DRAFT

Ecophysiology of southern Australian riparian vegetation

A literature review for the Department of Environment and Conservation

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Executive Summary

In response to the need to better assess and manage Australian riparian systems the Western Australian Department of Environment and Conservation (DEC) will, over the next several years, develop a decision tool to assist in the management of biodiversity assets threatened by altered hydrology in southern Australia, including within Natural Diversity Recovery Catchments (NDRCs). Under the State Salinity Strategy the Western Australian Government established the NDRC Program in order to recover and protect significant natural areas, particularly wetlands, from salinity. The objective of NDRCs is to maintain, and where practicable recover, biodiversity threatened by altered hydrology, particularly increasing salinity. The decision tool (Biorisk) will rely on a better understanding of the ecophysiology of riparian plants threatened by altered hydrology, and will include research on the particular requirements of key species in wetlands. Subsequently, such a tool will enable the objectives of NDRCs to be fulfilled. An important initial step in beginning the ecophysiological component of Biorisk is to gather existing information on the tolerances and thresholds of target groups of riparian plants.

The aim of this study was to review the state of knowledge concerning the ecophysiology of selected riparian taxa in terms of their tolerance limits and ecological thresholds to abiotic environmental stressors and to collate existing data sets which exist in relation to those thresholds of tolerance.

The literature that the review will be concerned with is constrained by taxonomic, ecological and environmental factors. Taxonomically the review will be concerned with *Eucalyptus*, *Melaleuca*, *Casuarina*, and Chenopodiaceae; ecologically it will be concerned with the riparian zones of southern Australia; and environmentally it will be concerned with the abiotic factors of water availability; soil and water quality; and erosion and sedimentation. The review will not be concerned with population or community level response.

Tolerance and ecophysiological response data for varying conditions of water availability are scant for riparian chenopods. Indeed, it appears as if the knowledge of Australian chenopod biology in general is incomplete (Grice & Muir, 1988). Flooding tolerance for some species in this group of plants appears to be associated with aerenchyma and adventitious tissue formation; however in species which exhibit low root porosity, shallow rooting depths in areas of the profile which are more aerobic may allow these species to tolerate short periods of waterlogging (Colmer, Timothy D. & Flowers, 2008). Halophytic chenopod species appear to be able to regulate shoot ion concentrations under hypoxic/anoxic conditions and this would account for their ability to inhabit riparian zones in which substrate would become frequently, or at least regularly, waterlogged (Colmer, Timothy D. & Flowers, 2008).

Waterlogging may reduce the germinative capacity of chenopods, likely due to low oxygen supply. Germination may also be inhibited by high concentrations of salts in the bracteoles, plants relying on rain or flood waters to flush salts prior to germination. It appears that in general the most sensitive life stages of halophytes to salinity are germination and early establishment of seedlings. As chenopods mature, many are highly salt tolerant and will exhibit as initial increase in yield with increasing salinity, with yield levels not decreasing until moderate levels of salinity are reached. Studies suggest that a number of chenopods require some level of sodium in their growing medium in order to protect against lethal concentrations of potassium accumulating within the plant. Ion accumulation in shoot tissues results in tissue potentials considerably lower than soil water
potentials allowing species of chenopods to survive in extremely saline environments. Interspecific variations in tolerance to salinity at all stages of the life cycle are apparent in *Halosarcia* spp.

The interacting effects of waterlogging and salinity appear to be more detrimental than if stresses occur independently. Zonation of species within riparian zones appears to reflect relative tolerances to waterlogging or drought and salinity. The ability to survive in drier zones appears related to plants establishing a deep root system relatively quickly, enabling water extraction from a depth greater than at least half a metre. Loch et al. (2003) have defined tolerance levels to salinity and waterlogging for two genera of chenopods (species of which occur in riparian zones). *Atriplex* spp. appear able to tolerate irrigation with seawater (EC 55 dS m$^{-1}$) and withstand waterlogging with saline water up to an EC of 40 dS m$^{-1}$ for up to 3 weeks (Loch et al., 2003). *Halosarcia* spp. appear able to survive when soil water EC is between 200 and 300 dS m$^{-1}$ with little adverse effect on growth when waterlogged with saline waters of up to EC 80 dS m$^{-1}$ (Loch et al., 2003). However, the studies reported by English (English, 2004; English et al., 2002) would indicate that generalising such high tolerance levels for *Halosarcia* does not hold due to interspecific variation in *Halosarcia* spp. to both salinity and waterlogging. While the high level of tolerance reported by Loch et al. (2003) may hold for some species of *Halosarcia* it clearly does not hold for the genera as a whole. There appears to be little discussion or evidence for intraspecific variation among species of Chenopodiaceae.

Limited research has been conducted into the ecophysiology of riparian *Casuarina* species. The majority of research on these species has been conducted to determine their ability to tolerate salinity, with some research into *Casuarina* tolerance to the combined stressors of salinity and waterlogging. The majority of this research appears to have been undertaken in the glasshouse. One would also assume then that the majority of the data is relevant to seedlings of the species studied, and therefore knowledge of tolerance at maturity is difficult to ascertain.

While subsoil drought can result in poor root development, the occurrence of waterlogging during *Casuarina* development can result in trees developing long lateral roots without a tap root (Yadav, 1981). The need to develop a long tap root is highlighted by the heavy reliance of *C. glauca* on groundwater sources in Queensland (despite average groundwater salinities of 11.1 dS m$^{-1}$ at one site), especially in areas of lower rainfall. The responsiveness of root development to varying soil conditions highlights the need for appropriate species selection if the species is to be planted for management.

Leaf conductance, water potential, osmotic potential and solute contents can vary considerably between *Casuarina* species, indicating that drought resistance is also likely to vary between species; provenance variation is also evident (El-Lakany, M. H., 1983). Drought avoidance may be facilitated by the efficient reduction of stomatal and cuticular transpiration, reducing transpiration at relatively high water contents and water potentials, implying a quick closure of stomata at the onset of water deficit (Withers, 1978). This quick response to water deficit means that transpiration is decreased before damage can occur (Withers, 1978).

Species of *Casuarina* which occur naturally in saline areas exhibit a greater tolerance to salinity. Such species exhibit smaller reductions in height growth and greater survival rates when exposed to high salinities (El-Lakany, M. H., 1983). Generally, while *Casuarina* species exhibit a wide range of responses to increasing salinity, germination percentage and rate, and seedling survival and growth will all be reduced under conditions of increasing salinity, whereas Na and Cl ion concentrations in
the stem and shoot increase and K ion concentrations in the root and shoot decrease (Aswathappa & Bachelard, 1986; Clemens et al., 1983; El-Lakany, M.H. & Luard, 1983; Ogden, 1997). El-Lakany (1983) lists 9 species of *Casuarina* in decreasing order of tolerance to salinity as *C. glauca*, *C. obesa*, *C. equisetifolia*, *C. glauca* x *C. cunninghamiana* hybrid, *C. cristata*, *C. cunninghamiana*, *C. stricta*, *C. littoralis*, *C. torulosa*, and *C. decaisneana*; although rankings of salinity tolerance may not hold in all instances and further confirmation between field and glasshouse studies is needed.

*C. glauca* has been shown to be highly tolerant of salinity in field trials, showing a 25% reduction in height production at an EC greater than 1.5 dS m$^{-1}$ relative to height production at 0.75 dS m$^{-1}$ (Dunn et al., 1994). The mean height production of *C. glauca* increased with increasing salinity indicating that this species prefers saline environments. *C. cunninghamiana* was shown to be moderately salt tolerant with a 25% reduction in height production occurring at an EC between 1.0 and 1.5 dS m$^{-1}$ with height production gradually decreasing with increasing salinity (Dunn et al., 1994).

Under glasshouse conditions, salinity tolerance in *Casuarina* spp. appears to be a factor of the amount of ion accumulation in the shoot (Aswathappa & Bachelard, 1986). Tolerant species accumulate little Na$^+$ and Cl$^-$ with concentrations decreasing from old to young needles; whereas sensitive species treated with 150 mM NaCl had shoot tip concentrations of the two ions 6-10 times that of control seedlings (Aswathappa & Bachelard, 1986; van der Moezel et al., 1989a). When the stressors of salinity and waterlogging are combined an increase in the uptake of salt ions is evident in all species regardless of tolerance to salinity (Carter et al., 2006; van der Moezel et al., 1989a).

*C. obesa* has been shown to be tolerant to sodium-induced alkaline conditions possibly related to the specie’s superior membrane control which allows it to exclude sodium under saline conditions (Bell, David T. et al., 1993). The species has been shown to survive at field pH levels of 8.8, although survival significantly increases at pH levels below this (Refer Table 15), indicating that this level of pH may be a survival threshold for this species and that some optimum level of pH exists below 8.8 for *C. obesa* (Bell, David T. et al., 1993).

No adverse effect on the survival of *C. obesa* or *C. glauca* is evident under conditions of saline waterlogging. In the glasshouse *C. glauca* and *C. obesa* exhibit few deaths after 12 weeks of waterlogging even at salinities of 5 600 mS m$^{-1}$. *C. equisetifolia* has been observed to survive field conditions of high salinity (14 – 28 mS cm$^{-1}$) in areas of high water tables (10 – 140 cm below the surface). Low survival has been noted for *C. equisetifolia* after 12 weeks of saline waterlogging under glasshouse conditions, with survival rates reducing after 10 weeks at 4 900 mS m$^{-1}$, indicating a survival threshold. *C. cristata* and *C. cunninghamiana* also demonstrate a survival threshold under conditions of saline waterlogging with survival rates reducing after 7 weeks of waterlogging at salinity levels of 4 900 mS m$^{-1}$. Some provenance variation was noted between provenances of *C. cunninghamiana* under conditions of combined environmental stressors. Waterlogging tolerance was attributable to the formation of a large proportion of aerenchyma in the roots of *Casuarina* spp.

Once again it would appear that a limited amount of research has been conducted on riparian Melaleuca species; with the majority of research concerned with the genera’s response to conditions of waterlogging and salinity. Little research has been undertaken in the response to drought and with the apparent drying of southern Australia, this area should be highlighted for further research. Natural patterns of flood zone species distribution indicate that *Melaleuca* species are generally
tolerant of waterlogging and salinity and have the ability to survive conditions when these stressors interact.

*M. halmaturorum* appear to perform as well or better under saline (average ECe 4 – 8 dS m\(^{-1}\)) than non-saline conditions even when soils become waterlogged, although the species appears inflexible in its regeneration requirements. Juvenile *M. halmaturorum* will produce adventitious roots and aerenchymatous tissue along with stem elongation in response to flooded conditions (Denton & Ganf, 1994). If flooded conditions persist the survival, height extension, growth-point production and relative growth rate of this species are inhibited. Regeneration of *M. halmaturorum* appears restricted by water level during germination, seedling establishment and the juvenile phase of growth (Denton & Ganf, 1994; Nicol & Ganf, 2000). The species also appears able to preferentially switch water source maintaining a large root mass, sections of which remain dormant when not actively sourcing water, and from which new growth can occur as water becomes available (Mensforth, L. J. & Walker, 1996). Leaf water potentials of this species followed those of surface soil water potentials at all times reaching a maximum in winter of -2.1 MPa and a minimum in summer of -7.4 MPa (Mensforth, L. J. & Walker, 1996). The species uses between 0.7 and 4.0 mm of water day\(^{-1}\) with differences in transpiration being controlled by leaf area index and sapwood area, and dependent on groundwater salinity and the presence of waterlogging (Mensforth, L., 1997). When groundwater salinity was high (63 dS m\(^{-1}\)) between 0.5 and 2.0 mm day\(^{-1}\) of water was used from this source, whereas when groundwater salinities were low (8 – 14 dS m\(^{-1}\)), 1.5 to 3.5 mm day\(^{-1}\) was used (Mensforth, L., 1997). When trees were exposed to long-term waterlogging combined with high salinity approximately 0.6 mm of water day\(^{-1}\) was used and was sourced from the top 20 cm of the soil profile.

*M. preissiana* was shown to express a vulnerability to xylem cavitation and exhibited poor xylem function meaning that the species is likely intolerant of conditions of water deficit (Froend, R. H. & Drake, 2006). This therefore restricts its range to areas of greater soil water availability such as the fringes of wetlands and areas where the depth to groundwater is less than 2 m (Froend, R. H. & Drake, 2006). *M. preissiana* also shows a wide difference between pre-dawn and midday xylem pressure potentials during drying periods, with data indicating that a 50% loss of conductance occurs at a tension of -1.4 MPa (Froend, R. H. & Drake, 2006; Lam et al., 2004).

*M. cuticularis* has been observed to tolerate flooding at Coomalbidgup Swamp in Western Australia, although this tolerance appears to decline if flooding is prolonged (for up to 3 years) (Froend, R.H. & van der Moezel, 1994). In the glasshouse this species has also been shown to tolerate conditions of saline waterlogging at concentrations of 400 mM NaCl for 22 days, and will generally maintain ion regulation and high rates of photosynthesis under these conditions (Carter et al., 2006). *M. cuticularis* also forms aerenchyma in adventitious roots under waterlogged conditions, enhancing internal root aeration, thus enhancing its ability to tolerate saline waterlogging (Carter et al., 2006).

*M. bracteata* has been shown in the field to exhibit a high tolerance to salinity, exhibiting a 25% reduction in height production at an EC of 1.73 dS m\(^{-1}\), exhibiting no mortality at these salinities (Dunn et al., 1994). Height production steadily decreased with increasing salinity. *M. cymbifolia* (syn. *M. halmaturorum*) and *M. thyoides* seedlings both showed a high degree of tolerance to salinity (highest level of salinity tested was 72 mS cm\(^{-1}\)) in terms of survival and growth (van der Moezel & Bell, 1987a). Species which showed a lower degree of tolerance to salinity when both
survival and growth tolerance were considered were, in declining order, *M. aff. calycina*, *M. cardiophylla*, *M. calycina* and *M. subtrigona* (van der Moezel & Bell, 1987a).

Percentage germination and germination rate of *M. cardiophylla* decreased with increasing salinity, with germination being suppressed at 300 mM and 400 mM NaCl (van der Moezel & Bell, 1987b). At 30°C and salinity levels of 16 g L⁻¹ germination was completely suppressed in *M. ericifolia*, while at the same temperature and half the salinity (8 g L⁻¹) only 5% germination was achieved (Robinson, R. W. et al., 2006).

*M. armillaris* and *M. lanceolata* appear to maintain better rates of growth under glasshouse conditions of increasing alkalinity compared with under conditions maintained near neutral and exhibited fair survival rates in the field at pH levels greater than 8.0 (47.7% and 78.0% respectively) with some individuals of *M. lanceolata* surviving soil pH of 9.93 (Bell, David T. et al., 1993). *M. halmaturorum* was also shown to tolerate alkaline conditions with 73.7% of plants surviving a field pH above 8.0 with individuals surviving up to a pH of 9.36 (Bell, David T. et al., 1993). In acid soils *M. alternifolia* has been shown to be tolerant of pH levels of 4.0 ± 1.0 and also tolerated high lead concentrations at an abandoned mine site (Archer & Caldwell, 2004). While *M. alternifolia* may appear to tolerate soils contaminated by heavy metals and acid conditions it would appear that there is some threshold to this tolerance for different life-history stages (Archer & Caldwell, 2004).

*M. ericifolia* seedlings are known to remain flexible and are able to lay over during flooding allowing for a quick recovery after flood waters drop (Abernethy, Bruce & Rutherford, 2000b, 2001). This indicates that *M. ericifolia* has the ability to tolerate frequent, high intensity flooding. *M. ericifolia* has also been shown to be able to germinate while submerged, indicating that the seeds are metabolically adapted to anaerobic conditions (Bell, David T., 1999). However, the strongly interactive effects of waterlogging and salinity have been observed to significantly impact on the success of *M. ericifolia* seedling establishment with greater than 90% mortality of seedlings at Dowd Morass near Lake Wellington in Victoria under such conditions (Raulings et al., 2007). The age of seedlings at planting and the depth of water were important factors determining the survival and growth of *M. ericifolia* seedlings (Raulings et al., 2007). Initial survival was greater in older seedlings, although after 8 months of continuous flooding survival of both 4- and 6-month-old seedlings (at time of planting) was considerably affected (Raulings et al., 2007). At low salinities *M. ericifolia* seedlings are highly tolerant to waterlogging but are unlikely to tolerate prolonged submergence, and at higher salinities this species appears intolerant of both waterlogging and salinity and will die rapidly after approximately 5 weeks of exposure to these conditions (Salter et al., 2007). Salinity has also been found to compromise the ability of *M. ericifolia* to recover and survive after re-exposure following submergence, which is not evident after submergence with fresh water (Raulings et al., 2007; Salter et al., 2008).

Further study of some 20 species of *Melaleuca* to conditions of salinity, waterlogging, and saline waterlogging has shown that all species could survive and maintain relative growth rates when waterlogged, whereas survival under saline conditions (to a maximum of 63 mS cm⁻¹) varied between species and between provenances (van der Moezel et al., 1991). Based on relative growth rate the most tolerant species in this glasshouse experiment to conditions of saline waterlogging were *M. sp. aff. lanceolata*, *M. lateriflora* and *M. thyoides* (van der Moezel et al., 1991). One provenance of *M. halmaturorum* had 100% survival after treatment with saline waterlogging,
suggesting some provenance variation exists for this species (van der Moezel et al., 1991). Generally, provenances which ranked high for salinity tolerance in this experiment also ranked high for tolerance of saline waterlogging (van der Moezel et al., 1991).

Of the genera discussed in this review, investigations into the ecophysiology of riparian *Eucalyptus* is by far the most comprehensive, and of the *Eucalyptus* species considerable research has been undertaken on *E. camaldulensis*.

*E. sargenti* appears to be a relatively higher consumer of water in areas affected by secondary salinisation. This species, along with *E. spathulata*, appeared to be the most promising species for reclamation of a saline seep, with 2 species showing high survival rates and good canopy size after 15 years (Greenwood et al., 1994). Despite perched water chloride contents up to 17 300 mg L$^{-1}$ and pH values ranging between 3.4 and 4.5 (with occasional values as low as 2.6), *E. sargenti* had survival rates of 100% over 6 years (Biddiscombe et al., 1989). *E. spathulata* performed better than 36 other species and provenances after 7 years on a saline discharge site (Benyon, Richard G. et al., 2001). Water use per tree in this species was 4 – 5 times greater than in other well performing species, primarily due to a large difference in tree size, a mean leaf area 4 – 5 times greater than other species, and a faster growth rate (Benyon, Richard G. et al., 2001).

*E. robusta* appears to tolerate waterlogging for extended periods (up to 80 days) forming adventitious roots and exhibiting stem hypertrophy (Clemens & Pearson, 1977). This species has shown low tolerance to salinity during field trials in Western Australia, with the majority of seedlings dying at soil salinities less than EC$_6$ 750 mS m$^{-1}$, with no seedlings surviving after 2 years on the saline site (Pepper & Craig, 1986). Dunn et al. (1994) found this species to be moderately salt tolerant in a field trial in southeast Queensland, exhibiting a 25% reduction in height at an EC$_6$ of 9.5 dS m$^{-1}$ (950 mS m$^{-1}$).

Transpiration rates of *Eucalyptus* spp. have shown to vary considerably, with variation occurring either seasonally or due to evaporative demand and water availability. Plantation *E. camaldulensis* exhibited transpiration rates anywhere between 0.24 mm day$^{-1}$ (in pre-monsoonal India) up to 22.8 mm day$^{-1}$ (in a flood irrigated plantation in Iran). Such variations in measured transpiration illustrate that *E. camaldulensis* has the ability to be a prodigious or economical user of water and indicates a level of ecological plasticity in the species (Edraki et al., 2007). Transpiration in *E. camaldulensis* appears unaffected by saline groundwater.

Reported transpiration rates of *E. largiflorens* are low – 0.3 mm day$^{-1}$ (Thorburn, Peter J. et al., 1993), between 0.05 and 0.4 mm day$^{-1}$ (Jolly, I. D. & Walker, 1996), and typically less than 1.0 mm day$^{-1}$ (Akeroyd et al., 1998) - regardless of whether trees had been recently flooded. During flooding, transpiration tended to fluctuate with evaporative demand indicating that stomatal closure does not occur in this species in response to flooding, regardless of flood length and the lack of adventitious root formation (Akeroyd et al., 1998). Further, lack of suppression of transpiration in response to flooding indicates that roots appear flood tolerant and that the extensive root system of this species may be able to vary the depth at which they are active in response to both water and oxygen, or lateral roots may be able to absorb oxygen at very low concentrations and at low rates under flooding (Akeroyd et al., 1998; Heinrich, 1990; Jolly, I. D. & Walker, 1996).
Both *E. camaldulensis* and *E. largiflorens* appear to be opportunistic users of water demonstrating maintenance of growth when flows are reduced but rainfall is high, or when rainfall is low and flows are moderate (George, Amy Kathryn, 2004). They will also preferentially source water from where it is most available, whether that be surface, soil (shallow and deep) or groundwater (Akeroyd et al., 2003; Cramer et al., 1999; Dawson & Pate, 1996; Engel et al., 2005; Holland et al., 2006; Jolly, I. D. & Walker, 1996; Mensforth, L. J. et al., 1994; Thorburn, Peter J. et al., 1993; Thorburn, P. J. et al., 1994; Thorburn, Peter J. et al., 1992; Thorburn, Peter J. & Walker, 1994).

Hatton et al. (1998) have found that tree water use scaled similarly with leaf area across species of *Eucalyptus* and between provenances, with a strong linear relationship between tree leaf area and mean daily water use. This indicates that leaf efficiency (water use per unit leaf area) appears to be independent of eucalypt species (Hatton, T. et al., 1998).

A significant correlation between distance from floodwater and xylem pressure potential has been observed in mature *E. camaldulensis*, with xylem pressure potential doubling from -4.91 MPa at the edge of a water course to -8.83 MPa at a distance of 7.5 m from the watercourse (Stone & Bacon, 1994). Xylem pressure potentials continued to decline with increasing distance from the watercourse, down to -12.53 MPa at a distance of 37.5 m (Stone & Bacon, 1994). Minimum xylem pressure potentials under conditions of water deficit (end of summer) appear to differ between provenances of *E. camaldulensis*, with a study in Israel showing that a provenance originating from a semi-arid region of southern Australia achieved lower xylem pressure potentials (-4.3 MPa) than a provenance from tropical northern Australia (-3.4 MPa) (Grunwald & Karschon, 1982). Despite the lower pressure potentials of the semi-arid provenance, tree growth appeared not to be affected (Grunwald & Karschon, 1982). Indicating that drought tolerance in *E. camaldulensis* may be related to the environment from which the provenance originates. Threshold water potentials for initiation of xylem embolism in two provenances of *E. camaldulensis* differ, with a provenance from an arid environment exhibiting slightly lower potentials (-3.3 MPa) than a tropical provenance (-3.0 MPa) (Franks et al., 1995).

There is a presumed link between recruitment and flooding for *E. camaldulensis* and *E. largiflorens* given that flooding is the primary source of moisture for germination and seedling establishment in the southern Australian environments in which these species occur (Dexter, 1967; George, Amy Kathryn, 2004; George, Amy K. et al., 2005). *E. camaldulensis* may also be able to adjust the timing of seed fall in response to favourable conditions, with extensive seed fall observed upon flooding of a wetland (George, Amy Kathryn, 2004). Flooding needs to occur at a time which allows seedlings to establish prior to the onset of dry conditions in summer. For this reason flooding is likely most effective for recruitment when it occurs in late winter/early spring. Prolonged submersion of seedlings less than 6 inches high will likely result in their death, while seedlings less than 9 inches in areas of low and medium elevation will likely succumb as well (Dexter, 1967). Flooding of 6-week-old *E. camaldulensis* for up to 40 days reduces growth, induces leaf epinasty, and reduces total dry weight (Sena Gomes & Kozlowski, 1980). Positive growth rates of *E. camaldulensis* and *E. largiflorens* appear to rely on moderate river flows coupled with average rainfall, while growth appears interrupted under saturated conditions (Bacon et al., 1993; George, Amy Kathryn, 2004).

The germinative capacity of *E. camaldulensis* appears significantly affected by moisture stress under glasshouse conditions (Edgar, 1977) Substrate potentials of -2 bars (-0.2 MPa) affect germination,
with little germinating occurring at -8 bars (-0.8 MPa) (Edgar, 1977). In general eucalypt species and provenances within species are specifically adapted to the moisture conditions of the environment in which they occur (Gibson, A. & Bachelard, 1987, 1989). Treatment with NaCl has also been shown to substantially reduce the rate and percentage emergence of *E. camaldulensis* provenances (Madsen & Mulligan, 2006) and riparian *Eucalyptus* species in general (Pearce-Pinto et al., 1990; van der Moezel & Bell, 1987b). The rate and percentage germination of *E. camaldulensis* provenances began to reduce at 100 mM NaCl (equivalent to approximately 11 dS m⁻¹) (Madsen & Mulligan, 2006). *E. occidentalis*, *E. loxophleba* and *E. sargentic* had high relative germination capacity at 100 mM NaCl, while *E. spathulata* was the only species to germinate at NaCl concentrations of 200 mM (Refer to Table 18) (Pearce-Pinto et al., 1990). Germination of all species was suppressed at 300 and 400 mM NaCl (van der Moezel & Bell, 1987b), while survival of established seedlings did not differ at NaCl concentrations of 300 and 400 mM NaCl (approximately 28 and 36 dS m⁻¹ respectively) (Madsen & Mulligan, 2006) and there was a lack of correlation between salt tolerance at germination and seedling tolerance (Pearce-Pinto et al., 1990).

Clonal differences in tolerance to waterlogging and salinity have been observed in *E. camaldulensis*. Earlier formation of adventitious roots in clone M80 appears to confer a greater tolerance to waterlogging in freshwater (Akilin, K. et al., 1997). No adventitious root formation occurs when *E. camaldulensis* clones (M80 and M66) are waterlogged with saline water (Akilin, K. et al., 1997). Clone M66 appears to be more salt tolerant than the M80 clone, up to groundwater salinities of 12 mS cm⁻¹ (Akilin, K. et al., 1997; Akilin, K. et al., 1997). As for the two clones (M80 and M66) waterlogging with saline water appears to restrict formation of adventitious roots in this species as a whole (van der Moezel, 1989 #967). Transpiration and photosynthetic rates of *E. camaldulensis* seedlings are lower under saline drained and saline waterlogged glasshouse conditions (van der Moezel, 1989 #967) (Marcar, 1993 #1131). *E. viminalis* and *E. ovata* both appear tolerant of waterlogging; developing adventitious roots and stem hypertrophy, although *E. ovata* may tolerate these conditions slightly better with a lower height reduction under waterlogging than *E. viminalis* (Ladiges, Pauline Y. & Kelso, 1977).

Investigating the level of salinity that trees tolerate in the field is difficult to determine accurately given that root growth may enable a tree to avoid exposure at sites of excessive salts (Morris, J. D., 1980). Considerable variation in tolerance to salt has been shown between provenances of *E. camaldulensis* with concentrations of NaCl from 466 to 636 mM causing mortality in seedlings under glasshouse conditions (Morris, J. D., 1980; Teulières et al., 2007). Variation in tolerance to salinity is once again likely due to the wide geographic distribution of the species. Apparent salt tolerance of eucalypt species may vary with growth stage, with tolerance appearing to increase with age (Morris, J. D., 1980).

Field trials in Western Australia have shown that *E. occidentalis* and *E. sargentic* resisted ECₑ values greater than 3 000 mS m⁻¹ with greater than 50% survival rates after 8 years (Pepper & Craig, 1986). *E. camaldulensis* showed poor health and vigour and low survival rates in this trial at ECₑ values greater than 1 000 mS m⁻¹ (Pepper & Craig, 1986). Field trials in southeast Queensland have shown that *E. camaldulensis* can tolerate salinity values greater than ECₑ 11.0 dS m⁻¹ (1 100 mS m⁻¹) before a 25% reduction in height is observed, and 100% of seedlings survived at salinities greater than ECₑ 1.75 1.75 dS m⁻¹ (approximately equivalent to an ECₑ greater than 1 160 mS m⁻¹) (Dunn et al., 1994). *E. occidentalis* has also been observed to perform well when planted near a saline seep, where
perched water was present within 1 m of the soil surface for extended periods, with a pH ranging between 4.3 and 6.8 and a chloride content as high as 9 500 mg l$^{-1}$ in autumn (Biddiscombe et al., 1989).

Glasshouse germination rates of *E. occidentalis* are directly related to temperature (between 15 and 30°C) and osmotic potential of the medium (between -9.1 and 0 bars) (Zohar, Y. et al., 1975). Optimum germination conditions exist when osmotic stress is not present at a temperature of 30°C, with an apparent threshold of tolerance to osmotic stress occurring at -9.1 bars (-0.91 MPa) at the same temperature (Zohar, Y. et al., 1975). Sands (1981) found intra-specific variation in germination of provenances of *E. camaldulensis* under saline conditions, with little to no germination evident for any of the provenance at NaCl concentrations of 200 mM; this may indicate a germination tolerance threshold for the species as a whole (Refer to Table 17).

In saline solution culture, *E. camaldulensis* exhibited a 50% mortality of seedlings at NaCl concentrations of 400 mM, *E. largiflorens* at 380 mM, *E. spathulata* at 220 mM (varying between 120 and 350 mM), *E. kondininensis* at 185 mM (varying between 170 and 200 mM), and *E. occidentalis* at 150 mM (varying between 130 and 170 mM) (Blake, T. J., 1981). Marcar (1989) however has since found that both *E. occidentalis* and *E. camaldulensis* could survive for 10 days at NaCl concentrations of 500 mol m$^{-3}$, with approximately 75% of *E. occidentalis* seedlings surviving this concentration for up to 45 days, albeit with severe leaf death and abscission.

Intra-specific variations in the survival of *E. camaldulensis* seedlings in response to salinity are evident. Leading provenances appear to be from semi-arid areas of high natural salinity. Provenance variation consistent with expected differences due to geographic distribution are also evident in this species in relation to the effects of NaCl and high pH (Marcar et al., 2002b). Provenances from Lake Albacutya were amongst the best performers based on height, while provenances from Petford and Lake Hindmarsh were the most salt tolerant (150 mol m$^{-3}$ NaCl) based on shoot dry weight (Marcar et al., 2002b). Two provenances from northern Western Australia were shown to be highly tolerant of high pH (9.5) with a less than 5% reduction in growth (Marcar et al., 2002b).

*E. halophila* seedlings have been shown to be tolerant of salinity in the glasshouse and likely reflects their ability to inhabit the margins of salt lakes where saline groundwater commonly occurs at depths of less than a metre (van der Moezel & Bell, 1987a). This species has also been shown to grow faster under alkaline-bicarbonate treatments in the glasshouse, exhibiting leaf production and maintenance of high leaf concentrations of iron under such conditions (James et al., 2002).

Several species of riparian *Eucalyptus* have exhibited a level of alkalinity tolerance in field trials in Western Australia (Bell, David T. et al., 1993). Of these *E. camaldulensis* clone M66 had the highest field survival rate at pH above 8.0, while clone M16 had one of the lowest survival rates at this pH level (Bell, David T. et al., 1993). This once again demonstrates the intra-specific variation of stress tolerance within this species. Other *Eucalyptus* species which exhibited tolerance to pH levels between 8.0 and 10.0 were *E. spathulata*, *E. kondininensis* and *E. occidentalis* (Bell, David T. et al., 1993). The relative tolerance to alkaline conditions generally held in the glasshouse.

For the portion of the bank above the minimum base flow the addition of *E. camaldulensis*, *E. amplifolia*, or *E. elata* roots can increase the factor of safety considerably (Abernethy, Bruce &
Rutherford, 2000b; Docker, Benjamin Brougham, 2003). When planting species for management of riverbank stability it is important to consider the sensitivity of seedlings to flooding. Further, the stabilising effect of a single tree will vary given its position on the riverbank, with different species being more effective in different locations within the riparian zone (Docker, Benjamin Brougham, 2003). As it appears that *E. camaldulensis* seedlings are sensitive to flooding in the first 2 years the species is better suited to planting on the floodplain, where floods are less frequent and of lower intensity (although the species has been shown to survive on in-channel benches) (Abernethy, Bruce & Rutherford, 2000b, 2001). Both *E. amplifolia* and *E. elata* would appear to be better suited to the upper-bank and floodplain given that it is these areas which the species occupy in riparian environments. It appears that there is a general rule that can be applied when considering species for bank stabilisation where the greater the quantity of roots present at the shear plane, the greater the increase in the shear resistance of the soil, with a clear linear relationship for all species between the increase in shear stress and the root area ratio (Docker, B. B. & Hubble, 2008). Further, important factors in the ability of trees to bind riverbank soil together are high individual root tensile and pull-out strengths (Refer to Table 22), as well as an even distribution of roots across the shear plane (Docker, B. B. & Hubble, 2008).