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Patterns of water uptake and rhizosphere salinity in *Casuarina Obesa* Miq. during a drying period at Lake Toolibin, Western Australia

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**PATTERNS OF WATER UPTAKE AND RHIZOSPHERE
SALINITY IN *Casuarina obesa* Miq. DURING A
DRYING PERIOD AT LAKE TOOLIBIN, WESTERN
AUSTRALIA**

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A Thesis Submitted in Partial Fulfilment of the Requirements for the Award of
Bachelor of Science (Honours) (Environmental Management)
Faculty of Computing, Health and Science
Edith Cowan University

Date of Submission: May 23, 2003



'If a man will begin with certainties, he shall end in doubts, but if he will be content to begin with doubts, he shall end in certainties.'

Francis Bacon, 1606

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

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Abstract

Lake Toolibin is one of a few remaining freshwater lakes in the central wheatbelt of Western Australia. Since monitoring began at Lake Toolibin in the early 1970's groundwater levels have risen to within 1-2 m of the lakebed with an accompanying migration of salt. The site-specific nature of water uptake in *Casuarina obesa* Miq. (the dominant lakebed tree species) and rhizosphere salinity were explored spatially through analyses of soil properties (groundwater depth and salinity, particle size and components of soil water potential Ψ_1). Plant water sources (using $\delta^2\text{H}$ signatures) and water availability (based on Ψ_{leaf} and Ψ_1) were measured to define water uptake within the rhizosphere. Plant response to these conditions was determined using critical indicators of plant water relations such as stomatal conductance (g_s) and water use. This investigation was conducted over a drying period (October 2002 – February 2003) on the lakebed.

The drying period coincided with a maximum in soil water potential (Ψ_1) and sites with shallower depths to groundwater had soil profiles dominated by osmotic potentials (Ψ_o) due to the accumulation of salts near the soil surface. At some sites groundwater was transmitted above the water table along films of coarse textured sands, forming perched systems of thin saturated soil (0.1 – 0.2 m). These were important mechanisms in the transport of saline groundwater to the rhizosphere. Patterns of water uptake for *C. obesa* across the lake appeared to be closely related to seasonal effects of the drying period and soil water and salt movement from the capillary fringe. Pre-dawn leaf water potentials (Ψ_{pd}), stomatal conductance and water use decreased during summer at all sites, especially where salt accumulation had occurred, but this species exhibited substantial tolerance to moisture deficits caused by salt accumulation. *C. obesa* obtains its summer moisture from relatively shallow depths (< 0.9 m) and regulates water loss through stomatal control during this period, allowing it to persist under these conditions.

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Glossary and Abbreviations

Capillary Fringe	The lowest subdivision of the aeration immediately above the water table in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held up above it by surface tension
Capillary movement	Movement of water through soil pores and interstices caused by a moisture gradient
Cone of depression	A lateral measure of the depression in the water table created by groundwater abstraction
Evaporation gradient	Changes in soil moisture from one point to the other, facilitating moisture movement
Gilgai mounds	Raised portions on a lakebed often resulting in small changes in elevation
Groundwater	The part of the sub-surface water that is in the zone of saturation, including underground streams
Hydrological cycle	The cycle pertaining to hydrological processes within a landscape
Leaf water potential (ψ_{leaf}) (MPa)	The physiologically available water content of leaves or stems
Matric potential (ψ_m) (MPa)	The affinity a soil has for soil water from adhesion and capillarity at the soil surface in the absence of salt concentration gradients arising
Osmotic potential (ψ_o) (MPa)	The attraction of water molecules by hydration due to the presence of solutes in the soil
Pressure chamber	Instrument used to measure the water potential of leaves or stems
Salinisation	The process of salt accumulation in soils from the mobilisation of salts in surface and groundwaters
Soil water potential (ψ_t) (MPa)	The amount of physiologically available water in the soil
Stomatal Conductance (g_s) ($\text{mmol m}^{-2} \text{s}^{-1}$)	A measure of stomatal opening based on the conductance of water that diffuses out of the leaf, minus the contribution of the boundary layer
Transpiration rate (E) ($\text{mmol m}^{-2} \text{s}^{-1}$)	The flux of water from a leaf
Water uptake	The process of water movement into the root interface and through the xylem tissues
Water use	The strategy of a plant that optimise productivity within its limitations

Chapter 1

Introduction

Soil salinisation has dramatic and far-reaching consequences for the Australian landscape. The South West region of Australia has experienced severe salinisation because of extensive land clearing in the latter half of the last century and the effect of this on regional hydrology. The presence and expansion of salinity in agricultural regions has led to it being perceived as an agricultural problem, with consequences affecting agricultural systems and production. Only in the last decade however, have we begun to focus on the consequences of salinity for native ecosystems and for biodiversity in general. Salinity-induced degradation of natural plant communities and their associated habitats will ultimately diminish the ecosystem services they provide.

The Northern Arthur River catchment is typical of the devastating signs of secondary salinisation (salt accumulation from groundwater intrusion), with more than 97% of this catchment cleared for farming (Froend *et al.*, 1997; George and Bennett, 1995). Ephemeral lakes located along paleodrainage contours often become discharge zones for groundwater flow within the catchment. Salts mobilised within these groundwaters are transported upwards into the surface sediments of these lakes. Lake Toolibin is situated at the head of a chain of ephemeral lakes that form the headwaters to the Northern Arthur River, and is one of a few remaining freshwater lakes in the central wheatbelt of Western Australia (Bell and Froend, 1990). When the lake is full it becomes an important breeding habitat for migratory birds and is recognised as a RAMSAR wetland (intergovernmental treaty for wetland conservation) of international significance due to these important conservation values (RAMSAR, 1990). Since monitoring began in the early 1970's groundwater levels have risen to within 1-2 m of the lakebed. As a result, salt has been leached from deep soil horizons and has migrated to the surface of the lakebed, leading to a decline in the associated tree community (Froend and Storey, 1996; Martin, 1986).

Previous studies have attributed the vegetation decline to the rising groundwater and salting in the upper soil profile (Bell and Froend, 1990; Froend *et al.*, 1987; Martin, 1986). The research undertaken has largely concentrated on community and population response to salinisation. Froend *et al.* (1987) studied community dynamics of lakebed and lake margin species and concluded that the combined effects of increased soil salinity and prolonged periods of water logging were responsible for vegetation decline. Population dynamics of *Casuarina obesa* Miq. on the lakebed were investigated by Ogden (1997) to ascertain recruitment requirements and population viability of this species. These and other studies have broadened our understanding of vegetation response to salinity disturbances at the population and community level. However, a thorough understanding of vegetation response at the micro site process level within the lakebed requires an understanding of rhizosphere (root zone of the plant) conditions and individual tree response. It is the spatial distribution of soil water within the rhizosphere and its salt concentration that will determine its availability to the plant. Therefore, the interaction of groundwater and surface water with lakebed tree species is of particular interest in assessing, monitoring and characterising the salinity disturbance at Lake Toolibin.

It is assumed that the rising groundwater beneath the lakebed will cause an upward movement of salt, above the water table through the process of capillary action whilst dry conditions persist on the lakebed. Given a shallow enough depth to groundwater, this process will lead to salt accumulation within the rhizosphere. The consequences for plant water uptake are that soil water availability is reduced. This may only restrict uptake to other areas of the rhizosphere where fresher water sources are available. Over time however, complete salinisation of the soil profile may occur, inducing drought conditions in the rhizosphere due to unavailable soil moisture. This generally accepted model of soil salinisation and vegetation response has been demonstrated in many field studies involving native riparian and wetland vegetation exposed to saline ground waters (Holland, 2003; Mensforth, 1995; Thorburn *et al.*, 1993b). This dynamic process has not been explored within an ephemeral lakebed system like Lake Toolibin, where a complex groundwater hydrology creates variability in terms of rates of salinisation and vegetation response. Lake Toolibin also represents a unique example where conservation attempts have

complicated the local hydrological system even further by pumping groundwater from beneath the lake, in a bid to lower the water table.

The temporal dimension of this process within a hydrological cycle consists of leaching events and drying phases that constitute important shifts in the rates of salt movement and accumulation within a soil profile. A drying phase may be characterised by prolonged periods of increased evaporation creating upward flow of soil moisture and groundwater leading to surface discharge. Conversely, *in situ* leaching events may reduce soil salinities by flushing salts beneath the rhizosphere. It is important then to characterise the patterns of salt accumulation and plant water uptake within the spatial and temporal context of the lake, at the level of the rhizosphere of this tree species.

The most dominant species on the lakebed floor *C. obesa* is also considered to be the most tolerant of present soil conditions, although relative vigour varies across the lake (Ogden and Froend, 2003). Much of the research on this species and its tolerance to salinity, involved glasshouse or laboratory trials (van der Moezel, 1989; Luard and El-Lakany, 1984) where treatments are unlikely to represent field conditions similar to that on the lakebed. The observed variability within the population under field conditions requires further investigation in order to better our understanding of tolerance mechanisms within the population and patterns of water uptake occurring at specific micro sites across the lakebed.

Stands of *C. obesa* at Lake Toolibin have been considered to be shallow rooted based on the root architecture of wind-felled trees and rooting depth estimates by Froend (1983). It is hypothesised here that the root system will have a limited vertical distribution and will rely heavily on surface water from precipitation events rather than groundwater. At sites where the capillary fringe is within the reach of the rhizosphere the tree may use this water provided that salt concentrations are within the tolerance limits of the plant. These characteristics may in fact make this species vulnerable to moisture deficits over summer due to rooting morphological limitations and source water unavailability. Incorporated into this notion of salt accumulation and plant water availability is the concept of a critical depth to groundwater that maintains plant water uptake and health. It is postulated that this critical depth will

be a function of soil and hydrological properties of a given site and regions of shallower water tables above this critical depth will exhibit a decline in tree health.

The site specific dimensions of water uptake and salt accumulation will be explored spatially through analyses of soil properties with depth and ecophysiological parameters across selected locations of the lakebed. Micro site variability within the soil profile will provide a detailed picture of soil water dynamics within the rhizosphere and will be interlinked with an analysis of water availability profiles and plant water sources. A plant water uptake model will define specific regions of water uptake within the rhizosphere, combining plant water source analysis with plant and soil status. Plant response to these conditions will be determined using critical indicators of plant water relations such as stomatal conductance and water use. The temporal scale of plant water uptake and rhizosphere salinity will be assessed within a drying period of the hydrological cycle under the assumption that this typically occurs on the lake during late spring through to early autumn, coinciding with the maximum period of groundwater discharge and evaporation. The specific research aims of this project are:

- 1) To evaluate the distribution and process of water and salt movement within the rhizosphere over a drying period on the lakebed.*
- 2) To determine the patterns of plant water uptake and water relations in response to micro site variability within *C. obesa* population (adult) during a drying period.*

This study will contribute to an expanding body of research on the water uptake strategies of trees exposed to salinity. Pre-existing environmental data will be incorporated into this study to consolidate and further our understanding of the processes leading to tree decline at Lake Toolibin. From an ecophysiological perspective, it will broaden our understanding of tolerance mechanisms, and characterise the soil salinisation process at Lake Toolibin. This will also have significant implications for management and the future direction of research. For the purposes of clarity, the project outline has been presented diagrammatically (Fig 1.1).

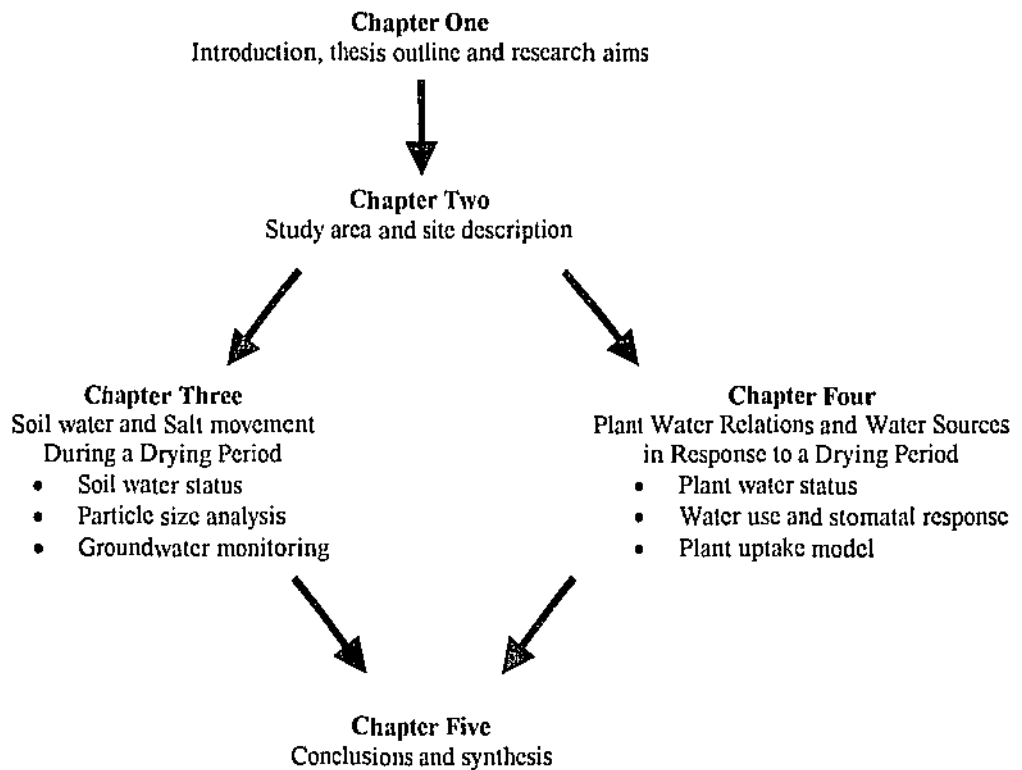


Figure 1.1: Project outline diagram, showing the two main focuses in Chapter 3 and 4. Components of these two Chapters (soil and water status and water sources) will be combined in the plant water uptake model to determine water uptake patterns.

Chapter 2

Study Area, Lake Toolibin

2.1 Location

Lake Toolibin is situated 45 km east of Narrogin, a central wheatbelt town in Western Australia ($32^{\circ}56'S$, $117^{\circ}11'E$). Situated in a broad flat valley, Lake Toolibin lies at the bottom of the Northern Arthur River catchment at the head of a chain of shallow ephemeral lakes that form the headwaters of the Arthur River.

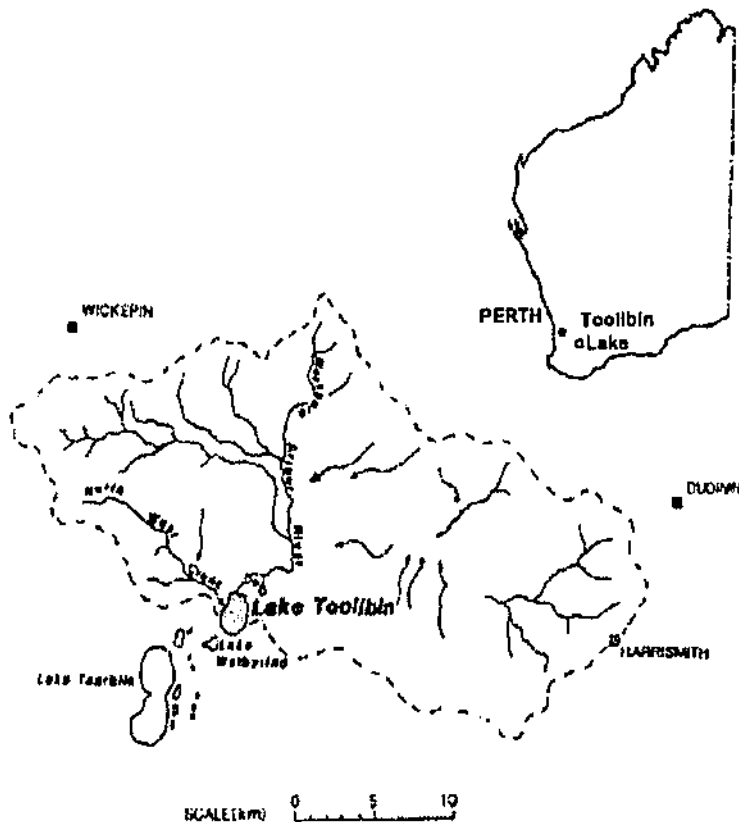


Figure 2.1.1: Location of Lake Toolibin within Western Australia and the Northern Arthur River catchment. (Wallace, 2001)

2.2 Climate

The central wheatbelt of Western Australia has a Mediterranean climate, typified by hot, dry summers, and cool, wet winters. Winter rainfall comprises more than 60 % of the mean annual rainfall of 410 mm (Wickepin met. station) (Casson, 1988).

However the recent trend in rainfall has been a decline in the predictable winter rains with only five winters since 1970 having above average rainfall. In the past five years summer rainfall events in 1998/1999, 1999/2000 and 2001/2002 (Fig. 2.2.1) have contributed significantly to total annual rainfall and may preclude a shift in seasonal rainfall patterns towards wetter summers and drier winters (IOCI, 2002). Average temperatures in summer are approximately 30 °C and average total evaporation in summer months is between 250 to 270 mm. (Casson, 1988) (Fig 2.2.2).

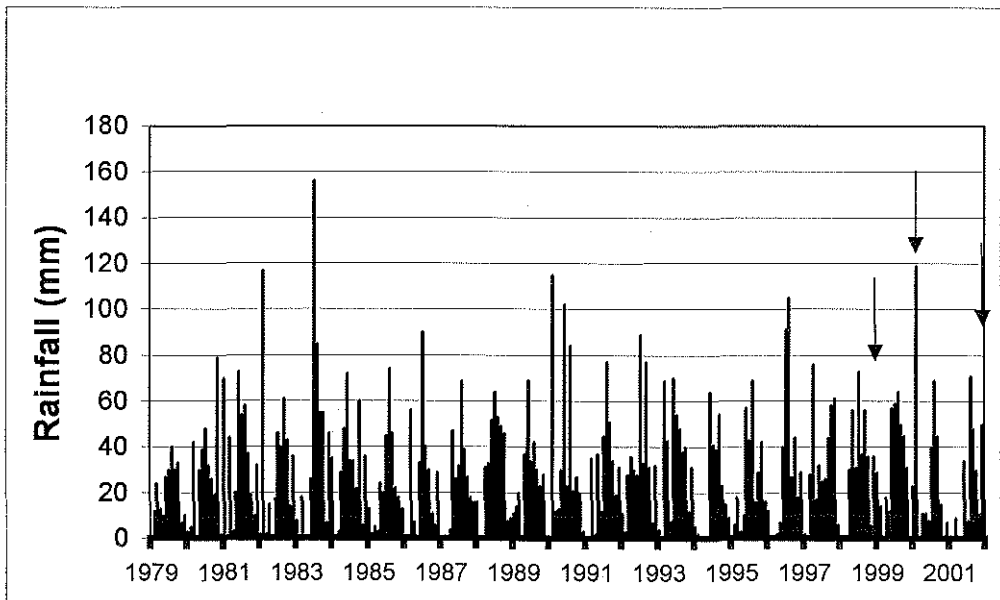


Figure 2.2.1: Rainfall data at Lake Toolibin, 1979 – 2002. Arrows point to major summer rainfall events over the last five years.

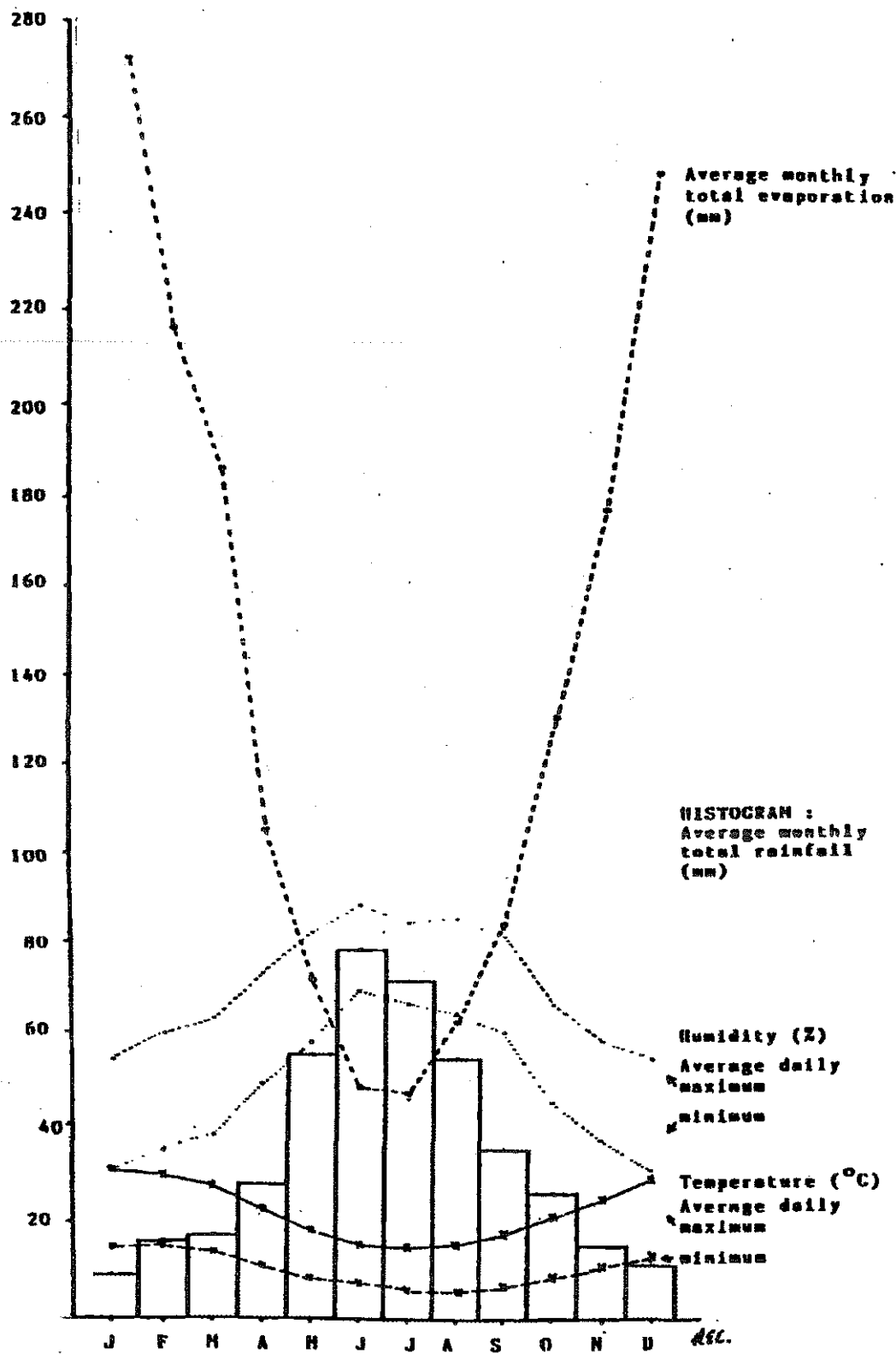


Figure 2.2.2: Climatic data for Lake Toolibin (from Narrogin except rainfall – Wickepin) (Casson, 1988)

2.3 Geology

The geology of the Northern Arthur River catchment (an area of 435 km²) is underpinned by Archaean granites, overlain by deep, mantled and laterised profiles, while lower valley floors contain fluvial deposits of lacustrine sand and sandy clays (Mulcahy, 1973). On catchment divides, dolerite dykes occur frequently and may have a significant influence on catchment drainage patterns. Up slopes consist of rocky outcrops in the Northwest Creek catchment, that are exposed Archaean granites of the Yilgarn block. Numerous soaks in the eastern parts of the catchment that are found between the upper sandy slopes and clay flats are indicative of perched water tables beneath these soils. To the northeast of Lake Toolibin, a sluggish drainage contour containing loamy duplex soils with clayey sub soils are the most salt-affected soils of the catchment.

Lake Toolibin lies in a broad flat valley typical of the Baandee (ancient drainage system), which has collected fluvial and aeolian deposits (GHD, 1992). These deposits contain calcareous and siliceous loamy soils of minimal development. In general, the profile consists of a thin alluvial layer (brown/grey pallid clay) at 0.1m to 0.7 m with layers of quartz and iron rich materials at various depths beneath this. A seismic refraction survey at Toolibin in 1980, indicated an unconsolidated layer less than 3.0 m thick. Underlying this are undurated lake sediments and/or weathered granite overlying fresh granite at depths of 27 - 46 m (George and Bennett, 1995). Dune systems (lunettes) typical of sand plain soils of the ancient Plateau have developed on the eastern sides of the lake, and shallow duplex soils with truncated profiles are found to the west of the lake. More recent hydrogeological studies (George, 1998) indicate a paleochannel beneath the lakebed centred around the southern central region of the lakebed. These studies also identify a divide in sediment types across the lakebed, with fine alluvial sediments in the western half of the lake and fine lacustrine sediments in the eastern regions.

2.4 Hydrology

2.4.1 Surface Water Hydrology

Episodes of inundation and drying at Lake Toolibin have significant implications for the ecosystem they support. Since documentation of surface hydrological data began in 1978, the lake has had four major periods of inundation (1981, 1983, 1990 and 1992) separated by dry years when there has not been a continuous body of water on the lake. The most significant of these inflow events occurred during the winter of 1983 in which $16671 \times 10^3 \text{ m}^3$ entered the lake (Froend and Storey, 1996). However, only three of these filling events (1983, 1990 and 1992) resulted in outflow downstream of the lake.

The previous rates of clearing in the catchment are not precise, but by 1932 approximately one-third of the catchment had been cleared, by 1962, 85 % and in 1972 this figure had increased to 90 %. Present day figures estimate that up to 98 % of the catchment has been cleared for agriculture (Froend and Storey, 1993). Gutteridge, Haskins and Davey (1992) estimate that inflow prior to catchment clearing represented only 25-50 % of the present inflow because of increase levels of surface runoff. Surface inflow into the lake occurred only 3 in every 10 years, whilst only one of these events resulted in a continuous body of water on the lake. Historical reports from local residents living in the area since 1904 claim that in wet years the lake always filled at least to the low lying areas in the centre, up until the drought in 1969. The steady decline in annual rainfall (discussed in section 2.2) has meant that inflow events have not greatly increased in frequency and magnitude.

Significant salt loading is associated with major inflow events, and has led to a noticeable increase in salt inputs since the early 1990's (Froend and Storey, 1996). These salt loads may vary between 2 and 6300 tonnes TSS. While stream flow salinities are generally lower in high flow events, the beginning of an inflow event (first flush) may have salinities in excess of 15.6 mS m^{-1} (NARWC, 1987). Overall storage levels of salts in the lake system have not been accurately determined,

however it is clear that a large proportion of salt entering the lake is not lost through outflow, but is stored in sediments and groundwater during recession of lake water during dry periods (Froend and Storey, 1996). This component of the lakebed hydrology will have important implications for this study, as rates of salt leaching into sub-surface sediments will be slow due to the fine textured nature of the sediments, and may re-enter the lake water following rainfall, inflow and rising lake levels. Salts from inflow events will also form a significant component of the salt store and may be mobilised by rising groundwater.

2.4.2 Groundwater Hydrology

Lake Toolibin forms part of a chain of ephemeral lakes that eventually flow into the Arthur River. While Lake Taarblin and other major lakes down stream have had a longer history of salinisation and vegetation decline, Lake Toolibin has a more recent history of salinity, due primarily to the groundwater flow patterns of the catchment. Stokes and Sheridan (1985) theorised that the predominant through flow pattern of groundwater passes beneath Lake Toolibin and discharges into Lake Walbyring and Taarblin. Minor discharge also occurs into minor lakes and salt pans to the north of Lake Toolibin, where evaporation generally exceeds discharge rates.

Trends in groundwater at observation bores on and around Lake Toolibin indicate a constant rising trend north of the lake at an average of 4.6 cm yr^{-1} and fluctuations in all other areas in accordance with rainfall. This suggests that groundwater levels may continue to rise in response to catchment clearing (NARWC, 1987). On the lakebed groundwater levels have risen to within 1-2 m of the surface, however existing data from existing monitoring bores highlights the complex flow patterns of groundwater, and variation in water table levels across the lake (Fig 2.4.2). Groundwater abstraction across the lake causes further irregularities in depths to groundwater (discussed in section 2.3.1).

There is a consistent two to four month lag between the onset of winter rainfall (initial period of recharge) and an increase in groundwater levels. This is caused by the low hydraulic conductivity in lakebed soils, and the complex, and delocalised nature of the groundwater system. Peak groundwater levels actually occur in mid to

late spring after much of the winter rainfall has evaporated and given dry lake conditions, upward flow due to capillary action is occurring. This may compound the levels of salt accumulation beneath the lakebed.

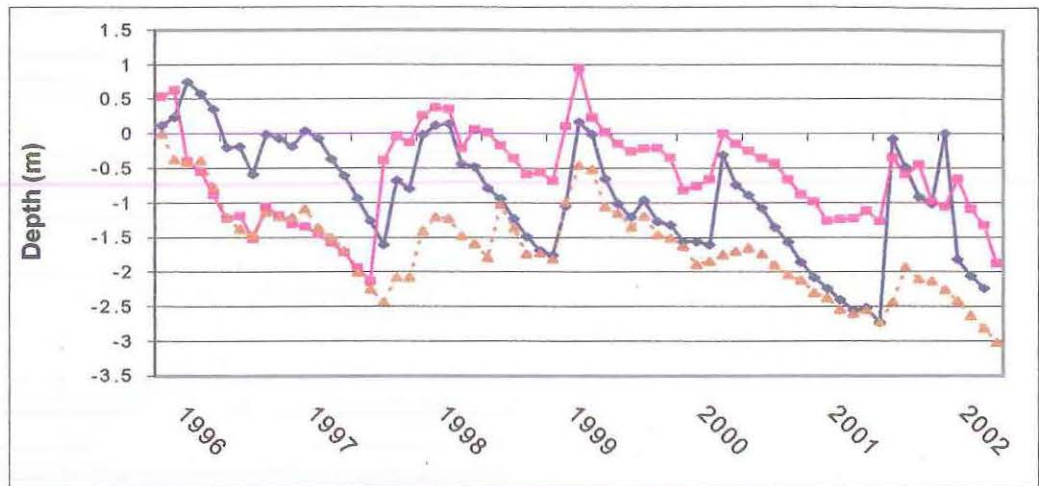
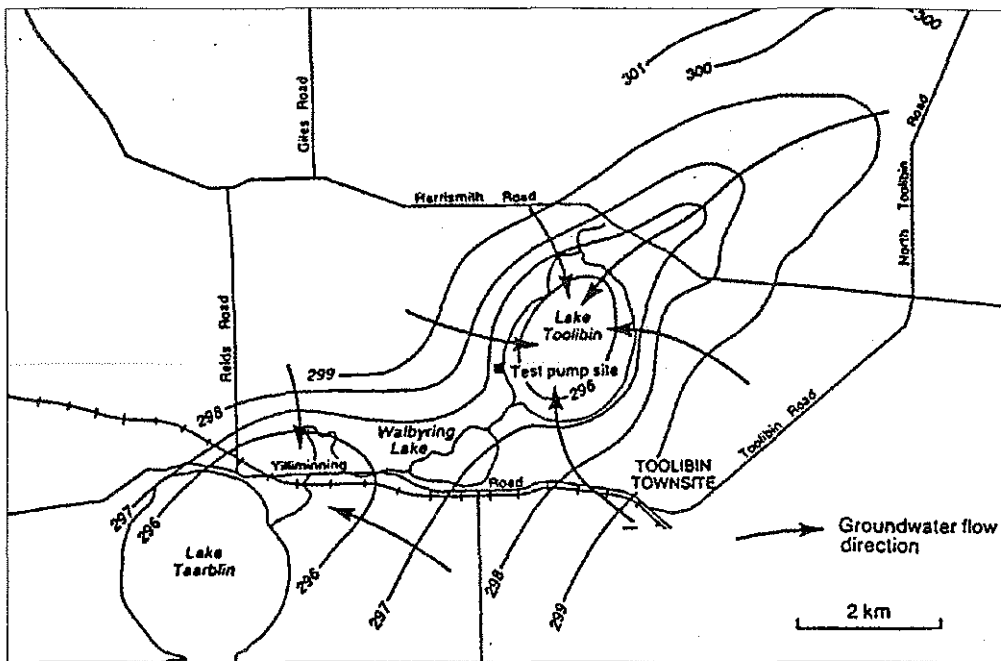


Figure 2.4.1: Groundwater levels at three observation bores across the lake (not affected by groundwater abstraction) for 1996 - 2002. The eastern edge (♦), middle (lower lying region) (■) and western side (▲). Measurements above depth 0.0 m indicates surface inflow.

Lakebed hydrology at Toolibin is influenced by inflow events and their magnitude. The complex groundwater system of Lake Toolibin, may vary between an open or closed system, depending on seasonal recharge and inflow events (Fig 2.4.2). Martin (1986) used potentiometric head measurements in and around the lake, which suggested that filling events on the lake result in a downward movement of groundwater and a corresponding discharge further downstream (an open system). As the lake dries this downward flow of the water table slows down but persists for some time after the lake is dry. Eventually upward flow of groundwater by capillary action leads to a discharge at the lakebed surface and the flow system reverts back to a closed one. However, even when the lake is dry salt balance studies have found some downward seepage of groundwater, that helps to flush some salt further down in the profile (Martin, 1986). Therefore there may be a critical depth of the water table at which upward flow of salts becomes the predominant pattern of groundwater flow. A depth to groundwater of 1.0 metre has been suggested by GHD (1992) to

(a)



(b)

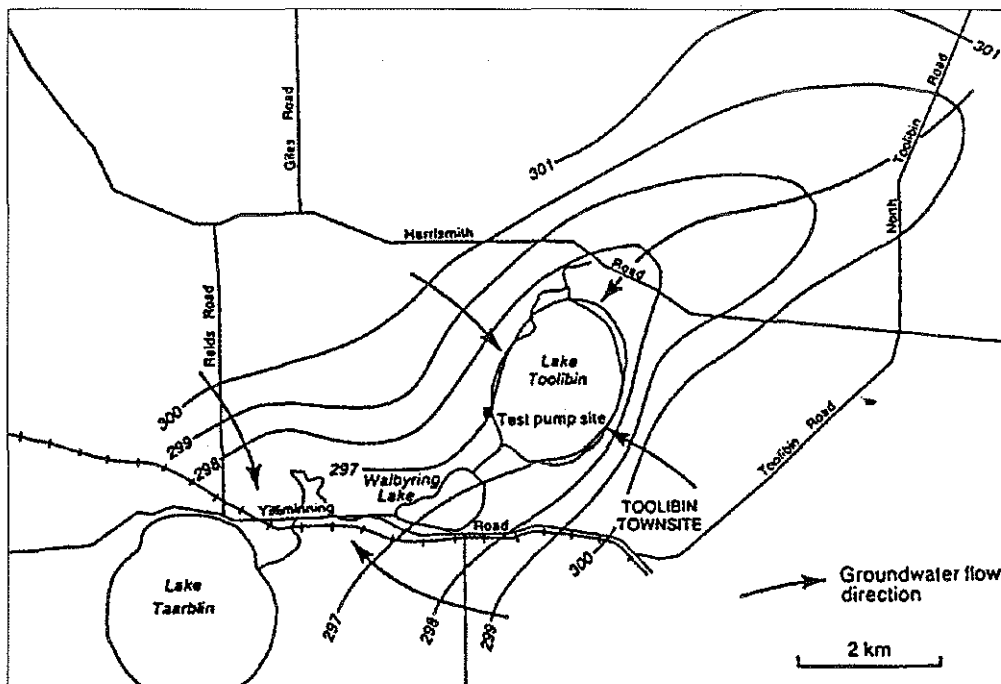


Figure 2.4.2: Groundwater contours and flow patterns within the Northern Arthur River wetlands, during (a) dry phase and (b) wet phase. These contours highlight the alternation of the groundwater system between a closed system; Lake Toolibin acts as a discharge zone (closed contours) and an open one; groundwater flow occurs southwards away from the lake (open contours) (Martin, 1990).

cause salt to accumulate by evaporation from the capillary fringe, however this critical depth has not been accurately determined in relation to lakebed tree community health. The elevation of water tables due to catchment clearing, the farming of shallow rooted annuals and the prolonged dry periods has meant discharge of saline groundwater to the lake when it is dry, has become more frequent. This continues to have significant implications for vegetation on the lake.

The salinity of the groundwater is generally high and ranges between 36.4 dS m^{-1} and 54.5 dS m^{-1} in groundwaters closer to the water table, however deeper groundwater ($> 40 \text{ m}$) may contain up to 109 dS m^{-1} (GHD, 1992). It has been observed that shallower bores on the lake are highly saline and this may indicate that salts become concentrated in the surface groundwaters when the lake is dry.

2.5 Vegetation

Lakebed vegetation comprises of *C. obesa* and *Melaleuca strobaphylla* woodland, occurring in very open to extremely dense thickets on raised gilgai mounds. Introduced and native annuals inhabit the understorey, and more recently halophytic species of *Halosarcia* have spread within the lakebed.

Monitoring of Lake Toolibin and surrounding areas began in 1977 (by Mattiske and Associates), after vegetation decline was observed in and around the lake. Long-term plots on nearby reserves and on the lakebed have mapped vegetation change for the past 26 years and highlight similar trends.

In general, stands of *C. obesa* and *M. strobaphylla* have shown a continued decline in vigour, with *M. strobaphylla* showing slightly increased mortality (Ogden and Froend, 2003). A significant recruitment of *C. obesa* seedlings was noted in 1998 on the west side of the lake around an abstraction bore (pump 9), and there numbers have since increased with favourable germination and establishment conditions. This successful recruitment of *C. obesa* however is only limited to this area on the lake, and suggests that recruitment requirements in other regions of the lakebed do not favour regeneration.

Terrestrial vegetation at the Toolibin reserves have shown little change since 1998, with stands *Eucalyptus loxophleba* and *Eucalyptus wandoo* showing a slight decline, while *Eucalyptus salmonophloia* and *Allocasuarina huegliana* are in good health. In the central region of the reserve north of Toolibin there has been significant regrowth of *E. salmonophloia*; *E. loxophleba*; and *E. wandoo* after bulldozing, clearing and burning activities occurred pre-1982. However woodland of *E. loxophleba* – *Acacia acuminata* on the lake fringe has continued to decline with little regeneration. *A. acuminata* seedlings (Ogden and Froend 2003).

On the southeastern fringe of the reserve *Banksia prionotes* is rapidly declining with more than 60 % mortality since monitoring in 1998 (Ogden and Froend, 2003). These changes have been attributed to a changed fire regime and the cumulative pressures of diminished water availability, insect herbivory and pathogen attack.

Ogden and Froend (2003) also stress that current drought conditions in this area will have significant impacts upon both wetland and terrestrial vegetation. The current deterioration of the *B. prionotes* populations indicate that this species is sensitive to shifts in water availability and the onset of drought conditions.

2.6 Drainage Alterations and Groundwater Abstraction

To control the rate of salinisation and vegetation decline at Lake Toolibin, several engineering solutions have been utilised as short-term solutions to a salinising lake system. While some of the surrounding catchment has been revegetated and drainage works in the vicinity of the Toolibin flats area aimed to reduce salinity in the Northern Arthur River, highly saline runoff from the surrounding catchment continued to enter the lake adding to the already elevated salt load. To address this issue, a separator gate was constructed to divert these highly saline ‘first flush events’ into a constructed channel running adjacent to the western edge of the lake. This 7 km diversion channel eventually runs into Lake Taarblin from Nepowie Road upstream. This design ensures the interception of saline flows into NorthWest Creek and subsequent discharges into Walbyring Lakes. Lake Taarblin is an already

degraded and highly salinised ecosystem and therefore the effects of the diversion of saline groundwater into this lake are considered to be minimal compared to the positive outcomes for Lake Toolibin.

The separator gate and channel were constructed in 1994/1995 to allow saline flows into the diversion channel or closed so that fresher flows are directed into the lake. There is evidence to suggest that this separator gate and diversion channel have been effective in lowering salt loads entering the lake, with an estimated 4000 tonnes being prevented from entering the lake and adding to the salt load (Wallace, 2001).

Groundwater abstraction was first suggested by the Northern Arthur Wetlands Rehabilitation Committee as a strategy to lower shallow groundwater levels. Several studies were conducted to investigate the specific hydrogeological processes occurring within the lakebed (Martin; 1982, 1986, 1990), focussing on the western region of the lake as it had shallower groundwaters than other parts of the lake (Froend, 1996). These studies concluded that at least nine pumping bores ('Stage 1') running north south along the western side of the lake were required to lower the water table by 1.5 m. The establishment and operation of these abstraction bores since 1988, has resulted in significant draw down close to all pumps and in some cases, this has extended to up to 180 m lateral distance from the pump (Wallace, 2001). The implementation of 'stage 2' has meant the establishment of 16 new abstraction bores in 1995, across other regions of the lake including the paleochannel around pump 13.

2.7 Study Sites

Three locations on the lakebed were chosen, to assess and describe the dominant processes with respect to water uptake and rhizosphere salinity in *C. obesa*. Three sites were chosen for this study due to effort and expense required to sample extensive areas of the lake. Therefore the sites chosen represent varying degrees of the effects of salinity and contrasting groundwater influences on lakebed tree vegetation. They were also selected so that pre-existing data at Lake Toolibin could

be used to characterise the site and the trends in vegetation health and groundwater depths over time.

An EM 38 (Geonics, Canada) was used along 20 m transects to give a general indication of surface and sub surface salinities to a depth of 1.5 m. Little variation was noted within transects and a salinity classification was determined based on relative comparisons between healthy and unhealthy sites. These were also compared to salinity data from the most recent vegetation survey of Lake Toolibin and surrounding reserves (Ogden and Froend, 2003) and classified in accordance with Agwest Soil Salinity Classes for Revegetation (Agwest, 2002). Vegetation health was established using pre-existing data from previous vegetation plots (Ogden and Froend, 2003) that were either in the site or adjacent to the site and characteristic of the area. Existing vegetation monitoring data is based on tree vigour index in accordance with Grimes (1987). Depths to groundwater were determined using pre-existing observation bores close to each of the sites, and were measured in September, 2002.

Site 1 was located on the western region of the lake next to pump 9, which is one of the oldest abstraction bores on the lake. This western region of the lake had shallow groundwaters (within 1.5 m of the surface) and soil salinities at approximately 0.27 % NaCl in 1986 (Froend *et al.*, 1987). However the instigation of groundwater abstraction bores for management in 1988, appears to have lowered groundwaters in the immediate area. Depth to groundwater now appears to be over 30 m. However it is unclear the extent to which draw down from this pumping will extend beneath the lakebed. Martin (1990) estimated draw down to extend laterally to 150 m from the base of the abstraction bore. The vegetation health has shown some improvement although only recent data (since 1998) is available for this site.

Site 2 in the southern central region of the lake, has largely intact areas of open *C. obesa* woodlands with denser thickets occurring on raised gilgai mounds. An abstraction bore (pump 13) is within 10 m of the study site and has been in operation since mid 2001. No significant change in health has occurred since monitoring began in 2000 but there is noticeable signs of tree stress.



Figure 2.7.1 Map of study sites (●) on the lakebed.

Table 2.1: Assessment of sites used in this study based on vegetation, salinity and depth to groundwater. Note vegetation health is based on the health of the majority of trees present on monitoring plots near the sites.

Site No.	Salinity	Vegetation Health	Depth to Groundwater
1	low	healthy	~ 30 m
2	high	stressed/healthy	~ 6.0 m
3	extremely high	stressed/dead	~ 2.5 m

Site 3 is located in the eastern region of the lake within 20 m of an abstraction bore (pump 15). Vegetation occurs on raised gilgai mounds, with relatively spaced individuals and there are numerous stressed and dead trees. Since 2000 tree health has declined with salinities remaining extremely high. Pumping started in mid 2001 but had stopped during 2002 due to blockages in the pipes.

Chapter 3

Soil Water and Salt Movement Over A Drying Period

3.1 Introduction

A key component in understanding the interaction of surface and groundwater with terrestrial vegetation in an ephemeral wetland such as Lake Toolibin, is determining the specific abiotic conditions that are affecting tree health. The mobilisation of salts through groundwater discharge is prevalent at Lake Toolibin and has been responsible for a decline in the lakebed tree community (Froend *et al.*, 1987). Highly saline water in the sub-surface layers creates salt fronts (concentrated regions of salts above the capillary fringe) in the rhizosphere. The persistence and survival of this community will hinge on the ability of the trees to extract water and maintain water use in the presence of salt in regions of plant water uptake.

Local soil characteristics within the rhizosphere will directly affect water availability and uptake. Temporal and spatial fluctuations in soil moisture and salt concentrations lead to variability in soil water status, which influences ease of plant water uptake. Apart from inherent characteristics of the soil itself (i.e. mineralogy), soil water status is influenced by surface and sub-surface hydrology as well as surrounding climatic conditions.

This Chapter will describe the processes and pathways of salt and water movement within the surface and sub-surface lakebed horizons, at various locations across the lake during a drying period in the hydrologic cycle. It will characterise the dominant components of soil water status, soil texture and groundwater movement within the soil profiles and identify the processes leading to the formation of salt fronts and moisture deficits.

3.1.1 Groundwater Discharge in Soils

The clearing of deep-rooted perennial species in south-western Australia has greatly changed the soil hydrology. The understanding of groundwater discharge through soils is pertinent to any investigation of salinity (whether it be within site, catchment or on a regional scale). Analysis of site processes on a smaller scales i.e. the micro site, is heavily driven by the nature of soils overlying saline groundwaters. The inherent soil conditions will influence discharge from the system through hydraulic conductivity and the potential of this water to be used by vegetation. Diffuse discharge through evaporation and through the plant's transpirational stream however, is difficult to quantify in many field situations.

Talsma (1963) formulated a concept of critical depth of groundwater in irrigated systems based on quantifying discharge flux. In general, vegetation growing in coarser textured soils will tolerate shallower depths to groundwater than sites with medium to fine textured soils, due to reduced hydraulic conductivity and the movement of the capillary fringe. This was adapted to dryland conditions where it was recognised that a greater depth to groundwater was necessary to maintain vegetation health (Peck, 1978). In a dryland system with fine textured soils this will increase the critical depth of groundwater even further. Under these conditions the system will alternate between dry periods and leaching events, where the magnitude and frequency of these cycles will determine surface discharge. It is widely recognised in native ecosystems that the periodicity of aridity and leaching determines long-term ecosystem integrity (Jolly, 2002).

These processes are very important in a ephemeral lake system, where flooding events may leach salts down into the soil profile, but may also increase the total salt load of the system, through highly saline inflows. Estimates of salt loads entering and leaving Lake Toolibin are complicated by the *in situ* leaching of salts after inflows within the heavy textured sediments of the lakebed. As previously mentioned (section 2.4.2), drying periods at Lake Toolibin are characterised by groundwater discharge through capillary rise further adding to salt in the soil. This

hydrological system reflects both catchment and inherent site properties that drive groundwater discharge and salt balance.

3.1.2 Soil Water Status

Soil water status describes the availability of water for plant water uptake. Although soil water content may provide some indication of soil water conditions, soil water status is of greater importance in understanding plant water relations (Marshall and Holmes, 1988).

The soil water status expressed as total soil water potential (Ψ_t) can be summarised as follows:

$$\Psi_t = \Psi_g + \Psi_m + \Psi_o + \dots\dots\dots$$

Where Ψ denotes potential and t, g, m, o, are total potential, gravitational potential, matric potential and osmotic potential respectively. The dots represent other potentials that are insignificant in this study.

Gravitational potentials are a result of the force of gravity on soil water. Water deeper in the soil profile will have a greater negative potential due to gravity, however this may be negligible for this study due to the relatively shallow depths of soil sampled.

Matric potential (Ψ_m) is a result of adhesion and capillarity and the affinity a soil has for soil water in the absence of salt concentration gradients (Leong, 2002). It is influenced by both soil structure and water content and may vary greatly in a heterogenous profile. Ψ_m is considered to have an increasing influence upon total soil water potential as soils dry (especially in fine textured soils).

Osmotic potential (Ψ_o) arises from the presence of solutes in the soil water. A high concentration of solute ions in soil attracts water molecules by hydration, thereby increasing the amount of energy required for a plant to uptake water (Leong, 2002).

Total soil water potential (Ψ_t) is determined by the addition of Ψ_m (how much water is available) and Ψ_o (reduced availability due to salts) and provides an overall indication of plant water availability. Sampling soils within the profile and measuring the components of soil water potential, will provide an indication of changes in plant water availability with soil depth. Obtaining these profiles seasonally, will also provide a temporal evaluation of soil water conditions.

3.2 Methods

Total soil water potential was assessed by analysing Ψ_m , Ψ_o and water content. Water content varies according to soil type, depth and season and gives only a limited indication of water availability. However combined with solute concentrations, it gives a measurement of soil water conditions. Particle size was analysed to investigate its influence on surface, sub-surface and groundwater movement. Groundwater depths and salinity were monitored to assess their impact upon the soil water potential in the root zone.

Soil Coring

A Sochaki Root Corer was used to obtain sub samples throughout the soil profile at each site during the study period. The corer consisted of a small frame, powered by a hand auger motor and attached to a chain pulley system to lower the drill head into the ground (S. Sochaki, pers com.). Soil sub samples were taken at depth increments of 0.15 m for the first 0.9 m and then 0.3 m until 3.0 m and 0.5 m until a consistently saturated horizon was reached, or in the case of site 1 a hardened clay layer prevented further coring. However this did not occur for all sampling holes because of draw down or depth limitations. Extra sub samples were collected when contrasting soil horizons were reached, to account for abrupt changes in the profile. The initial sampling run occurred in late October 2002, and was repeated the following mid-December and early February.

Soil water potential measurements of the bulk soil may not be entirely representative of rhizosphere conditions (Strizaker and Passioura, 1996). To overcome large spatial variation between the rhizosphere and bulk soils, all sub samples were collected within 4.0 – 5.0 m of the trees sampled at each site. Subsequent sampling holes were cored within 2.0 – 3.0 m of each other in order to reduce the effect of previously exposed soil columns.

3.2.1 Groundwater Depth and Salinity

Groundwater depths and salinity were monitored at sites 2 and 3 using pre-existing piezometers, which were in close proximity to the field sites, and piezometers installed in October. It was impossible to install a piezometer at site 1 with the equipment used and in the absence of a pre-existing piezometer, groundwater depths were measured at the abstraction bore at this site. A depth probe measured depth to groundwater (metres) for each sampling period. Groundwater was extracted from piezometers after bailing out stored casing water and analysed for electrical conductivity.

3.2.2 Soil Water Potential

Matric Potential (Ψ_m)

Ψ_m was measured using the filter paper method as developed by Greacen *et al.* (1989). Soil obtained at each increment was placed in airtight bags and stored in the field at room temperature (insulated container) until it was analysed in the laboratory. Filter papers (Whatmans No 42) were prepared by oven drying at 65 °C to ensure any stored moisture was removed. Plastic jars (300 ml) were filled to one quarter with soil and then flattened and one filter paper was placed on top using blunt tweezers, without touching the edge of the jar (Appendix 1). The jars were sealed with lids and electrical tape to ensure an airtight fit. All samples were transferred to a constant temperature room set at 20 °C. The equilibration time was 8 days for the soil and air (within the jar) to equalise in pressures.

Filter papers were then retrieved using tweezers and immediately weighed (± 1 mg) and then placed in an oven at 105 °C. After 2 hours each paper was reweighed and water content was recorded. Percent water contents were calculated and then fitted to a calibration curve for the specific filter paper (Appendix 2). This curve was chosen based on its accuracy when tested against other calibration curves calculated for Whatmans No. 42 (Leong, 2002). Total suction in log KPa was converted to potential MPa and the average of the three papers was tabulated.

Osmotic Potential (Ψ_o)

Total chloride content in soil water was used to calculate Ψ_o , and it was assumed that salt in the soil was present as NaCl. Soil sub samples obtained in the field were oven dried at 105 °C and a 1:10 suspension of soil and water (milliquat) was shaken with an orbital shaker for at least two hours to ensure full dissolution of chloride. This solution was centrifuged to remove soil particles from solution. A chloride analyser (Model 926, Hamersley Iron Pty. Ltd.) was used to titrate samples and obtain a chloride concentration in ppm. This concentration was converted to soil water concentration (mg L^{-1}) using the gravimetric water contents for each depth in the profile.

Water content was calculated gravimetrically by oven drying soil samples at 105 °C for two days. Based on the assumption that 1 M NaCl has an osmotic potential of 4.5 -MPa (and Cl molar mass is 35.5g) a conversion factor of 0.127 was multiplied by the chloride concentration (mg L^{-1}) to obtain a Ψ_o .

3.2.3 Particle Size Analysis

Particle size will have a significant influence on solute movement in the surface and sub-soil and will therefore influence total soil water potential (Ψ_t). Particle size analyses were carried out on three profiles obtained at each site in mid-December. The dispersion method (Gee and Bauder 1986) was used to measure percentage sand, silt and clay, and all organic matter was removed using hydrogen peroxide.

3.3 Results

3.3.1 Groundwater Monitoring

Groundwater levels were greatly influenced by current abstraction on the lakebed. Groundwater depths at site 3 were influenced by the commencement of pumping in November (Fig. 3.3.1). Groundwater sampling at both the pre-existing piezometer and the newly established piezometer in December, showed large draw down during November and December of 0.5 m and 0.3 m respectively, that was a result of the cone of depression created by the pump at this site. The shallow piezometer at site 2 may have measured fluctuations of a perched system above the true water table as the existing piezometer nearby, exhibited significantly greater depths (Appendix 3). Pumping at this site continued throughout the study and seemed to have little effect on the water levels. Site 1 had unrecorded depths due to the absence of pre-existing and established piezometers, however measurements of depths at pump 9 within 10 m of the study site, showed groundwater depths of over 30 m. It was assumed then that these deep groundwaters extended across the site, making groundwater influences minimal. Comparisons of groundwater histories at sites 2 and 3 showed site 3 had experienced shallower groundwater levels (smaller depths) after early 1997, and this trend continued until current sampling at these sites (Fig 3.3.2). Seasonal variation relating to recharge and discharge appeared to be similar, but summer and early autumn draw down was greater at site 2 than site 3. Groundwater levels at site 3 have remained closer to the surface for the last three years, suggesting greater translocation salt into the upper soil layers. Groundwater salinities remained relatively constant throughout the study ($\sim 45 \text{ dS m}^{-1}$), and there was little variation in salinities between sites and piezometers (Appendix 4).

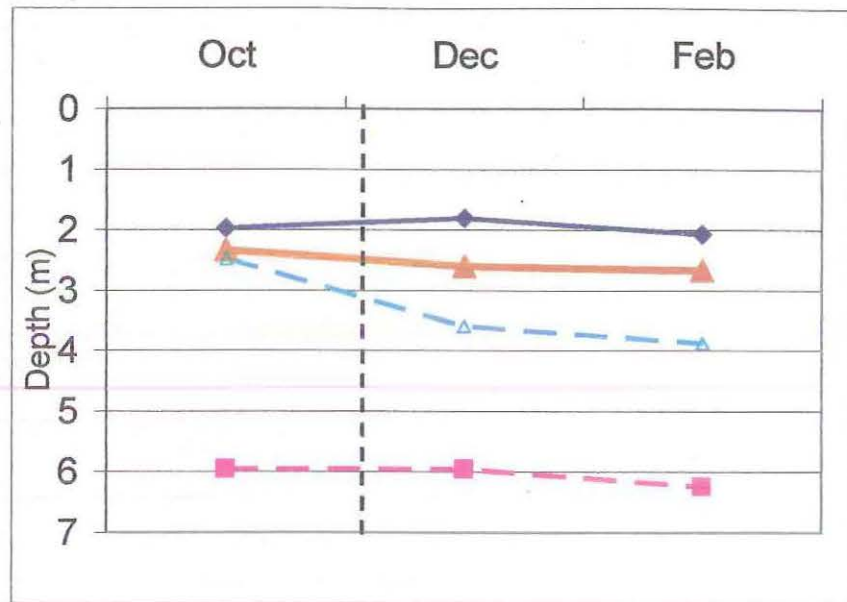


Figure 3.3.1: Groundwater depths for sites 2 (◆) and 3 (▲) at shallow piezometers (installed during study) and deeper pre-existing piezometers at site 2 (■) and site 3 (Δ). Dashed vertical line indicates commencement of abstraction at site 3.

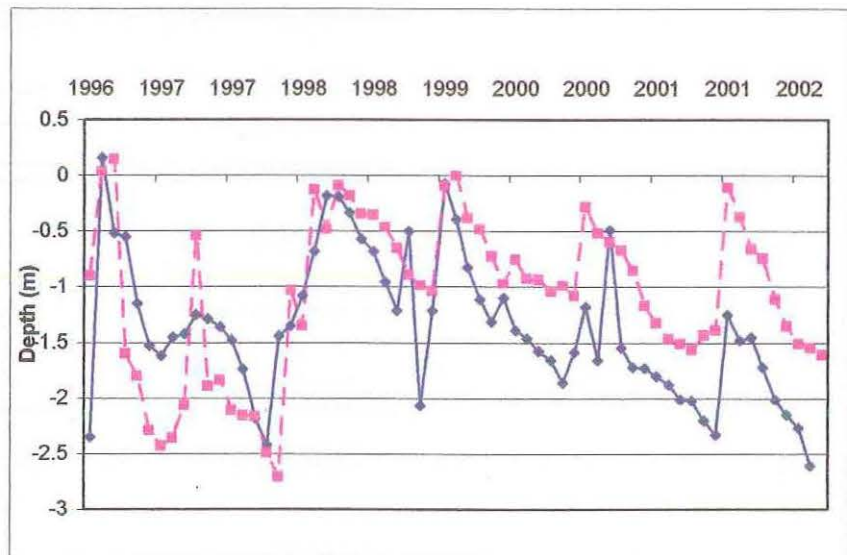


Figure 3.3.2: Groundwater levels at pre-existing piezometers close to site 2 (◆) and site 3 (■) from mid-1996 to mid-2002.

3.3.2 Soil Water Potential and Particle Size Analysis

Site 1 (Low Level Salinity)

Soil water potential Ψ_t and its components varied between sites (Fig 3.3.3). Site 1, which had lower surface and sub surface salinities, had a soil profile dominated by Ψ_m (Fig 3.3.4). The absence of shallow groundwater allowed the profile to dry throughout summer and therefore precipitation and surface flow were the main inputs of soil moisture. At shallower depths, evaporation on the surface created very negative potentials. Towards the end of summer highly negative Ψ_m extended deep into the profile up to 0.6 m ($\Psi_t < -10$ Mpa), as surface evaporation created dry surface soils. Below this depth Ψ_m gradually decreased, which indicated more plant available moisture at lower depths. These highly negative Ψ_m values created broad regions in the upper profile where moisture was unavailable to the plant. Greater variation in Ψ_t occurred between seasons, with October and December differences marked at greater depths (>1.2 m). Ψ_o made up less of Ψ_t , and the absence of a salt front did not create large regions dominated by Ψ_o .

Analysis of soil particle sizes at site 1 also revealed more uniformity in clay contents and textures (Fig 3.3.5). There were visible signs of mottled horizons at 2.0 – 2.4m depth and iron stone colouring, that suggested previous waterlogging and inundation of sub surface soils. Another striking feature of the profile is the presence of a hardened layer of kaolinite at 2.5 m below the surface, which was impenetrable to the machinery used to take core samples. This layer was slightly moister at its surface and downward seepage of moisture was blocked by this layer (Fig 3.3.6). The drier, hardened white clay beneath contained low salt concentrations and very little moisture. Overall this profile was lower in soil water chloride concentrations and dominated by matric influences, especially as the soil dried during summer.

Sites 2 and 3 (Medium to High Level Salinity)

Site 2 and 3 were characterised by a salinised profile with site 3 highly affected. Site 3 had moderate chloride concentrations in October, but by February high salt

concentrations in soil water had accumulated between the surface and 1.2 m (Fig 3.3.4). Low moisture contents and higher surface evaporation during this time concentrated salt and increased Ψ_m and Ψ_t accordingly. Evapotranspirative demands may also have exacerbated increased soil salt concentrations in regions of plant water uptake; these influences will be assessed and discussed in more detail in Chapter 4. This salt front formed well above the water table, which lay at 3.9 m in February. Site 3 also showed the highest water contents across all seasons suggesting a large amount of soil moisture was moving upward from the capillary fringe (Fig 3.3.6). Site 2's profile had a lesser degree of salinisation than site 3. A salt front had also formed at site 2 but did not decrease Ψ_t to the same extent as site 3.

Narrow saturated layers of soil water perched above the water table were observed at various depths between 2.3 and 3.0 m at sites 2 and 3 (Fig 3.3.6). At site 3 however, they tended to dry in February due to the effects of draw down. These moister soil layers decreased Ψ_m in these regions for all seasons and were slightly lower in chloride concentrations than many other regions of soil water. These soils had a larger proportion of quartz rich sands (30-55 %) in these regions that allowed for the transmission of groundwater above the water table.

Soil particle size analysis for all sites showed a broad layer of clays in the upper profile (0-0.7 m), ranging from 60 % clay to 35 % clay (Fig 3.3.5). This layer generally consisted of fine alluvial grey clay, and had a significant influence on Ψ_m , especially during summer as soil moisture decreased below $\sim 15 \text{ g g}^{-1}$. Moister layers below this clay rich band had a sandier texture (65-95 % sand) at (2.1 m – 3.4 m) for site 2 and 3 and Ψ_m were less negative accordingly. This layer however coincided with increased Ψ_o at these sites due to the upward movement of salt from the capillary fringe.

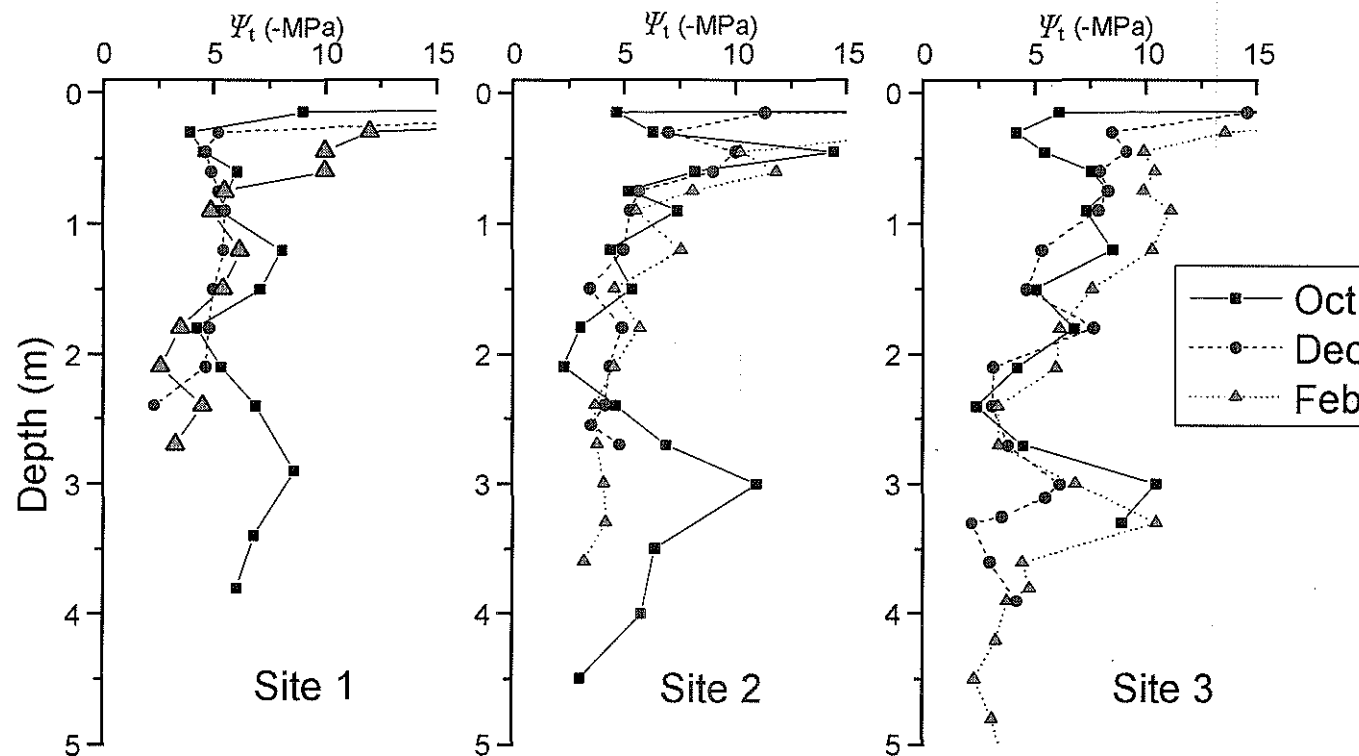


Figure 3.3.3: Ψ_t for all sites for October, December and February. All sites showed a decrease (more negative values) in Ψ_t towards February especially in the upper 1 m of the soil profile. Site 3 had very negative Ψ_t during February due to high salt concentrations in the upper profile.

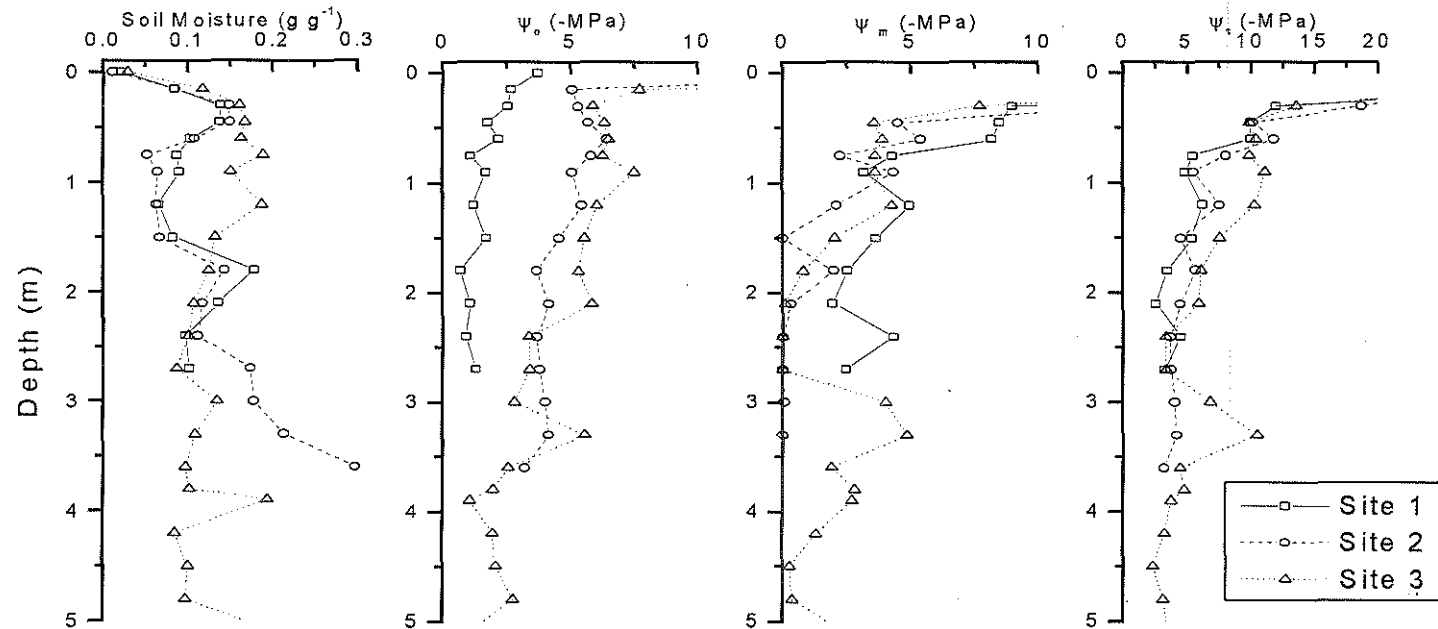


Figure 3.3.4: Soil water components (water content, Ψ_0 , Ψ_m and Ψ_t) between sites for February sampling period. Site 3 maintained moisture in the upper profile, whilst site 1 showed some drier soils below 0.45 m. Ψ_0 was more uniform at site 1 while site 3 had decreased Ψ_0 due to the formation of a salt front at approximately 1.0 m. Ψ_m was most negative at site 1 due to the dryness of this profile and higher clay contents.

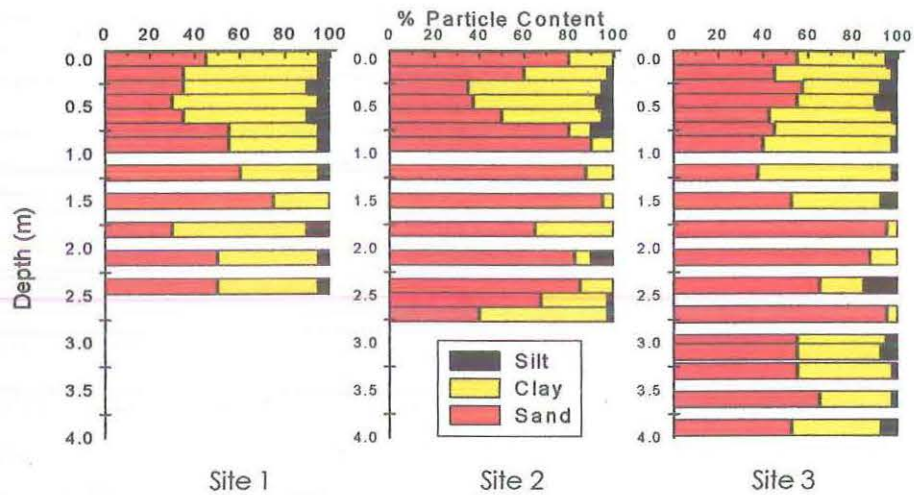


Figure 3.3.5: Particle size analysis for each site for December sub samples. All sites exhibited a similar clay rich band in the upper 0.7 m of the profile. Sites 2 and 3 contained coarse textured bands at various depths, while site 1 had a relatively uniform clay rich profile.

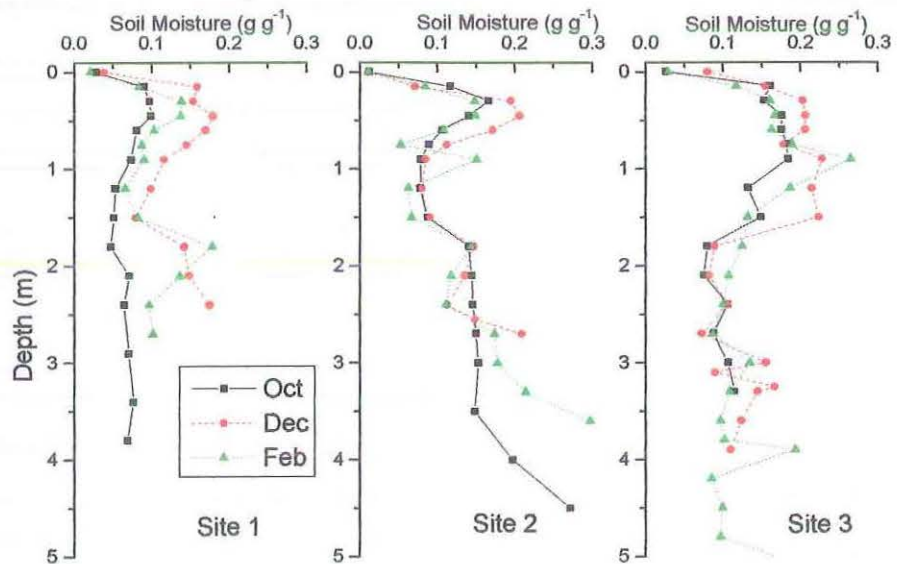


Figure 3.3.6 : Water content for all sites during October, December and February sampling. All sites had greater soil moisture during December and drier profiles in October and February. Note the spikes in soil moisture at site 2 (2.8 and 3.8 m) and at site 3 (3.0 m and 4.0 m) this increase in soil moisture is due to saturated layers of soil perched above the water table.

Water contents across all sites show a distinct wetting front in December and increased water contents. This was due to a rainfall event in mid-November when 32 mm fell over two days (Appendix 4).

3.4 Discussion

The Lake Toolibin sites investigated during this study showed temporal and spatial variation in soil water and salt conditions that are directly related to underlying groundwater hydrology and inherent soil qualities. These soil parameters evaluated salt and water movement and storage over the drying phase, and assessed availability of soil water in the root zone.

Site 1 (Low Level Salinity)

Initial analysis of site 1 using an EM 38 suggested that salt concentrations near the surface were a lot lower than at the other sites (section 2.7). The long history of groundwater abstraction at this site, resulted in greater depths to groundwater that suggested marked differences in the influences of saline groundwater at this site. This western region of the lake suffered extensive salinity when monitoring began in 1977, as groundwater levels were within 2.0 to 3.0 metres of the surface (Froend *et al.*, 1997). It is unclear how long groundwater levels at this site have been low enough to have little effect on vegetation, but these results showed low salt concentrations throughout the profile. The increased values of Ψ_o (more positive) component of Ψ_t supported these observations, and indicated that the soil solution was less concentrated in salts. This was also particularly evident in February as both sites 2 and 3 had Ψ_o in excess of -10 MPa at the surface, while site 1 was approximately -4 MPa (Fig 3.3.4). These site differences also indicated that any surface salts that were present in the upper profile were no longer limiting plant water uptake.

The most critical factor that explains the decreased levels of salt is that the greater depth to groundwater at this site, reduced the upward movement of salts via capillary action. This upward movement from a deeper water table would be less extensive because the moisture gradient required for capillary action will not be maintained at greater depths. Alternatively, at shallower depths to the water table, the moisture gradient is enhanced through plant water uptake and surface evaporation.

Downward seepage of groundwater (especially during summer) has also been demonstrated within the lakebed system (Martin, 1986), and this would help to flush salts deeper into the profile, provided there was little upward capillary movement. It was found that this profile (site 1) was dominated by Ψ_m , that tended to be more negative at the end of spring due to a below average rainfall in winter. Total soil water potential increased in December (less negative) by a significant rainfall event in late November, but most of this moisture was evaporated by February (Fig 3.3.3). The high proportion of clay in the profiles across all sites meant that Ψ_m was consistently more negative when water contents dropped to below $\sim 0.1 \text{ g g}^{-1}$. Additionally, the uniformity of higher clay contents in site 1's profile tended to accentuate the effect of Ψ_m as the soil dried. Ψ_t at site 1 may have also been over estimated in the drier months (October and February) as it has been suggested that Ψ_m and Ψ_o are not additive in a drying soil, because Ψ_m will dominate due to the effect of soil drying on root contact and the ability of plants to osmotically adjust, by using salts available in the soil (Shalhevet and Hsiao, 1986).

Sites 2 and 3 (Medium to High Level Salinity)

Osmotic potential at site 2 tended to be slightly increased than site 3, but had a similar salt front between 0.5 – 1.5m by February (Fig 3.3.4). The differences in soil water and salt conditions at site 2 and 3 can be attributed to groundwater histories and the presence of shallow groundwater levels during dry lakebed conditions. Groundwater levels in the past 5 years have been consistently higher at site 3, and draw down during summer and early autumn has been less extensive at site 3 (Fig 3.3.1). The presence of very shallow groundwater following recharge after winter has brought saline groundwater to within 0.3 m of the surface for four consecutive years at both of these sites. This movement deposits salt into clay rich horizons (0.1

– 0.7 m) where leaching is slow. In the following two years however, higher groundwater levels at site 3 and low winter rainfall resulted in greater salt accumulation at site 3 due to evaporation of discharged groundwater. The presence of shallow groundwater also explains the increased moisture contents at site 3 throughout the profile. Site 2 has obviously had lower groundwater levels in recent years, which restricted the movement of salt to lower regions of the profile and limit salt accumulation in the rhizosphere.

Adding to this process was the commencement of groundwater abstraction close to both sites in mid-2001, which affected rates of draw down but may have had little impact on salt concentrations at these sites due to the sporadic nature of the pumping regime and the already high concentrations of mobilised salts in these profiles.

The translocation of salt in the lakebed sediments is greatly influenced by the heterogenous soil layers particularly at sites 2 and 3, as highlighted by the particle size analysis and soil water content (Fig 3.3.5 and 3.3.6). Therefore it is important to relate salt movement to changes in soil hydraulic conductivity arising from different soil texture characteristics. Jolly and Thorburn (1993), recognised the importance of soil texture and characterising soil strata in modelling salt and water movement on the Chowilla floodplain. The authors found that using different texture classes in their models produced results closer to the observed data in relation to rates of salinisation.

The heterogenous nature of soil texture at site 2 and 3 permitted different rates of water and salt transport, as movement in sandier textured soils is faster than in soils with greater clay contents. However, the magnitude of groundwater movement through capillary rise is greater in fine textured soils due to the increased specific surface area of the soil medium. Peck (1979) highlighted this trend in calculating critical depths to groundwater in various soil types, and found that a greater critical depth were necessary in clay rich soils to maintain vegetation health. Leaching of salts from the surface was hindered by the common clay rich soils in the upper horizons found at each site. This created areas of very negative Ψ_t values from 0.10 – 0.75 m which were critical regions of the rhizosphere. Sites 2 and 3 also possessed layers of quartz rich sandy clays that tended to interrupt the clay rich profile at 2.0 –

3.0 m, resulting in some large deviations of Ψ_o within the profile that approached 0 MPa (Fig 3.3.4).

Site 2 was indicative of changing soil conditions as salt had begun to accumulate in the profile, which led to intermediate levels of salinity. Unlike site 1, fissures of groundwater were found in small perched systems, 0.1 – 0.2 m thick layers of saturated soil, in the more quartz rich sandy clay layers (Fig 3.3.6). These layers transmitted groundwater from deeper within the water table into shallower regions, allowing water and salt to be transported toward the surface by capillary action from these depths.

Site 3 was the most salinised site, with Ψ_i clearly dominated by Ψ_o . The greater moisture content in the upper horizons and the sandier sub soils maintained relatively low Ψ_m . During summer a salt front formed between 0.5 and 1.5 m and upward movement of saline groundwater, similar to that of site 2, transported salt into clay rich layers above these depths. It was evident that these perched systems were perhaps more significant in transporting salt than the capillary fringe of the water table because they were closer to the surface and the rhizosphere. The clay rich layers at 0.1 – 0.7 m were potential stores of salt from both these perched systems and previous salt loading from surface inflows. However it is evident from site 1 (where Ψ_o was relatively uniform with depth) that salt stored in the lakebed soils from previous inflow has not adversely affected water availability. It is the confounding influence of salts moving upward from saturated layers and the capillary fringe that led to a significant accumulation of salt.

The domination of Ψ_i by Ψ_o , has been found to occur in coastal wetlands such as mangrove fringe swamps (Lin and Sternberg, 1994). Salt accumulation via diffusion and evapo-concentration is in a dynamic equilibrium with leaching, as tidal sea water leaches concentrated surface salts further into the profile. This process is driven from the top down and therefore has limited relevance to this study involving shallow saline groundwaters. The processes described in other studies are of more relevance, because of the similarities in the nature of salt accumulation and movement from shallow saline groundwater (Jolly and Thorburn, 1993; Mensforth, 1995). Flooding

and leaching events in the presence of saline groundwater are considered necessary in maintaining plant water availability in these soils and was also true in this situation.

The site characteristics identified in this section can be highlighted using a simple schematic diagram (Fig 3.4.1), which places each site along a hypothetical time line of salinisation and remediation at Lake Toolibin. It is postulated that salinisation will increase dramatically when groundwater levels reach critical depths that may either lead to complete salinisation of the soil and possibly waterlogging or remediation through groundwater abstraction. In the case of site 1 this occurs over an extended time frame 10 – 15 years where by leaching processes are critical in removing salts in the profile. It must be stressed however, that this diagram simplifies the process on the lakebed and is based on only three site descriptions. It does however have implications for this sampling design in that this diagram allows for direct comparison between remediated and salinised sites, along a temporal scale.

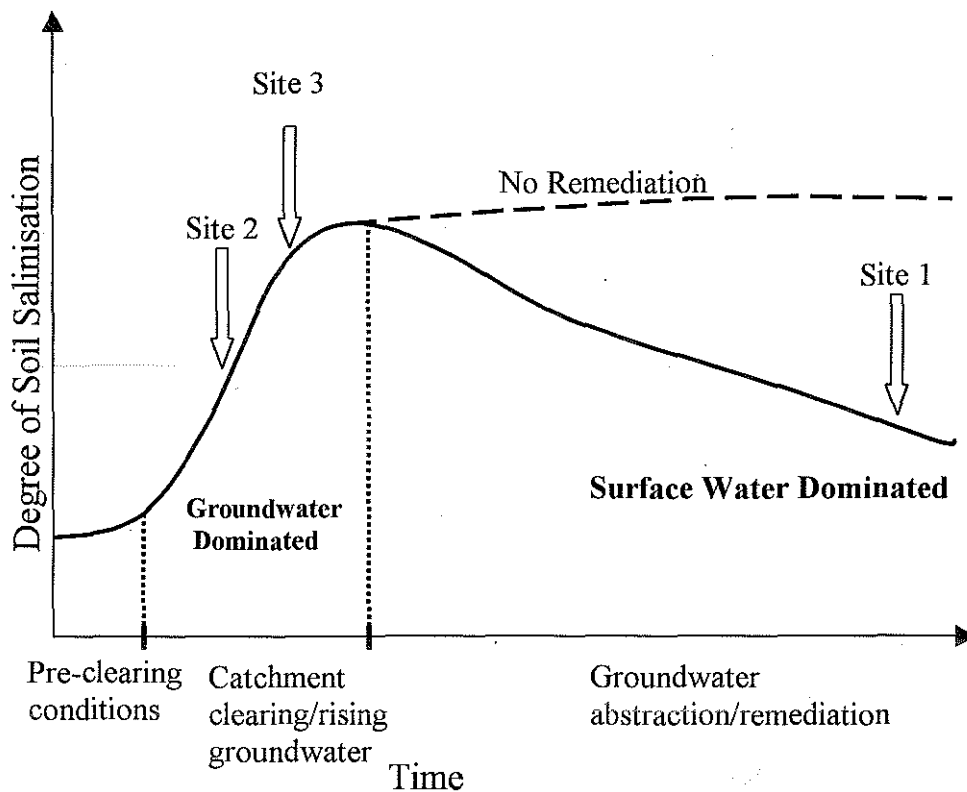


Figure 3.4.1: Schematic diagram representing the temporal processes of soil salinisation at any one location at Lake Toolibin during a drying period. Site 2 is undergoing salt accumulation and a rising groundwater, resulting in intermediate salinity levels. Site 3 is highly salinised, with a distinct salt front in the upper profile and tends to have higher water contents. Site 1 represents a site that has previously experienced high salinities, but because of remediation the profile is leached of some of those salts. Vertical dotted lines represent the changes in a groundwater dominated system and a surface water dominated system. The dashed line extending from the curve gives the likely scenario of salinisation with no remediation, which would lead to complete salinisation of the profile.

3.5 Conclusion

In this Chapter, the extent of soil water movement and salt accumulation within the rhizosphere has been evaluated over a drying period, by assessing variability in Ψ_t with depth at sites with contrasting soil conditions. Upward salt movement of saline groundwater is extensive over this period and is strongly driven by depth to groundwater, soil texture and the presence of significant perched systems that transmit groundwater above the water table. The magnitude of this salt accumulation will have adverse effects on lakebed tree species capacity to access water (within the rhizosphere) and will determine their ability to survive under these conditions.

Chapter 4

Plant Water Relations and Water Uptake in Response to Seasonal Drying

4.1 Introduction

Plant water uptake occurs in areas of the root zone where total soil water potential (Ψ_t) is greater (less negative) than plant water potential (Ψ_{plant}). Seasonal soil water fluctuations may require plant water uptake to occur at different depths of the soil profile to achieve this (Yakir and Yachieli, 1995; Thorburn and Walker 1993d). Coupled with this, salt movement caused by plant water uptake, evaporation, groundwater and surface water fluctuations, restricts water uptake by decreasing Ψ_t (more negative). Plants respond to moisture deficits by controlling water loss and limiting water use, through stomatal closure and increasing water use efficiency (rate of biomass accumulated relative to water lost). It is vital then to understand plant water uptake characteristics and water relations for plants with different exposures to salt and changing soil water availability, in order to quantify response of the individual tree and the plant's ability to adjust to seasonal fluctuations in water availability.

This Chapter will provide a detailed assessment of plant water status and will be incorporated into the analysis of soil water status (from Chapter 3) to provide a spatial indication of plant water availability within the rhizosphere over the drying period. It is assumed that all root activity and water uptake will be directed towards areas in the soil where soil water is physiologically available such that growth and photosynthesis can be maintained. Plant water status will also provide a good indication of relative water stress at each site and the ability of the plant to fulfil its water requirements. Plant water relations will also be assessed in terms of stomatal response and quantitative water use in order to understand the particular soil conditions that limit water use in this species when exposed to salinity. The ability

of *C. obesa* to control transpiration and maintain hydraulic conductivity within the xylem will be investigated to assess the ability of this species to control water loss when exposed to moisture deficits in the soil.

To ascertain discrete sources of water uptake, comparisons of stable isotope ($\delta^2\text{H}$) signatures between possible source waters (groundwater, rainwater, surface and sub-surface soil moisture) and plant xylem (twig) water will be made and the relative importance of each source will be determined. Temporal variation in these sources will identify the patterns of water uptake as soil conditions fluctuate in the rhizosphere as demonstrated by Chapter 3. By combining water source data with plant and soil water status, a plant water uptake model will give greater resolution in identifying patterns of plant water uptake.

4.1.1 Plant Responses to Salinity

Plants living in saline environments are exposed to a high concentration of soluble salts in both the soil and soil solution in which they grow (Flowers & Yeo, 1986). This affects the ability of the plant to absorb water from the soil surface through osmotic effects. Salt may also be absorbed into the plant leading to toxic effects. Munns (1993) stresses that osmotic effects arise immediately after the plant is exposed to considerable salt concentrations and ionic effects are secondary, and have an accumulative effect on plant growth (Munns, 2002; Munns, 1993; Munns & Termaat, 1986). Most salts in Australia are of marine origin and will therefore be comprised of Na^+ and Cl^- (Flowers and Yeo, 1986).

Plants can adapt to external stress by osmoregulating, a process whereby the internal osmotic concentration of the plant symplast is increased, thereby lowering Ψ_{plant} (Kozłowski and Pallardy, 2002). This regulation may require the production of osmoregulates (such as proline and glycinebetaine) or the absorption of salt from soil water so that a water potential gradient is maintained at the root-soil interface. The downside to such osmoregulates is that it diverts photoassimilates from active growth regions resulting in lower productivity (van der Moezel *et al.*, 1988). Salinity

induced osmotic stress is similar to water stress in that the physiological responses (stomatal closure, loss of turgor etc.) are almost identical.

Ion imbalances affect growth rates of many species through a reduction of leaf expansion and an increase in old leaf death (Munns, 1993). Exclusion or avoidance of salts at the root–soil interface can regulate the absorption of excess salts through reduced water use (Greenway and Munns, 1980). Salt intolerance in native species of *Eucalypt* and *Casuarina* species has been associated with high uptake of Na^+ and K^+ (van der Moezel *et al.*, 1988).

Directing salts into older senescent leaves is also postulated as an adaptive strategy to tolerate salinity (Munns, 1993; van der Moezel *et al.*, 1989). This mechanism may only limit salt build up periodically and minimise the salinity impact on the leaf cytoplasm. A reduction of leaf expansion is an initial response and may be caused by messenger signals from the roots to the shoot, having indirect effects on supply of assimilates or hormones to growing regions of the plant (Ortiz *et al.*, 1987; Munns & Termaat, 1986). However it has been argued that it is the build up of salt in the older leaves that leads to the plants demise (Munns, 1993). This is because salt accumulation is not generally found to occur in rapidly expanding tissues, as enlarging vacuoles are able to accommodate the incoming salts (Munns, 1993). Therefore salts are unlikely to build up in new shoots or root apices. A plant's ability to survive under sustained saline conditions will then depend on its ability to prevent salt from reaching toxic levels in older leaves through compartmentalizing salt into vacuoles and away from sites of transpiration and the senescence of older leaves. (Munns, 2002). Leaf area is ultimately reduced as a result, however accumulated salt is also lost in leaf drop.

Mechanisms to adapt to these stresses will seek to limit uptake of salt into the leaf cytoplasm. Transportation of salt out of the leaves is an exclusion strategy found in some *Atriplex* and Mangrove species (Sutcliffe, 1986). Salt is excreted through salt glands on the leaf surface or translocated in the phloem into salt bladders (Sutcliffe, 1986; Hill and Hill, 1976).

Waterlogging of the root zone is often associated with saline conditions, as areas affected by saline groundwater discharge are usually highly saline and often waterlogged for prolonged periods. There is much evidence to suggest that tolerance of waterlogged conditions is related to the production of adventitious root systems (van der Moezel *et al.*, 1988; Tang and Kozlowski, 1984; Sena Gomes and Kozlowski, 1980; Clemens *et al.*, 1978) although this relationship is not necessarily reliable (Pereira and Kozlowski, 1977).

There have been numerous studies involving *Casuarina* spp. in relation to salt tolerance and several of these have included *C. obesa* (van der Moezel *et al.*, 1988; Luard and El-Lukany, 1984). Screening trials conducted by van der Moezel *et al.* (1988), combined the effects of both salt and waterlogging using *C. obesa* and six *Eucalypt* species. *C. obesa* was found to be the most tolerant of both salt and waterlogging with little effect on growth rate. *C. obesa* excludes salt in younger growing shoots and directs Na and Cl into older shoots, and therefore maintains high growth rates (Aswathappa, 1986). Ratios of Ca/Na are also high, which is suggested to aid in the exclusion of sodium in saline conditions (Kent and Lauchli, 1984; Greenway and Munns, 1980). Tolerance of waterlogging in this species is attributed to the production of adventitious root systems and roots with aerenchyma (van der Moezel *et al.*, 1988). These root systems assist in providing a pathway of oxygen to the root and eliminate the production of toxic by products of anaerobic respiration such as ethylene (Blake and Reid, 1981). Among *Casuarina* species, *C. obesa* is amongst the most salt tolerant species and maintains higher water contents through lowering internal osmotic potential and regulating uptake of K^+ and Na^+ ions (Luard and El-Lukany, 1984).

The great body of knowledge on tolerance mechanisms related to salt tolerance generally stem from glasshouse trials involving seedlings or concentrate on particular life stages of the plant. Some researchers suggest that screening trials of this kind should involve entire life cycle histories and that there is no direct correlation between tolerance at germination and at later stages of seedling growth or maturity (Bell, 1999; Niknam and McComb, 2000). It is also obvious that comparisons of species in glasshouse and field environments are somewhat limited, as field

environments introduce a completely new dimension to plant water availability and salinity processes.

4.1.2 Mechanisms of Tree Water Use

The movement of water into and through a plant is a key process in the continued survival and growth of that plant. Tree water use, defined as optimisation of plant productivity within its physiological limitations, has important implications for soil water balance and a plant's ability to adjust to seasonal fluctuations in water availability. The soil-root-leaf-atmosphere continuum is influenced by many inherent properties of the plant and also site specific conditions occurring in the soil. Survival depends on the ability of a plant to maintain the movement of water upward from the root to the shoot by transpiration through conducting tissues and regulation of internal water potentials. The creation of a water potential gradient allows this movement to occur and the largest of these potential gradients is found to occur between the leaf and atmosphere (Monteith, 1995). Resistance is provided by stomata that may regulate the rate of water loss and CO_2 uptake and thus influence photosynthesis and growth.

Transpiration rate (E) is dependent on a number of influences inherent to the plant and the surrounding environment (Jarvis, 1981). For example leaf-to-air vapour pressure difference (VPD) in a purely passive system would determine transpiration rate (E). However stomata respond to VPD as well as other environmental variables such as soil water deficits and salinity to regulate transpiration and balance the amount of water lost relative to carbon gain. The contradictory requirement of stomata necessitates a pattern of stomatal conductance that compensates for the plant's requirements. Often stomatal closure will occur in the middle of the day while water demands are at a maximum and permit water loss in the morning and afternoon to maintain photosynthesis (Turner, 1986). During periods of drying in the soil, the resistance at the root soil interface may control water uptake and water stress and has been found to decrease the permeability of roots to soil water (Passioura, 1988). The ability of roots to actively penetrate towards sources of water may also determine transpiration and water use during dry conditions (Monteith, 1995).

Under saline conditions, the uptake of water into the transpirational stream becomes limited by osmotically imposed water deficits and a reduction in leaf area (Munns and Termaat, 1986). Water use is reduced through stomatal responses that may be regulated initially by hormonal messengers (eg abscisic acid) from the roots as a response to low potentials (Kefu *et al.*, 1991). By reducing water use, a plant avoids rapid accumulation of Na and Cl in its leaves and improve its water status (Munns and Termaat, 1986). The absorption of salts into the transpiration stream may bring salt to the expanding leaf, if it cannot be accumulated in the vacuole. This rapid accumulation of salt could result in a reduction of cell turgor and thus provide a signal for stomatal closure (Farquhar and Sharkey, 1982).

Transpiration rate and photosynthetic carbon uptake are tightly regulated under water limiting environments. It has been demonstrated in arid and semi-arid areas that plants must 'trade off' between these benefits of continued photosynthetic carbon gain and excessive water loss (Farquhar and Sharkey, 1982). Therefore the regulation of stomata and transpiration rates by plants in saline environments, is important in facilitating growth (Perera *et al.*, 1994).

Internal changes in cellular and xylem architecture is a critical response in plants as a result of drought conditions. Embolisms form in xylem lumens when xylem pressure becomes more negative than capillary forces in the pit membrane pores (Tyree and Sperry, 1989). As a result, embolisms can isolate portions of the tree and it has been hypothesised that a plant can sacrifice these embolised peripheries in order to maintain xylem conductivity in other branches and trunk (Zimmerman, 1983). Further adaptations such as small pit membrane pores within the xylem and conduits with smaller diameters have been hypothesised to reduce susceptibility to cavitation in the xylem. However, it is likely that these adaptations reduce hydraulic conductivity, which is considered to depress transpiration and growth rates (Farquhar, 1989; Franks and Farquhar, 1999).

Tausend (2000) examined the relationship between midday transpiration rate (E) and hydraulic conductivity of the soil to leaf pathway (G_l), based on the change in pressure across the transpiring pathway between pre-dawn and midday. G_l was

found to increase exponentially for a given E and supports the concept of coordination between stomatal control and hydraulic conductivity within the plant tissue. This is an important mechanism in saline and water stressed environments as it further reduces the risk of xylem embolisms. However tight stomatal control will limit photosynthesis and carbon assimilation.

4.1.3 Plant Water Status

Plants form a bridge in the gradient of water potential between soil and the atmosphere. As a result, water in xylem conduits is held under tension. The cohesion-tension theory suggests that the properties of water molecules and xylem conduits can sustain a continuous column of water even in tall trees (Tyree, 1997). Measurements of the water status of plants can provide insight into the water status of plants, particularly when assessed in conjunction with soil water potential.

$$\Psi_{\text{plant}} = \Psi_s + \Psi_p + \Psi_m + \Psi_g$$

The subscripts s, p, m and g correspond to solute, pressure, porous matrices and gravity respectively (Boyer, 1995). Variation in each component of Ψ_{plant} arises from external and internal gradients within the plant. Solute potentials will occur inside cells (symplast) and outside the cell (apoplast), however greater potential will exist within the cell. Potential forces due to gravity are often negligible in plants < 1.0 m. Matric potentials are dominant within the cell wall (apoplast), as cell wall architecture influences water movement in this region. Pressure potentials are based on volumetric changes within the cell. Negative solute forces generally balance positive pressure forces unless the cell is at full turgor. An equilibrium is established between the symplast and apoplast, with matric and solute potentials in the apoplast being equal to solute and pressure potentials within the cell.

Leaf water potential is seen as a reliable indicator of plant water status or Ψ_{plant} (Nadezhdina, 1998; Kramer and Kozlowski, 1983). This is because of nocturnal equilibration between Ψ_l and Ψ_{plant} . However in some instances, particularly in zones of high rainfall, significant disequilibrium between Ψ_l and Ψ_{plant} has been observed

(Donovan *et al.*, 2001; Crombie *et al.*, 1988). In this study it is unlikely that such disequilibrium will have occurred because the study site is located in a zone of relatively low rainfall. Leaf water potential can be used to estimate total cell water potential, based on a pre-dawn measure when transpiration has ceased. Midday Ψ_{plant} measures the change in cell water potentials, when water use and transpiration may be highest. It provides an indication of the plants minimum potential to extract water from the soil and the threshold of plant water uptake.

4.1.4 Plant Water Source Determination

Recent advances in stable isotope analyses of hydrogen and oxygen has greatly assisted our understanding of spatial and temporal plant water uptake. While analysis of stable isotopes of hydrogen and oxygen is a powerful tool in its own right, by combining this technique with more traditional plant water relations studies, definitive patterns of plant water uptake can be determined.

Plant water sources depend on the distribution of roots and the availability of water in the rhizosphere (Ehleringer and Dawson, 1992). This will vary seasonally especially in arid and semi-arid environments where water limitations determine the magnitude of water uptake. Characterisation of water uptake in trees using stable isotope analysis can distinguish between unsaturated zone, groundwater and surface water sources (Ehleringer and Osmond, 1989; White *et al.*, 1985). Stable isotope studies have been important in understanding the functioning of root systems, their seasonal dynamics and long-term water requirements (Thorburn *et al.*, 1993b; Ehleringer and Dawson, 1992; White *et al.*, 1985).

There are some clear advantages of stable isotope analysis over other methods of water source determination. It is a non-destructive technique, thus allowing for continued measurements over a study period. It is a quick and robust method and combined with soil data, accounts for heterogeneity of soils and requires very little water for analysis. Unlike other isotopic tracer techniques, it relies on natural variations in hydrogen and oxygen isotopes and therefore does not alter hydrological properties of the soil. Moreover, it is more definitive than comparisons of plant

water availability using Ψ_r and Ψ_{plant} , especially when groundwater is accessible to the plant.

The natural abundance of deuterium ($\delta^2\text{H}$) and oxygen 18 vary within different mediums and can be detected in small yet significant amounts. Stable isotope studies rely on certain conditions in the environment, where variation in isotopic signatures arise making it suitable for comparison in root systems (White *et al.*, 1985). These variations arise from atmospheric effects, geography and the processes of water movement through the soil (Dawson and Ehleringer, 1993; Thorburn *et al.*, 1993c; Barnes and Allison, 1988). Atmospheric factors affect isotopic compositions through phase transitions in the upper atmosphere and lithosphere and the transport and movement processes of precipitation (Barnes and Allison, 1984). Variations in rainwater occur across seasons and latitudinal and elevational gradients (Ehleringer and Dawson, 1992; Craig, 1961).

Evaporative fractionation occurs at the atmospheric-soil interface, as lighter isotopes become vapourised first, enriching the remaining water in $\delta^2\text{H}$ oxygen 18. Evaporative enrichment also occurs during transpiration from the leaf surface and may affect stem and leaf water close to the site of evaporation (Zimmerman *et al.*, 1967). Recharge of groundwater through surficial materials such as soils and rock has been shown to cause variation in isotopic signatures (Barnes and Allison, 1984). This means that groundwater signatures are usually distinct from isotopic signatures in the surface and sub-surface soils. Isotopic variation also arises in this sub-surface region (between the surface and saturated groundwater layers) known as the unsaturated layer. Zimmerman *et al.* (1967) showed that enrichment of $\delta^2\text{H}$ in soil water occurs exponentially with depth, leading to discernible differences throughout the profile, especially in the top 0.1 - 0.2 m.

The calculation of $\delta^2\text{H}$ (used in this study) signatures within plant and source water is based on the ratio $\delta^2\text{H}$ and ^1H (R) compared to a standard water source V-SMOW (Vienna standard mean ocean water) (Craig, 1961).

$$\delta^2\text{H} \text{‰} = (R_{\text{sample}} / R_{\text{V-SMOW}} - 1) \times 1000 \text{ (‰)}$$

Assumptions

Stable isotope investigations are based on some fundamental assumptions that require testing and validation before any field trials can accurately uncover information on plant water sources. Firstly, the species that is to be studied must satisfy the assumption that upon uptake into the roots, water is not fractionated in heavier or lighter isotopes. This has been tested using glasshouse validation trials, whereby seedlings are flushed and grown in enriched water of known isotopic composition (Lin and Sternberg, 1993; Thorburn *et al.*, 1993b). The stems are then harvested and isotopic signatures are compared to that of the enriched water to compare possible differences. In most species these trials have shown no fractionating processes in the root zone. However Lin and Sternberg (1993), tested a number of coastal halophyte species growing in fresh and saline waters and found that discrimination of $\delta^2\text{H}$ in red mangrove (*Rhizophora mangle*) did occur during periods of increased transpiration. They attributed this process to the ultrafiltration of salt occurring in the roots.

The second assumption states that that no significant evaporatively enriched water is transported to other parts of the plant. This is generally tested in the field, whereby different parts of the tree are sampled including: petioles; stems; branches; trunk sapwood; and roots (Mensforth, 1996). Isotopic signatures for each plant part are compared for variations to the xylem sap in the trunk assumed to be the mixture of source waters.

The basis of isotopic comparison assumes then that xylem water sampled below regions of evaporative enrichment in plants that do not discriminate isotopes while absorbing water, will provide an integrated measure of water uptake from all regions in the root zone that are extracting water (Ehleringer and Dawson, 1992). Sampling root water may provide a more detailed understanding of soil-root-canopy water pathways and provide further validation in assessing water source data (Thorburn *et al.*, 1993a).

4.1.5 Plant Water Uptake Strategies

Plants living in water-limited environments have long been studied to understand patterns of water uptake and rooting. However, previous excavation and coring studies of root systems have been somewhat limited, because they may only provide a one point in time estimate of rooting patterns, and root presence does not necessarily preclude root activity (Ehleringer and Dawson, 1992). Recent advances in techniques to assess these patterns have made significant advances in these areas, as more continuous field based studies reveal the true nature of plant water relations. By combining soil and plant water status data, stable isotope analysis and various methods of assessing water use, water uptake strategies can be assessed with little disturbance to the rooting zone and to the plant. Seasonal adjustments in water uptake can also be readily assessed, providing insights into water source utilisation during periods of variable soil moisture. Rooting density, structure and distribution are recognised determinants of the plants ability to access water within the root zone (Neuman *et al.*, 1994; Passioura, 1983; Bresler and Hoffman, 1986).

Riparian Systems

Riparian systems represent complex water uptake processes due to the addition of a fourth possible water source, stream water. Dawson and Ehleringer (1991) investigated tree water use in a semi-arid riparian ecosystem, using stable isotope investigations of five tree species with access to stream water. Their results did not support their hypothesis, that streamside trees would use stream water. Instead most trees used deeper areas of soil moisture to fulfill their summer water requirements. Responses in *Eucalyptus camaldulensis* to varying access to stream water in a Murray River anabranch system were investigated by (Thorburn and Walker, 1994). They found that soil moisture and particularly groundwater were vital and reliable plant water sources, as opposed to stream water which only supplemented riparian trees' water requirements due to its limited supply and fluctuating levels. This suggests that in some cases groundwater hydrology is of greater importance to even riparian vegetation, even when these sources are more saline (Thorburn *et al.*, 1992).

Phreatophytic Communities

Water uptake by phreatophytic vegetation is characterised by a dependence on groundwater supplemented by seasonal inputs of surface flows and precipitation. However, in many cases the degree of their dependence is unclear (Zencich *et al.*, 2002). Alterations of groundwater levels by anthropogenic influences such as abstraction, surface water diversions and augmentation increases pressure on vegetation relying on groundwater, necessitating further research into groundwater dependent ecosystems. Busch *et al.* (1992) highlighted the importance of groundwater to obligate phreatophytes (solely dependent on groundwater) in a floodplain environment. They attributed the decline of *Salix* spp. and *Populus* spp. to a lowering of water tables by multiple hydrologic uses, and exclusion by invasive facultative *Tamarix* spp (opportunistic groundwater user).

Coastal Environments

Mangroves must maintain favourable water relations in environments where they are subject to salinity gradients that vary seasonally (Ball, 1988). Red Mangroves (*R. mangle*) were found to rely heavily on surface waters but this also subjected them to stress due to salinity variation of available water (Lin and Sternberg, 1994; Lin and Sternberg, 1992; Naidoo, 1985). Seasonal salinity variation of source water creates stresses in these populations as pre-dawn water potentials responded to these changes in salinity (Lin and Sternberg, 1994). This growth form lacks a deep taproot and has a shallow distribution, with prop and drop roots extending only to shallow depths in the soil (Gill and Tomlinson, 1977). This rooting morphology is well developed for water uptake at shallower depths and adapted to waterlogged and anoxic conditions in the soil.

Saline Environments

The presence and mobility of salts within the profile alter water uptake patterns through osmotic potentials created by salt ions. Salt movement from groundwater sources will inhibit growth and the plant will seek to avoid highly saline zones by shifting uptake to fresher areas. The ability of the plant to do this however, is

dependent on its rooting morphology, the availability of other sources of water and the location of a salt front or capillary fringe.

Field trials involving tall wheat grass *Agropyron elongatum* growing in a moderately saline environment highlighted the dynamic shift in water uptake as seasonal fluctuations in soil moisture concentrated salts into the upper regions of the rhizosphere (Bleby *et al.*, 1997). Water availability due to salt accumulation and soil dryness affected water source utilisation that was determined using $\delta^2\text{H}$ analysis and soil/plant water potential data. It was found that this species utilised groundwater during summer and transferred uptake to surface soils in winter when salts were diluted by seasonal rainfall.

Analytical models using data from the River Murray anabranch system, produced general trends in uptake patterns that are relevant in many field situations (Thorburn *et al.*, 1995). They showed that groundwater depth and salinity were important variables influencing uptake and predicted time scales of whole profile salinisation and vegetation decline. Plant water uptake above a water table will cause drying in the immediate area around the roots and promote an upward movement of salts toward the roots (Thorburn *et al.*, 1995). Restriction of plant available moisture will occur as plants shift uptake above the salt fringe and in the process continue the salinisation of the sub soil.

Often saline environments will have an annually fluctuating groundwater system that requires seasonal adaptations to changes in soil water conditions. Mensforth *et al.* (1996) studying *Melaleuca halmaturorum* in a saline swamp showed that root water uptake was a seasonally dynamic process whereby the rooting system adapted to both moisture deficits and waterlogging in the soil by the concentration of root growth into suitable zones for water uptake.

4.1.6 Spatial and Temporal Scales

Understanding both groundwater and surface water fluctuations and their influence upon water uptake, within a temporal scale is of great significance to this study. The

time scale in which salt accumulates and is leached often allows tolerant species to survive in saline areas. However, once this dynamic equilibrium is altered, salt accumulation may exceed the rate of leaching causing plant death and ecosystem change. For example, these processes influencing Mangrove spp. in a tidal flat may operate on a daily time scale. Receding tidal waters leave salt to accumulate in surface sediments through convection until the rising tide leaches these salts out of the mangrove's rhizosphere by upward diffusion (Passioura, 1992). An annual cycle of this process can be seen in the example of *M. halmaturorum* on an inter-dunal flat, as groundwater fluctuations tend to accumulate and leach salt seasonally. Winter rainfall is critical in leaching salts that are concentrated in soil water during summer.

On a broader time scale, the accumulation and leaching of salts is defined by large flooding events and salt accumulation by vegetation on the River Murray floodplain (Holland, 2003; Jolly *et al.*, 2002; Jolly and Walker, 1996). Alterations to the flow regime of the River Murray has meant that leaching processes by flood events have become less frequent and shallower groundwaters have allowed salt accumulation to occur at a faster rate. This time scale is of the order of 15 – 20 years until complete salinisation of the profile under the present conditions of this system (Dawes, 2002; Walker, 1993).

Spatial scales in terms of water uptake and vegetation response will depend on the specific objective or research question. Often vegetation response involving salinity has focused on community or population dynamics in order to predict or understand the magnitude or pattern of change within the ecosystem. This may have important implications for the assessment of community or population viability but has limited scope in correlating physical characteristics inherent in the system. More recent investigations have focused on the process scale dynamics focussing on the interaction of local physical attributes of soil and hydrology with vegetation response at the individual and stand level. Holland (2003) extended the investigation of the 'patch' scale processes toward the landscape and regional scales in characterising Blackbox (*Eucalyptus largiflorens*) population response to groundwater discharge in the lower reaches of the River Murray floodplain environment. This demonstrates the application of research at this level to a broader context.

4.2 Methods

4.2.1 Plant Water Status

Plant water status was determined using leaf water potential (Ψ_{leaf}) and was measured with a Scholander-type pressure bomb (3005, Irricrop Technologies, Santa Barbara, California). Ψ_{leaf} was measured on twigs with the needle like cladodes intact, and it is assumed that these represented the leaf component of the plant. Ψ_{leaf} was measured in two phases, pre-dawn (Ψ_{pd}) and midday (Ψ_{md}) on a seasonal basis (late October, 2002; mid-December, 2002; February, 2003). Ψ_{pd} generally represents the soil water potential in the vicinity of the active root zone, since (E) at this period is essentially zero (Boyer, 1995). Midday measurements of Ψ_{leaf} were taken to represent the time of day when E is likely to peak.

Four trees per site were sampled for Ψ_{pd} and Ψ_{md} during each sampling period, and a single diurnal measurement for pre-dawn, mid-morning, midday and mid-afternoon was made in December. A freshly cut stem is promptly placed upside down in the pressure chamber lid that is sealed with a rubber bung and screwed on to the pressure chamber. Compressed air is fed into the chamber via a regulator until water beads or sap are seen on the cut stem surface. This point is noted on the pressure gauge and represents the end point. The end point is equivalent to a measure of the tension in the xylem because of the continuous liquid phase extending into the cell walls (Scholander *et al.*, 1965).

Site and seasonal differences in Ψ_{pd} were evaluated using a repeated measures ANOVA with a significance level of $\alpha = 0.01$. Season was classified as the repeated measure and specific parameter testing was used to test individual differences between specific sites and seasons.

4.2.2 Stomatal Conductance (g_s) and Transpiration (E)

A steady state null balance porometer (Li-cor model 610, Lincoln Nebraska) was used to measure transpiration rate (E) and stomatal conductance (g_s). The needle shaped cladode surface of *C. obesa* meant that a square aperture cap with meshing was used to clamp the leaves. A group of needles were clamped to cover the

aperture cap and allow for accurate readings based on 4 cm² leaf area. After clamping the cladode surfaces, the null balance needle was zeroed, and a reading was recorded for transpiration and stomatal conductance.

Transpiration rate and g_s were recorded at four trees per site (two readings per tree) over the course of the field study. Mid-morning, midday and mid-afternoon readings were taken for each sampling time to plot stomatal response and water loss over the course of the day. Leaf temperature measurements were also made at each tree and ambient humidities adjusted on the porometer at each site to allow for changes in conditions while sampling.

Site and seasonal differences in g_s were evaluated using a repeated measures ANOVA with a significance level of $\alpha = 0.01$. g_s was analysed for stomatal response as it provides a closer measure of the efficiency of the plant to lose water rather than just transpiration flux. Season was classified as the repeated measure and specific parameter testing was used to test individual differences between specific sites and seasons.

Apparent leaf area-specific hydraulic conductance of the soil to leaf pathway (G_t) was calculated according to Tausend et al. (2000):

$$G_t = E / \Delta \Psi$$

where E is the instantaneous transpiration rate at midday and $\Delta \Psi$ is the difference between the total soil water potential (Ψ_t) and midday leaf water potential (Ψ_{md}) on the same day of measurement of E . Total soil water potential was estimated from Ψ_{pd} .

Daily transpiration rates (E) values were converted to a daily rate of transpiration and plotted with G_t . This data was fitted to a logarithmic curve to determine the nature of this relationship.

4.2.3 Water Use Technique

Assessment of water use in woody plants has had important implications for understanding individual water relations, which has also been scaled to measure whole stand and catchment water relations.

Sap flow techniques introduce a tracer into the sapwood of plants to measure its movement through the sapwood. It has advantages over other techniques in that it is portable, easily automated and provides continuous data with high time resolution. Techniques involving plant chambers are generally not as effective as they may alter the plant's microclimate and generate low time resolution.

The heat pulse, or compensation method was first used in plant water relations studies by Huber (1932) to measure xylem sap velocities (Marshall, 1958). This method relies on the relationship between water flux rates through the sapwood, when a heat pulse is applied to the xylem. A sap flow velocity can be calculated based on the heat flux, which can be converted to transpirational water loss. Recent developments to this method have improved the accuracy of measurements through the analysis of wounding effects (caused by probe implantation in the sapwood) and low flow conditions (Barrett *et al.*, 1995; Hatton and Greensdale, 1992).

Water Use using Heat Pulse Velocity Technique

Tree water use at each site was measured using sap flow loggers and probes (Greenspan, Warwick Queensland) based on the heat pulse technique. The two probe sets consist of three 1.98 mm probes, having two thermistors, equally spaced, that fire heat pulses every 30 minutes. The time elapsed between the firing of the heat pulse and its movement to the centre probe is used to calculate a velocity. These velocities are stored on site by the sap flow logger until retrieval.

Two sets of sap flow loggers were installed at each site for all sampling times and remained inserted in the tree for approximately 10 days. Probes were installed using a jig to ensure correct placement of drill holes and to prevent probes bending when inserted. Heat pulse tests were conducted on all trees at each sampling time to

identify active sapwood (Appendix 5). This enabled probes to be positioned such that average sap flux velocities (sapwood area specific) could be calculated.

Retrieved data was downloaded, edited for errors and then converted to water use measurements, using a spreadsheet developed by Hatton (1990), based on the weighted average technique for the calculation of sap flow velocity (Swanson, 1981). Individual tree characteristics are incorporated into this spreadsheet and were calculated using the following methods.

The percentage or fraction of wood, water and air in the sapwood matrix was calculated on a dry and wet weight basis after a portion of the sapwood was hole sawed from a tree at each site (Appendix 6). A wounding width experiment was conducted to determine the effect of probe placement on the surrounding sapwood (Appendix 7). Sapwood and heartwood radii were determined by diameters at probes and by using heat pulse tests to determine area of active sapwood (Appendix 5). Water use was then calculated for $L \text{ day}^{-1}$ using the spreadsheet and normalised using sapwood area to sap flux density ($\text{ml cm}^{-2} \text{ hr}^{-1}$).

4.2.4 Water Source Determination

Areas of plant water uptake in the root zone were determined by comparing stable isotope ratios of deuterium ($\delta^2\text{H}$) in non-photosynthetic plant tissues, soil water, groundwater and rainwaters. To do this in the field the assumptions associated with this technique were tested in both glasshouse and field trials.

Glasshouse Validation

The glasshouse validation aimed to test the assumption that water taken up in the root zone does not undergo fractionation of $\delta^2\text{H}$. $\delta^2\text{H}$ had never been analysed in *C. obesa* before so it was necessary that this assumption be tested thoroughly under controlled conditions.

C. obesa seedlings, approximately two years old growing in a soil vermiculite mix were used in the validation experiment. The three treatment waters were prepared with pure $\delta^2\text{H}$ and NaCl. Treatment one consisted of doped water of 720 ‰ with no NaCl added. Treatment two consisted of doped water of 720 ‰ with a NaCl concentration of 20 dS m⁻¹. Treatment three consisted of doped water of 720 ‰ and a NaCl concentration of 30 dS m⁻¹. Each treatment water was shaken vigorously for half an hour to allow full dispersion of $\delta^2\text{H}$ and dissolution of NaCl. Six seedlings were used for each treatment and were flushed with their appropriate treatment five times before being sealed. Paraffin wax was heated to a malleable temperature and poured on to the surface of the potting soil, with stems wrapped in parafilm to avoid stem damage. Parafilm was also wrapped around the edge of the pot and wax to ensure a reliable seal. This seal prevented any evaporation and therefore any possible fractionation of soil water that would skew results. The seedlings were then placed in tubs and the treatment waters were poured in, to a depth of approximately 5 cm. Added to the surface of the treatment waters was silicon oil to prevent any evaporation from the tubs. All water levels were noted on the edge of the tubs before being placed in a glasshouse at constant temperature and humidity. After five days, when approximately half of the treatment waters had been taken up into the plants or transpired, the seedlings were harvested. Two stem samples (approx. 10 x 80 mm) were taken toward the base of each seedling. Two main taproot samples (approx. 10 x 50 mm) were taken at the same time along with a soil sample. All plant samples were wrapped in cling wrap and transferred to centrifuge tubes and soil samples in specimen jars and all samples were then frozen at -16 °C. Treatment waters and tap water were also sampled for $\delta^2\text{H}$ analysis. All $\delta^2\text{H}$ signatures in soil water, root xylem water and stem xylem water were compared using a one-way ANOVA with a significance level of $\alpha = 0.05$.

Field Validation

A field validation experiment was conducted at Lake Toolibin at the start of the sampling period in October. This experiment aimed to determine $\delta^2\text{H}$ variability within tree water and the extent to which evaporatively enriched water in the leaves may be transported to other parts of the plant. This also helped to define suitable sampling points on the tree for future sampling.

Two trees were selected at site 1 for this experiment with similar vigour and foliage cover. Small twigs (5-10 mm in diameter), larger twigs (10-15mm in diameter) primary branches and trunk sapwood were sampled at mid-morning and wrapped in cling wrap and stored at -16°C . $\delta^2\text{H}$ signatures in twig, large twig, branch and trunk xylem water were compared using a one-way ANOVA with a significance level of $\alpha = 0.05$.

Deuterium Assessment of Seasonal Water Uptake

Four trees at each site were selected for $\delta^2\text{H}$ sampling based on access to foliage and representative of each site's tree health and size. Four replicates of each tree were taken at four cardinal points around the tree to account for spatial variability and all samples were taken between 10:00 hrs and 12:00 hrs. Twigs of approximately 10 x 80 mm were cut and wrapped in cling wrap and placed in centrifuge tubes and promptly transferred to the portable freezer for storage at -16°C .

A soil corer was used to obtain sub samples throughout the soil profile at each site. The sampling of soil sub samples was done simultaneously (same depths) to other soil sampling (section 3.2.2). Freshly cored samples were placed in specimen jars and sealed and transferred to a portable freezer on site. All samples collected in the field sampling and glasshouse validation under went cryogenic distillation to extract sufficient water for analysis (Thorburn and Walker, 1993c). All samples were then analysed using a VG SIRA 9 mass spectrometer with an estimated precision of ± 2 ‰. Samples are expressed as $\delta^2\text{H}$ ratio in parts per thousand (‰) relative to V-SMOW (section 4.1.4).

4.3 Results

4.3.1 Plant Water Status

Pre-dawn leaf water potential indicated a general decrease (more negative values) over the study period (Fig 4.3.1). Both season and site were significant factors influencing Ψ_{pd} , however the effects of season on all sites were of similar magnitude. Site 1 individuals were not significantly different for any season, but were different to both sites 2 and 3 ($F=11.45$, $p<0.01$, $df=15$). Site 3 had lowest Ψ_{pd} reaching ~ -7 MPa in February. Significant differences did occur between October and December ($F=9.76$, $p<0.01$) and seemed to change slightly between December and February (not significant).

Diurnal Ψ_{leaf} in December showed little change in Ψ_{md} and Ψ_{pd} especially at site 2 and 3 (Fig 4.3.2). Site 1 showed some variation (0.45 MPa) between Ψ_{pd} and Ψ_{md} with Ψ_{leaf} decreasing towards mid afternoon (-3.93 MPa). Site 3 showed little variation up until mid-afternoon where there was a decrease in Ψ_{leaf} to -7.5 MPa. Differences in Ψ_{leaf} between Ψ_{pd} and Ψ_{md} highlighted seasonal trends in stomatal regulation (Fig 4.3.3). Site 1 had larger differences between Ψ_{pd} and Ψ_{md} throughout the study. Site 3 had a dramatic decrease after October and Ψ_{pd} remained similar to Ψ_{md} during summer.

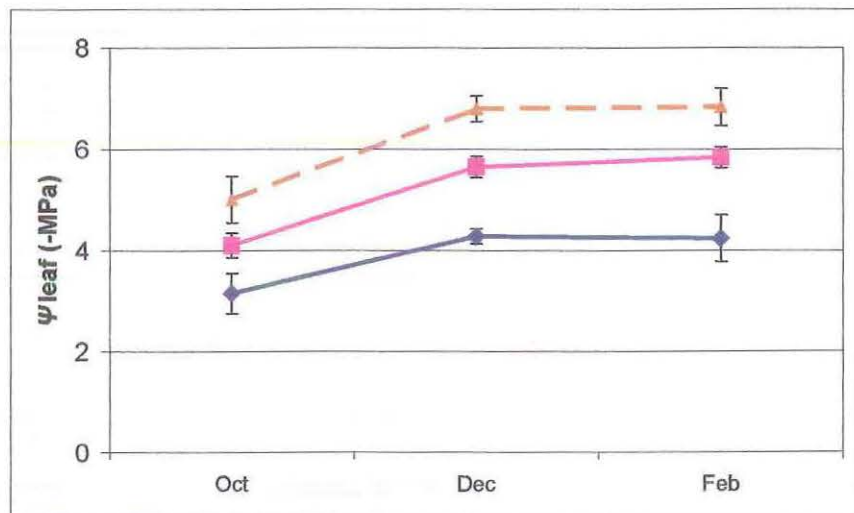


Figure 4.3.1: Pre-dawn leaf water potentials (Ψ_{pd}) for October, December and February. Site 1 (\diamond), showing less negative Ψ_{pd} , than site 2 (\blacksquare) and site 3 (\blacktriangle). All points represent mean \pm standard error ($n=6$).

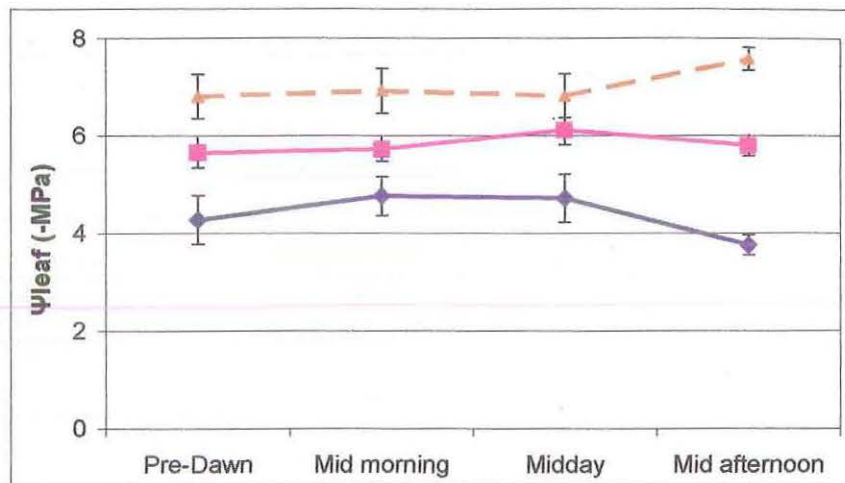


Figure 4.3.2: Diurnal shift in Ψ_{leaf} during the December sampling period. Site 1 (♦) displays less negative Ψ_{leaf} throughout the day than site 2 (■) and site 3 (▲). Site 3 shows little variation during the day until mid afternoon. All points represent mean \pm standard error ($n=6$).

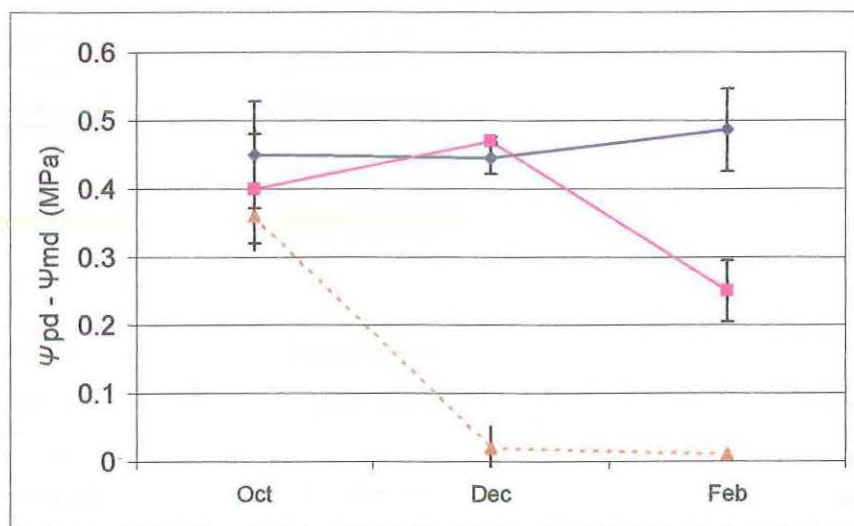


Figure 4.3.3: The difference between Ψ_{pd} and Ψ_{md} ($\Psi_{\text{pd}} - \Psi_{\text{md}}$) for October, December and February. Large differences in $\Psi_{\text{pd}} - \Psi_{\text{md}}$ are found at site 1 (♦) and site 2 (■) whereas site 3 (▲) shows very small $\Psi_{\text{pd}} - \Psi_{\text{md}}$ for December and February. All points represent mean \pm standard error ($n=6$).

4.3.2 Transpiration Rate (E) and Stomatal Conductance (g_s)

Stomatal response appeared to be dependent on site and season with both these factors being significant ($F=16.78$, $p<0.01$, $df=15$) (Fig 4.3.4). All sites except site 3, tended to follow similar patterns in stomatal response over the study. Mid-morning g_s for all seasons indicated individuals at site 1 consistently having higher g_s . Significant differences were found between site 1 and sites 2 and 3 ($F=14.56$, $p<0.01$), yet each site was influenced by season in the same way. Sites 2 and 3 had depressed g_s throughout the study that indicated very tight stomatal control. December saw a maximum in g_s values for the sampling period for all sites and a sharp decline for February.

Daily courses of transpiration in December showed a peak at mid-morning for all sites before tailing off until mid-afternoon (Fig 4.3.5). Once again, site 1 had the highest transpiration rates, consistently throughout the day.

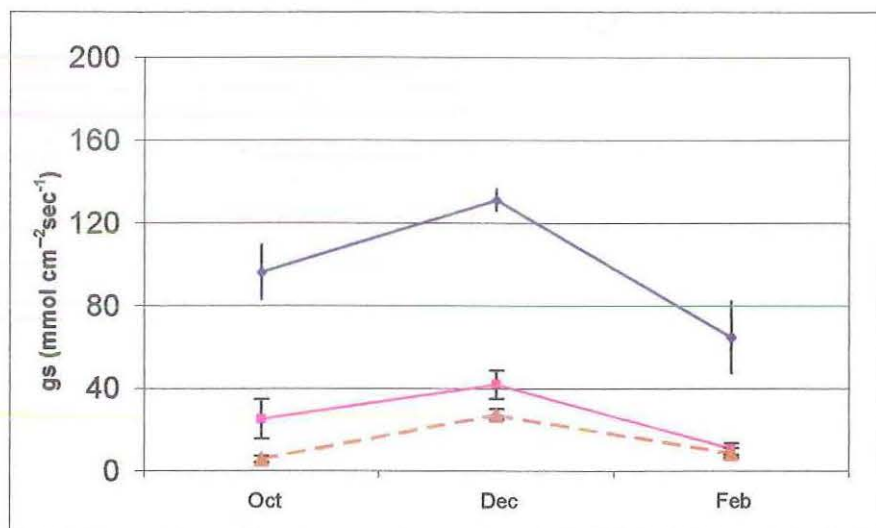


Figure 4.3.4: Stomatal conductance (g_s) for mid-morning measurements in October, December and February. Site 1 (\diamond) has consistently increased stomatal conductance indicating less stomatal control. Site 2 (\blacksquare) and Site 3 (\blacktriangle) showed decreased levels indicating tight stomatal control. All sites tended to peak in stomatal conductance during December. All points represent mean \pm standard error ($n=8$).

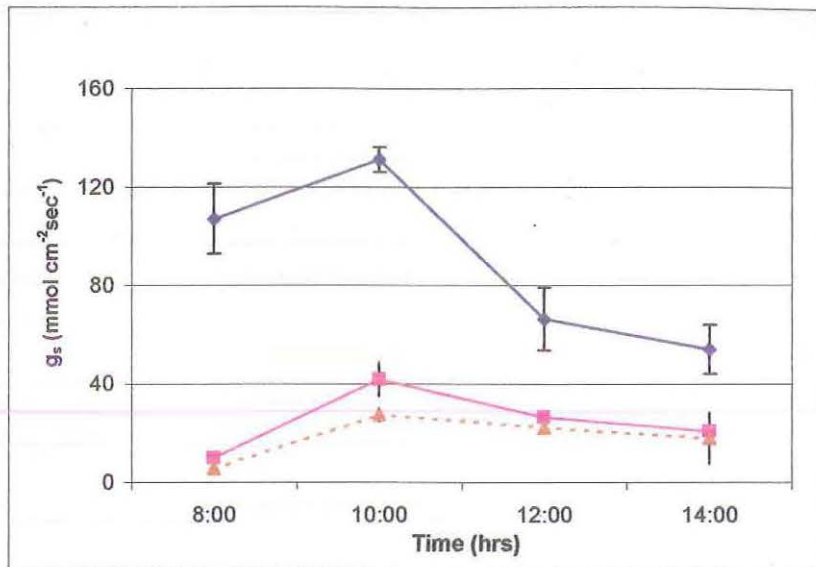


Figure 4.3.5: Daily course of stomatal conductance (g_s) for one day during December sampling for Site 1 (\diamond), site 2 (\blacksquare) and site 3 (\blacktriangle). All sites show a peak in g_s at mid-morning. All points represent mean \pm standard error ($n=8$).

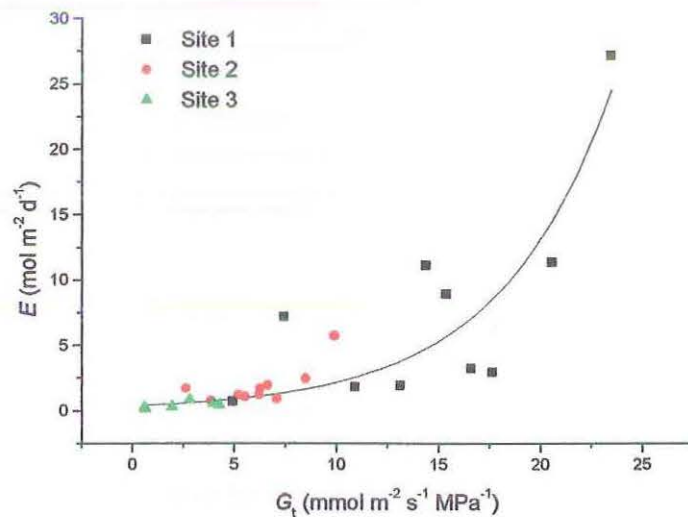


Figure 4.3.6: Daily transpiration rate (E) as a function of apparent hydraulic conductance of the soil to leaf pathway (G_t) for *C. obesa*. Note that plants growing at site 1 generally exhibited a higher apparent hydraulic conductance than the other sampled sites and that this corresponded to a higher daily transpiration rate. The fitted line is an exponential growth function: $y = 0.35e^{x/5.52}$ where $y = E$ and $x = G_t$ ($r^2 = 0.80$; $P < 0.05$).

Daily transpiration rate (E) was exponentially related to the apparent hydraulic conductance of the soil to leaf pathway (G_t) (Fig 4.3.6). Plants growing at site 1 generally displayed the highest G_t and E relative to plants growing at site 2 and site 3. There appears to be a grouping of sites within the scatter plot, with site 3 occupying areas of low E and low G_t and site 1 tending to occupy areas of high E and G_t .

4.3.3 Water Use

The vegetation at the various sites across Lake Toolibin, appeared to exhibit different trends of water use during the study. At site 1 sap flux density appeared to remain somewhat consistent across seasons, with a slight peak in flux during December (Fig 4.3.7). Sap flux density (February) in mid-summer at this site was four times greater than site 2 and 3. Site 2 sap flux density tended to decrease during the study with fluxes only slightly higher than site 3 by mid February. However, in October site 2 had the highest water use of approximately $250 \text{ ml cm}^{-2} \text{ day}^{-1}$. Site 3 sap flux density tended to increase in December and rapidly decreased by February to below $40 \text{ ml cm}^{-2} \text{ day}^{-1}$.

Analysis of diurnal patterns of water flux ($\text{L } \frac{1}{2}\text{hr}^{-1}$) showed water use reaching a maximum around 10:00 – 11:00 hrs during December (Fig 4.3.8). Site 1 appeared to have a more defined diurnal sap flux than site 2 and 3, which were more erratic. Daily sap flux at all sites started at similar times but site 1 appeared to maintain some sap flux later in the day.

Comparisons of water uptake before and after a rainfall event in February illustrated the shift in diurnal sap flux patterns following increased soil moisture (Fig 4.4.9). This rainfall event occurred on the 15/02/03 and 16/02/03 and 53 mm was recorded at Lake Toolibin (Appendix 4). At site one there was a definite increase in daily sap flux immediately after rain and sap flux occurred for a longer period during this time. Due to low sap flux in February for both sites 2 and 3 there was not such a clearly defined change between sap flux before the rainfall event and after.

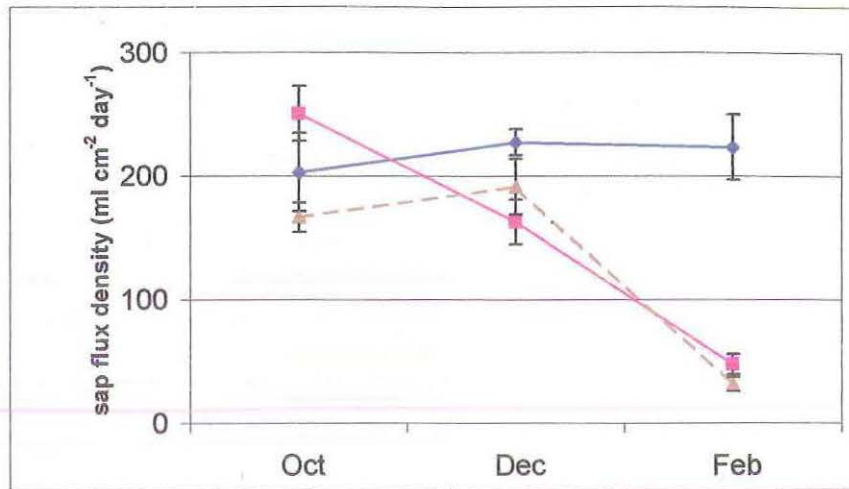


Figure 4.3.7: Sap flux density (based on sapwood area) for October, December and February (averaged over 5 days per season). Site 1 (♦) shows relatively constant sap flux density across seasons, site 2 (■) indicates a general decrease during the sampling periods and site 3 (▲) shows a slight increase in December and a sharp decrease for February. All points represent mean \pm standard error ($n=10$).

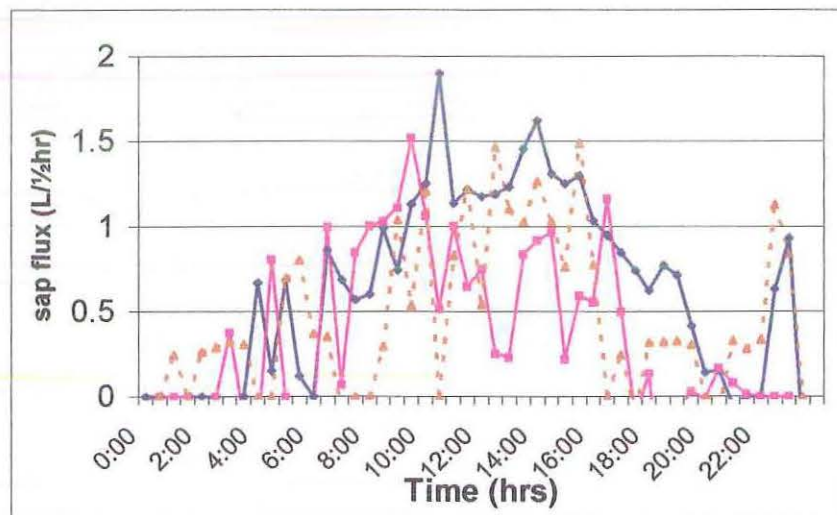
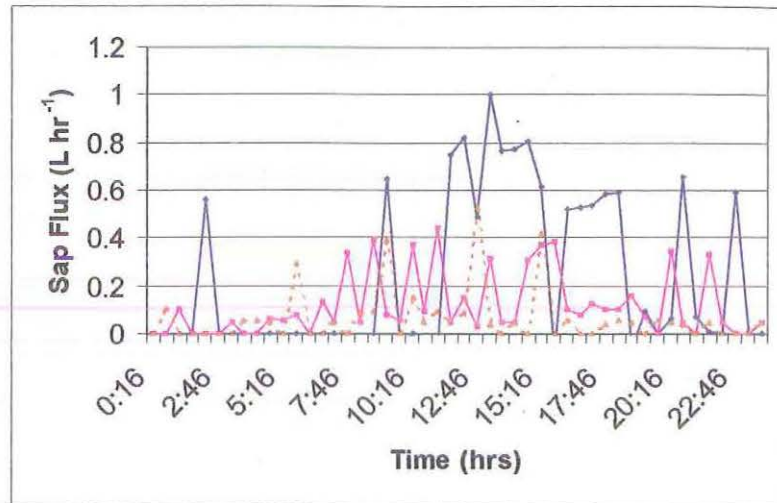


Figure 4.3.8: Diurnal sap flux for each site (one tree per site) for 15/12/02. Site 1 (♦) shows the highest sap flux during daylight hours with a peak around 11:00 hrs. Site 2 (■) and site 3 (▲) indicate greater fluctuations in sap flux during the day.

(a)



(b)

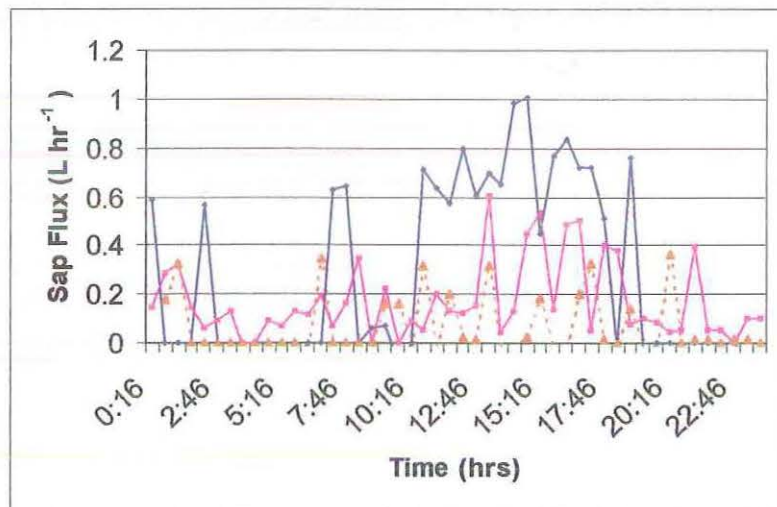


Figure 4.3.9: Diurnal sap flux during two days in February(14/02/03 and 17/02/03)(one tree per site). (a) 14/02/03 represents sap flux before a rainfall event when soil conditions were drier. (b) 17/02/03 represents sap flux one day after two days of rain. Site 1 (♦) shows distinct increase in both magnitude and duration of sap flux throughout the day. Sites 2 (■) and 3(▲) have slight increases however low sap flux conditions makes it difficult to accurately determine a shift in water use.

4.3.4 Plant Water Availability Model (based on Ψ_{pd} and Ψ_t)

The upper 1 m of the soil profile is assumed to be crucial to *C. obesa* for its water requirements. The rooting depth for this species was estimated by Froend (1983) to be between 0.6 – 0.9 m and this is supported by observations of root presence in the soil cores taken during this study. Fine roots were evident at depths to 0.9 – 1.1 m but root presence did not occur beyond these depths. This rooting depth is expected for this species as wind-felled trees on the lakebed show a root system highly concentrated in the upper 0.5 m and they exhibit an absence of any major taproots (Appendix 8).

Total soil water potential (from chapter 3) was combined with Ψ_{pd} to provide an indication of plant water availability with depth at all sites during the sampling period (Table 4.1). Site 1 seemed to have limited matches with the top 2.0 m of the profile over all seasons, however soil water potential (dominated by Ψ_m) might be over estimated for this site. There was a definite trend in this data in relation to shallower depths of soil moisture becoming unavailable to the plant with the onset of summer drying conditions. The available moisture was 0.45 – 0.6 m in October but was confined to 0.9 m by February.

Site 2 and 3 also showed a similar pattern, however site 3 had the most important depths unavailable (in terms of plant water uptake) by February with only depths below 1.8 m accessible to the plant.

Table 4.1: Regions in the soil where Ψ_{pd} and Ψ_t match within the profile, based on the assumption that the plant will equilibrate with regions of water uptake and similar Ψ_t overnight. These depths give an indication of plant water availability over three seasons.

Season	Site 1	Site 2	Site 3
October	0.45 – 0.6 m	0.15; 1.3 – 2.4 m	0.2 – 0.4 m; 1.5 m and 2 – 2.7 m
December	0.75 – 1.7 m	0.75 – 2.7 m	1.2 – 1.5 m; 2.0 – 2.8 m
February	0.9; 1.7 – 2.7 m	0.9 – 3.6 m	1.8 – 3.0 m

4.3.5 Assessment of Seasonal Water Sources

Glasshouse validation experiment results showed no significant change in soil, twig or stem xylem $\delta^2\text{H}$ signatures (Appendix 9). Field validation results suggested some movement of evaporatively enriched water to other tree parts but may be insignificant for this study (Appendix 10).

Comparisons of all source waters (soil, groundwater and rainwater) across sites during October indicated water uptake occurring in the surface and subsurface soils. For site 1 twig values matched soil values at depths between 0.15 - 0.6 m (Fig 4.3.10). Site 2 only matched in the upper most layer of 0 - 0.15 m and site 3 matched at 0 - 0.45 m. Twig $\delta^2\text{H}$ values at sites 2 and 3 were also similar to that of rainwater and groundwater, which suggested uptake of water from both sources (groundwater and rainwater). Enrichment processes have also altered the surface and subsurface soil water $\delta^2\text{H}$ signatures, creating differences in twig $\delta^2\text{H}$ and soil $\delta^2\text{H}$ values.

In December twig $\delta^2\text{H}$ values seemed to be consistent at greater depths at site 1 (0.75 m and 2.4 m) and also overlapped with rainwater values (Fig 4.3.11). At site 2 twig values tended to match soil $\delta^2\text{H}$ values at depths of 0.1 - 0.6 m and 1.5 - 2.6 m, with groundwaters just within the range of twig values. A small spike of enriched soil $\delta^2\text{H}$ values at 0.15 m at sites 2 and 3 were related to the leaching of rainwater into the profile that caused a deviation of more depleted $\delta^2\text{H}$ values lower in the profile. However at site 3 twig $\delta^2\text{H}$ values did not coincide with any soil values with depth. February also displayed a similar pattern at site 3 with very enriched twig $\delta^2\text{H}$ values that did not match any source (Fig 4.3.12).

February $\delta^2\text{H}$ values for site 1 were consistent with depths of 0.3 - 0.9 m, while site 2 twig $\delta^2\text{H}$ values matched with 0.15 - 0.3 m, 0.75 m and 3.0 m, with groundwater $\delta^2\text{H}$ values close to that of the twigs. Soil $\delta^2\text{H}$ at this site also reflected soil properties in the soil, with the upper clay rich layer exhibiting distinct signatures to the more sandy clay layers beneath. This was most evident in December with a shift in surface values at 0.75 m (coinciding with the change soil texture) to more enriched values below this.

Table 4.2: Groundwater and rainwater $\delta^2\text{H}$ (‰) values for October, December and February at all sites. Samples were taken from abstraction bore for site 1 and freshly cored holes at sites 2 and 3.

Season	Site 1(g/w)	Site 2 (g/w)	Site 3 (g/w)	Rainwater
October	-15.91	-19	-19.65	-21.12
December	-16.47	-20.80	-21.45	-1.23
February	-16.89	-21.54	-22.42	None

Two rainfall events in mid-September and mid-November provided the two sources of rainwater (Table 4.2). Comparisons of $\delta^2\text{H}$ signatures for this rainwater showed a large variation.

Groundwater values for all sites and seasons indicated enriched $\delta^2\text{H}$ values at site 1 compared to sites 2 and 3 that had similar values (Fig 4.3.10 – 4.3.12). This was attributed to the large depth to groundwater at site 1 and the complex flow patterns beneath the lakebed, which may have altered the isotopic signatures of the groundwater (section 2.4.2). Groundwater $\delta^2\text{H}$ values generally did not match any twig $\delta^2\text{H}$ values of site 1 or any of the soil $\delta^2\text{H}$ values suggesting this was not a possible source of water involved in water uptake (Table 4.2). Groundwater values however did show similarity with soil at sites 2 and 3 across all seasons. This is in agreement with data from chapter 3 where it was implied that groundwater was a major component of soil water in the profiles at these sites. It is not established within these results to what degree groundwater is transported upward through the profile as soil $\delta^2\text{H}$ values were matched with groundwater at many different depths throughout these sites.

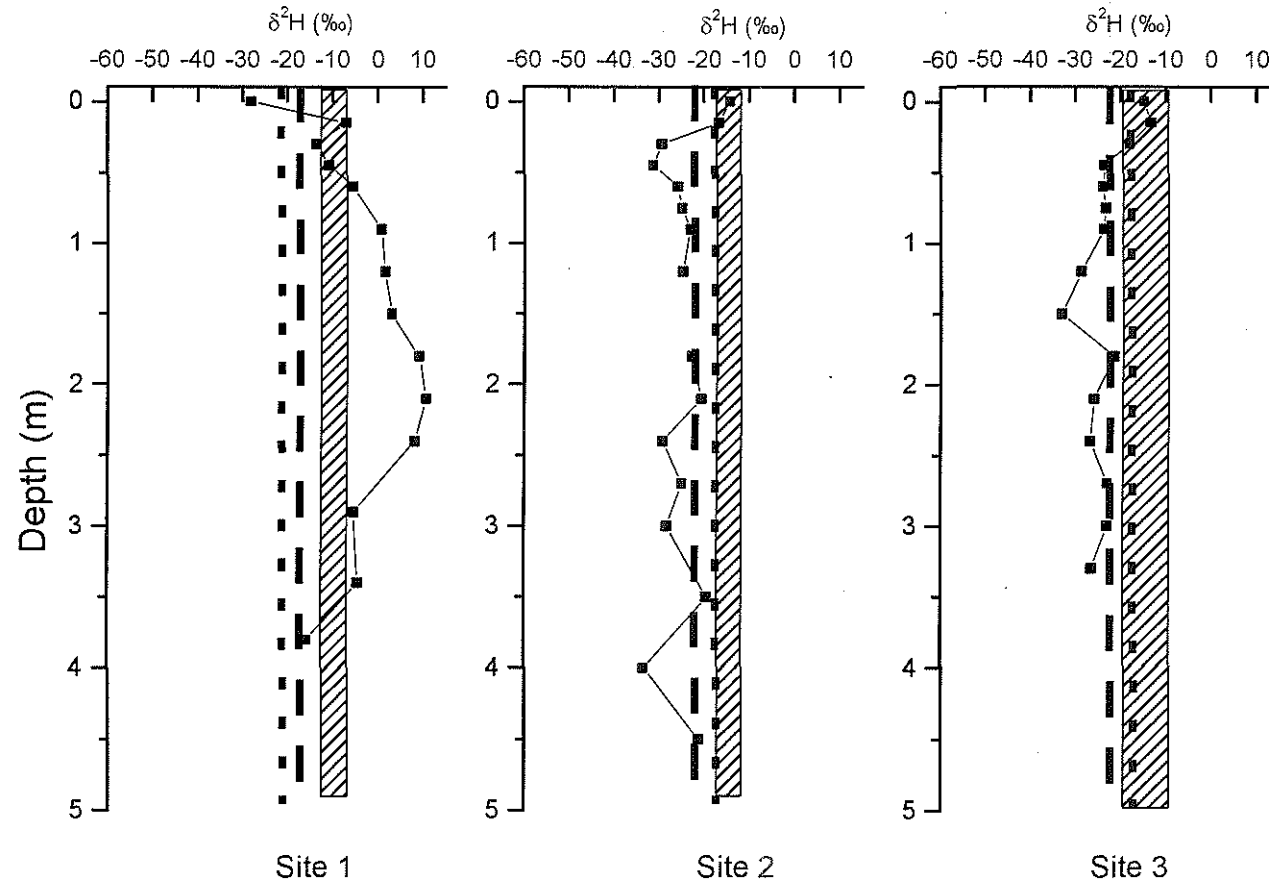


Figure 4.3.10: $\delta^2\text{H}$ values of soil water (■), twig xylem (▨) (these values span mean \pm se, $n = 16$) groundwater (—) and rainwater (.....) for all sites during October. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values indicates possible water source within the profile. Site 1 shows a match at 0.15 – 0.6 m, site 2 shows a match at 0 – 0.15 m and site 3 at 0 – 0.3 m. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3.

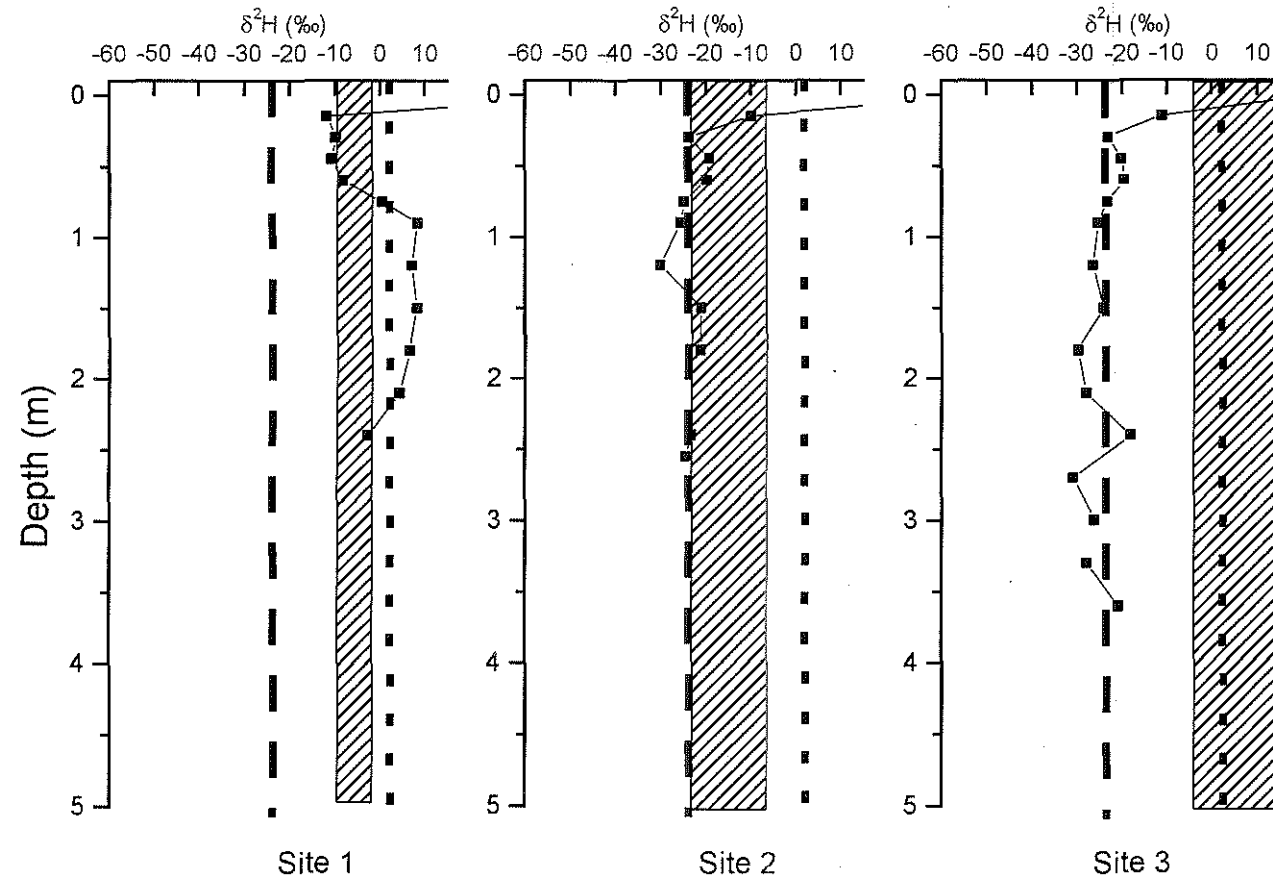


Figure 4.3.11: $\delta^2\text{H}$ values of soil water (■), twig xylem (▨) (these values span mean \pm se, $n = 16$), groundwater (---) and rainwater (.....) for all sites during December. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values indicates possible water source within the profile. Site 1 shows a match at 0.75 and 2.4 m, site 2 shows a match at 0.15 – 0.6 m and site 3 had no matches. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3. Site 1 shows distinct soil $\delta^2\text{H}$ values to groundwater $\delta^2\text{H}$.

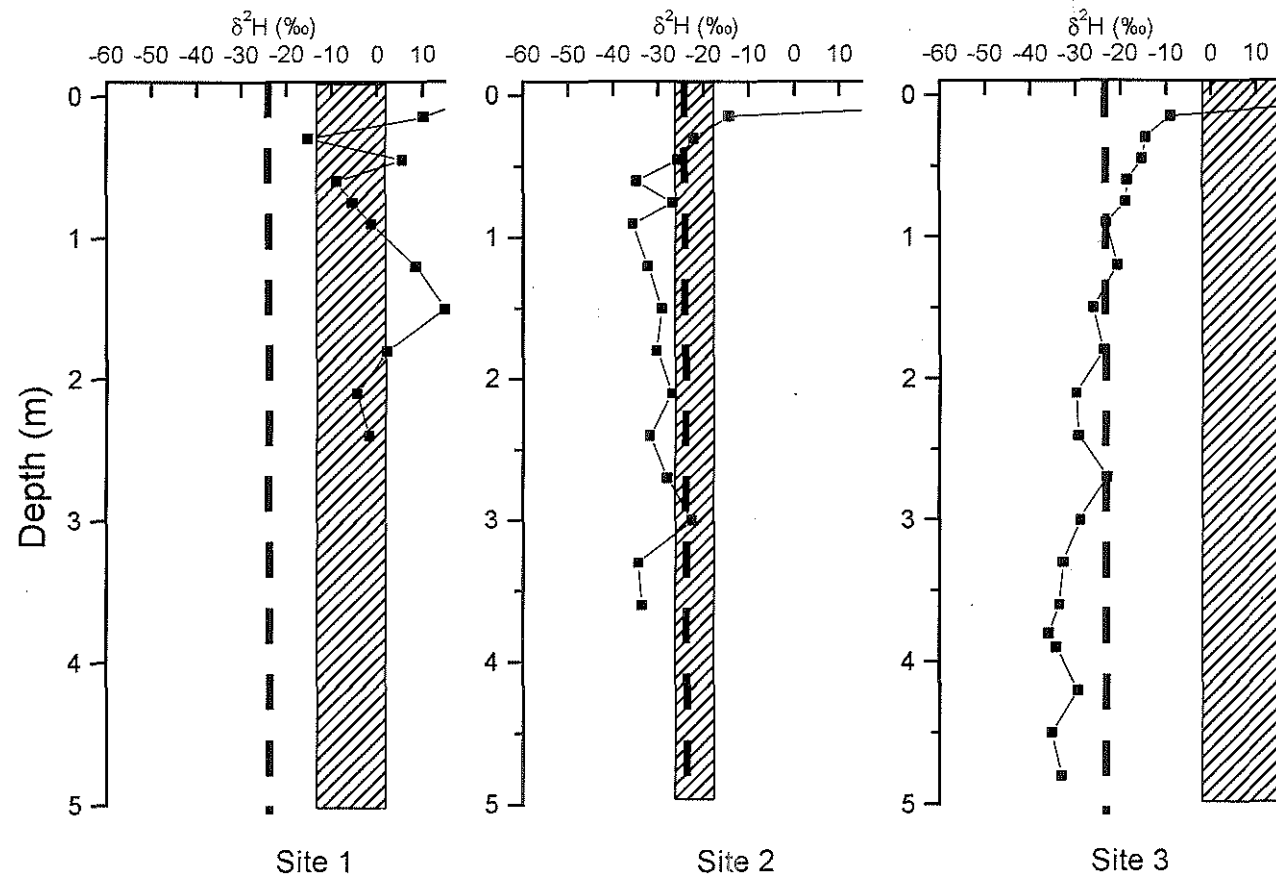


Figure 4.3.12 : $\delta^2\text{H}$ values of soil water (■), twig xylem (▨) (these values span mean \pm se, $n = 16$), groundwater (—) and rainwater (.....) for all sites during February. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values indicates possible water source within the profile. Site 1 shows a match at 0.3 – 0.9 m, site 2 shows a match at 0.15 – 0.3 m, 0.75 m and site 3 had no matches. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3. Site 1 shows distinct soil $\delta^2\text{H}$ values to groundwater $\delta^2\text{H}$.

4.4.6 Plant Water Uptake Model

The incorporation of soil and plant water potential data with the $\delta^2\text{H}$ data added greater definition to inferences concerning water sources. The plant water uptake model for October, December and February tended to narrow down possible depths of water uptake (Fig 4.3.13 – 4.3.15). For example $\delta^2\text{H}$ data indicated uptake occurring at a depth region of 0.5 m – 0.9 m, however plant water availability data indicated that only at depths of 0.7 – 0.9 m was water physiologically available to the plant. The model also provided information on the availability of water at more than one depth, which may not apply to this species due to its shallow root system.

It is clear that at site 1 water uptake occurred at 0.45 - 0.6 m during October (Fig 4.3.13) and moved deeper into the profile to 0.7 m in December where only a small depth was available to the plant (Fig 4.3.14). Water uptake continued to occur at deeper depths to 0.9 m by February (Fig 4.3.15). This water uptake model inferred that uptake was occurring generally at one depth and this depth increased over the study period.

Application of the model to site 2 showed uptake occurring at 0.15 m in October, down to 0.75 m or 1.5 m – 2.6 m by December and for February this model indicated that uptake could occur at 0.75 m, however at this depth ψ_{plant} is only slightly more negative than ψ_1 . For site 3 uptake occurred at 0.3 m for October but by December and February there were no matches in the model.

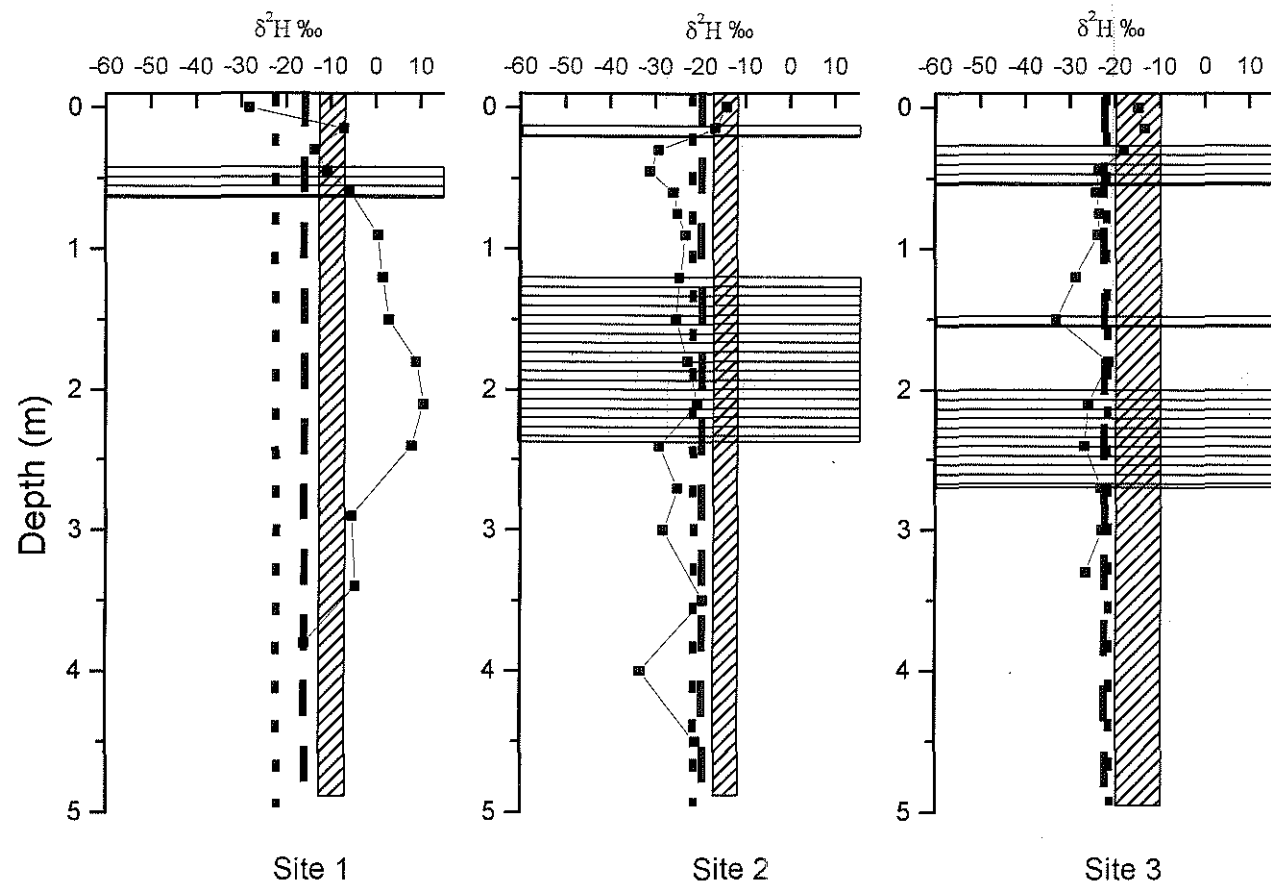


Figure 4.3.13: $\delta^2\text{H}$ values of soil water (■), twig xylem (▨), groundwater (— —) and rainwater (····) for all sites during October combined with water potential data to provide a model of plant water sources and availability. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values and horizontal shading (≡) indicates where Ψ_{plant} and Ψ_t match possible water sources within the profile. Site 1 shows a match at 0.45 – 0.6 m, site 2 shows a match at 0.15 m and site 3 at 0.3 m. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3.

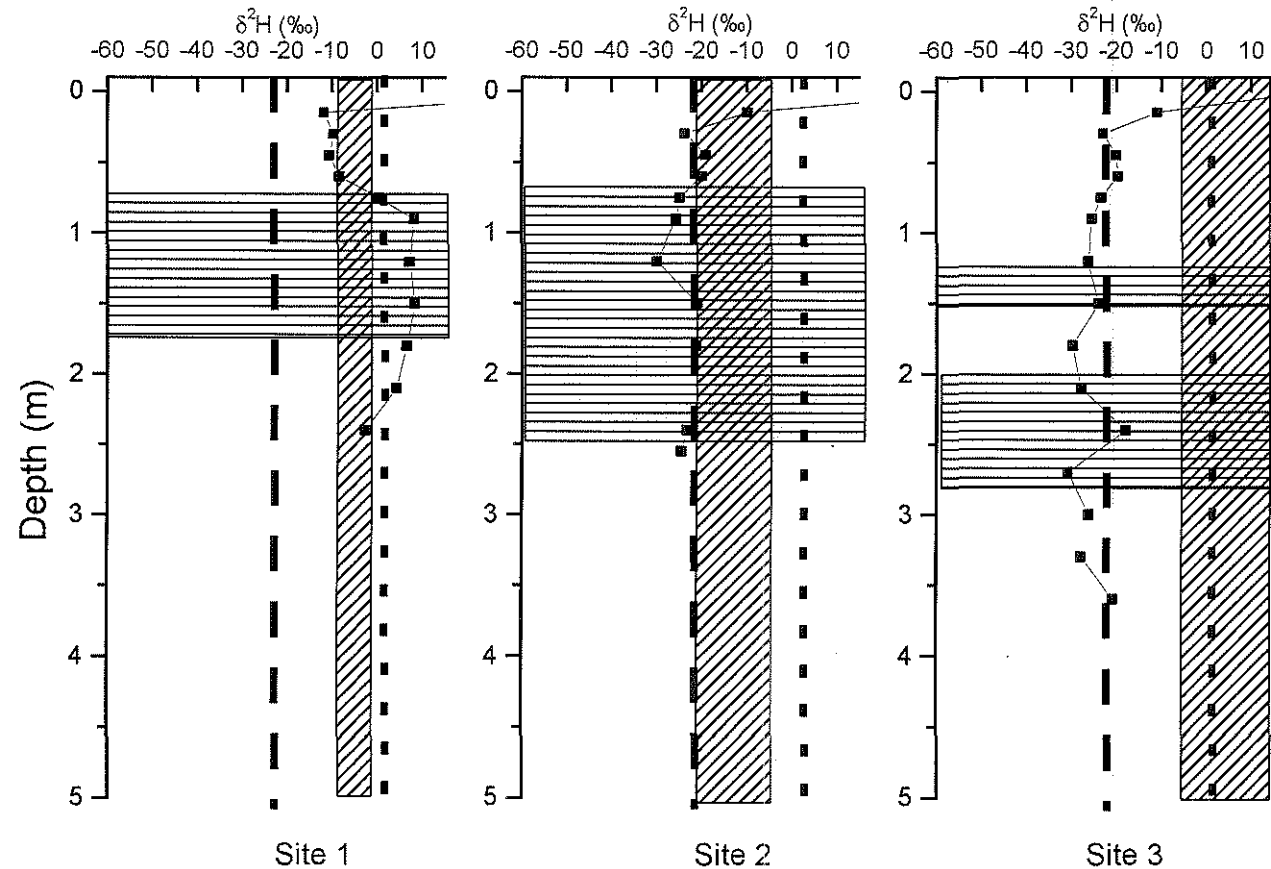


Figure 4.3.14: $\delta^2\text{H}$ values of soil water (■), twig xylem (▨), groundwater (— —) and rainwater (···) for all sites during December combined with water potential data to provide a model of plant water sources and availability. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values and horizontal shading (▨) indicates where Ψ_{plant} and Ψ_t match possible water sources within the profile. Site 1 shows a match at 0.75 m, site 2 shows a match at 0.75 and 1.7 – 2.3 m and site 3 there were not matches. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3.

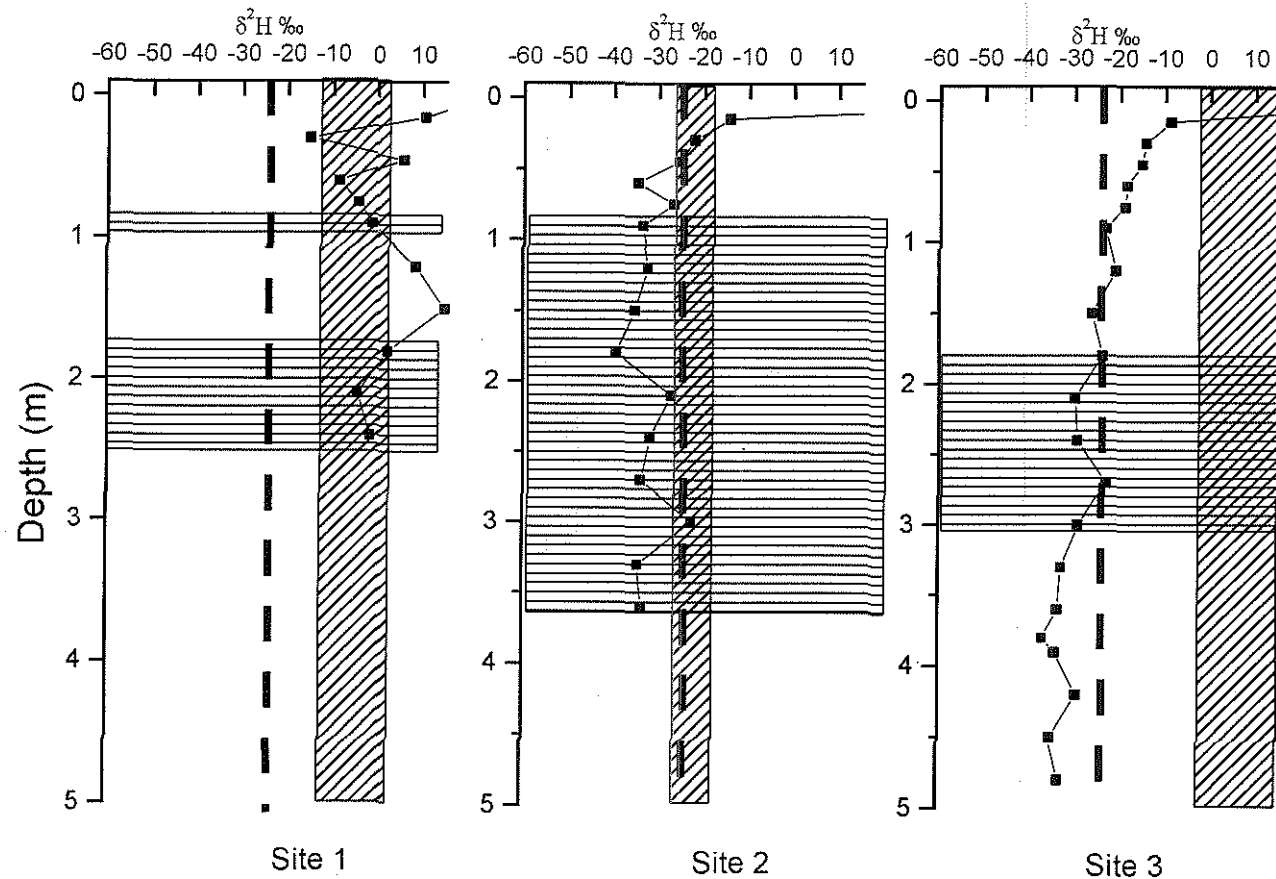


Figure 4.3.15: $\delta^2\text{H}$ values of soil water (■), twig xylem (■), groundwater (---) and rainwater (....) for all sites during February combined with water potential data to provide a model of plant water sources and availability. Where soil $\delta^2\text{H}$ values match $\delta^2\text{H}$ twig values and horizontal shading (■) indicates where Ψ_{plant} and Ψ_s match possible water sources within the profile. Site 1 shows a match at 0.45 – 0.6 m, site 2 shows a match at 0.75 m and no matches were found at site 3. Groundwater values are similar to soil water $\delta^2\text{H}$ at sites 2 and 3.

4.4 Discussion

Seasonal plant water relations were closely related to levels of salinity in soil water and the drying processes in the soil. As a relative measure between sites on the lakebed, plant response enabled comparisons to be made at the individual level. The ecophysiological parameters measured gave a point in time estimate of plant water stress, stomatal response and quantitative water use across a spring to summer period.

4.4.1 Plant Water Status

Plant water potential gave an indication of relative plant water stress, by comparing sites and seasonal differences. Ψ_{pd} potentials represented Ψ_{plant} when equilibrated with the region of water uptake overnight (assuming that hydraulic capacitance has been achieved). Like Ψ_i , it tended to decrease through summer with February having the most negative potentials at all sites (Fig 4.3.1). This suggested that trees at all sites had to lower Ψ_{plant} during summer to maintain a water potential gradient. In the presence of excessive salts in the soil, this will make uptake difficult, as salts are concentrated due to plant water uptake and evaporation. The very negative potentials measured at all sites could be attributed to osmotic adjustment, which is not unexpected due to the availability of salts in the soil for this to occur. The ability of plants to lower potentials for continued water uptake has been found in various deserts, halophytic and non-halophytic plants living in saline environments (Scholander *et al.*, 1968; Galloway, 1993; Mensforth, 1996). The process of osmotic adjustment in *C. obesa* when compared to other species appears to be less energy expensive due to the relative availability of inorganic ions (van der Moezel *et al.*, 1988). This species also tends to direct Na^+ and Cl^- into older shoots to avoid a reduction in photosynthesis and growth enabling it to continue uptake of more saline soil water (Aswathappa and Bachelard, 1986).

The difference between Ψ_{md} and Ψ_{pd} was used in this study to estimate differences in the ability of *C. obesa* to regulate its transpiration rate (E) with respect to site and seasonal differences. In this way it was assumed that any difference from Ψ_{pd} would

be determined by the ability of stomata to respond to environmental variables such as soil water potential, leaf-to-air VPD and air temperature. *C. obesa* growing at site 3 showed the smallest $\Psi_{pd} - \Psi_{md}$, an indication of tight stomatal control of E . In contrast trees at site 1 exhibited a larger $\Psi_{pd} - \Psi_{md}$ over all sampling periods, an indication of relatively lesser control of E . Assuming that all other environmental variables are consistent across sites, this would confer the advantage of occupying areas where Ψ_t is high (less negative), allowing this species to operate with wider stomatal aperture and therefore assimilate proportionally more carbon.

4.4.2 Transpiration Rate (E) and Stomatal Conductance (g_s)

Stomatal response data highlighted these trends in plant response to seasonal change, giving a clear indication of the ability of trees to limit water loss because of salt induced osmotic stress. It was clear that trees at site 3 were barely opening stomata during the day, due to the unavailability of water (Fig 4.3.4). The process of limiting water loss in plants exposed to saline soil water, is thought to be related to hormonal messengers like abscisic acid, that are released in the roots when a moisture deficit is experienced (Munns and Termaat, 1986). Therefore it was not necessarily ambient conditions (i.e. VPD) at the leaf surface, and within the stomata that was limiting water loss in this instance, but a 'feed forward response' that seeks to limit transpiration before the onset of xylem cavitation or embolisms. This has detrimental consequences for continued growth and photosynthesis, usually resulting a lowered growth rate and increased water use efficiency, but may also assist in limiting uptake of excessive levels of salt that may reach toxic levels.

Daily stomatal conductance (g_s) showed a similar pattern of stomatal activity in December across all sites with a maximum period of transpiration at mid-morning (Fig 4.3.5). This daily pattern was also highlighted by daily sap flux data at most sites with maximums around 10:00 hrs. This pattern of stomatal activity allowed the plant to begin using water and photosynthesising earlier in the day when leaf-to-air VPD was relatively low and soil moisture content in the rhizosphere was still high. The decrease in g_s towards the end of the day allowed the plant to limit water uptake during the afternoon and fulfill its water demands overnight. At site 3 where osmotically induced water deficits occurred, the plant may have limited water loss to

a minimum, this limited photosynthesis and growth forcing the plant into a near dormant state, where death is imminent. Visible signs of this were apparent in trees sampled with many dead leaves, and only the new smaller leaves showing any signs of active photosynthesis. The presence of dead trees also indicated that death was close, and conditions at this site had reached the threshold of this specie's salt tolerance.

The association between E and G_1 (Fig 4.3.6) was consistent with the general notion that stomatal function is inherently coordinated with the hydraulic conductance of the pathway between soil and leaves (Brodribb and Field, 2000; Franks and Farquhar, 1999; Tausend, 2000). Such coordination presumably reduces the possibility of drought-induced xylem embolisms by lowering Ψ_{leaf} under water stress. In this study it can be seen that those plants growing in the most salinised, and therefore water stressed, sites showed the lowest daily transpiration rate and apparent hydraulic conductance between soil and leaves, which is in line with this general notion. The down side to such a response is reduced carbon sequestration and therefore productivity. At site 1 increases in E permitted greater hydraulic conductivity, as trees at this site demonstrated less stomatal control due to the presence of available soil water. Unlike species characterised as high water users with reliable water sources, such as phreatophytic *Banksia* spp. (Zencich *et al.*, 2002), *C. obesa* has evolved to operate under growth limiting conditions such as waterlogging and moisture deficits, with a rooting pattern that leaves them vulnerable to water stress. Therefore tight stomatal control is an important mechanism for withstanding environmental stresses such as a summer drying period.

4.4.3 Water Use

Water use data displayed some difference to the patterns found in the other ecophysiological parameters. However it was still clear that February imposed severe drought conditions on trees at sites 2 and 3 as sap flux density was drastically lower than all other seasons. Analysis of sap flux data for sites 2 and 3 in February showed daily sap flux measurements were very erratic and characteristic of low sap flux conditions. It has been suggested in some tree water use studies that the sap

flow technique over estimates water use at low sap fluxes (Barrett, 1995; Hatton, 1990). Therefore sap flux may have been even lower for some trees especially at site 3. This error was minimised by accurate testing of time out values or a lower threshold at which sap velocity is negligible (Appendix 5).

Sap flux density data did support the assumption that site 1 maintained water uptake at an increased rate and did not appear to be greatly constrained by late summer water deficits. This consistency in quantitative water use across seasons implies that there were sufficient soil water stores within the reach of the rhizosphere, and alternatively site 2 and 3 were experiencing moisture deficits due to salt accumulation. Some daily sap flux data was included in these results to highlight the differences in daily sap flux between sites (Fig 4.3.8). Site 1 tended to have a distinct diurnal pattern in sap flux corresponding to stomatal conductance data and a peak in sap flux at around 10:00 hrs. Site 3 on the other hand had sporadic sap flux patterns and zero values during day light hours that were indicative of low flow conditions.

A pre-rain day and post rain day were also compared at two sites to help illustrate the effect of increased soil moisture and fresher water sources on sap flux across sites. The increased sap flux after rain at site 1 demonstrated the reliance of these trees on surface moisture and the ability of these trees to respond to increased soil moisture by increasing water use. These differences were not as marked at sites 2 and 3 making it hard to draw conclusions in terms of sap flux and increased surface moisture. It could be possible that the rain served to leach some salts that had accumulated in the surface further down into the rhizosphere, but was not sufficient to alleviate drought conditions in this region of the profile.

4.4.4 Plant Water Availability Model (based on ψ_{pd} and ψ_t)

Plant water availability results gave an indication of where soil water is available to the plant over the seasons. This was determined using ψ_t data with depth from Chapter 3 and matching these with ψ_{leaf} to identify regions of water that was physiologically available to the plant. Site 3 had much of the upper 1.50 m

unavailable by February due to a salt front in this region (Table 4.1). This indicated that salt accumulation in the area of the rhizosphere restricted uptake to lower regions in the profile (below 1.5 m). It clearly demonstrated the impact of high salt concentrations in soil water and its effect on plant water availability, even though there were higher water contents in the soil at this site. However it also indicated regions of unavailable soil water at site 1, due to the increased Ψ_m in the upper profile due to the drying effect of clay. It is possible that some of this was due to plant water extraction and its drying effect at these depths as well as potential evaporation on the surface. Mentioned previously, total soil water potential is over estimated in drying soils because Ψ_m becomes the dominant force and may not be additive with Ψ_o (Shalvet and Hsiao, 1986). Water uptake at this site required uptake from deeper regions where there was increased soil moisture and evaporative processes on the surface had little effect on soil water content. Soil moisture alone determined regions of uptake that were available to the plant at this site, as opposed to salt concentrations that restricted uptake at sites 2 and 3. In this way plant response indicated that there was sufficient moisture in the profile to maintain tree water use throughout the summer at site 1.

4.4.5 Assessment of Seasonal Water Sources and Plant Water Uptake Model

Predominant water uptake patterns of *C. obesa* were reflected in the $\delta^2\text{H}$ data and were further illustrated by the plant water uptake model. The glasshouse validation experiment also confirmed the suitability of this species for this type of investigation in a highly saline environment (Appendix 9)

Field validation results suggested that there was some variation occurring within different parts of the tree, but it was not necessarily due to translocation of evaporatively enriched water (Appendix 10). There were more enriched $\delta^2\text{H}$ values within the small twig but the significance of this was only slight as indicated by the p value. Twig and branch values were also similar suggesting that enriched water transported from the twig via the phloem was mixing with xylem water in the branches or that differences observed here were due to sampling or analytical error

from the twig. With this in mind however it was considered that sampling from small twigs would give a valid indication of the source waters provided that variability of $\delta^2\text{H}$ signatures within the twig was regarded.

It was obvious from the data that a clear distinction could be made between water sources at site 1 and sites 2 and 3. As previously demonstrated, site 1 had deeper groundwaters, lower salinity and was dominated by surface water and that was also highlighted by the $\delta^2\text{H}$ data. The distinction between groundwater $\delta^2\text{H}$ signatures and twig and soil $\delta^2\text{H}$ signatures during this study emphasised these site characteristics. Because of these characteristics, soil $\delta^2\text{H}$ signatures with depth at site 1, reflected enrichment and depletion processes determined by inherent properties in the soil such as pore size, water content, temperature and extent of mixing between precipitation and stored moisture (Walker *et al.*, 1992). This clear distinction in $\delta^2\text{H}$ values with soil layers allowed for a more definitive assessment of water sources possibly showing a shift from more recent precipitation near the surface and older surface stored moisture deeper in the profile. Alternatively sites 2 and 3 had soil and twig $\delta^2\text{H}$ values that closely matched those of groundwater that supports the assumption of a groundwater dominated system at these sites.

Differences in $\delta^2\text{H}$ signatures for September and November rainfalls were very pronounced and reflected seasonal shifts in $\delta^2\text{H}$ signatures due to meteorological influences. It is well known that there are marked differences in the isotopic composition in summer and winter precipitation due to the movement of predominant weather systems over the ocean and land (Ehleringer and Dawson, 1992). Variation also occurs from latitudinal gradients which may be significant in this case due to the origin and movement of low pressure systems over the land mass. The winter and spring rainfall was derived from low-pressure systems moving straight off the ocean usually occurring from the south. In summer precipitation events are generated from low-pressure systems traveling more vast distances across the land originating from the north.

Water uptake at site 1 followed a somewhat predictable pattern over the drying period; water was drawn from deeper regions as moisture availability in the upper profile diminished. Further evidence of water uptake from surface moisture was seen

in the temporal shift of twig $\delta^2\text{H}$ signatures to more enriched values towards summer and early summer precipitation values (-1.25 ‰) (Table 4.2). This signified uptake of water undergoing enrichment processes, i.e. water near the surface or from precipitation inputs. Tang and Feng (2001) demonstrated a similar relationship using both $\delta^2\text{H}$ and oxygen 18 values with a reference line representing seasonal precipitation inputs (known as the meteoric water line), it was possible to attribute stem values to the origin of precipitation (seasonal precipitation) and the degree of enrichment occurring in the soil given that the species under investigation used water at shallow depths. In this study, mixing of precipitation and stored soil moisture was also evident during December in the surface (0.15 m) as $\delta^2\text{H}$ values were closer to rain sources but were mixed with more depleted water due to the limited magnitude of the rainfall event. This was represented by a noticeable spike in enriched values at 0.15 m (especially at sites 2 and 3). The infiltration of water into the rhizosphere after precipitation occurred through soil pores and by preferential flow along root pathways. This latter process allowed precipitation to penetrate deeper in to the profile, increasing soil water content within the root zone, and diluting any accumulated salt. It may have also lead to a mixing of enriched rainwater with stored surface moisture and groundwater deeper in the profile. Twig $\delta^2\text{H}$ values at site 2 did not tend to increase (more enriched) towards summer suggesting partial uptake of groundwater derived soil moisture that was transported vertically along evaporative gradients.

Applying the plant water uptake model for site 3 only seemed to generate plausible results for October where uptake was found to be occurring at depths of 0.30 m. The highly enriched twig $\delta^2\text{H}$ values for December and February did not allow for assessment of water sources in the soil or groundwater. Reasons for this may be attributed to enrichment processes occurring in the tree branches and twigs at this site due to poor health. Diffusion processes in twigs may be a result of low sap velocities (described in this Chapter) allowing adequate time for enrichment through bark and twigs. Cracking in the trunk and broken limbs were noticeable features at this site and are possible regions in the tree where enrichment was taking place. Although care was taken to collect twigs from areas with signs of growth (green shoots), mixing of evaporatively enriched waters is a likely explanation. It was during December and February that tree health and water use declined which probably

exacerbated this skew in twig $\delta^2\text{H}$ values, preventing any reliable assessment of water sources. Additional deviation in these twig $\delta^2\text{H}$ signatures may be attributed to error arising due to partial extraction of water from twigs. Little evidence is found in the literature, however Walker *et al.* (1992) concluded that extraction from dry soils could lead to a large degree of error in isotopic composition, and this error can also extend to twig water extraction.

The main findings of this chapter in relation to water uptake, plant water status, rooting depth and water sources are presented in Table 4.3. These general trends are also illustrated schematically (Fig 4.3.16) in order to conceptualise the predominant pathways of soil water into the plant originating from various sources. It was evident that extensive mixing of sources occurred at sites with a shallower depth to groundwater, especially in the presence of perched layers of groundwater.

The patterns of water uptake summarised at sites 2 and 3 indicated partial and possibly complete restriction of water uptake during summer. Site 2 still appeared to maintain uptake during summer, however it was obvious from water relations data that this became limited. Firstly, location of highly concentrated salts from a capillary fringe (of the perched layer) beneath the rhizosphere was restricting water uptake at the base of the rhizosphere. Secondly dry soil conditions above ~ 0.50 m restricted water uptake to below this depth. A pattern of plant water uptake was modeled by Thorburn *et al.* (1995) and showed that the presence of a shallow water table meant that water uptake shifted upward with the advance of a capillary fringe (caused by plant water uptake and evaporation) to fresher available moisture located above this. In their study plants were able to maintain uptake above the capillary fringe, however for *C. obesa* it appeared that rooting limitations meant that there was only a limited region where uptake could occur (0.70 – 0.90 m) during summer, and at site 3 it was evident that these critical depths were highly concentrated in salt. Plant response indicated tight stomatal response, decreased water use and very low Ψ_{pd} as a result.

Table 4.3: Summary of patterns of water uptake and water relations of *C. obesa* during a drying period. Available water was based on results of plant water source model; note site 3 had no clear matches in December and February. Source type is denoted by RW (rainwater), SSM (stored soil moisture) that includes soil water from previous inflow, and precipitation events that has penetrated deeper into the profile and GW (groundwater). Plant water status is shown as an indicator of relative plant stress and possible regions of uptake were assessed on whether they were within the root zone (maximum rooting depth estimated to be ~ 0.95 m).

Season/Site	Available water	Source type	Plant water status (Ψ_{pd} , MPa)	Within the root zone
Site 1				
October	0.45 – 0.60 m	RW/SSM	-3.2	0.45 – 0.6 m
December	0.70 m	RW/SSM	-4.2	0.70 m
February	0.90 m	RW/SSM	-4.3	0.90 m
Site 2				
October	0.15 m	RW/SSM	-4.1	0.15 m
December	0.75 and 1.5 – 2.60 m	RW/SSM/GW	-5.6	0.75 m
February	0.75 and 3.0 m	SSM/GW	-5.8	0.75 m
Site 3				
October	0.30 m	RW/SSM	-5.0	0.30 m
December	unknown	RW/SSM/GW	-6.8	-----
February	unknown	SSM/GW	-6.8	-----

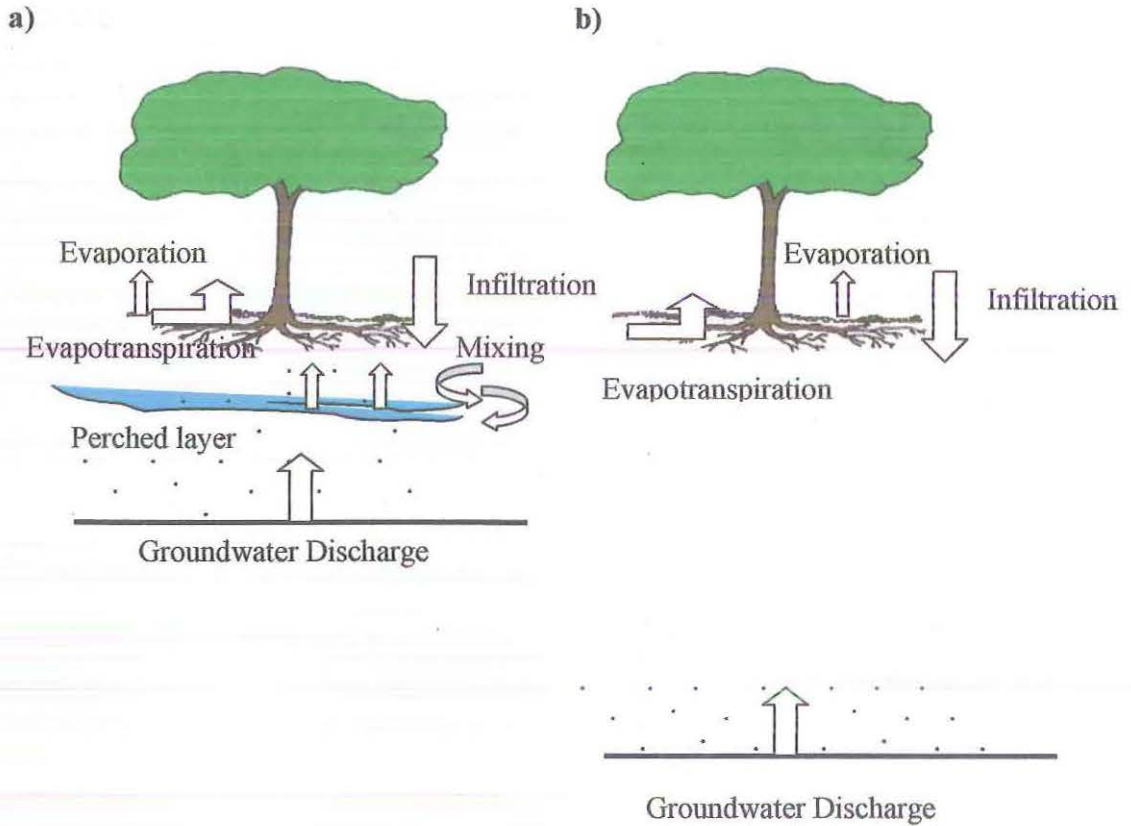


Figure 4.4.14: A schematic illustration of the predominant source water components and the processes influencing plant water uptake. (a) Shows the processes typical of sites 2 and 3 where groundwater discharge (from capillary fringe and perched layers) are bringing salts toward the surface and are mixing to some degree with infiltrated water (rainwater, surface inflow) and stored soil moisture. Evapotranspiration and surface evaporation are maintaining an evaporation gradient in the upper profile causing further capillary movement of groundwater and restricting water uptake to areas of lower salt concentrations. (b) Is typical of site 1 which has a lowered groundwater level, where groundwater is not influencing water uptake or water availability. Infiltration and stored soil moisture are the predominant water sources and evapotranspiration and evaporation is restricting uptake to deeper regions of the profile where stored soil moisture is available

4.6 Conclusion

Patterns of water uptake for *C. obesa* across the lake appeared to be closely related to seasonal effects of the drying period and soil water and salt movement from the capillary fringe. It is evident that the drying period creates moisture deficits through evaporative moisture loss and the concentration of salts (where groundwater levels are shallower) in the surface regions of the profile.

Plant water potential (represented as Ψ_{plant}) was shown to decrease in response to changes in soil moisture and increased salt concentrations. The presence of a salt front may decrease Ψ_t beyond the limits of Ψ_{plant} , forcing the plant to adjust Ψ_{plant} , restrict water loss through tight stomatal control and low water use. This was observed at all sights in varying degrees, with site 3 closing stomata to the point that photosynthetic processes and carbon assimilation were compromised. It was obvious that this eventually led to leaf senescence and tree death. In the absence of a salt front, trees at site 1 were still restricted to uptake soil water from deeper in the profile to the depth limits of the root zone (0.90 m). Evapotranspiration and evaporation were responsible for reducing moisture availability, but the water relations data indicated that these trees were still able to maintain a relatively consistent water use and E during the drying period. Site 2 was representative of intermediate salinity conditions and showed some decreased Ψ_{plant} during summer and some stomatal control. Water use was found to rapidly decline during this drying period yet plant water status and the plant water availability model indicated soil moisture within the limitations of the root zone.

$\delta^2\text{H}$ data helped to reinforce the concept that groundwater was not a possible water source of trees at site 1, yet was directly influencing water uptake at sites 2 and 3. It was evident that rainwater during the drying period supplemented some of the trees water requirements at all sites, however stored soil moisture was critical for trees during summer.

Chapter 5

Conclusion

Lake Toolibin is an important example of an attempt to manage salinity in an area of high conservation status. The continued functioning of this ecosystem is finely balanced by the interaction of regional, catchment and lakebed processes. The integrity of such a system is only readily established by an understanding of critical processes on a number of scales in order to assess future vegetation response and persistence. However there is a paucity of research that has provided an understanding of the salinity process within the root zone of the lakebed tree species. Therefore this study concentrated on the site-specific scale of salt and soil water pathways to the root zone of *C. obesa* and the consequences this had for plant water uptake. The conclusion will be structured to address the specific research aims and current and future management and research strategies:

5.1 To evaluate the distribution and processes of water and salt movement within the rhizosphere over a drying phase on the lakebed

Through the analysis of microsite scale dynamics within a drying period, this study provided a limited yet crucial understanding of temporal shifts in rhizosphere salinity during periods of high salt accumulation and plant stress. Soil water and its impacts on salt transmission and accumulation were found to have a direct consequence on water uptake and vegetation health. The nature of salt accumulation and movement however were not easily characterised by a simplistic model of groundwater discharge within a homogenous soil profile.

At sites 2 and 3, groundwater was transmitted above the water table along films of sandier textured soils, forming perched systems of thin saturated soil (0.10 – 0.20 m). The perched systems interrupted a relatively dry profile and became important mechanisms in the transport of saline groundwater to the rhizosphere and surface sediments. Water table depth was a major determinant of salt accumulation, as site 3 had the most shallow groundwater and had a severely salinised profile relative to the

other sites studied. However the addition of perched layers that promoted an upward movement of salt to shallow depths (0.10 – 0.70 m) enhanced salinisation in two ways. Firstly, the potential for downward leaching was reduced due to decreased hydraulic conductivity in this soil horizon. Secondly, salts were concentrated in these soils due to evaporation, increasing the influence of Ψ_o (highly saline soil water) and Ψ_m (due to the drying effect of clay) components of Ψ_i . Accordingly, this water was unavailable or became limited to this lakebed tree species. It was obvious then that this site was dominated by fluctuations in groundwater levels, and leaching events would be critical in maintaining suitable soil conditions for plant water uptake. Alternatively, site 1 which had a greater depth to groundwater exhibited no significant groundwater discharge and Ψ_i was dominated by Ψ_m due to decreased water contents.

5.2 To determine the patterns of water uptake in response to micro site variability within *C. obesa* population (adult) during this drying phase.

Plant water uptake was a direct function of soil water processes, because a restriction of plant water availability during this time was a direct consequence of salt accumulation and drying processes within the rhizosphere. This study does not support the assumption that *C. obesa* has a significant contribution on groundwater discharge directly. However this species enhances the rate of salt accumulation and upward migration of groundwater derived soil moisture in the rhizosphere, through maintaining an evaporation gradient above the capillary fringe. This study does imply that this species is reliant on stored soil moisture during the drying period and adequately maintains its water requirements in the absence of high salt concentrations. It does this by accessing soil water at progressively deeper regions of the soil profile, consequently soil water is drawn from the base of the rhizosphere (0.90 m) towards the end of summer. Rainfall events during the summer months were effective in supplementing this species' water requirements, although they did not adequately leach or dilute salts in the rhizosphere at sites with high salt concentrations.

The rooting pattern of *C. obesa* confined the location of water sources to the surface sediments (0.10 – 0.90 m). Therefore salts at the surface, even at moderate salinities reduced growth and water loss through providing a trigger to promote stomatal

closure. *C. obesa* displayed resilience to desiccation and mortality through limiting water use and the uptake of excess salts allowing individuals to osmotically adjust internal plant water potentials to maintain uptake in the presence of saline soil water (van der Moezel *et al.*, 1988). Stomatal regulation and water use appeared to be tightly controlled by osmotically induced water deficits. In regulating E , *C. obesa* may also successfully avoid the onset of drought-induced embolisms within the xylem. The threshold of this species tolerance to saline soil conditions during the drying period was demonstrated by the most salinised site having groundwater depths of 2.70 m (October) and groundwater salinities of $\sim 45 \text{ dS m}^{-1}$ that eventually led to a rapid decrease in tree vigour or tree death. A dramatic decline in water use and transpiration occurred at this site due to an inaccessibility of moisture at the most crucial rhizosphere depths required for continued plant water uptake.

The management of Lake Toolibin hinges on balancing the upward discharge of groundwater during dry periods and the leaching of salts by rainfall and inflow events. Currently, salt loads from previous inflow appear to be minimal in the surface soils and are probably leached further into the sediments adding to rhizosphere salt loads. This alone does not constitute a harmful level of salt within the rhizosphere, but in addition to groundwater derived salts, has had detrimental consequences for tree health. The current strategy to divert saline inflows away from the lakebed has helped to limit the addition of salt into the lakebed sediments after rainfall. Any decision to allow inflow into the lakebed must balance the risk of adding significant salt loads to the upper 1.0 m of the lakebed, with the benefit of providing a substantial volume of water that will leach salts out of the rhizosphere. However the previous eight years of winter rainfall has not provided sufficient surface flow to allow this to occur. This suggests a significant inflow event at Lake Toolibin is urgently required to rejuvenate the lakebed tree community and may also promote further regeneration in this species (Ogden, 1997).

Groundwater abstraction has had a noticeable effect on vegetation health in areas where the migration of salt from the capillary fringe is beyond the reach of the rhizosphere. Where groundwater abstraction was occurring (site 1), the vegetation displayed the greatest water use and E , in the absence of high Ψ_o . Groundwater abstraction enabled trees at this site to utilise deeper surface soil water during

summer without being restricted by osmotically induced water deficits, due to a saline capillary fringe. This ensured adequate water uptake under summer conditions of high potential evaporation. Soil water dynamics at this site are driven by surface water influences and are representative of successful re-establishment processes following a salinity disturbance. Sufficiently leached of salts, it is evident that this site's vegetation has stabilised and may persist under current pumping regimes. Leaching processes and the extent of drawdown created by the pumping regime will drive the temporal scale of this process of remediation.

5.3 Research and Management Considerations

Further research and monitoring is needed to address the regulation of surface water inflow and groundwater abstraction impacts on the health of the lakebed tree community. These may include :

- An investigation into the lateral extent of drawdown in terms of plant vigour and water relations. This could incorporate existing vegetation plots, but may also involve the sampling of other areas at varying distances from the abstraction bores.
- An extension of this study through an entire hydrological cycle including possible inflow events and inundation, and the effect of these events on soil water conditions and tree health.
- An increase in sampling points to gain better resolution in defining a critical depth to groundwater for the lakebed tree community, and the degree of abstraction required to achieve this.
- A study of the water relations and water sources of other tree species within the lakebed (*M. strobaphylla*) and on the lake bed margins (*E. rudis*; *B. prionotes*). These species are probably more sensitive to salt accumulation

and water availability than *C. obesa* and are therefore critical in the assessment of any recovery program at Lake Toolibin.

Clearly the only long-term solution for the recovery of Lake Toolibin is the revegetation of the Northern Arthur River catchment. This will ensure the long-term viability of the lakebed tree community. However catchment modelling predicts that even revegetation of one third of the catchment will not adequately slow the rate of salinity and the upward trend of groundwater movement (GHD, 1992). Therefore the current short-term remediation strategies serve an important purpose: to conserve an important ecosystem within a degraded landscape. The process of recovery is slow as a hydrological balance disrupted by degrading land management must be re-established before ecosystem integrity can persist without prevailing remediation strategies.

Reference List

- Agwest (2002) *Salinity Measures Units and Classes*.
- Aswathappa N. & Bachelard E.P. (1986) Ion regulation in the organs of *Casuarina* species differing in salt tolerance. *Australian Journal of Plant Physiology*, **13**, 533-545.
- Ball M.C. (1988) Ecophysiology of Mangroves. *Trees*, **2**, 129-142.
- Barnes C. & Allison G. (1984) The distribution of deuterium and ^{18}O in dry soils. 3. Theory for Non-isothermal Water Movement. *Journal of Hydrology*, **74**, 119-135.
- Barnes C. & Allison G. (1988) Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology*, **100**, 143-176.
- Barrett D.J., Hatton T.J., Ash J.E. & Ball M.C. (1995b) Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest species of south-eastern Australia. *Plant Cell and Environment*, **18**, 463-469.
- Bell D.T. (1999) Australian trees for the rehabilitation of waterlogged and salinity damaged landscapes. *Australian Journal of Botany*, **47**, 697-716.
- Bell D.T. & Froend R.H. (1990) Mortality and growth of tree species under stress at Lake Toolibin in the Western Australian Wheatbelt. *Journal of the Royal Society of Western Australia*, **72**, 63-66.
- Blake T.J. & Reid D.M. (1981) Ethylene, water relations and tolerance to waterlogging to three *Eucalypt* species. *Australian Journal of Plant Physiology*, **11**.

- Bleby T.M., Aucote M., Kennet-Smith A.K., Walker G.R. & Schachtman D.P. (1997) Seasonal water use characteristics of tall wheatgrass [*Agropyron elongatum* (Host) Beauv.] in a saline environment. *Plant Cell and Environment*, **20**, 1361-1371.
- Boyer J.S. (1995) Pressure Chamber. In: *Measuring the Water Status of Plants and Soil* (ed A. Press), pp. 174-198.
- Bresler E. & Hoffman G.J. (1986) Irrigation management for soil salinity control theories. *American Journal of Soil Science*, **50**, 1552-1560.
- Brodribb T.J. & Feild T.S. (2000) Stem hydraulic supply is linked to leaf photosynthetic capacity: evidence from New Caledonian and Tasmanian rainforests. *Plant, Cell and Environment*, **23**, 1381-1388.
- Busch D.E., Ingraham N.L. & Smith S.D. (1992) Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A stable Isotope Study. *Ecological Applications*, **2**, 450-459.
- Casson N.E. (1988) *Lake Toolibin and Reserves Interim Managment Guidelines*. Resource Document, CALM.
- Clemens J., Kirk A.-M. & Mills P.D. (1978) The resistance to waterlogging of three *Eucalyptus* species. *Oecologia*, **24**.
- Craig H. (1961a) Isotopic variation in meteoric waters. *Science*, **133**, 1702-1703.
- Crombie D.S., Tippet J.T. & Hill T.C. (1988) Dawn water potential and root depths of trees and understorey species in South West Western Australia. *Australian Journal of Botany*, **36**, 621 - 631.

- Dawson T.E. & Ehleringer J.R. (1993) Isotopic enrichment of water in the woody tissues of plants: implications for plant water source, water uptake, and other studies which use stable isotopes. *Geochimica et Cosmochimica Acta*, **57**, 3487-3492.
- Donovan L.A., Linton M.J. & Richards J.H. (2001) Pre-dawn plant water potential does not necessarily equilibrate with soil water potential under well watered conditions. *Oecologia*, **129**, 328 - 335.
- Ehleringer J.R. & Dawson T.E. (1992) Water uptake by plants: perspectives from stable isotope composition. *Plant, Cell and Environment*, **15**, 1073-1082.
- Ehleringer J.R. & Osmond C.B. (1989) Stable Isotopes. In: *Plant Physiological Ecology Field Methods and Instrumentation*. (ed R.W. Pearcy, Ehleringer, J.R., H.A. Mooney and P.R. Rundell.), pp. 281-300. Chapman and Hall Ltd, London.
- Farquhar G.D. & Sharkey T.D. (1982) Stomatal conductance and photosynthesis. *Annual review of plant physiology*, **33**, 17-45.
- Flowers T.J. & Yeo A.J. (1986) Ion relations of plants under drought and salinity. *Australian Review of Plant Physiology*, **28**, 75-91.
- Franks P.J. & Farquhar G.D. (1999) A relationship between humidity response, growth form and photosynthetic operating point in C₃ plants. *Plant, Cell and Environment*, **22**, 1337-1349.
- Froend R. & Storey A. (1996) *Monitoring Design and Data Analysis Toolibin Lake and Catchment*. Froend Bowen and Associates, Wetland Research and Management.
- Froend R.H., Halse S.A. & Storey A. (1997) Planning for the recovery of Lake Toolibin, Western Australia. *Wetlands Ecology and Management*, **5**, 73 - 85.

- Froend R.H., Heddle E.M., Bell D.T. & McComb A.J. (1987) Effects of salinity and waterlogging on the vegetation of Lake Toolibin, Western Australia. *Australian Journal of Ecology*, **12**, 281-298.
- Galloway R. & Davidson N.J. (1993) The response of *Atriplex amnicola* to the interactive effects of salinity and hypoxia. *Journal of Experimental Botany*, **44**, 653-663.
- Gee G.W. & Bauder J.W. (1986) Particle Size Analysis. In: *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods* (ed A. Klute). American Society of Agronomy Inc., Soil Science.
- George R. (1998) *Evaluation of Airborne Geophysics for Catchment Management Program, Drilling Results, Explanatory Notes and Drill logs*. Catchment Hydrology Group South-Western Rivers Region.
- George R. & Bennett D. (1995) *Toolibin groundwater management program, drilling results*. Unpublished report for the Dept. of Conservation and Land Management.
- GHD (1992) *Lake Toolibin Hydrological Studies*. Gutteridge Haskins and Davey Pty Ltd.
- Gill A.M. & Tomlinson P.B. (1977) Studies on the growth of red mangrove (*Rhizophora mangle* L.). IV. The adult root system. *Biotropica*, **9**, 145-155.
- Greacen E.L., Walker G.L. & Cook P.G. (1989) *Evaluation of the filter paper method for measuring soil water suction*. Paper presented at the Measurement of Soil and Plant Water Status, Int. Meeting at University of Utah 1987.
- Greenspan (1996) *Sapflow sensor user manual*, Warwick, Queensland.
- Greenway H. & Munns R. (1980) Mechanisms of salt tolerance in nonhalophytes. *Annual Review of Plant Physiology*, **28**, 149-190.

- Grimes R.F. (1987) *Crown Assesment of Natural Spotted Gum (Eucalyptus maculata) and Ironbark (Eucalyptus fibrosa, Eucalyptus depranophylla) Forest*. Queensland Department of Forestry.
- Hatton T., Catchpole R.A. & Vertessy R.A. (1990) Integration of sap flow velocity to estimate plant water use. *Tree Physiology*, **6**, 201-209.
- Hatton T., Greenslade D. & Dawes W.R. (1992) Intergration of sap flow velocity in elliptical stems. *Tree Physiology*, **11**, 185-196.
- Hill A.E. & Hill B.S. (1976) Mineral Ions. In *Transport in Plants II. Part B, Tissues and Organs*. In: *Encyclopedia of Plant Physiology* (eds U. Lettge & G. Pittman).
- Holland K. (2003) *Blackbox (Eucalyptus largiflorens) tree health and groundwater discharge on the lower River Murray floodplain, South Australia: Linking temporal and spatial scales*. PhD, Flinders University.
- Indian Ocean Climate Initiative I.O.C.I (2001) *Climat Variability in the South West of Western Australia*. Department of Environment.
- Jarvis P.G. (1981) *Stomatal conductance, gaseous exchange and transpiration*. In: *Plants and the atmospheric environment*. Oxford: Blackwell Scientific.
- Jolly I.D., McEwan K., Cox J., Walker G.R. & Holland K. (2002) *Managing Groundwater and Surface Water for Native Terrestrial Vegetation Health in Saline Areas. Technical Report 23/02*. CSIRO Land and Water.
- Jolly I.D. & Thorburn P.J. (1993) Salt accumulation in semi-arid floodplain soils with implications for forest health. *Journal of Hydrology*, **150**, 589 - 614.
- Jolly I.D. & Walker G.R. (1996) Is the field water use of *Eucalyptus largiflorens* F. Muell. affected by short-term flooding? *Australian Journal of Ecology*, **21**, 173-183.

- Kefu Z., Munns R. & King R. (1991) Absisic acid levels in NaCl-treated barley, cotton and saltbush. *Australian Journal of Plant Physiology*, **18**, 17-24.
- Kent L.M. & Lauchli A. (1984) Germination and seedling growth of cotton: salinity-calcium interactions. *Plant Cell and Environment*, **8**.
- Kozlowski T.T. & Pallardy S.G. (2002) Acclimation and adaptive response of woody plants to environmental stresses. *Botanical Review*, **68** (2), 270-334.
- Kramer P. & Kozlowski T.T. (1983) *Physiology of woody plants*. Academic Press, New York, Moscow.
- Leong E.C., He L. & Rahardjo H. (2002) Factors affecting the filter paper method for total and matric suction methods. *Journal of Geotechnical Testing*, **25**, 1-14.
- Lin G. & Sternberg L. (1992) Comparitive study of water uptake and photosynthetic gas exchange between scrub and fringe red mangroves (*Rhizophora mangle* L.). *Oecologia*, **90**, 399-403.
- Lin G. & Sternberg L. (1994) Utilization of surface water by red mangrove (*Rhizophora mangle* L.): An isotopic study. *Bulletin of Marine Science*, **54**(1), 94-102.
- Luard E.J. & El-Lakany M.H. (1984) Effects on *Casuarina* and *Allocasuarina* Species of Increasing Sodium Chloride Concentrations in Solution Culture. *Australian Journal of Plant Physiology*, **11**, 471-481.
- Marshall D.C. (1958) Measurement of sap flow in conifers by heat transport. *Plant Physiology*, **33**.
- Marshall J.K. (1993) *Year long water uptake by Jarrah (Eucalyptus marginata) in intact Jarrah forest*. Abstract. Paper presented at the International Symposium on Forest Hydrology, Canberra.
- Marshall T.J. & Holmes J.W. (1988) *Soil Physics*. (2nd ed.). Cambridge University Press, Cambridge.

- Martin M.W. (1986) *Hydrogeology of Lake Toolibin* (Record 1986/13). Geological Survey of W.A., Report 1986/ 13.
- Martin M.W. (1990) *Salinity control by groundwater pumping at Toolibin Lake, Western Australia*. Geological Survey of Western Australia Report No. 1990/30.
- Mensforth L. (1996) *Water use strategy of Melaleuca halmaturorum in a saline swamp*. PhD Thesis. PhD, University of Adelaide.
- Mensforth L. & Walker G.R. (1996) Root dynamics of *Melaleuca halmaturorum* in response to fluctuating saline groundwater. *Plant and Soil*, **184**, 75-84.
- Monteith (1995) Accomodation between transpiring vegetation and the convective boundary layer. *Journal of Hydrology*, **166**, 251 - 261.
- Mulcahy M. (1973) Landforms and soils of South Western Australia. *Journal of the Royal Society of Western Australia*, **56**, 16-22.
- Munns R. (1993) Physiological processes limiting plant growth in saline soils: some dogmas and hypotheses. *Plant Cell and Environment*, **16**, 15-24.
- Munns R. (2002) Comparative physiology of salt and water stress. *Plant Cell and Environment*, **25**, 239-250.
- Munns R. & Termaat A. (1986) Whole-plant Responses to Salinity. *Australian Journal of Plant Physiology*, **13**, 143-160.
- Nadezhdina N. (1998) Sap flow index as an indicator of plant water status. *Tree Physiology*, **19**, 885-891.
- Naidoo G. (1985) Effects of waterlogging and salinity on plant-water relations and on the accumulation of solutes in three mangrove species. *Aquatic Botany*, **22**, 133-143.
- NARWC (1987) *The Status and Future of Lake Toolibin as a Wildlife Reserve*. Water Authority of Wstern Australia, No. WS 2.

- Neuman P.M., Azaizeh H. & Lean D. (1994) Hardening of root cell walls: a growth inhibitory response to salinity stress. *Plant Cell and Environment*, **17**, 303-310.
- Niknam S.R. & Mc Comb J. (2000) Salt tolerance screening of selected Australian woody species - a review. *Forest Ecology and Management*, **139**, 1 - 19.
- Ogden G. & Froend R.H. (2003) *Vegetation Monitoring of Toolibin Lake and Surrounding Reserves, 2002* (2002-15). Edith Cowan University.
- Ogden G.N. (1997) *Recruitment requirements of Casuarina obesa at Toolibin Lake, Western Australia. Bsc Hons Thesis*, Edith Cowan University.
- Ortiz A., Martinez V. & Pallardy S.G. (1987) Effects of osmotic shock and calcium growth and solute composition of *Phaseolus Vulgaris* plants. *Plant Physiology*, **91**, 468-476.
- Passioura J.B. (1988a) Water transport in and to roots. *Annual Review of Plant Physiology and Molecular Biology*, **39**, 245-246.
- Passioura J.B. (1988b) Water transport in and to roots. *Annual Review of Plant Physiology and Plant Molecular Biology*, **39**, 476-481.
- Passioura J.B. (1992) Mangroves may salinise the soil and in doing so limit their transpiration rate. *Functional Ecology*, **6**, 476-481.
- Peck A.J. (1978) Salinisation of non-irrigated soils and associated streams: a review. *Australian Journal of Soil Research*, **16**, 157 - 168.
- Peck A.J. (1979) Groundwater recharge and loss: In *The Hydrology of Low Precipitation*. pp. 361 - 370 (IAHS - AISH).
- Pereira J.S. & Kozlowski T.T. (1977) Variations amongst woody angiosperms in relation to flooding. *Physiological Plant*, **41**.

- Perera L.K.R.R., Mansfield T.A. & Malloch A.J.C. (1994) Stomatal responses to sodium ions in *Aster tripolium*: A new hypothesis to explain salinity regulation in above-ground tissues. *Plant Cell and Environment*, **17**, 335 - 340.
- RAMSAR (1990) <http://www.ramsar.org/key> - sitelist.
- Revesz K. & Woods P.H. (1990) A method to extract soil water for stable isotope analysis. *Journal of Hydrology*, **115**, 397-406.
- Ritchie G.A. & Hinckley T.M. (1975) The pressure chamber as an instrument for ecological research. *Advanced Ecological Research*, **9**, 156-254.
- Scholander P.F. (1968) How mangroves desalinate seawater. *Physiological Plant*, **21**.
- Scholander P.F., Hammel H.T., Bradstreet E.D. & Hemmingsen E.A. (1965) Sap pressure in vascular plants. *Science*, **148**.
- Sena Gomes M. & Kozłowski T.T. (1980) Effects of flooding on *Eucalyptus camaldulensis* and *Eucalyptus globulus* seedlings. *Oecologia*, **46**, 139-142.
- Shalvet J. & Hsiao T.C. (1986) Salinity and drought. A comparison of their effects on osmotic adjustment, assimilation, transpiration and growth. *Irrigation Science*, **7**, 249-264.
- Stokes J.R. & Sheridan R.J. (1985) *Hydrology of Lake Toolibin* (WH2). Water Authority of W.A.
- Strizaker R.J. & Passioura J.B. (1996) The water relations of the root-soil interface. *Plant Cell and Environment*, **19**, 201-208.
- Sutcliffe J.F. (1986) *Salt Relations of Intact Plants*. Paper presented at the Water and Solutes in Plants.
- Swanson R.H. & Whitfield D.W.A. (1981) A numerical analysis of heat pulse velocity theory and practice. *Journal of Experimental Botany*, **32**, 221-239.

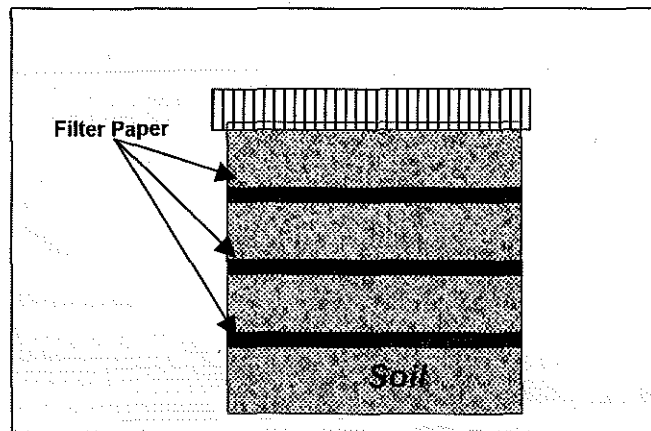
- Talsma T. (1963) The control of saline groundwater. *Mededelingen Van De Landbouwhogeschool*, **6**, 1 - 68.
- Tang Z.C. & Kozlowski T.T. (1984) Ethylene production and morphological adaptation of woody plants to flooding. *Canadian Journal of Botany*, **62**, 159-164.
- Tausend P.C., Goldstein G. & Meinzer F.C. (2000) Water utilization, plant hydraulic properties and xylem vulnerability in three contrasting coffee (*Coffea arabica*) cultivars. *Tree Physiology*, **20**, 159-168.
- Thorburn P.J. & Mensforth L. (1993a) Extraction of water from *Medicago sativa* for analysis of stable isotopes of water. *Communications in Soil Science and Plant Analysis*, **24**, 549-557.
- Thorburn P.J., Walker G. & Hatton T. (1993b) The source of water transpired by *Eucalyptus camaldulensis*: soil, groundwater or streams? In: *Stable Isotopes and Plant Carbon-Water Relations* (eds J.R. Ehleringer, A.E. Hall, & G.D. Farquhar), pp. 511-527. Academic Press Inc., San Diego.
- Thorburn P.J. & Walker G.R. (1994) Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. *Oecologia*, **100**, 293-301.
- Thorburn P.J., Walker G.R. & Brunel J.-P. (1993c) Extraction of water from *Eucalyptus* trees for analysis of deuterium and oxygen-18: laboratory and field techniques. *Plant Cell and Environment*, **16**, 269-277.
- Thorburn P.J., Walker G.R. & Hatton T. (1992) *Are River Red Gums Taking Water From Soil, Ground Water or Streams?* Paper presented at the Catchments of Green: A National Conference on Vegetation and Water Management, Vol. B, Adelaide.
- Thorburn P.J., Walker G.R. & Jolly I.D. (1995) Uptake of saline groundwater by plants: An analytical model for semi-arid and arid areas. *Plant and Soil*, **175**, 1-11.

- Turner N.C. (1986) Adaptation to water deficits: a changing perspective. *Australian Journal of Plant Physiology*, **13**, 175 - 190.
- Tyree M.T. (1997) The cohesion - tension theory of sap ascent: current controversies. *Journal of Experimental Botany*, **48**, 1753 - 1756.
- Tyree M.T. & Sperry J.S. (1989) Vulnerability of xylem to cavitation and embolism. *Annual Review of Plant Physiology and Plant Molecular Biology*, **40**, 19 - 38.
- van der Moezel P.G., Watson L.E., Pearce-Pinto G.V.N. & Bell D.T. (1988) The Response of Six *Eucalypt* Species and *Casuarina obesa* to the Combined Effect of Salinity and Waterlogging. *Australian Journal of Plant Physiology*, **15**, 465-474.
- Vertessy R.A., Hatton T., Reece P., O'Sullivan S.K. & Benyon R.G. (1997) Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. *Tree Physiology*, **17**, 747-756.
- Walker G.R., Brunel J.-P. & Kennet-Smith A. (1992) *Using stable isotopes of water to trace plant water uptake*. (Water Resources Series No. 7). CSIRO Div. Water Res.
- Wallace K.J. (2001) *Salinity Management at Toolibin Lake, Western Australia Innovative and Practical Engineering Systems*. Department of Conservation and Land Management.
- White J.W.C., Cook E.R., Lawrence J.R. & Broecker W.S. (1985) The D/H ratios of sap in trees: implications for water sources and tree ring D/H ratios. *Geochimica et Cosmochimica Acta*, **49**, 237-246.
- Yakir D. & Yechieli Y. (1995) Plant invasion of newly exposed hypersaline Dead Sea shores. *Nature*, **374**, 803-805.

- Zencich S.J., Froend R.H., Turner J.V. & Gailitis V. (2002) Influence of groundwater depth on the seasonal sources of water accessed by *Banksia* tree species on a shallow, sandy coastal aquifer. *Oecologia*, **131**, 8-19.
- Zimmerman M.H. (1983) *Xylem structure and the ascent of sap*, Springer-Verlag, Berlin/Heidelberg/New York/Tokyo.
- Zimmerman U., Ehhalt D. & Munnich K.O. (1967) *Soil-water movement and evapotranspiration: Changes in the isotopic composition of the water*. Paper presented at the Isotopes in Hydrology. Proc. Int. Symposium., 1966. IAEA, Vienna, pp. 567 - 585.

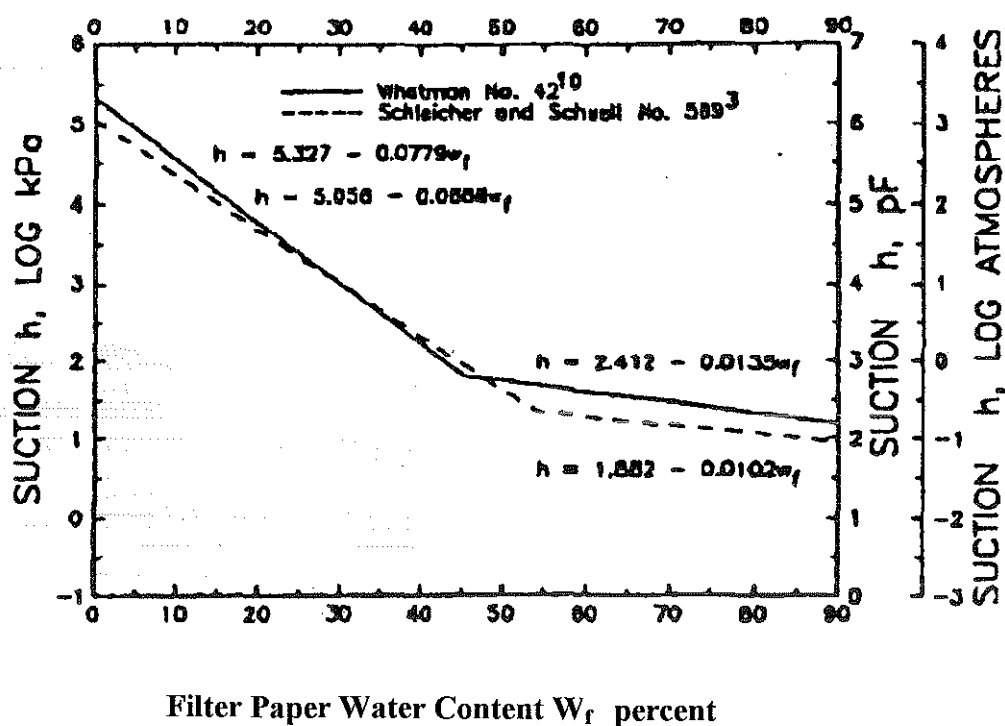
Appendices

Appendix 1: Filter Paper Arrangement (Layered) for Matric Potential



The arrangement of filter paper and soil in jars using the contact method for measuring matric suction. Note all soil was compressed using a rubber stopper to ensure full contact with filter papers.

Appendix 2: Calibration Suction-Water Curves for Wetting of Filter Paper



Appendix 3: Groundwater Piezometer Specifications, Depths and Salinity

Groundwater Specifications

Site/Piezometer	Total length (m)	Screened area (m)	Depth below natural surface (m)
Site 2/IP	5.53	1.5	4.50
Site 2/CALM	41	23	38.64
Site 3/IP	4.5	1.5	3.34
Site 3/CALM	28	10	25.58

Groundwater Depths (m)

Site	30/10/02	14/12/02	4/02/03
1/AB	30	32	33
2/IP	1.97	1.8	2.07
2/CALM	5.95	5.95	6.24
3/IP	2.33	2.6	2.67
3/CALM	2.48	3.6	3.87

Groundwater Salinity

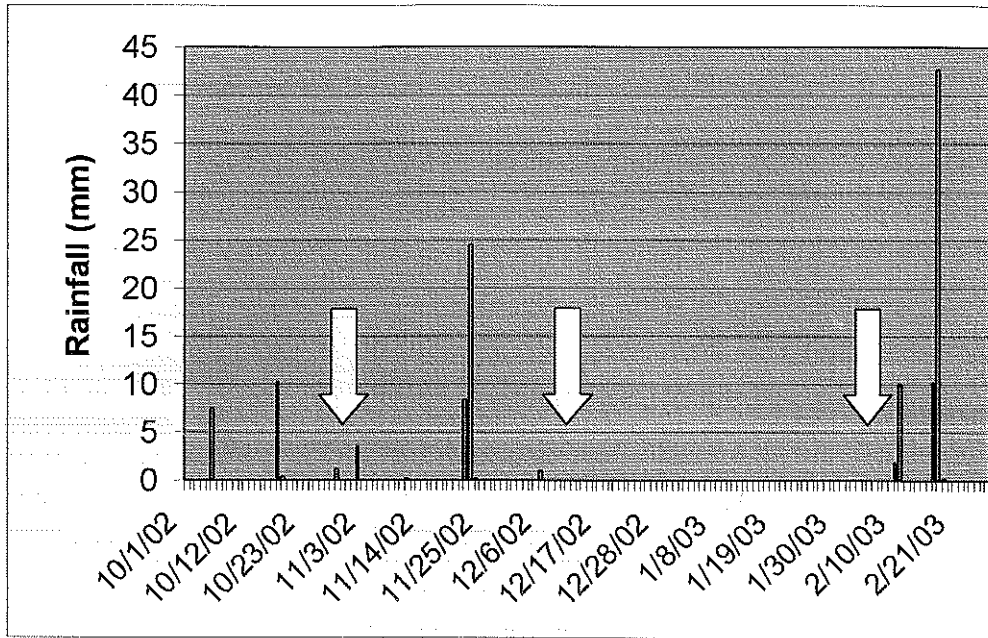
	30/10/02		14/12/02		4/02/03	
Site	NaCl (mg/L)	dS/m	NaCl (mg/L)	dS/m	NaCl (mg/L)	dS/m
1/AB	22,300	40.5414	22,500	40.905	23,300	42.3594
2/IP	23,400	42.5412	23,600	42.9048	24,600	44.7228
2/CALM	25,400	46.1772	24,600	44.7228	26,700	48.5406
3/IP	23,700	43.0866	22,900	41.6322	25,600	46.5408
3/CALM	26,800	48.7224	26,500	48.177	27,900	50.7222
Average	24,320	44	24,020	44	25,620	47

AB: Abstraction bore

IP: Installed piezometer (during study)

CALM: Department of Conservation and Land Management observation bore

Appendix 4: Rainfall Events During the Study Period



Appendix 4 :Rainfall from 1 st October 2002 until the 28th February 2003 from the Water and Rivers gauging station at Lake Toolibin. Arrows point to the commencement of field sampling and coring.

Appendix 5: Calculation of Sapwood Area from Probe Tests

Example:

Site 1 Tree 1

Test 1

Probe Set/No.	Probe Depth (mm)	T ₁ Value (secs)
1/1	0	150
1/2	10	100
2/1	5	110
2/2	15	115

Site 1 Tree 2

Test 2

Probe Set/No.	Probe Depth (mm)	T ₁ Value (secs)
1/1	0	150
1/2	10	100
2/1	10	150
2/2	20	130

T₁ represents the time taken for the heat pulse to reach the probe implanted upstream. For example the lower T₁ value the faster the sap flux, which is indicative of active sapwood. T₁ values above 120 seconds are often too slow for an accurate estimation of sap flux.

For this example sap flow probes were inserted at depths of 0, 10 mm and 5 and 15 mm to cover the area of active sapwood. It was calculated that the active sapwood boundary at the heartwood was 20 mm and 5mm from the cambium, giving a sapwood thickness of 15 mm. This was then used to calculate total sapwood area from diameter at probe measurements.

Appendix 6: Determination of Volumetric Wood and Water Contents

Methods

1. A holesaw was used to obtain a sample of the sapwood, and placed in airtight container.
2. A fresh weight was made (W_f).
3. A beaker of water was placed on a balance and tared. The sample was immersed and weighed, which is equivalent to the weight of the displaced water (W_i).
4. The sample was oven-dried at 105 °C for 48 hours and then reweighed (W_d).
5. The volume fraction of water (V_h) was calculated as:

$$V_h = (W_f - W_d) / W_i$$

The volume fraction of wood (V_w) was calculated as:

$$V_w = W_d / (1.53 \times W_i)$$

Results

Sample	W_f	W_i	W_d	V_h	V_w
S1T1	11.091	8.514	8.206	0.338	0.630
S1T2	8.193	6.600	6.109	0.319	0.610
S2T1	8.923	6.730	6.598	0.345	0.641
S2T2	12.357	10.114	9.021	0.329	0.599
S3T1	11.451	9.231	8.420	0.328	0.593
S3T2	9.965	8.153	7.456	0.310	0.597
Average				0.328	0.617

The volume fraction of water = 0.33

The volume fraction of wood = 0.62

Appendix 7: Tree Wounding Experiment

Methods

A tree wounding experiment was conducted on trees at each site on Lake Toolibin during December to determine wounding width from probe implantation. Six trees (two from each site) were drilled and a blank probe was implanted into each tree. Two probes were removed after: one week; two weeks and three weeks, to assess wounding width over time. A wood specimen of each hole was collected using a hole saw around the probe hole and stored in an airtight container. Each specimen was cut longitudinally through the centre of the hole for analysis. Specimens were placed under a microscope and discolouration or xylem disruption was classified as wounding around the probe hole. The width from the edge of the drilled hole was recorded as the wounding width to be used in calculation of sap flux.

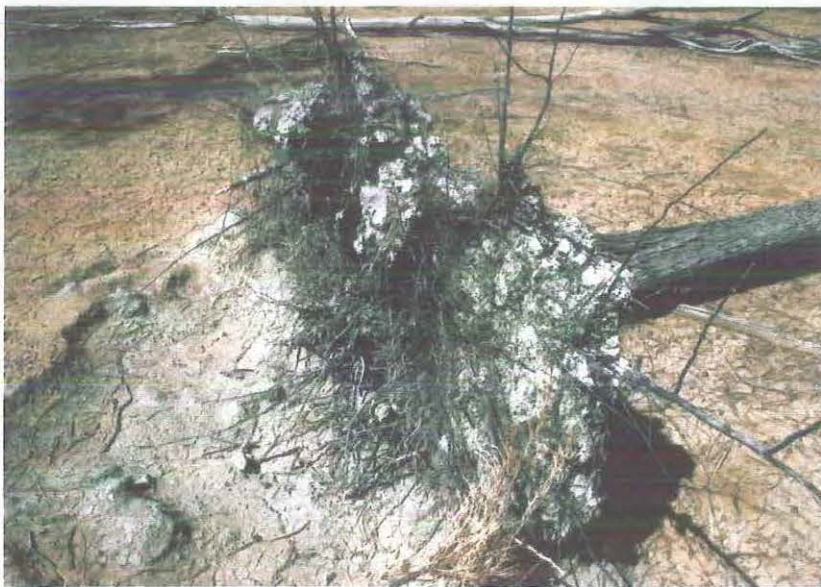
Results

Site No./Tree No.	Wounding Duration*	Wounding width (cm)
S1T1	one week	0.18
S1T2	two weeks	0.26
S2T1	two weeks	0.27
S2T2	three weeks	0.27
S3T1	one week	0.23
S3T2	three weeks	0.26
	Average	0.245

* It was assumed that probes would remain in the tree for no longer than two weeks

Average wounding depth = 0.25 cm

Appendix 8: Root Observations

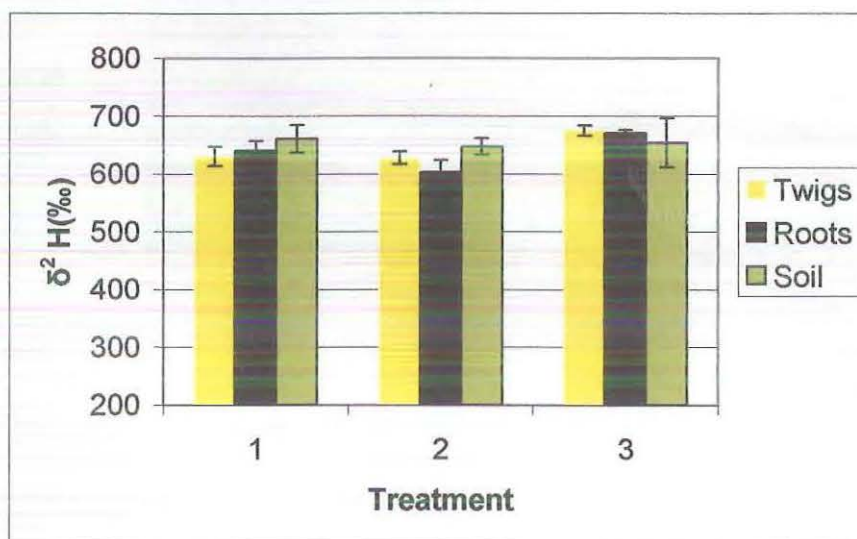


Appendix 8: Two pictures of wind felled mature *C. obesa* trees on the lake bed floor. Note the presence of large roots extending laterally from the base and the absence of significant tap roots (Froend, 1983).

Appendix 9: Glasshouse Validation Experiment Results

Glasshouse Validation

Comparisons of soil, root and twig $\delta^2\text{H}$ values for *C. obesa* seedlings showed no significant differences within each treatment using a one way ANOVA (fig 6). No pattern of isotopic discrimination appeared to exist between root and soil, as values were relatively consistent across this interface. This also does not occur in seedlings exposed to different levels of salinity as shown by similar results in treatments 2 and 3. The enriched or doped water therefore appears to be taken up into *C. obesa* without undergoing fractionating processes making it suitable species for water source determination in the field.

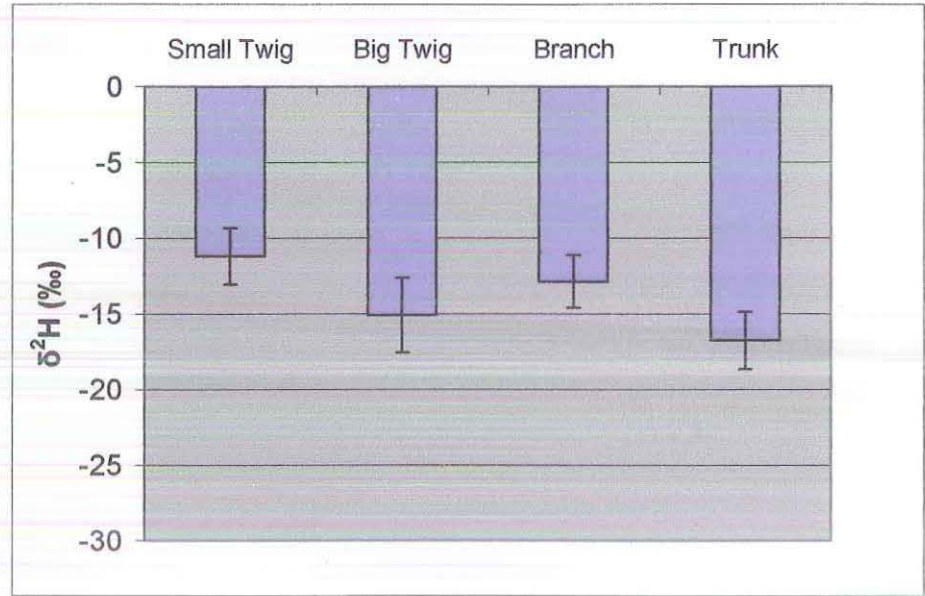


Appendix 9: Glasshouse validation results showing treatment type (1 = doped water no NaCl; 2 = doped water, 20 dS m⁻¹; 3 = doped water, 30 dS m⁻¹). Vertical bars represent standard errors.

Appendix 10: Field Validation Results

Field Validation

A field validation trial comparing different parts of mature *C. obesa* indicated significant differences between small twig and large twig (fig 7)($p = 0.042$, $df = 12$) twig and trunk ($p = 0.043$, $df = 12$), however comparison of small twig and branch was not significant.



Appendix 10: Results from field validation experiment. Vertical bars represent standard errors.