Chapter 2. Soil Hydraulic Parameters

2.1 Soil Hydraulic Parameters

Several soil hydraulic parameters including soil hydraulic conductivity, infiltration rate, water holding capacity and watertable depth, are required for various water management activities including selection of and design of irrigation systems, design of drainage systems, supply infrastructure planning and catchment management. However, different water management applications require different hydraulic parameters and some hydraulic parameters are required more commonly than others. Measurement of soil hydraulic properties is costly. Therefore, there was a need to target a selected number of soil hydraulic parameters.

2.2 Selection of Soil Hydraulic Parameters

Critical soil hydraulic parameters were identified for each management activity and these parameters were arranged based on frequency of their need in various applications. The top three hydraulic parameters were selected for measurement under this project, these are presented in Table 2.1.

Table 2.1 Critical Soil Hydraulic Parameters

Management Activity	Application/Scale	Critical Hydraulic Parameters Selected for Measurement
1.Irrigation	Selection of enterprise and irrigation method, design of farm irrigation systems	- K_{sat} of restricting layer / final infiltration rate - Saturated hydraulic conductivity of surface soil - Water holding capacity of root zone
2. Infrastructure planning & review	Layout & design of regional supply infrastructure	
3. Drainage	Farm surface & sub surface drainage design	
4. Catchment Management	The above information will help in recharge estimation & prioritisation for management change	

The saturated hydraulic conductivity of the surface soil and restricting soil layer (Horizon B), final infiltration rate, and soil water holding capacity were recognised as the most critical hydraulic parameters and were selected for measurement. In addition, a number of soil physical and chemical parameters such as soil texture, bulk density and exchange cations of Horizons A and B1 were taken for measurement as background information.

2.3 Selected Parameters for Measurement

2.3.1 Soil Water Holding Capacity

Soil water holding capacity is a measure of the ability of a soil to store water for plant water use. Pasture and other shallow rooted crops uptake water from both Horizons A and B1, therefore water holding capacity of both Horizon A and B1 Horizons was selected for measurement. Knowledge of the amount of water held at various soil water potentials such as saturation (S), field capacity (FC), refill point (RP), and permanent wilting point (PWP) is required for many purposes and is frequently used in agronomic, engineering and environmental applications. Figure 2.1 shows a typical soil water retention characteristic curve.

The water content at the following soil water suctions was selected for measurement of soil water holding capacity:

- 0 kPa (saturation)
- 10 kPa (field capacity)
- 60 kPa (refill point)
- 1500 kPa (permanent wilting point)

In addition to the above, water content at 1, 5, 8, 80, and 200 kPa were also measured on a few soil types.

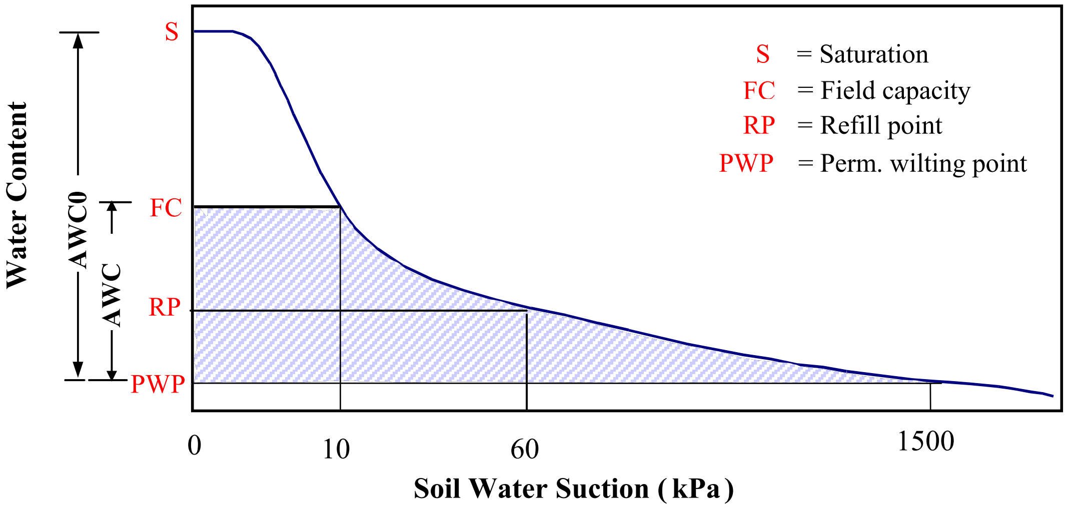

Figure 2.1 Typical Soil Water Characteristics Curve

(1) Field capacity

Field capacity is the amount of water held in the soil after excess gravitational water has drained away and after the rate of downward movement has materially decreased. The redistribution of draining water in a soil profile is a continuous process, which may be influenced by many factors including antecedent moisture conditions, depth of wetting, soil texture, type of clay present, organic matter and the rate of evapotranspiration. The field capacity concept is most acceptable for well-drained soils where static or equilibrium-state is more easily defined. The concept is difficult to apply to the duplex soils of this region, where the sub-soil often restricts free drainage. The soil water suction values generally used for field capacity approximation range from 5 kPa for coarse-texture soils to 10 kPa for samples that retain their original structure (McIntyre, 1974; Marshall, 1982). In this project, water content at a soil water suction of 10 kPa is used as field capacity.

(2) Permanent wilting point

Permanent wilting point is defined as the water content at which the leaves of a growing plant reach a stage of wilting from which they do not recover. Different plants have different values of soil water suction at wilting point. Since the change in water content is small between 800 kPa and 3000 kPa for most soils, a suction of 1500 kPa based on wilting studies with dwarf sunflower is generally taken to be an approximation of permanent wilting point (Reeve and Carter, 1991).

(3) Refill point

Not all water in the soil is readily available to the plant. Readily available water (RAW) is the volume of water that the plant can readily remove from soil. When all the readily available water has been used, the plants cannot easily extract further water. This stage is referred to as the refill point (RP), and this is generally considered the time to irrigate. Water content at a suction of between 50 and 70 kPa is generally used as the refill point for crops in the SIR. For this project, water content at a suction of 60 kPa was taken as the refill point.

(4) Available water capacity

Two soil water capacity measures were used in this study. The first one is the conventional "available water capacity (AWC)" defined as the amount of water that can theoretically be extracted by plants from a soil initially at field capacity (McIntyre, 1974). It was calculated as

$$AWC = \theta(FC) - \theta(PWP) \qquad (1)$$

where $\theta(FC)$ and $\theta(PWP)$ are water contents at the field capacity and permanent wilting point respectively.

The second soil water capacity measure is an extension of the conventional available water capacity. It was calculated as

$$AWC0 = \theta(S) - \theta(PWP) \qquad (2)$$

where $\theta(S)$ is water content at saturation.

The rational behind this second measure, AWC0, is that many soils in SIR are duplex with low soil permeability at Horizon B1, and thus available water above the field capacity can often be utilised by plants. AWC0 indicates the upper bound of available water capacity.

(5) Available water (AW)

For a given soil depth, the available water AW can be calculated by multiplying AWC by the soil depth d.

$$AW = AWC \times d \qquad (3)$$

Depth of Horizon A was measured to determine available water in surface soil.

2.3.2 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) is used to define the rate that water moves through the soil pore system when it is saturated. Soils of this region are duplex with a Horizon B (sub soil) underlying a Horizon A (surface soil). The layer in a soil profile that has the lowest hydraulic conductivity is defined as the restricting layer. In the SIR, the restricting layer is located at or below the interface with Horizon B, which can be divided into Horizon B1 and B2 for most soils of the region. Saturated hydraulic conductivity of the surface soil is required for agronomic and water management purposes including design of irrigation systems. Saturated hydraulic conductivity of the restricting layer is needed for environmental and engineering purposes such as recharge estimation and drainage design.

The saturated hydraulic conductivity was measured using a disc permeameter at three soil depths, which were the top of Horizon A (soil surface), top of Horizon B1 and top of Horizon B2. The deepest measurement did not exceed 0.5 m from soil surface.

Hydraulic conductivity analysis

The Ankeny et al. (1991) method was adopted for determining in situ hydraulic conductivity near saturation from steady state infiltration rates measured using a disc permeameter. The advantage of this method is that it does not require knowledge of the initial water content of the soil. In this method, hydraulic conductivity was determined from measured steady state infiltration rate based on the solution derived by Wooding (1968). The Wooding solution assumed an exponential form of $K(\psi)$ relationship expressed by Gardiner's equation (1958).

$$K(\psi) = Ksat \exp(\alpha\psi) \quad (4)$$

where Ksat is the saturated hydraulic conductivity (mm/h), α is the exponential slope and ψ is the soil water potential (mm).

Wooding proposed an algebraic expression based on the assumed exponential $K(\psi)$ relationship for unconfined steady-state water infiltration (zero ponding) into soil from a circular source of radius r described by:

$$Q = \pi r^2 K + 4 r \phi \quad (5)$$

where Q (mm^3/h) is the steady state infiltrating flux, K (mm/h) is hydraulic conductivity and ϕ (mm^2/h) is the soil water flux potential. In Eq (5), it is assumed that K at initial soil water potential ψ_i is much less than K at wetting soil water potential ψ. The soil water flux at soil water potential ψ can be given by:

$$\phi(\psi) = \int_{\psi_i}^{\psi} K(\psi)\, d\psi \quad (6)$$

Accordingly, if two infiltrating steady flow rates $Q(\psi_1)$ and $Q(\psi_2)$ are measured at supply potential ψ_1 and ψ_2 then we obtain the following two equations.

$$Q(\psi_1) = \pi r^2 K(\psi_1) + 4 r \phi(\psi_1) \quad (7)$$

$$Q(\psi_2) = \pi r^2 K(\psi_2) + 4 r \phi(\psi_2) \quad (8)$$

The unknowns are $K(\psi_1)$, $K(\psi_2)$, $\phi(\psi_1)$, and $\phi(\psi_2)$. To solve for these unknowns, we must obtain at least two more equations. One equation can be obtained by assuming constant ratio between K and ϕ (Philip, 1985)

$$A = K(\psi)/\phi(\psi) = \text{constant} \quad (9)$$

A second equation is obtained by deriving an approximate expression for the difference $\phi(\psi_1) - \phi(\psi_2)$ from Eq (6):

$$\phi(\psi_1) - \phi(\psi_2) = \Delta\psi\,[K(\psi_1) + K(\psi_2)]/2 \quad (10)$$

Eqs (9) and (10) were substituted into Eqs (7) and (8) and then solution of Eqs (7) and (8) resulted in following two equations:

$$K(\psi_1) = \frac{Q_1}{\pi r^2 + 2\Delta\psi r(1+Q_2/Q_1)/(1-Q_2/Q_1)} \quad (11)$$

$$K(\psi_2) = \frac{Q_2 K(\psi_1)}{Q_1} \quad (12)$$

The equations (11) and (12) were used in this project for determining saturated hydraulic conductivity using measured steady flow rates at soil water potential (ψ) of 0 and -10, -10 and -20, and -20 and -30 mm. The estimates of $K(\psi)$ at 0, -10, -20 and -30 mm soil water potential were determined using following equations.

$$K(0) = K(0)_{0,10} \quad (13)$$
$$K(-10) = [K(0)_{0,10} + K(-10)_{10,20}]/2 \quad (14)$$
$$K(-20) = [K(-10)_{10,20} + K(-20)_{20,30}]/2 \quad (15)$$
$$K(-30) = K(-20)_{20,30} \quad (16)$$

where $K(\psi_1)_{\psi1,\ \psi2}$ is hydraulic conductivity at ψ_1 soil water potential determined from two measured steady state flow rates at soil water potential of ψ_1 and ψ_2.

2.3.3 Final Infiltration Rate

Infiltration rates were measured from an infiltration ring for up to 24 hours. The infiltration rate decreases with time to a constant steady rate while the cumulative infiltration (the time integral of the infiltration rate) increases with time but with a decreasing slope. The cumulative infiltration rates Z(t) with time (t) were plotted (Figure 2.2). The cumulative infiltration Z(t) can be expressed by the following empirical equation:

$$Z(t) = kt^a + f_o t + c \quad (17)$$

where k, a, c are constant parameters, and f_o is final infiltration rate.

The initial term kt^a of Eq (17) describes a decreasing infiltration rate in the initial part of the Z(t) curve, and the slope of remaining part of the curve f_o is the final infiltration rate (Figure 2.2).

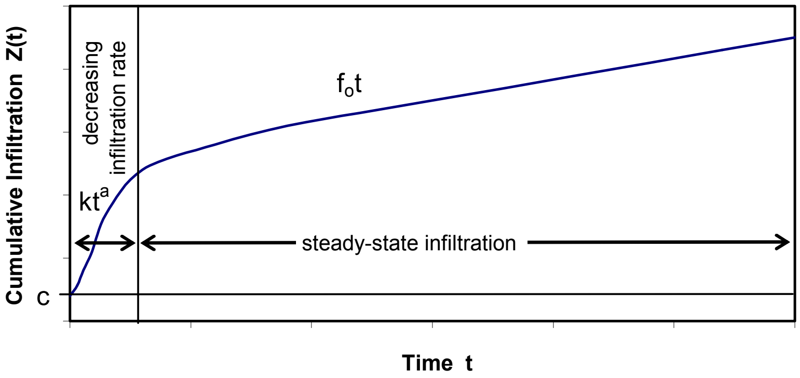

Figure 2.2 Typical Cumulative Infiltration Curve

2.3.4 Explanatory Soil Parameters

The direct measurement of hydraulic properties is expensive and time consuming, and indirect methods are increasingly used to predict hydraulic properties from easily measurable soil parameters such as soil texture and bulk density. The use of pedo-transfer functions is the most commonly used indirect method (Wosten et al, 2001). Soil texture, bulk density, and a number of soil chemical properties were selected for measurement.

(1) Soil texture

Particle size distribution represents relative percentages of various particle sizes in a soil (e.g. clay, silt, sand, gravel). It has a significant impact on many hydraulic properties and can be used on a first 'best-bet' basis for assessment of infiltration characteristics.

(2) Bulk density

Bulk density is used in determining the degree of compaction, soil aeration status (moisture content is also required) and in converting soil moisture from gravimetric to volumetric basis. It was measured for both Horizons A and B1.

(3) Soil chemical properties

Electrical conductivity (EC) is used to appraise soil salinity. Plants vary considerably in tolerance to salts, and salinity can also affect the hydraulic properties of soil. pH is a useful indicator of other soil properties (e.g. pH>8.5 usually indicates high exchangeable sodium levels and presence of carbonates). High levels of exchangeable sodium cause increased dispersion and swelling, reducing water movement and affecting aeration, whereas high exchangeable calcium flocculates colloids and reduces swelling tendencies (Loveday, 1974).

Selected chemical properties for measurement in both Horizons A and B1 were:
(i) EC and pH in 1:5 soil water suspension
(ii) Organic matter
(iii) Exchangeable cations such as Ca, Mg, Na and K.