3. Measurement of Soil Hydraulic Properties

3.1 Soil Hydraulic Parameters

The saturated hydraulic conductivity of the surface soil and sub-soil (Horizon B1), final infiltration rate, and soil water holding capacity were recognised as the most critical hydraulic parameters based on their applications in various water management activities and were selected for measurement. In addition, a number of soil physical and chemical parameters such as particle size distribution, bulk density and exchange cations of Horizons A and B1 were taken for measurement as background information. The measured soil properties are described in the following sections.

3.1.1 Soil Water holding Capacity

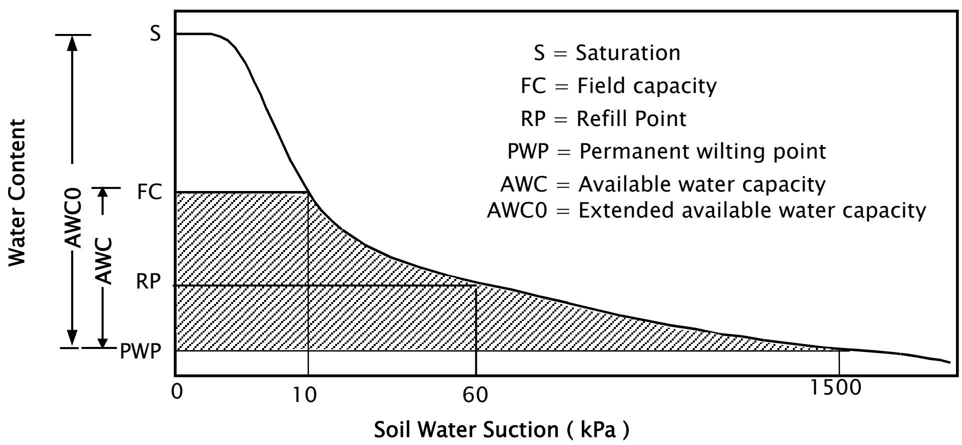
Soil water holding capacity is a measure of the ability of a soil to store water for plant water use. Pasture and other shallow rooted crops uptake water from both Horizons A and B1, therefore water holding capacity of both Horizons A and B1 was selected for measurement. Knowledge of the amount of water retained at various soil water suctions 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.

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 was also measured on a few soil types.

The following diagram shows a typical soil water retention characteristic curve.



Typical Soil Water Retention Characteristic 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 that 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 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). For this document, water content at a soil water suction of 10 kPa was 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 further extract 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. 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 document. 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 θ (FC) and θ (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 θ (S) is water content at saturation.

The rationale behind this second measure, AWC0, is that many soils in the 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 limit of available water capacity. The results of AWC0 are not presented in this document, however it can be calculated from given soil water retention characteristic data using Equation (2).

(5) Available water (AW)

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

$$AW = AWC \times d \tag{3}$$

Depth of Horizon A and B1 was measured to determine available water.

3.1.2 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) is used to define the rate that water moves through the soil pore system under a unit hydraulic gradient 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 typically located at or below the interface with Horizon B, which can be divided into Horizon B1 and B2 for most soils of the region. The relative magnitude of Ksat of surface soil and restricting layer is important. A permeable surface soil overlaying restricting sub-soil is particularly prone to waterlogging.

Saturated hydraulic conductivity of the surface soil is important for agronomic and water management purposes including design of irrigation systems. Saturated hydraulic conductivity of the surface and restricting layers is also important for environmental and engineering purposes such as recharge estimation and drainage design.

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). Steady state infiltration rates Q_1 and Q_2 measured at soil water potential ψ_1 and ψ_2 were used to determine hydraulic conductivity $K(\psi_1)$ and $K(\psi_2)$ from the following two equations.

$$K(\psi_1) = \frac{Q_1}{\pi r^2 + 2\Delta\psi r\left(1 + Q_2/Q_1\right)/(1 - Q_2/Q_1)} \tag{4}$$

$$K(\psi_2) = \frac{Q_2 K(\psi_1)}{Q_1} \tag{5}$$

where r is radius of the base of disc permeameter and $\Delta\psi = \psi_1 - \psi_2$.

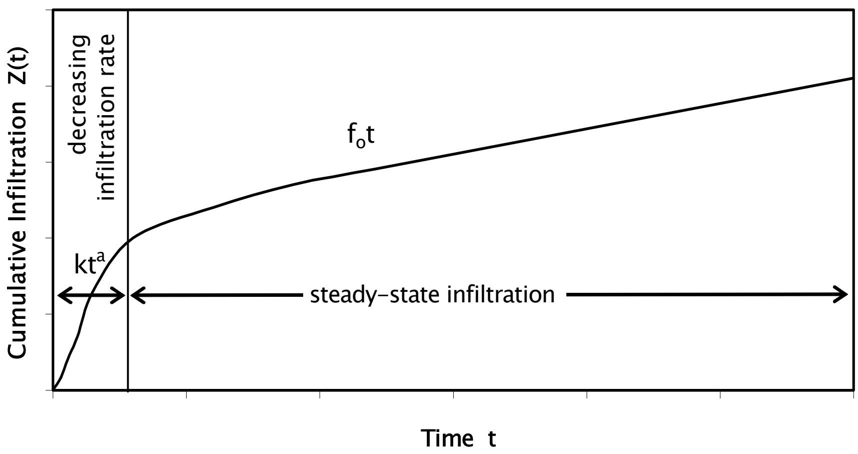
3.1.3 Final Infiltration Rate

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 in the diagram below. The cumulative infiltration Z(t) can be expressed by the modified Kostiakov equation (Austin and Prendergast, 1997):

$$Z(t) = kt^a + f_o t \quad (6)$$

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

The initial term kt^a of Equation (6) 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 (see following diagram).



Typical Cumulative Infiltration Curve

3.1.4 Background 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 particle size distribution and bulk density. The empirical equations that are used to describe the relationship between soil hydraulic property and easily measurable soil properties are known as pedotransfer functions (PTFs). The use of pedotransfer functions is the most commonly used indirect method (Wosten *et al.*, 2001). Particle size distribution, bulk density, and a number of soil chemical properties were selected for measurement.

(1) Particle size distribution

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 and in converting soil moisture from a gravimetric to a volumetric basis. It was measured for both Horizons A and B1.

(3) Soil chemical properties

Soil electrical conductivity (EC) indicates the amount of salts dissolved in the soil water. This gives a quick indication of the level of soil salinity. Soil pH measures the intensity of acidity or alkalinity. Soil pH is a useful indicator of soil health and other soil properties (e.g. pH> 8.5 usually indicates high exchangeable sodium level 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). The soil cations play a large part in supplying plant nutrients and in forming and maintaining good soil structure.

There are two techniques of measuring soil pH. One measures the pH (H_2O) of soil in a pure water solution and the other measures pH ($CaCl_2$) of the soil in a calcium chloride ($CaCl_2$) solution. Soil pH (H_2O) better reflects the soil conditions at the time of measurement, while pH ($CaCl_2$) is a more useful measure of long term soil pH because it shows less seasonal variability than pH (H_2O).

Selected chemical properties for measurement in both Horizons A and B1 were:
(i) EC in 1:5 soil to water suspension
(ii) pH (H_2O) in 1:5 soil to water suspension and pH ($CaCl_2$) in 1:5 soil to solution of 0.01 M $CaCl_2$
(iii) Organic matter
(iv) Exchangeable cations such as Ca, Mg, Na and K
(v) Exchangeable sodium percentage

3.2 Field Measurement

3.2.1 Sampling Sites

Sampling sites for measurement of hydraulic properties on selected soil types were determined using existing soil maps and aerial photos. The sampling sites were selected in such a way that major or typical soil types of the three irrigation areas were included for measurement and the sites were located in the middle of large block of the soil type to be measured. Figure 3 shows the location of sampling sites where field measurements of hydraulic properties were conducted. The following table presents the number of sampling sites for each soil group in the three irrigation areas.

Distribution of Sampling Sites

Irrigation Area	Number of Sampling Sites						Total Sampling Sites
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	
Murray Valley	2	8	4	-	1	5	20
Shepparton-Central Goulburn	4	7	14	6	2	1	34
Rochester-Campaspe	5	4	6	5	3	2	25
Total	11	19	24	11	6	8	79

3.2.2 Sampling Points

To capture variability in the measurements, two to eight sampling points were selected for measurement at each sampling site. Global Positioning System (GPS) readings were taken to identify sampling points. Sampling points were selected based on the topography and paddock layout.

For intensive measurement at 29 sites, an electromagnetic induction (EM) survey was conducted to identify sampling points at the selected paddock. The EM survey measures soil EC which is a function of soil salinity, clay content and water content. In areas of low soil salinity, EM measurements could provide an estimate of within-field variation of clay content and water content (Williams and Hoey, 1997). Soil hydraulic properties are generally correlated with clay content. Therefore, an EM survey may provide an indication of clay content variability within a paddock and help in identifying points of low, medium and high clay content in a paddock. Hydraulic properties were measured on selected points based on EM reading to capture variability of soil hydraulic properties in a paddock.

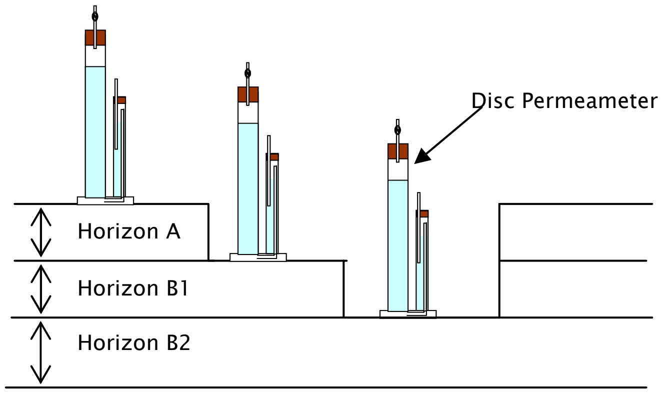
The EM38 instrument manufactured by Geonics Limited was selected for EM survey as it is most suited for EM measurement of shallow soil depths. An EM survey using an EM38 instrument was conducted on a regular grid of a minimum 10 m x 10 m to a maximum of 20 m x 20 m depending upon the size of the paddock. The EM38 was operated manually in both horizontal and vertical dipole modes. EM38 response to soil EC varies as a nonlinear function of depth. Sensitivity in the vertical dipole mode is highest at about 0.4 m from the instrument while sensitivity in the horizontal dipole mode is highest near the soil surface. The coordinates of the grid were recorded by a GPS instrument manufactured by Thales. The EM data were analysed to determine minimum, maximum, 25, 50 and 75 percentile values in both horizontal (EM_h) and vertical (EM_v) modes. These calculated values were used to select 4 to 8 field sampling points in a paddock.

3.2.3 Soil Profile

Soil profile was observed from a soil core taken by a 25 mm diameter core tube to a depth of 600 mm. The Horizons A, B1, B2 were identified by the change in soil colour, soil texture and depths described in the literature (Skene and Poutsma, 1962; Skene, 1963; Skene and Harford, 1964; Johnston, 1952). Depths of Horizons A and B1 were measured at sampling points in a paddock. Soil profiles were generally consistent with those described in the literature.

3.2.4 Saturated Hydraulic Conductivity

Field measurement of saturated hydraulic conductivity was conducted at 79 sites typically 4 to 5 days after irrigation. At each sampling point, field measurements were conducted at the top of Horizon A (soil surface) and the top of Horizon B1 and on some sites field measurements were also conducted at the top of Horizon B2, in a 50 cm x 75 cm soil pit as shown in the following diagram. The greatest depth of measurement did not exceed 0.5 m from soil surface.



Measurement of Hydraulic Conductivity at Three Depths

Disc permeameters of 200 mm base diameter were used for the measurement of hydraulic conductivity. The site was levelled and cleaned of grass and debris. Care was taken to avoid smearing of the soil. A ring (200 mm in diameter and 5 mm thickness) was placed on the levelled surface, and the area within the ring was filled with fine sifted sand to prepare a 5 mm thick leveled sand bed. The sand layer was to ensure good contact between the base of the disc permeameter and the soil below. A permeameter filled with water was placed on the sand bed and small soil water potential of -30 mm was applied. After four consecutive readings of steady infiltrate rate, water potential was changed to -20 mm. Similar processes were followed for -10 and 0 mm. Standard channel water of 0.1 dS/m EC was used for all the sites.

Hydraulic conductivity measurements were taken at small negative soil water potentials (0 to -30 mm soil water potential) to avoid crack flow through preferential pathways. This makes it possible to compare matrix flow of different soil types. Hydraulic conductivity near saturation changes very rapidly with small variations in soil water potential, and 5 mm depth of contact material (sand bed) can have a large influence on the soil hydraulic conductivity. The soil water potential at the soil surface was approximately represented by adding the depth of sand bed into the applied soil water potential at the disc permeameter membrane (Reynolds *et al.*, 1996).

3.2.5 Final Infiltration Rate

A ring infiltrometer of 350 mm diameter was used to measure final infiltration rate. A soil pit to the top of Horizon B1 was dug adjacent to the location of hydraulic conductivity measurement. The infiltration ring was inserted to a depth of 150 mm with care being taken to minimise disturbance of the soil surface and the soil structure. Standard channel water of

0.1 dS/m EC was used for all the sites. The water was poured slowly on side wall of the ring to minimise disturbance of soil. The ring was filled with water to a depth of about 100 mm and the water level in the ring was measured manually for 4 hours using a vertical ruler. The length of time required to achieve steady infiltration rate ranged from 1 to 4 hours depending upon soil type, texture, and antecedent soil water conditions.

3.2.6 Soil Sampling

Two undisturbed cores of 73 mm diameter and 64 mm height and one undisturbed core of 73 mm diameter and 31 mm height were taken from the middle of both Horizons A and B1 at all sampling locations on 79 sites. These samples were used for determination of bulk density, water holding capacity, and particle size distribution in the laboratory.

In addition, one bulk sample of 500 g was taken from one point from both Horizons A and B1 at all sampling sites. These samples were used for chemical analysis in the laboratory for determination of exchangeable cations, organic matter, EC, pH (H_2O) and pH($CaCl_2$) of soil.

3.3 Laboratory Measurement

3.3.1 Bulk Density

Undisturbed core samples of 73 mm diameter and 64 mm height were weighed and oven dried for 48 hours at 105°C temperature. Dry bulk density is the mass of unit volume of oven-dry soil.

3.3.2 Soil Water Retention Characteristic

Undisturbed core samples (73 mm diameter x 64 mm height; and 73 mm diameter x 31 mm height) were taken from both Horizons A and B1 at each sampling location for measurement of soil water retention characteristic in the laboratory. The soil water contents at 0, 10, 60 and 1500 kPa soil matric suction were measured to determine the soil water capacities of all soil samples.

Soil water that is in equilibrium with free water is by definition at zero soil matric suction or at saturation. Soil cores were placed on a sand bath for six weeks to slowly reach saturation by capillary flow from the bottom of cores. Soil cores were weighed when they achieved saturation.

Ceramic suction plates were used to measure water content at soil matric suction in the range of 10 to 80 kPa. A bubble tower apparatus was used for adjusting water suction. Attainment of equilibrium with applied suction was judged by regularly measuring the outflow of water until outflow ceased or became minimal. Soil cores were weighed after attaining equilibrium with applied soil matric suction of 10 kPa, placed back on the ceramic plate and allowed to equilibrate with next desired soil suction.

A pressure plate extractor was used for a soil matric suction range of 200 to 1500 kPa. The pressure extractor accommodated several soil samples which were in contact with a porous ceramic plate. Once the extractor was sealed, an air pressure was applied to the air space above the samples, and water moved downward from the samples through the plate for collection in a measuring bottle. Attainment of equilibrium was judged when outflow of water ceased or became minimal, which generally took six weeks. The cores were then removed, and water content was determined gravimetrically.

3.3.3 Particle Size Distribution

Particle size analysis was carried out using a hydrometer method (Gee & Bauder, 1986), which allows for non-destructive sampling of suspensions undergoing settling. By taking multiple measurements of suspension density, detailed particle size distributions can be obtained. An ASTM 152H hydrometer with Bouyoucos scale in g/L was used for particle size analysis. The hydrometer readings (R) were taken at 0.5, 1, 3, 10, 30, 60, 90, 120, and 1440 minutes. A hydrometer reading (R_L) in a blank solution was used to correct hydrometer readings ($C=R-R_L$).

The USDA texture classification system was adopted for particle size analysis as this method was used in the previous published soil surveys. Sand, silt and clay percentage were determined using particle size limits of the USDA soil textural classification (Minasny *et al.*, 2001), which are presented in the following table.

USDA Soil Texture Classification System

	Particle Size Limits
Clay	< 2 μm
Silt	2 – 50 μm
Sand	50–2000 μm

3.3.4 Chemical Analysis

Bulk soil samples were air dried for several days, then crushed and sifted through a 2 mm sieve. The sifted soil samples were sent to DPI Werribee Centre for chemical analysis. The soil samples were analysed for exchangeable cations Ca, Mg, Na, K, organic matter, soil EC, soil pH(H_2O) and soil pH($CaCl_2$). Soil EC and pH were determined first in a 1:5 soil water suspension, and based on these results the appropriate method for determination of exchangeable cations was selected.

3.4 Data Analysis

Statistical parameters such as mean, standard deviation (Std), and 25, 50 and 75 percentile values of measured data were calculated for each soil group. These parameters were also determined for those soil types which had four or more measured data. Statistical software GenStat version 6 was used for the statistical analysis of measured data sets. Linear interpolation was used to determine percentile values of a soil parameter (X) having a few measured data, after sorting the Xs from smallest to largest.

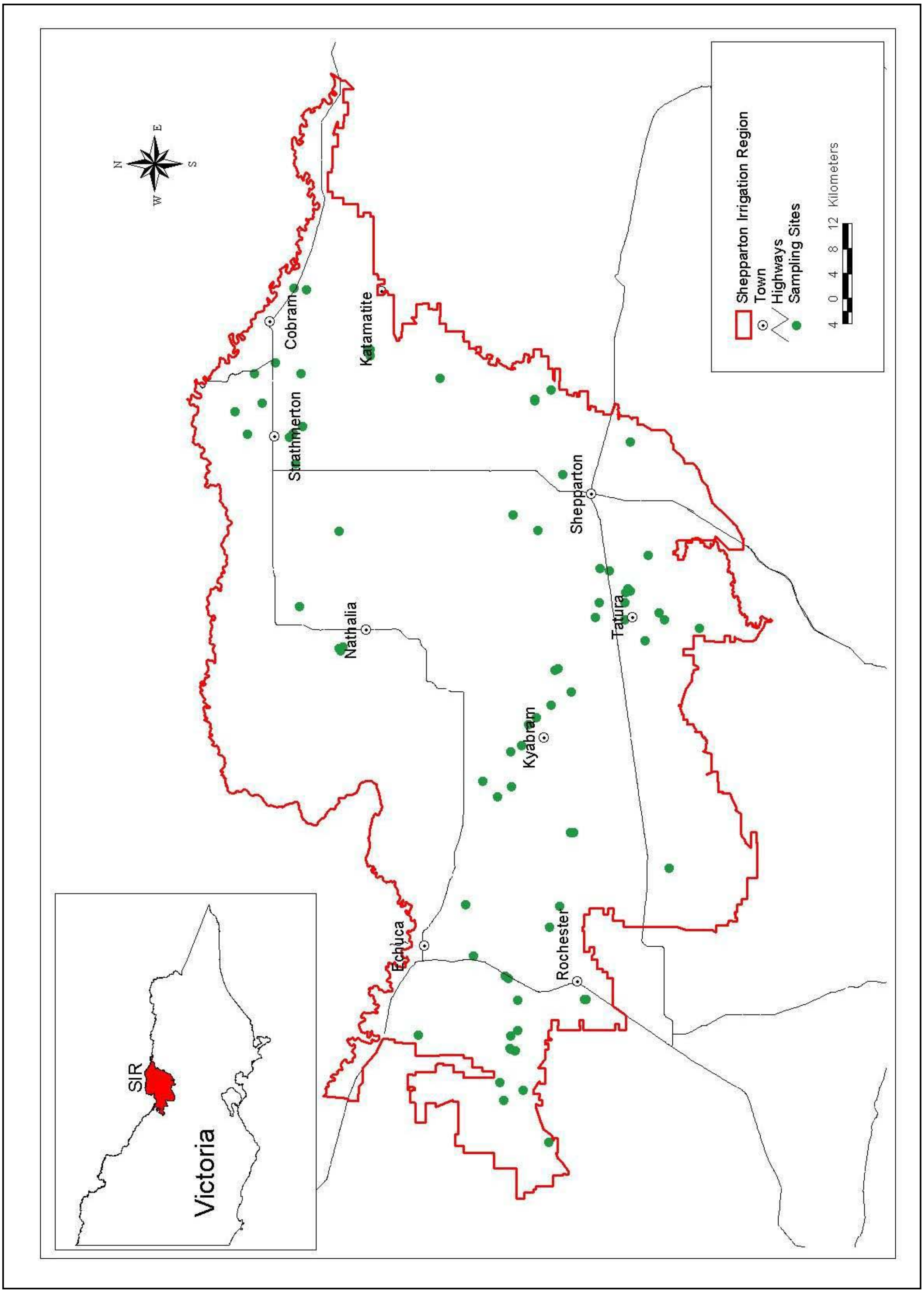


Figure 3 Sampling Sites