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Factors affecting the infiltration of agricultural soils: review

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Abstract

Soil infiltration refers to the soil's ability to allow water movement into and through the soil profile. It allows the soil to temporarily store water, making it available for uptake by plants and soil organisms. The infiltration rate can be restricted by poor management. Under these conditions, the water does not readily enter the soil and it moves downslope as runoff or ponds on the surface, where it evaporates. Thus, less water is stored in the soil for plant growth, and plant production decreases, resulting in less organic matter in the soil and weakened soil structure that can further decrease the infiltration rate. Runoff can cause soil erosion and the formation of gullies. It also carries nutrients and organic matter, which, together with sediment, reduce water quality in streams, rivers, and lakes. Excessive runoff can cause flooding, erode stream banks, and damage roads. Runoff from adjacent slopes can saturate soils in low areas or can create ponded areas, thus killing upland plants. The soil and vegetation properties that currently limit infiltration and the potential for increasing the infiltration rate must be considered in any management plan. Suggested that management strategies such as increase the amount of plant cover, especially of plants that have positive effects on infiltration, decrease the extent of compaction by avoiding intensive grazing and the use of machinery when the soils are wet, be considered. This paper investigates the influence of water in the soil and its influencing factors to be studied.

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Introduction

Infiltration is defined as the process by which a fluid passes through or into another substance travelling through pores and interstices (Simpson and Weiner 1989). For surface irrigation that fluid, water, is ponded on the soil surface and the infiltration rate, intake rate or infiltrability describes the flux into the soil profile. For many types of irrigation systems and natural rainfall events the application rate does not exceed the potential for infiltration. In these circumstances, the water flux is governed by, and limited to, the water application rate. As long as this application rate remains appreciably below the infiltration potential and the soil characteristic is non-limiting, the uniformity of water applied should be distinctly defined by the irrigation system design. Where this is not the case, such as for surface irrigation, the soil hydraulic properties will govern the infiltration rate and surface ponding. The water volume that does not infiltrate immediately remains on the soil surface and can then move under gravity to other parts of the field. In this way, the distribution of water will be partly determined by the infiltration at other locations in the field.Water movement within the soil is governed by Darcy's law, which states that the flux is equal to the hydraulic conductivity multiplied by the hydraulic gradient. The hydraulic gradient is comprised of the gravity, pressure, osmotic and matric (movement of water from wet or full pores to dry soil) potentials (Singer and Munns,1999). Starting with a dry soil the suction gradient (matric potential) is high causing a high infiltration rate. As the pores fill with water the suction gradient decreases and time permitting approaches zero (Lal and Shukla 2004). The infiltration rate experiences a similar reduction until at saturation is almost entirely reduced to that caused by the forces of gravity and pressure.

Inherent factors affecting soil infiltration, such as soil texture, cannot be changed. Soil texture (percentage of sand, silt, and clay) is the major inherent factor affecting infiltration. Water moves more quickly through large pores of sandy soil than it does through small pores of clayey soil, especially if clay is compacted and has little or no structure or aggregation depending on the amount and type of clay minerals, some clayey soils develop shrinkage cracks as they dry. The cracks are direct conduits for water entering the soil, causing clayey soils to have high infiltration rates under dry conditions. Where cracks do not occur, clayey soils have slow infiltration rates. Also the majority of factors influencing the infiltration rate have a direct effect on the soil structure namely the soil porosity. Porosity refers to the ratio between the volumes of solid and fluid components of a soil sample. However, for infiltration the average pore size, distribution of pore sizes and connectivity of pores are of greater importance. The soil pores must be large enough and offer sufficient continuity in order for infiltration to occur.

Soil erosion is the process by which material is dislodged, transported and deposited elsewhere in the landscape via the effects of wind or water. Disregarding wind, the severity of erosion is determined by the soil particle size, field slope and water flow velocity. In furrow irrigation, maximum flow velocity is realised close to the inlet and gradually declines over the furrow length. In the infiltration process water enters the soil surface due to the combined influence of gravity and capillary forces. Both forces act in the vertical direction to cause percolation downward. Capillary forces also act to divert water laterally from larger pores (feeder canals) to capillary pore spaces which are much smaller in dimension, but may be very numerous. As the process continues, the capillary pore spaces become filled and with percolation to greater depths the gravitational water normally encounters increased resistance to flow due to reduced extent or dimension of flow channels, increased length of channels, or an impermeable barrier such as rock or clay. At the same time there may be increased resistance to inflow of water at the soil surface due to the surface sealing effect as a result of the mechanical action of raindrops in breaking down the soil aggregates and subsequent in wash of the finer soil particles. The result is a rapid reduction of infiltration rate in the first few hours of a storm, after which the rate remains nearly constant for the remainder of the period of storm rainfall excess.

The soil is a combination of mineral, liquid, gas and living components. Living soil organisms include micro-organisms (invisible to the naked eye), larger animals living in and on the soil surface and finally the roots of crops and weeds. Most of these organisms influence the soil hydraulic conductivity by influencing aggregate stability, pore sizes and pore connectivity.

Factors influencing infiltration

The infiltration rate is determined by the interaction of a number of physical and chemical soil characteristics. These soil properties vary from one location to another and change over time due to cultural practices (e.g. tillage and compaction), water management and biological processes (e.g. macro and micro-organisms). This section provides a summary of the various factors that influence the soil infiltration rate within a surface irrigated field.

Soil Texture

The hydraulic conductivity of the soil is strongly influenced by the soil texture, i.e .the relative proportions of sand, silt and clay. Clay particles are particularly important as their small size makes them able to fill the voids between larger particles while their charge orientation gives them a crucial role in binding the soil matrix into larger structures. For a media with a single particle size the hydraulic conductivity is approximately proportional to the square of the particle diameter (Iwata *et al.* 1995) .However, in a natural soil the particle sizes range from the microscopic clay colloids (<0.0002 mm) to the much larger sand grains (0.05 - 2 mm) up to large boulders (Singer and Munns, 1999). The textural composition and soil properties vary considerably between soil types therefore attempts are commonly made to position field and property boundaries based on the soil characteristics. However, the field layout, particularly in the case of furrow irrigation, is usually based on regular sized rectangular shaped fields. Hence, it is likely that a single field may contain a number of distinct soil types.

Hydraulic properties which are strongly influenced by texture and structure vary considerably even within a single soil class.It was also found that the hydraulic conductivity declined significantly with depth between the surface and 400 mm depth for these soils .One might expect coarser sandy soils to have higher infiltration due to larger pore sizes. Regions of lighter textured, or sandy soil within a field often have higher intake rates (Childs *et al.*, 1993). However, van Es *et al.* (1991) found a positive correlation between the clay content and the initial infiltration rate while the silt content was negatively correlated. Also, stones within the soil matrix can serve to reduce the pore areas available for water storage and transport (Mehuys *et al.*, 1975). Attempts have been made to correlate the hydraulic conductivity with soil texture with the promise of predicting infiltration using measurable physical properties. For example, Bresler *et al.* (1984) found that between 24-45% of the variability in K_s could be related to the sand content and 10-25% was explained by the interaction between electrical conductivity and sand content.

Variations in soil horizon thickness and texture may have significant effects on the spatial variation in soil infiltration rates, particularly as the wetting front reaches that layer. Considering a vertical soil column, the long term infiltration rate is determined by the most restrictive layer. The existence of a coarse sand layer within a finer textured loam or clay soil has been found to reduce rates of infiltration and upwards movement from a water table (Brady and Weil, 2002). The larger pores within the sand cannot generate the same level of matric potential therefore no water passes through that layer until the moisture content of the finer soil rises sufficiently to generate the same level of matric suction.

The natural topography of the land is inherently random in nature and is determined by geological features and history of erosion. Hence, fields are often graded using laser guided or manual scrapers and buckets to aid in drainage and irrigation management. Consequently, soil is excavated and relocated to other areas. In parts of the field, this may uncover underlying soil horizons with differing chemical and hydraulic properties. Brye *et al.* (2003; 2006) found that field levelling altered soil texture and increased the average bulk density by 3% for a clay loam and 12% for a silt loam. However, the variance decreased due to the compaction and exposure of the denser subsoil. Brye *et al.* (2006) also observed changes in the spatial variability as the bulk density became spatially auto-correlated while the silt content became more spatially independent after levelling.

Soil Erosion

Soil erosion is the process by which material is dislodged, transported and deposited elsewhere in the landscape via the effects of wind or water. Disregarding wind, the severity of erosion is determined by the soil particle size, field slope and water flow velocity. In furrow irrigation, maximum flow velocity is realised close to the inlet and gradually declines over the furrow length. Hence, the sediment load generally increases throughout the first quarter of the field length and steadily declines over the second half of the field (Trout, 1996). Soil erosion from the upstream end can be up to six times (Fernandez-Gomez *et al.*, 2004), or 20 times greater (Trout, 1996) than the furrow average. Some of the eroded material may be removed in the tail water but a majority of the suspended load is deposited before the water reaches the end of the field. Despite this, erosion is usually only considered a problem where soil material is removed from the field even though any degree of erosion along the furrow length will result in non-uniform re-distribution of soil particles . The suspended load for a given particle size is deposited once the flow declines below a threshold velocity. Therefore, the gradual reduction in velocity observed in furrow irrigation will introduce systematic heterogeneous conditions as the soil particles are deposited spatially according to size and density. Surface seals may form in areas where fine sediment is deposited and consolidated, creating areas of low infiltration at the downstream end of the field. Infiltration rates have been observed to be 50-100% higher (for a silt loam) at the upstream compared to the downstream end of the furrow (Brown *et al.*, 1988). The effect of this decline becomes even more significant considering the tendency for shorter opportunity times at the downstream end of the field. Brown *et al.* (1988) found that the addition of fine sediment to the supply water could replace the sediment removed from the upstream end of the field and hence increase the uniformity of applied depths. In some cases, soil colour can be used as a remote indicator of soil erosion. van Es *et al.* (1991) found that the colour development equivalent (a combination of redness and chroma) was the best predicative variable for initial infiltration rates as it was related to the clay and silt contents.

In the field, erosion is often observed as alterations in furrow cross section (Horst *et al.,* 2005). Furrows are typically formed into a V shaped cross-section at the start of the season. A combination of soil erosion and slumping causes the channels to widen and become shallower with a flat bottom (Izadi and Wallender, 1985; Kemper *et al.*,1988; Segeren and Trout, 1991). This decreases the dependency of the wetted perimeter on the flow depth and discharge, in some instances overcoming the otherwise strong relationship between inflow rate and infiltration that occurs at non-erosive discharges (Antonio and Alvarez, 2003). In contrast, furrows in fields with steeper slopes tend to become deeper and narrower (Trout and Kemper, 1983). The alteration in cross section is also affected by the flow regime as surge inflow was found to remove greater amounts of material from the side walls (which is deposited on the furrow bed) compared to continuous inflow (Horst *et al.*, 2007).

Soil Structure and Compaction

The majority of factors influencing the infiltration rate have a direct effect on the soil structure namely the soil porosity. Porosity refers to the ratio between the volumes of solid and fluid components of a soil sample. However, for infiltration the average pore size, distribution of pore sizes and connectivity of pores are of greater importance. The soil pores must be large enough and offer sufficient continuity in order for infiltration to occur. Soil pores are classified by size into macropores (> 0.075 mm), mesopores and micropores (< 0.03 mm) (Singer and Munns, 1999). Soil pores may be created or altered through biological activity, shrinkage from temperature or moisture effects, formation of ice lenses, cultivation and collapse or plugging of larger pores (Lal and Shukla, 2004). Intuitively, the infiltration should be associated with the pore size distribution. However, Baker (1979) failed to find any direct relationship due to the complex interactions between other soil properties. The bulk density is calculated by dividing the mass of solid material by the volume that it occupies. Hence, it is inversely proportional to the porosity for a fixed particle density. Several attempts have been made to link the bulk density to the saturated hydraulic conductivity or infiltration rates with mixed results. House *et al.* (2001) found that 58% of the variability in $Ln(K_s)$ was due to differences in bulk density. Jaynes and Hunsaker (1989) found that only 25% of the variation in infiltrated volumes could be explained by the variance in surface bulk density but they expected that the correlation would increase when considering a greater depth of soil. Compaction and tillage are the two major cultural practices that affect soil hydraulic properties. Compaction will generally result in increased bulk density while tillage should have the opposite effect providing that it does not destroy the soil structure .Compacted layers may occur naturally but in agricultural soils usually form due to farming practices. Soil compaction may be caused by livestock (Shafique and Skogerboe, 1983) or repeated cultivation at the same depth resulting in the formation of plough plans. However, for cultivated fields, the primary source of compaction is machinery wheel traffic. The greatest compaction was found to occur during the first machinery pass of the season or following tillage (Allen and Musick, 1992) and subsequent passes did not result in a significant further decrease in infiltration rates .The severity of compaction also increases with increasing soil moisture content (up to the optimum water content) during machinery operations (Allen and Musick, 1997).

Some have attempted to link changes in the infiltration rate to the incidence of compaction. For example, Trout and Mackey (1988a) measured a 20% higher infiltration rate in uncompacted furrows in Idaho and more than a 50% reduction in alternate wheeled furrows for two Colorado fields. Focussing on individual infiltration curve parameters, Hunsaker *et al.* (1999) found that the Kostiakov k parameter (Eq. 1) and cumulative infiltration at four hours were 25% lower for wheeled furrows while a also tended to be lower. However, the greatest effect is observed in the value of the steady infiltration rate f0 (Elliott and Walker, 1982), with reported declines in the order of 50% (Trout and Kemper, 1983), 70% (Fattah and Upadhyaya, 1996) and 75-80% (Li *et al.*, 2001). The large difference suggests that modelling may require one set of input parameters for freshly tilled soil and a second set for compacted soil (House *et al.*, 2001). Wheel-slip associated with machinery traffic acts to further reduce infiltration rates. On a self-mulching Vertisol in the Lockyer Valley, Queensland, increasing the wheel-slip from 3% to 10% had a notable effect (Li *et al.*, 2001), with no further significant reduction in infiltration rates with further increases in wheel-slip. The wheel-slip influence increases as the soil moisture content approaches the plastic limit, which is significant since cultivation and sowing often occur soon after rainfall. The well known Kostiakov equation (Walker and Skogerboe, 1987) is given by $z=Kt^a$ Eq(1)
Where a and k ($m^3\ min^a\ m^{-1}$) are empirical constants that must be calibrated.

The recent introduction of controlled traffic farming restricts compaction to the same locations with each pass, thereby resulting in a small number of furrows with high compaction and the remainder with little or no compaction. For surface irrigated fields, the decrease in intake associated with soil compaction causes an increase in water advance rates, ultimately improving the uniformity of applied depths in those furrows but increasing the variance between wheeled and non-wheeled furrows. This complicates irrigation management since the advance rates can differ by as much as 45% (Allen and Musick, 1992) between adjacent furrows in the same irrigation.

Furrow smoothing and/or compaction by dragging a torpedo shaped object behind a tractor (Hunsaker *et al.*, 1999) or by using weighted v-shaped wheels (Fornstrom *et al.*, 1985) can be used to decrease infiltration rates, increase advance velocities and improve uniformities. Furrow smoothing can reduce Manning's n (surface roughness coefficient) by up to a factor of five but increasing the flow rate tends to overcome any advantage (Hunsaker *et al.*, 1999). Allen and Musick (1992) found that machinery traffic can reduce the intake rates by 17% for the first irrigation after tillage and reduce the cumulative applied depth by an average of 13% with no adverse effects on yield.

Soil tillage will usually result in higher infiltration rates due to the increase in porosity and decrease in bulk density. Often the first irrigation of the season experiences greater infiltration rates and excessive deep drainage due to the loosened soil conditions through tillage and winter frost action (Allen and Musick, 1992). The tillage effect is greater for medium and fine textured soils and is influenced by the initial moisture content (van Es *et al.*, 1999). Although soil cultivation acts to reverse the effects of soil compaction, machinery traffic during planting, cultivation or even from previous seasons can influence the variability of intake rates (Trout and Kemper 1983). Ripping of compacted furrows can reduce the bulk density to a value lower than that of the uncompacted soil (Allen and Musick, 1992). The practice of minimum tillage in sugarcane has been found to result in decreased infiltration rates (Raine and Bakker, 1996). However, in sugar cane the presence of crop residues on the soil surface may impede surface irrigation advance thereby increasing infiltration.

Soil Moisture Content and Cracking

In an unsaturated soil, the initial infiltration rate is dominated by the matric potential, which is an inverse function of the moisture content. Hence, the soil hydraulic properties are strongly linked to the water content and its distribution within the soil profile. In addition, the moisture content will change both spatially and temporally due to rainfall (Raine *et al.*, 1998), uniformity of previous irrigations, evaporation and plant extraction. However, surface irrigation events tend to reduce the spatial variability of soil moisture contents (e.g. a reduction in the coefficient of variance (CV) of 2 to 3% (Jaynes and Hunsaker, 1989)) because the dryer areas of the field tend to have increased intake rates and vice versa.

Soil water content also has a direct impact on the degree of soil cracking which in turn has a large impact on the infiltration function (Mailhol and Gonzalez, 1993). Cracking occurs within many clay soils, (e.g. those found in the irrigation areas of Queensland and New South Wales) where the soil shrinks excessively on drying. During irrigation, these cracks serve as pathways through which water can quickly enter the soil. Furrow irrigation is particularly sensitive to cracked soils as the advancing water front may be effectively brought to a standstill while a large crack is filled. Generally ,the variability of infiltration rates is greatest during the initial stages of ponding .Therefore, soil cracking appears to be a significant source of variation in applied depths (Bautista and Wallender, 1985 Bali and Wallender, 1987), particularly under conditions where the surface water is flowing (Izadi and Wallender, 1985). However ,Hodges *et al.*, (1989) found that increased levels of soil cracking need not affect the level of infiltration variability. Compared to the lighter textured soils, the cracking nature of heavy clay soils and the resultant shape of the infiltration curve may make them more suitable to furrow irrigation (Mitchell and van Genuchten, 1993). It is possible to achieve uniform water application with minimal deep percolation since the majority of infiltration occurs in the initial moments of water ponding and the cracks serve as paths for lateral subsurface re-distribution between furrows.

Despite the obvious influence of moisture content, it is not explicitly represented in empirical infiltration functions such as the Modified Kostiakov equation (Bautista and Wallender, 1985). Bakker *et al.* (2006) replaced the infiltration equation with a single crack-fill term determined by the moisture deficit prior to irrigation. They found this approach worked best for broad furrows but failed with deep V-shaped furrows . Others have accounted for the crack fill by using a linear infiltration function (Eq.2-8) (Mailhol *et al.*, 1999) or adding the C term to the Modified Kostiakov (Walker, 2003). (Eq. 2).

$$Z = Kt^a + f_0 t + C \qquad \text{Eq (2)}$$

Since the crack fill volume is strongly related to moisture content, its value can be estimated by multiplying the soil moisture deficit, measured using soil probes or estimated from ETc values by a constant factor (e.g. 0.75 (Robertson *et al.*, 2004) or 0.67 Mitchell and van Genuchten, 1993)). Enciso-Medina *et al.*, (1998) devised a system of equations to relate crack formation to moisture content and the coefficient of linear expansion. They accounted for the infiltration that occurs through the sidewalls of large cracks by assuming standard crack geometry.

Considering the linear infiltration equation (Eq. 3) the magnitude of the cracking term can be inferred from the water advance velocity. A 30% variance in f0 only results in a 2% difference in the advance time whereas the advance is much more sensitive to variations in the crack term (Mailhol *et al.*, 1999). In addition, the variance of the C term is positively correlated with its mean (Mailhol *et al.*, 1999). Hence, a dryer soil will have greater crack volume variability. Where infiltration parameters are calibrated from advance measurements, ignoring soil cracking will cause the estimated infiltration curve to over predict infiltration volume at large times (Bali and Wallender, 1987). Where the cracking term is omitted from the infiltration function the influence of the crack volume and hence the initial soil moisture content is reflected in the terms of the infiltration function responsible for initial intake rates (i.e .a and k from the Kostiakov and Modified Kostiakov and S from the Philip equation).

$$Z = C + f_0 t \qquad \text{Eq (3)}$$

Most soils, regardless of the existence of cracks, tend to exhibit a strong inverse relationship between initial infiltration and moisture content. Experimentation by Robertson *et al.* (2004) has shown that this dependency follows a strong linear relationship. However, Gish and Starr (1983) could not find any correlation between the initial moisture content and the cumulative infiltration at 15 minutes. Numerical studies using HYDRUS 1D (Furman *et al.* 2006) found that the Modified Kostiakov k had similar values at saturation over a range of soils and followed an inverse relationship with moisture content that differed between soil types. Unexpectedly, the sensitivity of k to the moisture content was greatest for a sandy loam soil (i.e. non-cracking). Similar work failed to find any significant relationship between f0 or a and the initial moisture content (Robertson *et al.,* 2004 Furman *et al.*, 2006).

Water Quality and Soil Structural Stability

Water quality has significant impacts on the crop yield (Wallender *et al.*, 1990), however it also has a profound influence over the infiltration rate. The composition of irrigation water, through its effect on soil surface conditions, may be more important than the chemical properties of the soil itself (Oster and Schroer, 1979). Some farmers may have the ability to choose between different water sources but the majority rely on a single supply. In addition, the tail-water collected from the end of the field may have significantly altered chemistry, increased temperature and elevated levels of suspended material compared with the initial water supply.

Wastewater is becoming increasingly popular as a source for irrigation due to the tightening competition for limited water supplies. This water may contain suspended solids and dissolved chemicals that can influence crop growth and alter the hydraulic properties of the soil. With wastewater application both loam and clay soils experience a decrease in the infiltration rate that appears to be restricted to clogging of the soil pores in the top layers the profile (Viviani and Iovino, 2004). This decline in intake rates increased with sediment loading whilst a clay soil exhibited the greatest sensitivity. However, the infiltration rates were restored by microbial breakdown of the organic material combined with soil expansion and shrinkage, and was accelerated through cultivation (Viviani and Iovino, 2004).

Sediment loading also affects infiltration. Trials have shown that clay suspension levels of 5 g L^{-1} caused a 50% reduction in the saturated hydraulic conductivity (Ragusa *et al.*, 1994). However, turbidity levels in irrigation supply water rarely reach this high loading. Sediment-laden water can form a thin surface seal on the wetted perimeter that reduces infiltration (Brown *et al.,* 1988) and creates a tension gradient of 0.5 to 1.0 kPa. This seal is self-enhancing since the resultant tension increases the ability of the surface to hold onto the fine particles. Brown *et al.* (1988) suggested that for the silt loam studied, significant amounts of fine sediment applied to the supply water can reduce the risk of erosion and increase the irrigation uniformity.

Surface seals and crusts are typically thin (1 to 6 mm), relatively impervious layers (Chiang *et al.*, 1993) characterised by high bulk density and low porosity, formed at the soil surface due to soil aggregate breakdown. These layers may impede crop emergence and have significantly lower hydraulic conductivity than the underlying soil and therefore govern the infiltration rate. The severity of a surface seal is influenced by soil texture, chemistry, aggregate stability and organic matter content . Soil aggregate stability is positively related to the moisture content, particularly in the near-surface layer (Trout and Kemper, 1983). Surface seals are not easily modelled . The most appropriate technique to include the effect of a surface seal is to divide the soil profile into a number of layers with each having a unique infiltration curve (e.g .the three level Green-Ampt model by Enciso-Medina *et al.* (1998).

Aggregate breakdown takes place by slaking and/or dispersion (Young and Young, 2002). Slaking is a physical process where water moves into the soil aggregate and displaces and compresses the air contained within. As the compressed air escapes, it exerts a force that may overcome the strength of the soil aggregate. Often the smaller particles will coalesce to form a hard-setting mass on drying. Soil slaking is prevalent under furrow irrigation since the surface soil is initially dry and is then suddenly immersed in water. Furrow pre-wetting with drip tape may reduce the severity of aggregate breakdown and resultant soil erosion (Bjorneberg *et al.*, 2002).

The physical aggregate breakdown of non-slaking soils is caused by external energy inputs including raindrop impact (Glanville and Smith, 1988), and surface water flow .Crust formation intensity has been found to be strongly correlated with the raindrop kinematic energy (Lal and Shukla, 2004). Heavy rainfall events are common during the summer cropping season in southeast Queensland. Field trials within this region have indicated that significant aggregate breakdown occurs within the initial minutes of rainfall for both covered and bare soil (Glanville and Smith, 1988). However ,further breakdown was only detected in the unprotected soil. In addition, it was found that the soil slaking in the absence of raindrop impact did not influence infiltration (Glanville and Smith, 1988). The reduction in hydraulic conductivity as the result of heavy rainfall occurs rapidly on sandy soils but for loam and clay soils the decline occurs slowly over durations that may exceed 60 minutes (Chiang *et al.*, 1993) .Flowing water exerts forces on soil aggregates causing them to break into smaller pieces that roll and bounce along the furrow bed. The resultant particles impact with the furrow perimeter causing further structural breakdown (Kemper *et al.*, 1988).

Soil dispersion is a chemical process governed by the attraction of cations to clay and humus particles. Clay particles will quickly dissociate in water since their surfaces are covered in repelling negative charges. In the soil, positively charges ions are attracted to these particles to help bind them into larger aggregates. Cations like magnesium and calcium have the best ability to flocculate and bind soil colloids while the attractive power of sodium is easily overcome by water. As such, those soils with higher exchangeable sodium percentage (ESP) (as a percentage of total exchangeable cation capacity), termed sodic soils, tend to disperse upon wetting (Young and Young, 2002). A similar term, the sodium adsorption ratio (SAR) is used to describe the ratio of the concentration of sodium ions ($[Na^+]$) to the concentrations of calcium ($[Ca^{2+}]$) and magnesium ($[Mg^{2+}]$) ions (mmol L^{-1}) in the soil solution (Brady and Weil, 2002).

$$SAR = \frac{[Na^+]}{(0.5[Mg^{2+}]+0.5[Ca^{2+}])^{1/2}} \quad \text{Eq (4)}$$

Sodic soils are generally described as those with an ESP > 15% whilst sodic water has a SAR > 13 (Brady and Weil, 2002). Sodic soils are prone to structural decline as the clay and humus particles readily dissociate in water in conditions of low salinity (Singer and Munns, 1999). The severity of dispersion and flocculation cannot be described by the sodium ratio (SAR) alone, the total salt load must also be considered. The salinity is often measured by and expressed in terms of the electrical conductivity (EC). Ragusa *et al.* (1994) provided two expressions to predict the critical thresholds for flocculation (Eq. 5) and dispersion (Eq. 6) in irrigation water:

Flocculation: Ec>0.1(SAR)+0.3 Eq (5)

Dispersion**:** Ec<0.056 (SAR)0.06 Eq (6)

When the EC is greater than the value given by Eq. (5) the hydraulic conductivity will increase by over 15% due to flocculation. Hence, the addition of saline water will result in increased seepage rates. Emdad *et al.* (2004) found that final infiltration rates declined for successive irrigations early in the season regardless of water quality but the decline only continued (15% lower than the control) in the later part of the season for those soils receiving high SAR and EC water. The quality of the irrigation water did not affect the thickness of the surface seal but it did influence the density of that layer. The additional application of low EC water (i.e. rainfall) to those fields with the poor water treatment is expected to cause further aggregate breakdown and reductions in infiltration (Emdad *et al.*, 2004). Similarly, Oster and Schroer (1979) found that the intermittent application of high SAR water with distilled water resulted in the greatest reduction in infiltration. Hence, fields receiving poor quality water to supplement natural rainfall are at greatest risk of aggregate dispersion and crust formation. In soils with high sodicity, calcium application through addition of gypsum can greatly improve infiltration rates (Dowling *et al.*, 1991). Similarly, the application of CaCO3 as agricultural lime has been shown to increase infiltration rates (Ersahin, 2003).

Segeren and Trout (1991) lined the perimeter of a flow furrow infiltrometer to observe the decrease in infiltration rates as the result of sealing under normal field conditions. The surface seal reduced the intake rate and cumulative infiltration at 300 minutes by 57% and 46%, respectively. Ben Hur *et al.* (1987) found that sealing arising from raindrop impact reduced the infiltration rate from 57.8 to 8.6 mm hr^{-1} on the comparison of a sprinkler and ring infiltrometer. Surface seals may have no effect on the variability of infiltration rates (Segeren and Trout 1991) while Ben Hur *et al* .(1987) found that seals reduced the variability of the final intake rate and caused the frequency distribution of measurements to become more positively skewed. Soil cracking tends to reverse the decline in infiltration due to surface soil crusts. For layers less than 6 mm thick, cracking entirely overcomes the reduction in hydraulic conductivity (Fattah and Upadhyaya, 1996). On a cracking soil, crusts with thicknesses between 8.7 and 13.5 mm reduced the transient infiltration rates. For thicker crusts (> 13.5 mm) the soil cracks swelled shut on wetting to reduce the intake from 45.3 mm hr-1 to 35 and 9.2 mm hr-1 for initially dry and wet soil, respectively (Fattah and Upadhyaya, 1996).

The application of water will gradually alter the chemical composition of the soil solution. Depending on the irrigation management, the surface layer of soil will tend towards a similar electrical conductivity (EC) (Emdad *et al.*, 2004) and SAR (Oster and Schroer, 1979) to that of the water source. Soil changes at greater depths will depend on the leaching rate and plant uptake of both water and solutes. High water infiltration volumes, either from infiltration or rainfall will result in the leaching of mobile ions hence, potentially lowering the EC and SAR (Wichelns and Oster, 1990). The opposite will occur in areas of low infiltration where the presence of any dissolved salts in the irrigation water may slowly build up in the soil profile if not leached.

Soil Organisms

The soil is a combination of mineral, liquid, gas and living components. Living soil organisms include micro-organisms (invisible to the naked eye), larger animals living in and on the soil surface and finally the roots of crops and weeds. Most of these organisms influence the soil hydraulic conductivity by influencing aggregate stability, pore sizes and pore connectivity.

The crop is not simply a passive inhabitant of the soil environment. Plants extract nutrients and moisture from the soil at different rates depending on the location in the profile, spatial distance from the plant line, growth stage and plant species. As the crop matures the root zone extends and increases the soil volume available for extraction, hence altering the matric gradient component of infiltration. The crop can also influence the large-scale variability in hydraulic properties through spatial variations in crop growth from a combination of the non-uniformities in nutrient availability, disease, sowing density, soil type or previous irrigation applications . Plant cover and crop residues left on the soil surface also influence infiltration through protection of the soil from raindrop impact or the restriction of advance hence increasing ponding depths (e.g. for squash, Shafique and Skogerboe, 1983). Li *et al.* (2002) observed a strong linear relationship between the straw residue and steady infiltration which increased by 0.66 mm hr^{-1} for each percent increase in residue cover.

When roots die, they leave behind relatively large interconnected macro-pores that serve as channels for accelerated rates of infiltration. Root channels may be responsible for a large fraction of the variability in late season infiltration rates (Gish and Starr, 1983). Similarly, living organisms such as earthworms, ants and termites create pathways as they move through the soil profile. The resulting macro-pores have the greatest effect when the soil is close to saturation as they serve as paths for preferential flow. Laboratory measurements may employ techniques such as refrigeration, electrical currents or chemicals to suppress organic activity (McKenzie and Cresswell, 2002). However, in agriculture these organisms are usually encouraged due to the benefits of improved soil structure and increased aeration.

Micro-organisms can cause significant reductions in the hydraulic conductivity through the destruction of soil structure and production of gases and other metabolic products which accumulate in soil pores (McKenzie and Cresswell, 2002). Ragusa *et al.* (1994) discovered an inverse linear relationship between the polysaccharide (an example of a metabolic product) content in the top 5 mm of soil caused by algal and bacterial growth and the hydraulic conductivity of the soil in an irrigation channel .Interestingly the algal growth was not influenced by the addition of phosphorus or nitrate to the soil. Land levelling can decrease the magnitude of bacterial and fungal biomass in the soil by over 50% (Brye *et al.*, 2003 Brye *et al.*, 2006) since the majority of microbial activity is situated within the top 100 mm of the profile. Microbial activity has been correlated with soil properties (e.g. bulk density and sand content (before and after levelling but the relationships are often difficult to generalise (Brye *et al.*, 2006).

Other Irrigation Water Effects

Water viscosity, also known as the fluid friction, quantifies a liquid's internal resistance to flow and is inversely related to its temperature. Viscosity directly affects the furrow hydraulics by reducing the flow velocity of surface water but more importantly, it determines the flow rate of water through soil pores. Corrections for temperature variations are seldom considered during field measurements even though this effect may be a potential source of error (McKenzie and Cresswell, 2002). The measured hydraulic conductivity can be converted to a reference temperature using:

$$K_{rt} = K_t \frac{\eta_t}{\eta_{rt}} \qquad \text{Eq (7)}$$

Where K_t and K_{rt} are the hydraulic conductivities at the measured and reference temperatures, respectively while η_t and η_{rt} are the dynamic viscosity of water at the same temperatures. Note that the value of K at a water temperature of 35˚C is twice that of a temperature of 7˚C (Iwata *et al.,* 1995).

The temperature of water supplied to the field may change both seasonally and diurnally by as much as 10˚C (Lentz and Bjorneberg, 2001). More importantly, the soil, ambient air and sunlight will cause the temperature to vary significantly over the furrow length. For example, Duke (1992) measured temperature increases over the furrow length of 22˚C for unshaded and 2˚C for shaded conditions. A temperature increase of 22˚C reduces the viscosity sufficiently to increase the hydraulic conductivity by 70% (Duke, 1992) and may result in an improvement in the distribution uniformity of applied depths. Lentz and Bjorneberg (2001) found that average infiltration increased by 2.3% $^{\circ}C^{-1}$ for furrow measurements but in some cases declined back to the original values after 0.5 to 1.5 hours. Where the infiltration rate is governed by the properties of the surface layer it may be more sensitive to changes in temperature (Duke, 1992).

The majority of infiltration equations (e.g. section 2.2.1) neglect the influence of the ponding depth even though it has a direct impact on the hydraulic gradient at the soil surface. However, on a dry soil the high matric potential caused by negative pore pressures far outweighs any influence as large variations in ponding depths only translate to infiltration changes of a few percent (Strelkoff and Souza, 1984). In furrow irrigation, the significance of surface water depths is almost entirely dependent on the importance of the wetted perimeter available for infiltration. Furman *et al.* (2006) identified relationships between the parameters of the Modified Kostiakov and surface water depths but concluded that the dependencies were soil type dependent. A sandy loam displayed the greatest sensitivity to changes in ponding depth compared to silt or loam soils. Both k and a increased with increasing water level along with a slight decrease in fo. The nature of the infiltration equation indicates that the ponding depth should principally influence the final infiltration term (fo) as at higher ponding times the soil intake rate is exclusively determined by the gravity potential.

Conclusion

The hydraulic properties of the soil are influenced by many physical and chemical factors, the majority of which are difficult to measure and almost impossible to control. Both spatial and temporal infiltration variability is present within fields. Some of this variation can be linked to observable soil factors while much of it remains unexplained. Infiltration variability poses a significant problem for the performance of surface irrigation systems. Not only does it reduce the existing and potential irrigation performance, it also limits the ability to specify improved irrigation strategies. The nature of soil properties does not facilitate direct measurement of the infiltration function. In addition, many of the soil physical measurement techniques do not re-create the same physical phenomena, and therefore cannot reflect the behaviour, of a furrow irrigated soil. Hence, there is a genuine need to estimate the parameters of the chosen infiltration function using measured field data. The high variance of soil properties means that these measurements must be collected during or close as possible to the irrigation event using a representative sample of the field area. There are a number of alternative irrigation strategies that have been proposed to improve irrigation performance. Some of these strategies also offer the potential to reduce the variability of infiltration rates or minimise its influence over the distribution of applied depths. The initial testing and ongoing evaluation of these and the traditional irrigation strategies requires (a) the collection of accurate soil infiltration information and (b) the use of hydraulic simulation models which may need to be specifically designed for that irrigation technique. The complexity of the soil-water interactions prevents direct measurement of the field distribution of applied depths and hence also hinders in measurement of the irrigation performance. For this reason, simulation models are often utilised to study the hydraulic behaviour of surface irrigation. In cropping system that do not involve tillage, organic matter accumulates on and near the soil surface, and structural changes develop deeper in the soil. Both of these features allow more rapid infiltration of water, greatly reducing the changes of runoff or erosion. Even with tillage, if depth of tillage and burial of surface residues is minimized, increased organic matter the soil surface result in greater infiltration capacity than traditional moldboard-plow tillage. The soil and vegetation properties that currently limit infiltration and the potential for increasing the infiltration rate must be considered in any management plan. Where water flow patterns have been altered by a shift in vegetation, such as a shift from grassland to open-canopy shrub land, restoration of higher infiltration rates may be difficult or take a long period, especially if depletion of organic matter and/or soil loss have occurred. Excessive grazing of forage can impair infiltration.

Management strategies include

• Increase the amount of plant cover, especially of plants that have positive effects on infiltration.

• Decrease the extent of compaction by avoiding intensive grazing and the use of machinery when the soils are wet.

• Decrease the formation of physical crusts by maintaining or improving the cover of plants or litter and thus reducing the impact of raindrops.

• Increase aggregate stability by increasing the amount of organic matter added to the soil through residue decomposition and vigorous root growth

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