STORAGE OF INDENSED WATER IN SOILS

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Key words: Indensation, soil hydraulic conductivity, plant water potential, soil water infiltration, soil water storage

Abstract

Physical controls on the storage and movement of water in soils are examined to identify the constraints to plants using soils to store indensed water.

Introduction

Water movement in soils determines the availability of water to plants as well as surface flows into rivers and drainage into groundwater systems. The controls on such water movement are well if incompletely known, and simplified situations can be variously modeled. However, the most models address artificial situations that need bear little resemblance to what actually occurs.

The disconnect between theory and practice is illustrated by models simulating the infiltration of rainfall into soils and its flow in groundwater systems. The soil is either represented as a black box that supplies water to a groundwater system, or two models are used. One model simulates processes in the soil while the other simulates groundwater flows.

Reasons for this situation include the complexity of flows in soils and their disparate nature compared to groundwater flows. Gravity is invariably taken as being the sole driving force for groundwater flows as other forces are considered to be insignificant. Gravity similarly controls water flows in saturated soils but this does not arise with water infiltrating into dry soils, or with water flows in unsaturated soils. With unsaturated soils the soil water potential can be the dominant force determining the flows of water.

The contribution to groundwater of unsaturated drainage from soils is often considered to be insignificant, and this allows treatment of soils as a black box that absorbs rainfall and produces drainage when the profile becomes saturated. However, for vegetation the unsaturated flows are of most importance. Most of the water transpired by plants flows to roots through unsaturated soils. Knowledge of the characteristics of unsaturated flows of soil water is therefore crucial to an understanding of the relationships between vegetation and the environment.

Most of the information presented here is readily available. The purpose of the compilation is to provide a comprehensive picture of the processes useful for communicating issues associated with plants using soils to store indensed water.

Binding of Water in Soils

Water is a bipolar molecule (Fig. 1) and so can bind with many of substances. The bipolar structure produces a high affinity with other substances and makes it a highly effective solvent.

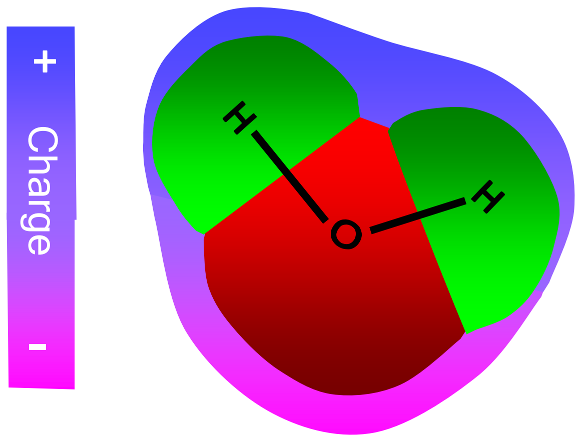


Fig. 1
Graphic representation of the charge distribution on a water molecule.

This affinity is seen in water rising up a capillary tube (Fig. 2). The binding forces between water and the tube surface are sufficient to hold a weight of water against gravity. The greater the surface contact relative to the weight of water the higher the water rises.

The force drawing water up the tube arises from the immediate surface contact between water molecules and the tube. However, the drawing of water up the tube additionally depends on the forces binding water molecules. Without binding between water molecules the water in the tube would be a film one molecule thick. The concave meniscus identifies that the forces between the water molecules are less than between the water and the material in the tube.

The binding of water in soils is variously ascribed to different forces such as capillary, matric, osmotic, and hygroscopic, but all derive from surface interactions. The underlying mechanism for each identified force is intrinsically the same and they differ only in relation to coarse structural constraints. The different categories relate to differences in structural characteristics of soil materials.

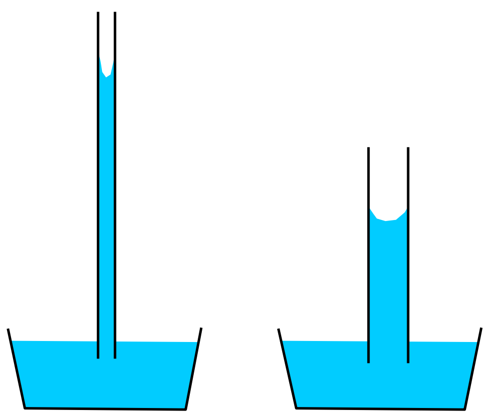


Fig. 2
Graphic representation of water rising up capillary tubes of different diameters.

Capillary water is as illustrated in Fig. 2 in relating to large (macroscopic) voids. Matric relates to microscopic structures such as the surface of clay platelets. Hygroscopic relates to the binding of water to individual molecules and hence is sub microscopic. Osmotic is effectively hygroscopic but where the molecules are free to move in the water. Capillary, matric, and hygroscopic water therefore relate to structural components of the soil but osmotic relates to substances dissolved in the water (solutes).

The net outcome with the binding of water to soils reflects the size distribution of the structural components. This may exhibit localised peaks but in general there is a smooth transition is size distribution. The relationship between the force holding water in a soil and the amount of water held is therefore a smooth curve (Fig. 3).

The force holding water in soils is termed the water potential, and this represents the unavailability of soil water relative to pure water at the same temperature and pressure. As binding reduces water availability, the water potential in soils is negative. Soils are effectively at zero soil water potential when saturated.

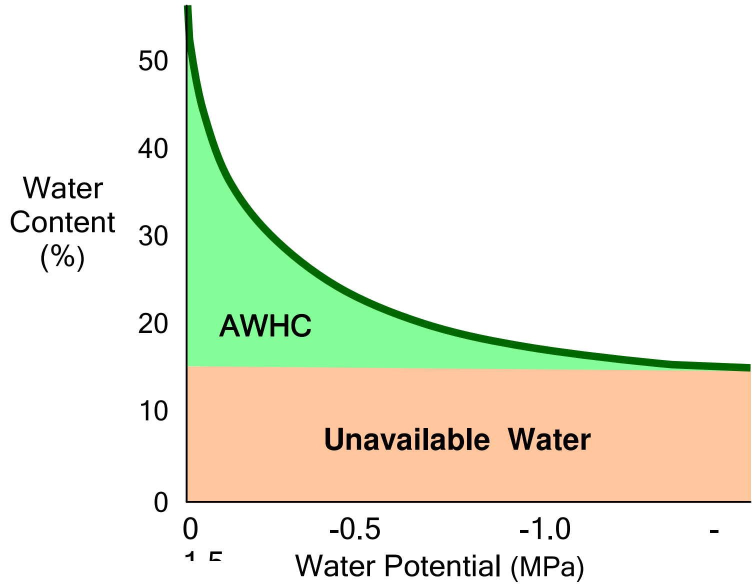


Fig. 3

'Soil water release curve'

Change in soil water content with decrease in water potential.

Water potential is sometimes expressed as a water pressure but particular structural constraints are needed for this to occur. With the capillary example a force is required to reduce the height of water in the tube (Fig. 4). The force required to produce the displacement is equal to the weight of the water column, which is the displacement Z by the cross sectional area assuming no change in the height of the pond. Normalising this to a unit area gives the pressure. Water potential is expressed as a pressure and hence is in Pascals (Pa)

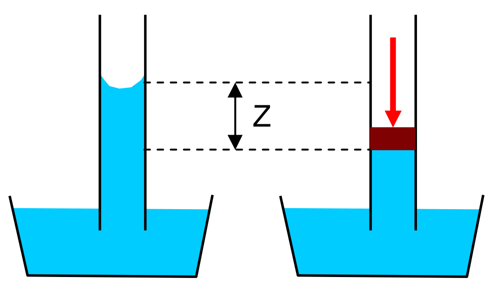


Fig. 4
Displacement of water rising in a capillary by the application of a force

In the example in Fig. 4 a positive force is used to counter part of the negative potential of water in the tube. This illustrates that a negative water potential translates into a negative pressure where a negative pressure represents a tension. This naturally occurs in the stems of plants where the water is under tension, and transmission of this tension from leaves to roots allows plants to withdraw water from soils.

While some question the existence of this mechanism for plants obtaining water from soils it is physically sound and has abundant observational evidence. This includes direct measurement of the tension in tree trunks as well as listening to water columns snap when plants become severely stressed.

The snapping of water columns identifies a key requirement for plants to withdraw water from soils. There must be sufficient cohesion between water molecules for them to remain bonded when under tension. The situation is no different to tensioning wire or an elastic band except there is no evidence of water stretching. With human operations that lift water in tubes, as with pumping water, the water column snaps (vacuolates) at around 60 kPa.

Experiments tensioning water in fine capillaries using centrifuges indicate that water can withstand tensions around 10 times the nominal wilting point of -1.5 MPa. Water can withstand the tensions necessary for plants to withdraw water from soils, but that depends on plants having an appropriate structure. With centrifuge experiments the water must be pure and the tube scrupulously clean. The water must also have a high affinity for the tube material. Axiomatically the cells used to transport water in plants have evolved to address the requirements as what lives is adapted to live, and for plants to live they must withdraw water from soils.

Withdrawing water from soils

The simplest demonstration of water withdrawal from soils is to saturate a fine sponge with water. Considerable water drains from the sponge when left standing as the force holding the water is initially less than gravity. This freely drained water content represents the condition where the force holding water in the soil balances gravity. The field capacity is the amount of water held by a freely drained wet soil.

A force additional to gravity must be applied to the sponge to extract more water, as with squeezing. With slight squeezing a large amount of water is initially released but the pressure applied must be continuously increased to extract further water. The relationship between the force applied and the water extracted is as in Fig. 3.

The curve in Fig. 3 identifies that, while soils hold considerable water when saturated, the force applied to extract water must be continuously increased to continue to extract water. Alternatively, as water is withdrawn the water potential of the remaining water decreases, with the decrease increasing markedly as the soil dries.

A feature of this response is that, when saturated, all soil water has zero water potential. At the nominal wilting point for plants of -1.5MPa all of the water in the soil has a water potential of -1.5MPa. That is, any subdivisions of water into categories such as matric and hygroscopic has no relevance with this representation of the forces.

The nominal wilting point of -1.5 MPa arises because that was the direst condition plants were thought to produce in soils. Plants were thought not to be able to extract water when soils were drier. While this conclusion was a consequence of limitations in measuring equipment and a focus on crop plants, this nominal wilting point is still a useful criterion. This arises because the amount of water in soils below -1.5MPa that is available to plants is usually negligible.

The amount of water held in soils below the wilting point is unavailable water. The term unavailable is used to replace the normally applied term of bound water as bound water has a specific meaning relating to the binding of water to surfaces of clays and organic matter involving the dissociation of water (Soil HoH, Tunstall 2009). The term unavailable water has no basis other than identifying an amount of soil water that is unavailable to plants, but that alone makes it useful.

A colour code is used to identify different components of soil water important in determining how systems function. The difference between saturation and field capacity is blue water as such water typically drains from the soil and contributes to groundwater systems and streams.

The difference between field capacity and the wilting point is green water as this water is potentially available to plants. Unavailable soil water is colour coded brown.

The amount of water held by soils differs depending on their structural characteristics (Fig. 5), noting that this is a highly generalised representation. Blue water is held in large voids where the surface forces are insufficient to hold water against gravity. The amount of blue water is large for coarse textured soils such as sands but declines to a minimum with the finest textured soils in clays.

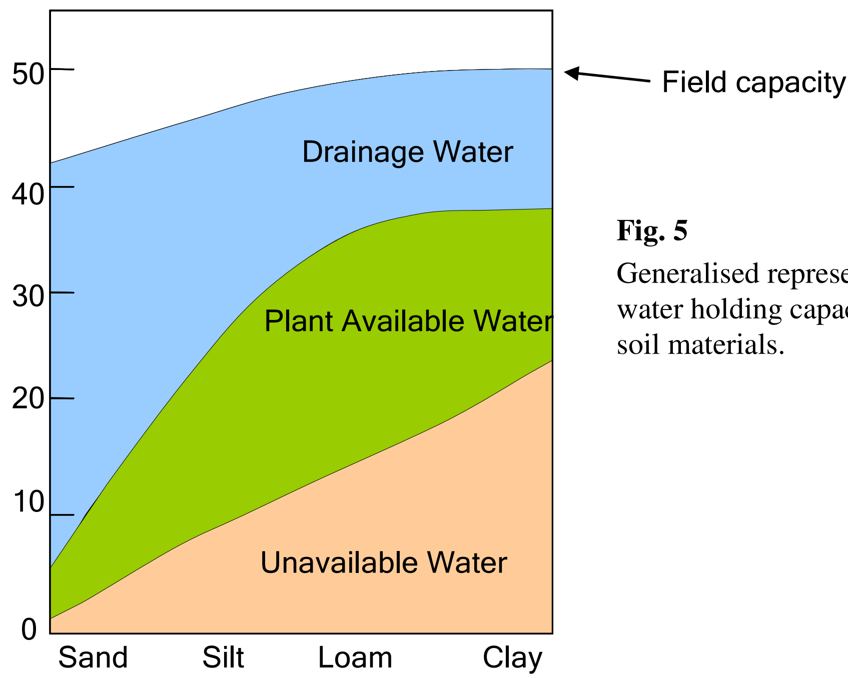


Fig. 5
Generalised representation of the water holding capacity of different soil materials.

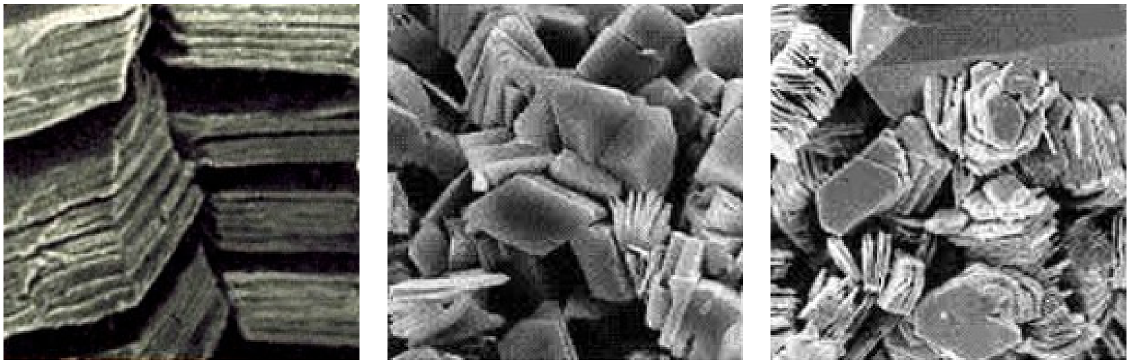
Sands hold little water in the range of water potentials available to plants because of their particle size distribution. The coarse structure produces a low ratio of surface area to volume compared to clays. There is little force to hold water in coarse textured soils.

While clays hold a large amount of water much of the water is unavailable to plants because of the strong surface forces. This arises because of the fine colloidal nature of clays and their structural arrangement. Fig. 5 illustrates that loams hold more green water than clays. Much of the water held by clays is bound too tightly to be available to plants.

Fig. 6a illustrates a platelet arrangement for a clay mineral that produces an exceptionally high surface area to volume ratio. Different clay minerals have different structures (Fig. 6b,c) and that affects their water holding characteristics. The form as well as amount of clay is important.

The plant available water, or green water, can be further subdivided to address practical applications such as irrigation (Fig. 7). With irrigated crops a slight water deficit at any time can reduce yields hence irrigation schedules are arranged to prevent the occurrence of plant water stress. Soils are kept wet as the costs of additional water are small compared to the costs of lost production. The water typically addressed in irrigation is termed readily available water.

With crops such as grape vines used for wine production (viticulture) the requirement is to maintain a balance between vegetative growth and fruit development. Luxuriant foliage is undesirable hence favourable soils hold considerable water at potentials that restrict the supply of water. High levels of moderately available water are desirable. Slowly available water effectively represents survival water as it allows plants to survive but not grow.



Expanded clay mineral — Ilmenite — Kaolin

Fig. 6 Micrographs of different clay minerals.

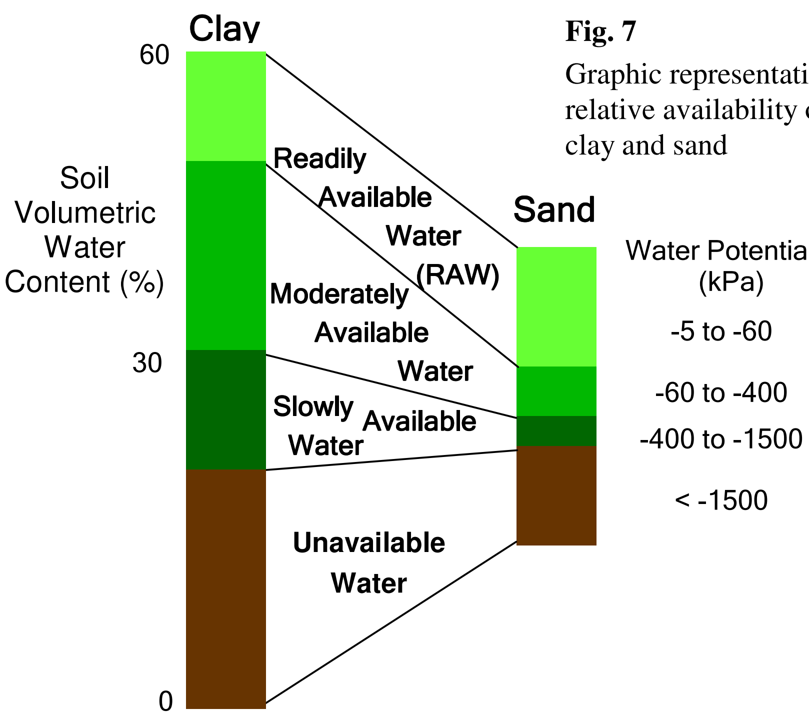


Fig. 7

Graphic representation of the amounts and relative availability of soil water storage in clay and sand

Water potential measurement

The total soil water potential at a point (Ψw)[1] is the sum of the component potentials which are matric (Ψm), osmotic (Ψs).

$$\Psi w = \Psi m + \Psi s$$

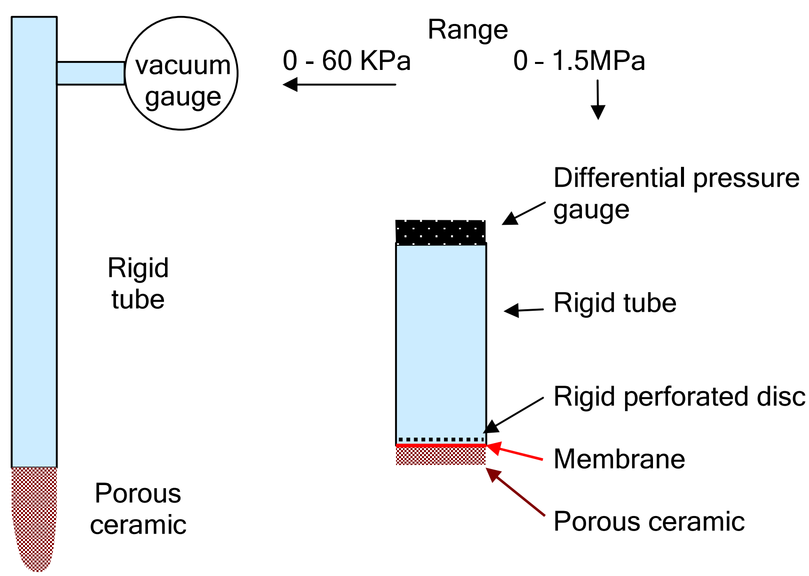
[1] Ψ is pronounced psi

A gravitational potential (Ψg) is usually also identified but this is relative in relating to the difference in height between two separated points.

Tensiometers (Fig. 8) are used to measure Ψm for very wet soils where these measure the vacuum in a closed column of water that is coupled to soil water via a porous ceramic cup. The ceramic cup prevents water draining from the tube under gravity because of its air entry pressure, but it allows for water flows between the soil and the tube in response to water potential gradients. Tensiometers employing vacuum gauges cease to function when the water column vacuolates at around -60 kPa.

Other mechanical devices that employ water to block the entry of air into porous ceramics can measure soil water potentials to around -1.5MPa. Laboratory devices place soil samples on wet ceramic plates in a pressure chamber where the flow of water but not air through the plate subjects the soil water to a tension, provided there is connection between water in the ceramic and the soil. Field devices usually additionally employ a semi permeable membrane to help retain water in a measurement tube where the tension is electronically measured (Fig. 8). Where ceramic plates alone are used the devices measure Ψm without a direct contribution of Ψs. Where membranes are used the estimate may include Ψs.

Fig. 8 Tensiometer designs



The best defined measure of soil water potential is obtained by measuring the humidity of air in equilibrium with the soil. These measurements can be obtained in the field or laboratory provided temperatures are sufficiently stable. Given the high humidity involved, typically greater than 98%, small fluctuations in temperature can cause water to condense.

The other key requirement relates to reliable measurement of humidity. Dew point hygrometers can provide coarse estimates for large samples of very dry soils but peltier effect thermocouple psychrometers are used for the range of water potentials of interest with plants. A current is used to cool a thermocouple and thereby condense water on the junction. When the current is stopped the thermocouple cools through evaporation of the condensed water and the temperature reached with evaporation provides a measure of the dryness of the atmosphere.

The thermocouple psychrometer measurement is technically demanding. Fine thermocouples are needed to minimise the amount of water condensed and to provide a rapid response through low thermal inertia. Measurement is difficult because the signal levels of interest can be less than one microvolt, which is essentially the lower limit for voltage measurement. As the signal is highly transient the measured value typically reflects the interaction between the response time of the voltmeter and the cooling of the thermocouple. Different thermocouple units have different responses making it essential to calibrate each unit against solutions of known water potential. Thermocouple psychrometers measure Ψm + Ψs.

Soil Water Movement

The forces producing water movement in soils are gravity and water potential. Gravity alone is important for water at zero water potential, which is the blue water in Fig. 5. Gravity and soil water potential determine flows at other times. As gravity equates with 100 kPa, the soil water potential increasingly dominates water movement as soils become dry.

Water flows are determined by what can be termed resistances and/or conductivities as well as the forces. Conductivities are determined by measuring flow rates at different potential gradients, and are termed hydraulic conductivity (K). Ksat relates to saturated flows, and unsaturated hydraulic conductivity to water flows in wet and moist soils. Plant unavailable water is effectively static except at the soil surface.

The saturated hydraulic conductivity (Ksat) represents the maximum flow rate for water through a soil but, when it occurs, it is a highly transient. Fig. 9 illustrates the flow rate of water into a soil from a ring infiltrometer that maintains a shallow pond of water on the soil surface. The infiltration rate is initially high and declines with time.

The decline in the rate of infiltration of water into the soil with time arises for several reasons. These include the surface soil being drier than at depth (the water potential gradient decreases as water permeates the soil), and soils typically becoming finer textured with depth. However, the main reason is because the path length for water flow increases as the water permeates the soil. The relationship is given by Beer's Law for the absorption/extinction of radiation penetrating a homogeneous medium. The decline in infiltration with the depth of infiltration is exponential for a homogeneous soil.

On commencement of infiltration the flow path length is effectively zero, and this gives the Ksat. In Fig. 10 the path length for flow after 12 hours is around 45cm. This increase in the flow path length with time gives the characteristic decline in infiltration with time illustrated in Fig. 9. Figures 9 & 10 reflect coarse textured soils with high permeability's.

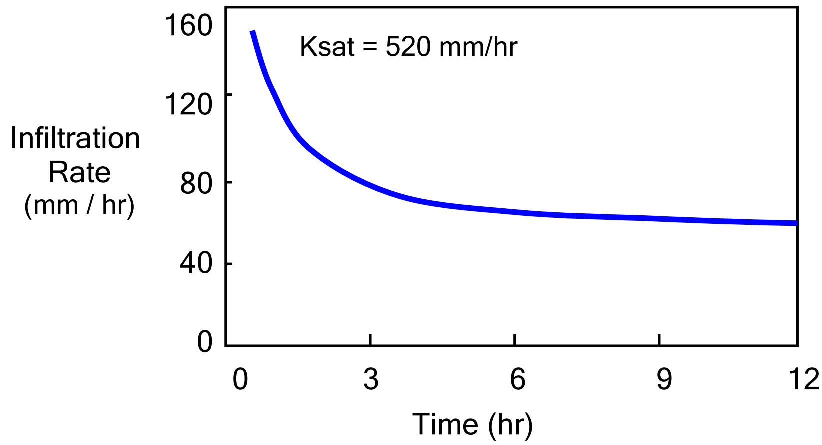


Fig. 9
Change in the rate of infiltration with time with water ponded on a dry soil.

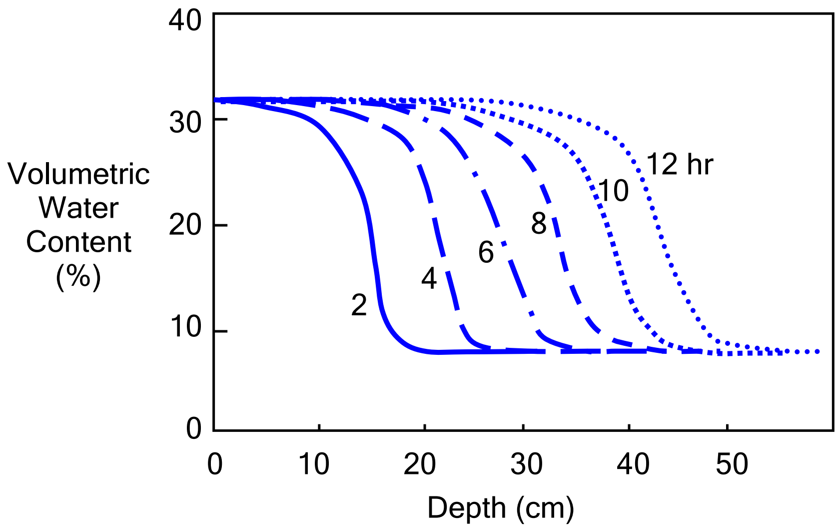


Fig. 10
Movement of the wetting front with infiltration of water into a dry soil from a surface pond.

Measurement procedures for hydraulic conductivity produce considerable uncertainty in the estimates. Field measures of Ksat are typically obtained by ponding water on the soil surface wherein flow from the pond moves laterally in the soil as well as down. Flow arises through the water potential difference between the pond and the soil as well as gravity, and this produces lateral as well as vertical flows.

Procedures used to adjust for the lateral flow include use of a dual pond system with an outer pond confining flows from the inner pond, and mathematical estimations the proportion of flows in a vertical column beneath the pond. The reliability of the adjustments is uncertain.

A ‘refinement’ involves augering holes and producing ponds with a constant head at desired depths. Dispersion from a small pond is nominally spherical for water potential gradients, and initially hemispherical for gravity, but with the gravitational force decreasing with departure from the vertical. Flow under water potential gradients alone is unsaturated and only some of the gravitational flow is saturated. The confounding between saturated and unsaturated flows and the complex geometry are difficult to unravel.

Errors associated with lateral flows can be addressed by confining the test sample within a column. However, this raises issues associated with preferential flow along the walls of the confining tube, and fracturing of the soil when producing the cores. Where consistency is required tubes are packed with material to a desired density. While the resulting homogeneity produces consistent results it does little to characterise the field situation.

Estimates of unsaturated flows into the surface soil are obtained using a shallow pond of water on the surface soil subject to sufficient tension to support it against gravity. These instruments are permeameters and emulate the situation with low intensity rainfalls. Water is drawn from the permeameters by the difference in potential between the pond and the soil surface without an effect of gravity. The need to account for lateral flows is usually greater than for surface infiltrometers because permeameters typically have smaller diameter ponds.

The capacity for water to flow through different materials is very coarsely indicated in Fig. 11. This provides an extremely general categorisation of the significance of materials for groundwater flows in aquifers. The main feature is that the Ksat values for materials that can comprise soils cover the range of 10^3 to 10^{-7} mm day^{-1}, which is ten orders of magnitude.

Fig. 11 Indicative hydraulic conductivities for different materials

Aquifer	Good					Poor				None			
K (mm/day)	10^5	10^4	10^3	10^2	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Permeability	Pervious				Semi-pervious				None				
Sand	Gravel		Sand & Gravel			Sand, Silt, Loam							
OM & clay					Peat		Clay			Heavy clay			
Rocks	Very fractured			Oil			Sandstone		Limestone			Granite	

The saturated hydraulic conductivity of soils covers an extremely large range and, because of the spatial heterogeneity in soils, exhibits very high spatial variability. As the hydraulic conductivity depends strongly on the soil moisture content, it also exhibits extremely high temporal variability. The extreme variability means that any semblance of accuracy is illusory.

Cumulative infiltration represents the increase in soil water storage with rainfall or irrigation. The patterns of cumulative infiltration reflect hydraulic conductivities with differences between soils being large (Fig. 12). After one hour the cumulative infiltration into the gravely sandy-loam is more than 10 times greater than into clay, and the magnitude of the difference increases with time. Fig. 12 also illustrates that land management can have a pronounced effect on the infiltration of water into soils. After two hours the cumulative infiltration into the sandy loam under pasture is 2.5 times greater than with wheat.

Characterisation of saturated water flows in field soils is fraught with difficulties, but measurement of unsaturated flows is close to impossible because of the very low rates and extreme spatial variability. The relationships in Fig.13 are indicative only but they illustrate the key feature that the hydraulic conductivity declines dramatically as soils become dry. The hydraulic conductivity for sand changes by three orders of magnitude from zero to -60 kPa, where -60 kPa represents a very wet soil. The decline in hydraulic conductivity is less with finer textured soils but for loams the decline is still three orders of magnitude for the small change in water potential from 0 to -120 kPa.

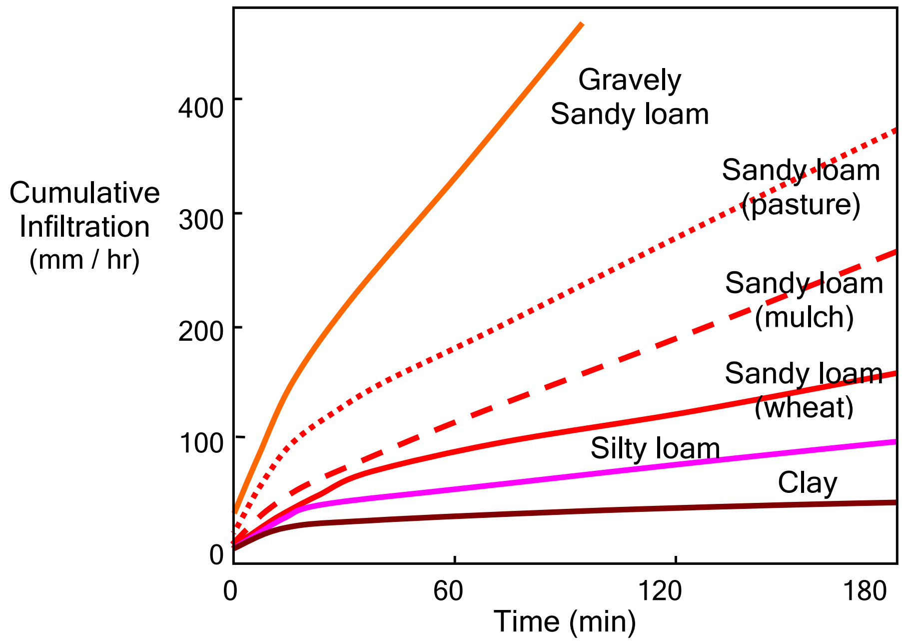


Fig. 12 Cumulative infiltration into dry soils from a saturated surface for soils with different textures and land management.

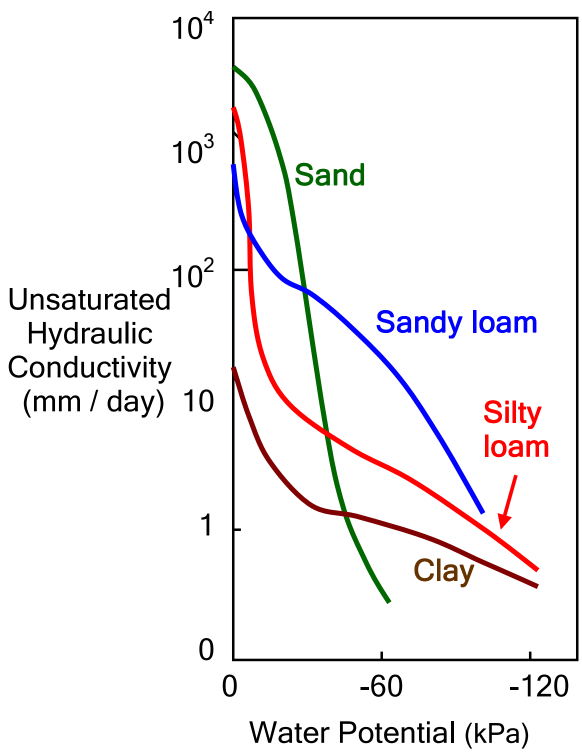
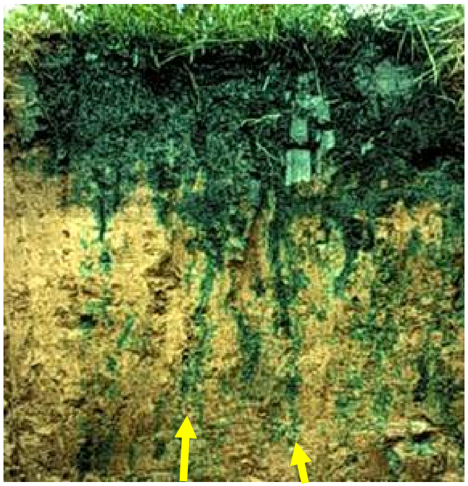


Fig. 13
Change in unsaturated hydraulic conductivity with decrease in water potential for wet soils of different textures.

Realised Patterns of Water Distribution

The above examples are for homogeneous materials. With models soils are generally regarded as being layered with different hydraulic conductivities being assigned to the surface and subsoils. Soils are treated as a homogeneous porous medium that is horizontally uniform and vertically stratified. Given the high variability in hydraulic conductivities in soils there is little point in identifying more than two layers for soils.

The significance of non homogeneity can be simply illustrated by tracing patterns of water infiltration using dyes. In Fig. 14 the assumption of homogeneity is reasonable for the surface soil but invalid for the subsoil. Even in the reasonably coarse textured soil illustrated the water flows to depth are primarily along preferred pathways typically formed by the growth and decay of plant roots. Flow along tubes representing old root channels is much faster than through the bulk of the soil matrix.



Dye traces patterns of water infiltration

Fig. 14
Pattern of infiltration into a coarse textured soil marked using a dye.

This difference between homogeneous and non homogeneous soils is schematically illustrated in Fig. 15. With homogeneous materials the wetting front is flat and parallel to the soil surface. With inhomogeneous soils the wetting front becomes spiky and highly irregular.

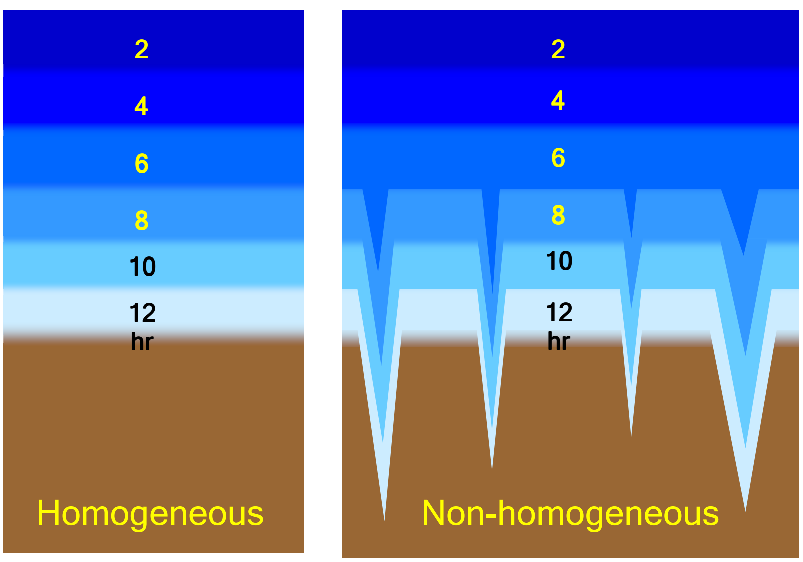


Fig. 15
Diagrammatic representation of water infiltration into homogeneous and non-homogeneous soils.

Water infiltrates more rapidly into non-homogeneous soils than homogeneous soils. Moreover, for a given application of water, water penetrates to a greater depth. Water is more likely to penetrate to depths below the rooting zone with non-homogeneous and thereby contribute to groundwaters. Non-homogeneous soils tend to be leaky.

The example in Fig. 14 illustrates changes in infiltration due to plant roots. While these are universally important the same effect can arise for other reasons. Cracks that develop in heavy clays rapidly transport water to depths in soils that would never be wetted with uniform clays (fig. 16). The columnar structure of some subsoils means that subsoil water flows are invariably in the gaps between columns. These structural features arise from swelling and shrinking associated with soils wetting and drying. Innumerable examples exist where flows in soils are altered by structural arrangements to the extent that the occurrence of homogeneity in field soils either represents a rare exception or an anomaly produced by land use.

Crack in heavy clay Vertical section Surface

Columnar B Horizon

Fig. 16 Structural features in soils developed through shrinking and swelling with wetting and drying.

Realised Patterns of Soil Water

The above involves application of simple physical principles to a complex system. While the physics are valid the complexities of soil structure usually result in the reality having little semblance to approximations in simulation models. The difference between infiltration into homogeneous and non homogeneous soils is an example.

Osmotic potential by definition arises from dissolved substances that are free to move with water. Salinity is not generally recognised as affecting the distribution of water in soils as salts can move with the water. However, the extreme wet and dry soil water profiles for a heavy cracking clay supporting brigalow are closely aligned with salinity (Fig. 17). This coincidence between salinity and moisture arises in all soils examined that were associated with native vegetation.

The simple explanation is that this coincidence arises from water flowing along pathways of least resistance. Movement of salts via leaching is therefore essentially confined to narrow corridors. As salts in the bulk of the soil remain in situ they contribute to the water potential and therefore to the soil water content. Osmotic potential influences patterns of soil water content because most water flows along preferred pathways while water in the bulk of the soil is effectively static.

The increase in soil moisture content with salinity observed in the field is pronounced, but the magnitude of association depends on the soil water content. The change in osmotic potential with water content is roughly linear but the change in the soil matric potential is a power function (Fig. 18). At high water contents a small change in soil water content has little effect on the soil matric and osmotic potentials. At low water contents a small change water content similarly has little effect on the osmotic potential but the change in matric potential is large. Consequently, salinity has little effect on the soil water content - water potential relationship at high soil water contents but has a marked effect at low water potentials. Saline soils at -1.5 MPa have much higher water contents than non-saline soils.

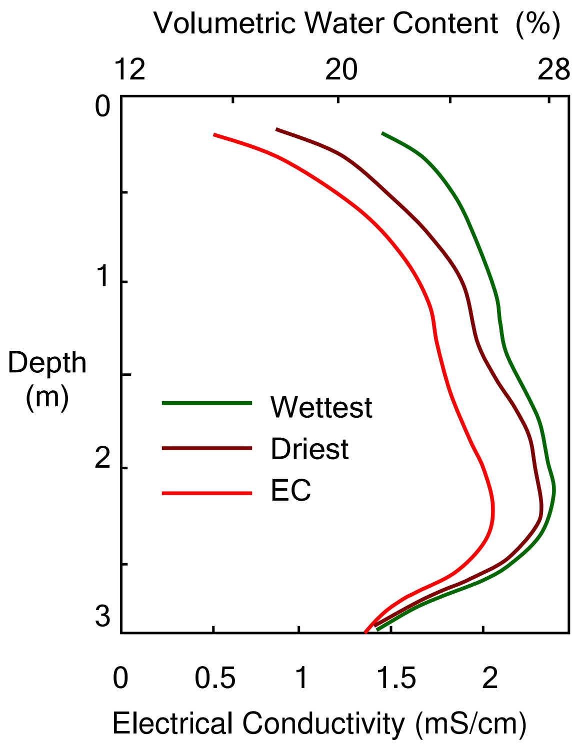


Fig. 17

Wettest and driest soil profiles recorded in a heavy cracking clay supporting brigalow together with the profile of soil salinity.

This effect is compounded by the occurrence of bound water. In the traditional model used to calculate the osmotic potential in soils the water is assumed to be fully available to the osmotic and matric components. That is, water associated with the surfaces of clays is assumed to be also available to solutes. The Soil Heat of Hydration (Soil HoH) demonstrates that this assumption is invalid. Water bound to the surface of clays is unavailable to dissolve salts. The consequential reduction in the availability of water to salts increases the osmotic potential.

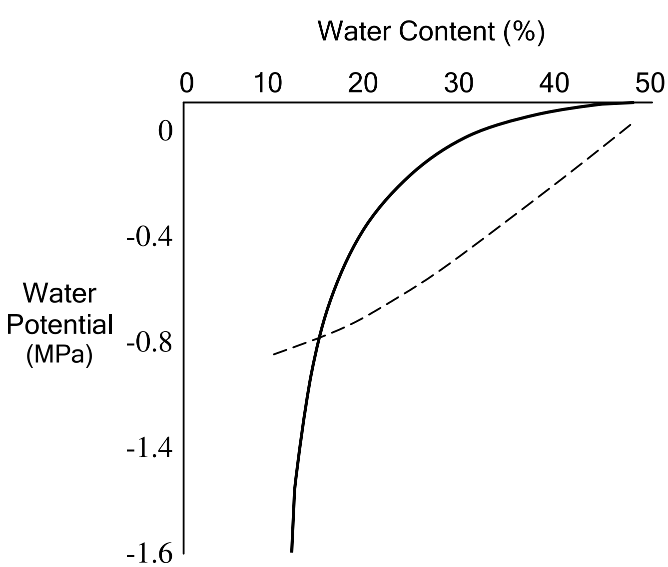


Fig. 18

Indicative change in matric and osmotic potentials with change in soil water content.

—— Ψm

– – – – Ψs

The consequences of this partitioning of water between different surfaces are most pronounced in dry soils.

The basis for the form of salinity profile in Fig. 17 is given in Fig. 19. The average long term pattern of net downward flow of water through the soil for the brigalow example is as indicated in Fig. 19a where this is a consequence of water only infiltrating through the surface but being extracted from the entire profile. The potential for drainage from the brigalow soil is exceedingly small as a change in water content below a depth of 1.2mm occurred only once in almost 3 years.

The main characteristic of the generalised but observed pattern of soil salinity in poplar box in Fig. 19b is the leaching of salt from the surface with accumulation in the subsoil. However, some salt accumulates at the surface due to evaporation of water from the soil surface. While upward flow of water occurs in the surface soil its magnitude is small compared with the downward flow. Also, leaching of salt apparently occurs from the bottom of the subsoil due to the very small but apparently significant leaching through percolation of water. Such salinity patterns can be used to infer patterns of water flows, albeit with some significant assumptions.

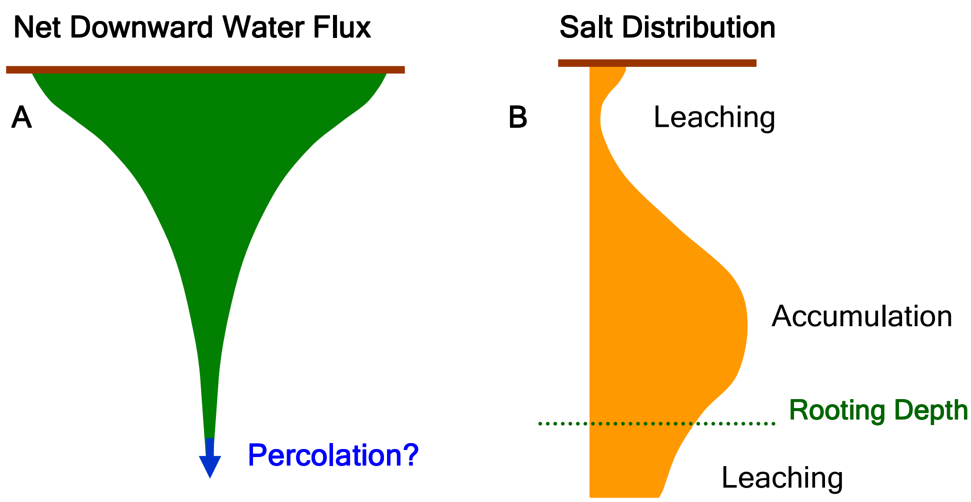


Fig. 19

A Long term average of the wetting depth in a heavy clay soil under brigalow

B Generalised profile of salt distribution in a poplar box soil

The results in Fig. 20 give profiles of soil water content for brigalow on occasions when the soil had been drying for around one month. Under such conditions the dawn water potential of the plants should be closely equilibrated with the soil, with current theory at least. This figure therefore gives a composite picture of the pattern of drying of the soil profile under the full range of conditions experienced over almost three years.

Changes in soil water content occur at all depths to three meters, but the magnitude of change reduces with depth in the profile (the slopes of the lines decrease with depth). Also, for the 0.9m depth and below, there is a range of plant water potentials where the soil water content remains constant, and this range increases with depth.

Measurements of the relationship between soil water content, salt content and water potential indicate that the soil at depth usually has a water potential of -4.5 MPa. This relates well to plants withdrawing water from soil depths when the dawn plant water potential is below -4.5 MPa. Wetting of the soil below 1m is highly infrequent and for most of the time the soil below 1m has a water potential of -4.5MPa.

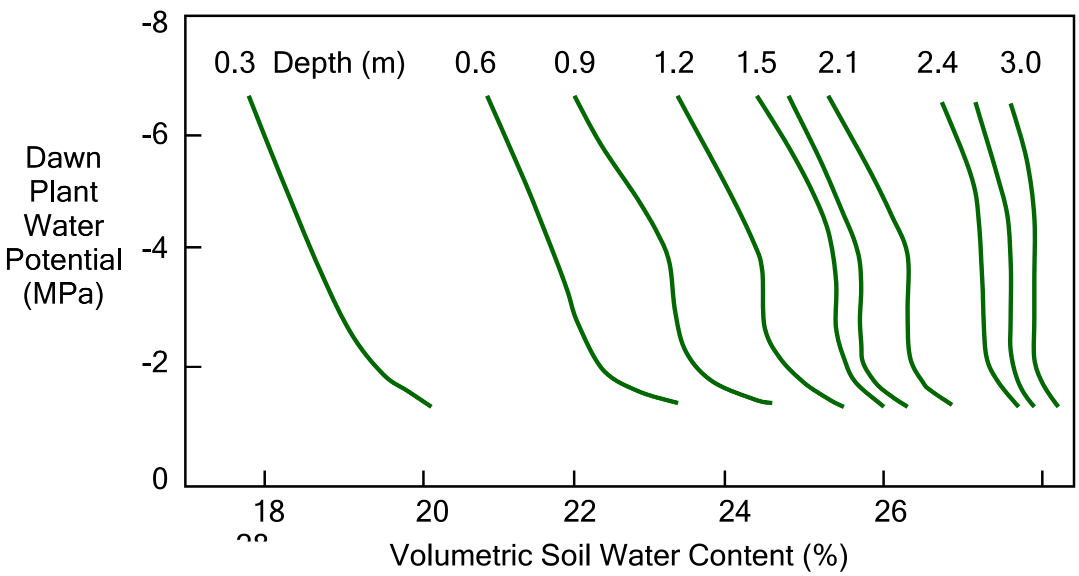


Fig. 20 Soil water contents at different depths v the dawn plant water potential for brigalow on a heavy clay soil. All records obtained following a substantial period without rain.

The increase in water content at depth occurred only once in almost three years, and it amounted to only 1.5mm of rainfall. For plant water use the deep heavy clay soil is effectively sealed with all water entering the top being lost through transpiration or evaporation from the soil surface. However, from the decline in salinity at the bottom of the soil profile there could be leaching. The decrease in soil salinity below 2.5m may reflect leaching, but it also could simply reflect the depth of penetration of water into the soil. Salt will not appreciably accumulate below the depth of movement of infiltrating water.

Implications for Indensation

Indensation should be prominent at night due to the diurnal increase in the concentration of atmospheric water vapour and the decrease in potential evaporation. Plants therefore have a requirement to store water indensed at night for later use. Some plants have purpose designed water storage structures, as with cacti and succulents, but most plants don’t. For plants without internal storage the soil is the only potential reservoir for indensed water.

Use of the soil by plants for water storage involves transport of water from the leaves through stems to the roots with absorption by the soil. The flow is along a water potential gradient from the leaf to the soil wherein the purpose designed structures within plants can provide reasonably low resistances to flows. However, at the soil - root interface, and in the soil, the issues are the same as for infiltration of water into soils. There can be high resistances to water flows.

Given the quantities of water lost by plants in photosynthesis any water flows into very dry soils would be too small to make a significant contribution. Soils must be reasonably wet. However, the water potential of roots must be lower than for leaves for water to flow down a plant. For water to flow to the soil the water potential of the soil must be lower than for the roots. Flows of water from the root to the soil would therefore be unsaturated.

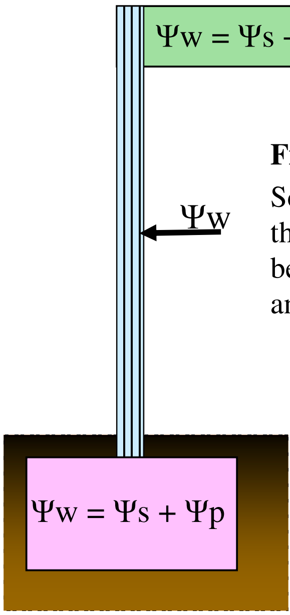
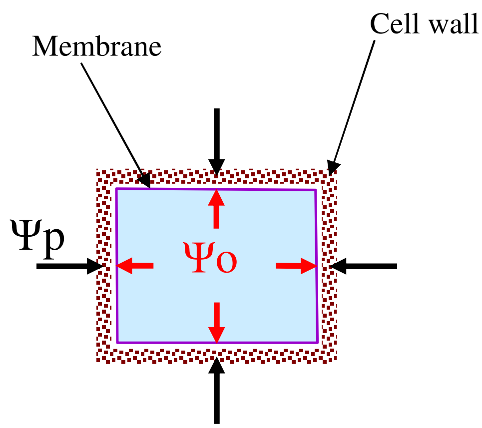


Fig. 21
Schematic representation of the hydraulic arrangement between plant leaves, stems and roots.

Fig. 22
Schematic representation of the hydraulic arrangement of a plant cell.



The dependence on unsaturated flows for the uptake, storage and retrieval of indensed water in soil represents a key constraint. Factors that can be used to mitigate the constraint relate to the change in unsaturated hydraulic conductivity with decrease in water potential, and the transport distance.

Homogeneous clay soils have the lowest saturated hydraulic conductivities but they are least affected by drying. The decrease in hydraulic conductivity with decrease in water potential in clays is considerably less than for other soils. Moreover, clays have a large capacity to store water in the range of water potentials available to plants where, for a given root density, the storage capacity determines the width of soil around a root needed to adsorb a given quantity of water. Clays minimise transport distances.

Insufficient is known about the indensing characteristics of plants to clearly identify the constraints to effective storage of water in soils, but there are some obvious examples of good solutions. Grasses have very high densities of fine roots, and they preferentially occur on fine textured soils. The fine texture provides high water storage without a sharp cutoff in hydraulic conductivity as the soil dries. The high root density minimises the distance for water movement from and to the root.

Many plants have root densities that are orders of magnitude greater than needed to extract rainwater from wet soils. However, this disparity is apparent rather than real as high root densities are needed to maintain flow rates into the plants with unsaturated flows, particularly in clay soils.

Realised soil water storage

The degree of unsaturation of indensed water flows in soils would vary with conditions. With soils previously wet by rainfall the plant water potential could be high but the soil water potential would be higher. In this situation the water potential gradient in the plant from the leaf to root would effectively be zero given the occurrence of indensation. There would be no transport of indensed water from the leaf to the soil, and this appears to be the reason for the accumulation of water on plant leaves with overt indensation (Tunstall 2010). All observations of overt indensation occurred when soils were wet following rain.

Dry soils appear necessary for their use in storing water indensed by plants. This places a premium on a high root density, and the soil having a high water storage capacity and maintaining reasonable rates of unsaturated flow. Additional to the soil properties previously mentioned soil organic matter would be important.

Potential Active Transport in Plants

Cells in plant leaves are connected to cells in roots via a network of capillary tubes that run through the roots, stems and leaves (Fig. 21). This structural arrangement allows use of the dryness of the atmosphere to draw water from the soil and transport it to leaves. A diversity of anatomical structures addresses the requirements but the basics are:

- Cells in roots and leaves having membranes lining the inside of structural walls
- The cells in roots and leaves being hydraulically connected via capillaries
- Parts of the cell surface in leaves being exposed to the atmosphere through stomata
- Cells in roots being hydraulically connected to soil water.

The driving force for water movement from the soil to the atmosphere is a concentration gradient in water vapour between the atmosphere and air within plant stomata. Water flow from the cell to the atmosphere involves a change in state of water from a liquid to a vapour where the energy essential for this change derives from the atmosphere as sensible heat.

The flow of water from the soil through plants to the atmosphere has been presented as a Soil-Plant-Atmosphere-Continuum (SPAC) where this derives from work in the 1960s. The SPAC concept was particularly useful when introduced but has promoted incorrect views as to how the system functions. The phase change of water from liquid to vapour in the leaf produces a physical discontinuity. This change in state represents a major disjunct from water flowing along a water potential gradient to being driven by a concentration gradient. Moreover, passage of water through membranes in the roots and/or leaves means that plants can exert active (metabolic) control of water movement. The existence of active controls prevents water movement through plants from being treated as simple physical continuum if the mechanisms are to be understood.

The structure of plant cells provides the mechanism for conversion of evaporation from a cell to the development of a water potential to draw water from the soil and through stems (Fig. 22). A semipermeable membrane lines cell walls where the walls are effectively rigid but permeable to water. The membrane is complex in providing for active transport of solutes as well as the passive flow of water, but for water relations can be viewed as being permeable to water but not solutes. The membrane holds solutes within the cell but allows the passage of water.

A cell takes up water until the osmotic potential of the cell contents is countered by the pressure applied by the 'rigid' cell wall (Fig. 22). A positive pressure is used to counter the negative osmotic potential, as with pressure being used to counter the negative surface force in a capillary (Fig. 4). Where water is freely available this continues until the pressure in the cell balances the osmotic potential. The water potential of the cell is then zero.

Allowing the cell to loose water through evaporation decreases the osmotic potential slightly but greatly reduces the pressure exerted against the cell wall. A small loss of water can produce a large change in water potential due to the rigidity of the cell wall.

The water potential of leaf cells is transmitted through stems to roots via a hydraulic connection that is under tension. Given the effective incompressibility of water the rate of transmission of changes in tension are very rapid.

This mechanism for water uptake is passive in not requiring energy from plants, but plants exercise considerable control. Stomata control evaporation from leaves. Structures such as Casparian Strips associated with cells in plant roots can modify the pathways for water movement. The osmotic potential of cell contents can be altered by the production of solutes, as with sugars deriving from photosynthesis and the interconversion between starches and sugars.

The indensation mechanism is passive similarly to evaporation in not requiring metabolic energy. The energy used to draw water into leaves against a concentration gradient does not derive from metabolic energy. Plant structures have evolved to acquire the energy needed for indensation from the perfield and, while the requirements for obtaining energy from the perfield are very specific, they have been integrated with the requirement to obtain solar radiation for photosynthesis.

Energy from the perfield is captured similarly to solar radiation but with pronounced structural differences relating to differences in wavelengths of the radiation. Many features of plants considered to be adaptations to intercepting solar radiation are adaptations to the perfield.

The controls exercised by plants on the transport of indensed water appear to be the same for transpiration. That is, the controls on water flow through the plant appear to be the same regardless of whether the movement is up or down.

The use of metabolic energy to transport indensed water from roots to soils is possible but unlikely. As with transpiration, actively transporting the volume of water involved in indensation would more than deplete the energy reserves of plants. Moreover, dissociation of water to produce hydrogen ions is central to nutrient uptake in roots. As active transport in plants is through ions any active transport of water would interfere with nutrient relations.

References

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