}+q_rL_r \qquad (16)$$

where $\psi_w = \psi_m + \psi_\pi$, q_r is the water absorption rate per an unit length of adsorptive roots which is plant-physiologically decided, and L_r is the root length per an unit volume of soil matrix, i.e. density of absorptive roots. Let us consider the water absorption rate in terms of water flow toward the adsorptive roots in the surrounding soil matrix. The radial water flow toward the surface of a cylindrical root in soils may be expressed by the following equation using cylindrical coordinates with the origin at the center of the roots:

$$C(\psi_w)\frac{\partial\psi_w}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial\psi_w}{\partial r}\right) \qquad (17)$$

where k is the unsaturated hydraulic conductivity of the surrounding soil matrix, and r is the distance from the center of roots. Hence, the water absorption rate q_r per an unit length of adsorptive roots is given by $q_r = 2\pi a(kr(\partial\psi_w/\partial r))_{r=a}$ where a is the radius of adsorptive roots and is associated with water transfer through conductive roots and the stems of plants. Considering the whole water transfer in each individual plant, the water transfer in plants is expressed as follows:

$$C_p\frac{\partial\psi_p}{\partial t}=\frac{\partial}{\partial z}\left\{K_p\frac{\partial}{\partial z}\left(\psi_p+\psi_g\right)\right\}+A_rq_rL_r \qquad (18)$$

where subscript p shows the amount in plants, and A_r is the surface area of soil volume occupied by the root.

To estimate the changes of water content in soils with vegetable cover, it is necessary to use three time the depth of root zone in the computations since roots will cause decreases of soil water in the underlying soil layer of root zone as shown in Figure 7.

One also must note that the radial water flow toward the surface of a cylindrical root accumulates chemical substances in the soil matrix around roots and draws up chemical substances of the underlying soil layer into the root zone. The accumulation of chemical substances at the soil surface which is covered by vegetation will be less than that attributable to evaporation in a bare soil.

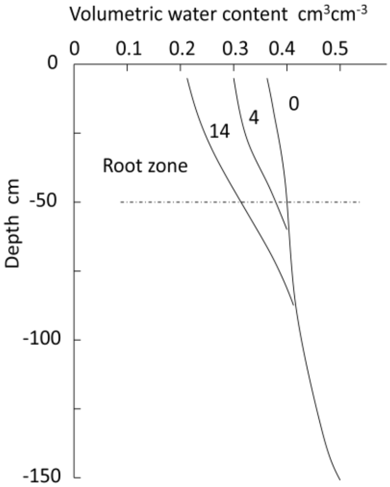


Figure 7: Water depression in the case where vegetation (soybean) covers the surface of top soil (loam). Numbers in graph show the elapsed time (days) after infiltration and redistribution. (Data offered by Ishida and Nakano)

7 Freeze and Thaw

In regions where winter temperatures fall significantly below the freezing point of soil water in the freezing season, it is important to study two kinds of water flow. Firstly, in the frozen zone, flow of unfrozen water (Figure 8) occurs locally toward the ice crystals and ice lenses, resulting in the growth of the ice crystals and ice lenses and consequently the destruction of soil structure, i.e. the changes of the hydraulic properties of soils. This flow occurs in response to the water potential gradient (especially the osmotic potential gradient) and the temperature gradient, resulting in the accumulation of chemical substances in the unfrozen water surrounding the ice crystals and ice lenses. These phenomena are often called the salt exclusion or sieve effect of salt. The kinetics of this flow will be similar to that shown in water absorption by plant roots under transpiration, while the shape and property of the sink is different. Secondly, water flow to the bottom of the frozen layer from deeper location in the underlying unfrozen layer occurs – mainly due to the gradient of the total potential of water, and to a much lesser extent by the temperature gradient. The accumulation of chemical substances occurs at the bottom of frozen layer due to the upward water flow from the underlying unfrozen soil. The kinetics of this water transfer must be close to the kinetics of water flow in the underlying water-depression layer under transpiration. In the thawing seasons, the thawing water of the covering snow and ice on the soil surface migrates into the top soils and the thawing water of ice crystals and ice lenses in frozen soil move down in the soil. These flow phenomena are considered to complicate the analyses of the whole water transfer through soils because of the random existence of the ice lenses in the frozen layer. Water migrating from the soil surface runs into the ice lenses and will flow along the surface of them, resulting in downward flow at the edges of the lenses. This flow could be funneled flow since random water flow will repeatedly run into the underlying ice lenses. The thawing water of the ice lenses also will flow down in the same manner in soils. The downward flow of thawing water could dissolve chemical substances accumulated in the surrounding soil matrix around the ice lenses and transfer them to the deeper location in unfrozen soil layer. This water flow could occur all over a cross section of soils, resulting in infiltration into the underlying unfrozen soil layer.

It is suggested that one needs to have better information about the kinetics of water transfer in soils in freezing and thawing seasons.

8 Conclusions

(1) Cyclic water transfer in soils occurs as a result of repetition of the downward and upward flow of water in soils, such as infiltration to evapo-transpiration or vice-versa. The downward flow of water could transport chemical substances to the underlying soil layers, and the upward flow could accumulate them to soil surface. When one tries to theoretically predict water transfer, how one sets the initial condition is of the utmost importance.

(2) When water flow reverses its direction, i.e. downward to upward or vice-versa, water transfer is influenced by both water retention hysteretic phenomena and unsaturated hydraulic conductivity hysteresis phenomena, especially water retention hysteresis phenomena. Hysteresis will be larger in coarse-grained soils than that in fine-coarse soils. One needs to know which process in the hysteresis loops follow are involved in interest water transfer, i.e. one must note pay attention to the water content – from where water will start to flow downward or upward in cyclic water transfer (Figure 9).

(3) The soil surface changes hydraulic properties of soils, with impacts on the applied water, drying, and accumulation of chemical substances – macroscopically resulting in the formation of dried crusts and salt crusts, and the opening of macro pores, cracks and fissures. Accordingly, one needs carefully to set the boundary condition at the soil surface.

(4) Top soils continue to undergo changes in soil composition and properties over the course of time, resulting in the changes of soil structure, especially under vegetation. One should note that theoretical predictions undertaken under certain states or soil properties are not useful over long term. Theoretical prediction of water transfer should be undertaken by taking account all the changes of soil properties that will occur in the distant future.

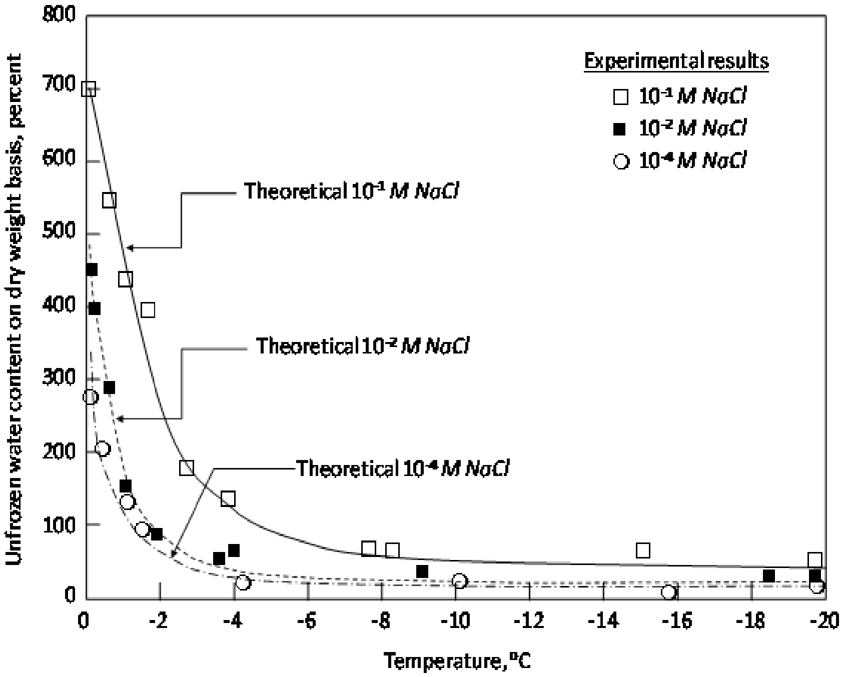


Figure: 8 Uunfrozen water content of *Na*-montmorillonite with three different sodium chloride concentrations. Initial unfrozen water content was 700%. (Data reported by [11])

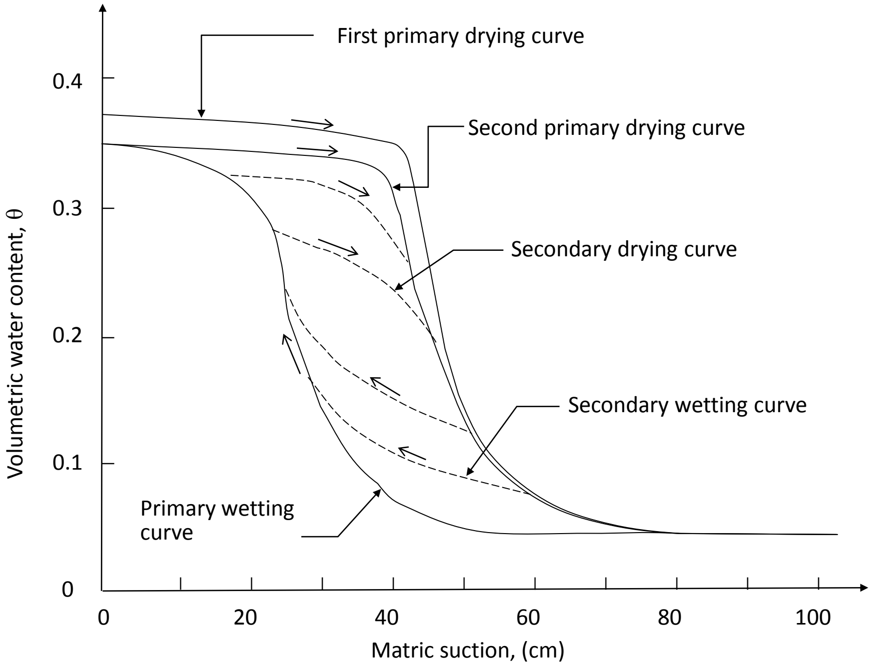


Figure: 9 Hysteretic phenomena observed for water characteristic curves for sand. Arrows indicate wetting and drying processes [12].

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