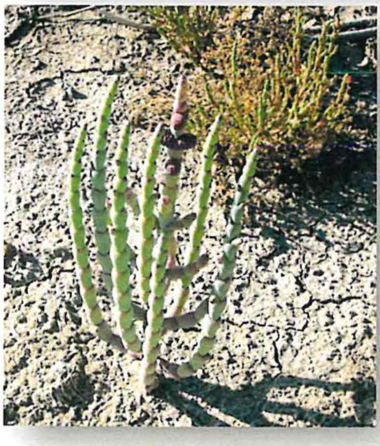
Hydrology and environmental gradients of the *Muehlenbeckia horrida abdita* Threatened Ecological Community (TEC) at Lake Bryde and East Lake Bryde, Western Australia.



Simon Judd

Kathrine Goldsmith

Ray Froend

Tonja Boyd

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EDITH COWAN UNIVERSITY

CENTRE *for* ECOSYSTEM MANAGEMENT
EDITH COWAN UNIVERSITY

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1. INTRODUCTION

The health and persistence of wetland vegetation is invariably connected to hydrological regimes, principally the timing and duration of surface and/or groundwater availability. The timing and duration of inundation can be a key ecological driver which determines the spatial and temporal arrangement of vegetation on a lake bed. An individual plant's response to water availability and physico-chemistry along spatial and temporal environmental gradients will depend upon life history strategies and physical location in wetland topography. Vegetation response to changing conditions may be observed by a change in distribution, abundance and health (e.g. canopy cover) sometimes along discernable hydrological and habitat gradients. Cramer & Hobbs (2002) observed that changing hydrological regimes in Western Australia often results in a concomitant reduction in structural diversity and floristics and ultimately changes in species composition.

Changing vegetation patterns at the broad scale influences the way in which water moves through the landscape. Clearing of native vegetation worldwide has resulted in increased waterlogging and development of secondary salinisation in areas of low topography; this has occurred in the USA, Thailand, Canada, South Africa, Turkey, India, Argentina and Australia (Farmer, Stanton & Coles, 2002) . In south-western Australia the introduction of agriculture has resulted in the conversion of natural perennial vegetation into areas of seasonal broad-acre farmland. In many areas native vegetation has been reduced to little more than disconnected fragments of remnant bushland (Hobbs, 1993).

Prior to broad-scale clearing of native vegetation, water movement through the landscape was much slower in south-western Australia. Native vegetation intercepted rainfall and interrupted the surface water flow thus increasing the time water spent in higher parts in the catchment. This increased the lag time between water moving from upper to lower slopes and from lower slopes to the valley floor. As a result, water infiltration rates were much higher throughout the catchment and significant rainfall events were required to produce inflows onto the valley floor. The frequency and duration of inundation of freshwater in low-lying areas was therefore lower. Farmer *et al.* (2002) suggested that cleared native catchments have a 3:1 surface-flow ratio while Hatton, Ruprecht & George (2003) suggested an even higher ratio of 5:1. The frequency, duration, depth and extent of inundation of the vegetation and soils experiencing waterlogging lower in the landscape will therefore increase.

These anthropogenic changes to water regimes have resulted in the mobilisation of salts stored throughout the soil profile to the soil surface. Depending upon a number of factors, including the hydrology, vegetation, rainfall and topography within catchments (Cullen, 2004), these stored salts will be redistributed within the catchment. Farmer *et al.* (2002) found that cleared agricultural regions have experienced increases in saline water shedding from the catchment into low-lying areas. Small rainfall events will result in higher localised concentrations, while large rainfall events flush salts into low-lying zones.

Rising salinity levels not only directly affect the productivity of agriculture lands it also affects remnant bushland within agricultural catchments. Terrestrial and aquatic environments within remnant areas of bushland have, and are prone to, greater loss of biodiversity, buffering capacity and connections with other ecosystems (Hart *et al.*, 2003). Farmer *et al.* (2002) point out that frequent and prolonged inundation has resulted in widespread vegetation degradation of valley floors. Further, high salinity and increased waterlogging have an antagonistic relationship, giving rise to declines of structure and complexity of both vegetation (Hart *et al.*, 2003) and soils (Kozlowski, 1997). As a result, plant productivity is reduced for as long as the condition exists. If conditions do persist, plant deaths occur thereby reducing biodiversity and further threatening remnant, stressed ecological communities (Cullen, 2004). Vegetation deaths lead to open patches and the distributional changes of intolerant species provide an opportunity for the encroachment of species better suited to modified ecological conditions within the wetland. Highly evolved species that have adapted to specific environmental conditions within a wetland will be likely to show declining populations and ultimately extinction.

1.2 The threat of salinity and waterlogging

In the south-west of Western Australia 94% of perennial vegetation has been cleared for agriculture (Davis *et al.* 2003). This extensive clearing has increased the number of wetlands threatened by rising water depths, salinity levels and permanency of water regimes (Davis *et al.*, 2003). Studies have predicted that salinity will affect the productivity of 1500 species and the possible extinction of up to 450 plant species within south-western Australia alone (George & Short, 2006). Freshwater wetland vegetation is particularly susceptible to increases in salinity levels.

Increasing soil salt concentrations in the root zone affects wetland plant productivity and can lead to deaths. Long periods of waterlogging leads to anaerobic soils due to water displacing air from the sediments. While some plants can tolerate such conditions, the frequency in which waterlogging occurs in an altered regime may affect species' ability to adapt, resulting in loss of health and or death. The tolerance and niche range of wetland plants will dictate the degree of response to the build up of salt ions; which affects the soil osmotic potential and hence the ability of the plant to draw nutrients and water from the soil (Charman & Wooldridge, 2007).

Salinity and waterlogging threaten the health and persistence of valley ecosystems throughout the Western Australian wheatbelt. Catchment specific information provides managers with the ability to identify salinity hot-spots and the limitations of the landscape itself (ANRA, 2000). There are a number of steps involved in the protection and conservation of at risk catchments and wetlands. From a National perspective, the Federal Environmental Protection and Biodiversity Conservation (EPBC) Act provides the international direction and Australian jurisdiction for listing endangered species. The Act provides a mechanism for agencies at a state level to draft and implement recovery action plans. In Western Australia, the agency responsible is the Western Australian Department of Environment and Conservation (DEC) and many of its recovery plans are implemented at the catchment scale. Agencies are also involved in commissioning investigations and out-sourcing experts for the purpose of identifying linkages between biotic components and key stressors (Hart *et al.*, 2003) and habitat alterations. At a catchment level, steering or catchment groups are set up to manage this information and oversee the implementation of designated action plans (Phillimore, Giraudo, & Brown, 2003). One such example of endangered species being managed by such a process is *Muehlenbeckia horrida* at the Lake Bryde catchment.

1.3 The importance of the Lake Bryde Catchment

The Lake Bryde catchment (hereafter referred to as 'the catchment') is located in the southern wheatbelt of south-west Australia (Figure 1.1) and has been subject to excessive inundation and secondary salinisation since the clearing of native vegetation for agriculture (Hamilton-Brown & Blyth, 1999). Altered hydrology is also threatening the few remaining freshwater wetlands within the catchment area. This catchment is regionally significant because there are very few freshwater wetlands extant in the wheatbelt. Studies have shown diversity in the catchment to be equal to or better than wetlands on the Swan Coastal Plain (Hamilton-Brown & Blyth, 1999). The catchment contains two significant shrub-dominated wetlands (Halse, Pearson, & Patrick, 1993). These wetlands are Lake Bryde and East Lake Bryde (Figure 1.1).

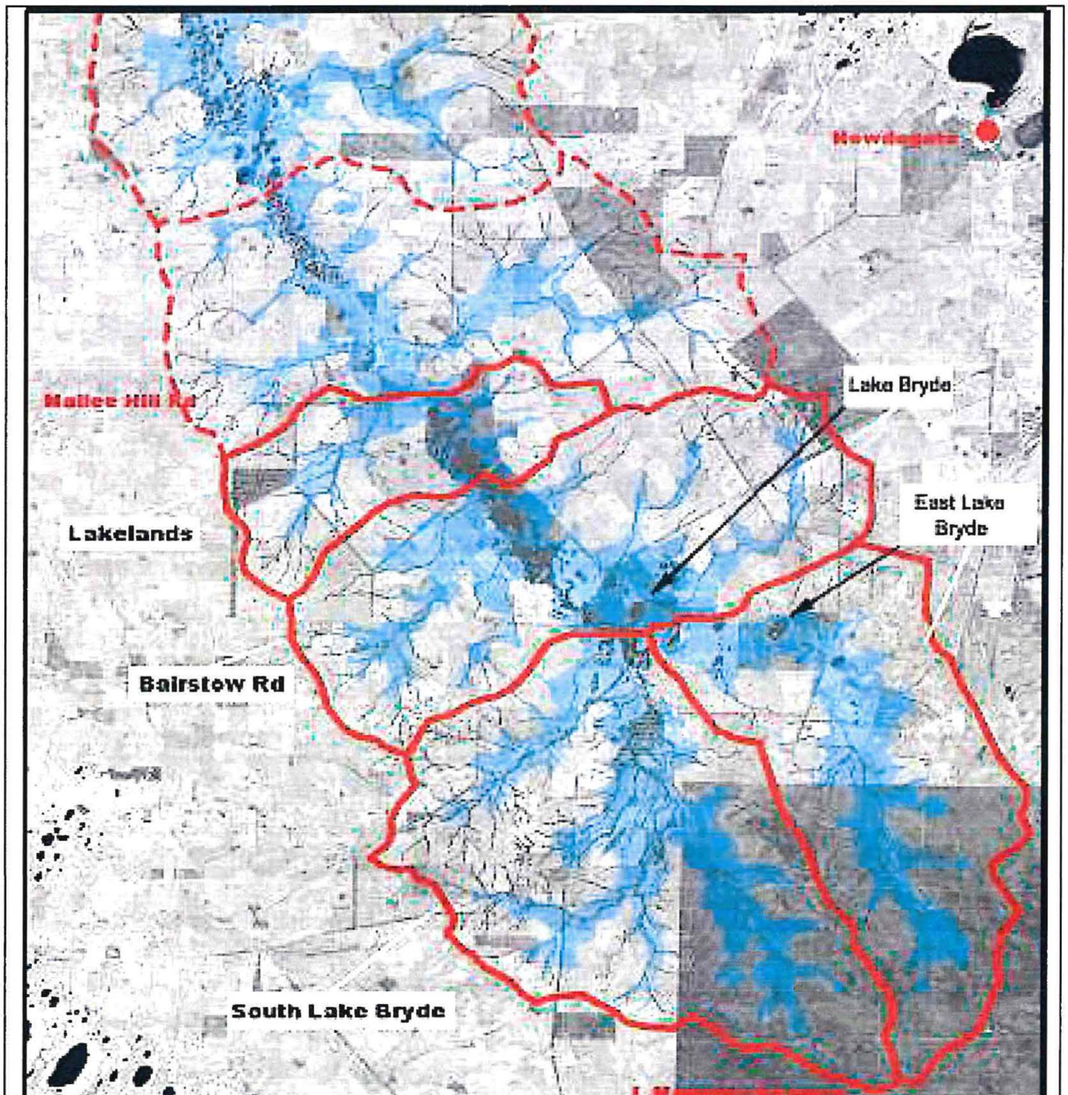

Figure 1.1. Map showing the Lake Bryde catchment with locations of Lake Bryde (33°21"06'S 118°49"39'E) and East Lake Bryde (33°21"39'S 118°54"25'E). Sub-catchments are shown in red and flood modelling in blue. Source: Modified from Farmer *et al.* (2002).

Lake Bryde and East Lake Bryde contain the only known populations of *Muehlenbeckia horrida abdita* which is declining in abundance and recruitment and is the subject of a management recovery plan. These two locations are experiencing increasing salinity levels. *M. horrida abdita* is a lignum shrub that can tolerate extended periods of drought and inundation. Fewson (2003) compared the structure of Lake Bryde and East Lake Bryde *M. horrida abdita* populations and found that the Lake Bryde population was the tallest and oldest as well as highest canopy cover and recruitment, however this population also exhibited the highest mortality rate. In contrast, the population at East Lake Bryde was healthy but shorter in stature, had less canopy cover and lower recruitment. Fewson (2003) also concluded that *M. horrida abdita* at Lake Bryde and East Lake Bryde had different population structures.

1.4 Lake Bryde Interim Recovery Plan – the need for research

The declining population of *M. horrida abdita* was formally recognised in 1999 as part of a Threatened Ecological Community (TEC); subsequently an Interim Recovery Plan was implemented for the investigation, protection and conservation of this declared rare species. This prompted investigations into the specific nature of the stresses affecting *M. horrida abdita* and to identify and document changes in population composition and structure. Critical to the successful management of the population is the need to understand water and salinity thresholds. This is needed to assist managers in planning or mediating hydrological and salinity regimes to best ensure the survival of the species at the two lakes. *Tecticornia verrucosa* is the co-dominant species of the TEC and is found throughout Western Australia. Being widespread and able to tolerate a broad range of inundation and salinity regimes, particularly higher salinities, it provides a good contrast. A brief description of the ecology of the two species follows.

1.5 Muehlenbeckia horrida abdita

Muehlenbeckia horrida abdita (Remote Thorny Lignum) is a subspecies of the *Muehlenbeckia horrida* species in the family of Polygonaceae. *M. horrida abdita* is endemic to Western Australia and found only in the IBRA subregion of the Western Mallee (Spooner, 1997). This lignum shrub ranges from 0.6-1.2 metres in height and has little or no leaves. Flowering occurs in August through to September (Spooner, 1997) or perhaps earlier around the edges of the wetland (observations by B. Loudon cited in Phillimore *et al.*, 2003). This is suggestive of a relationship between flowering and inundation. Mallinson *et al.* (cited in Phillimore *et al.*, 2003) suggested that viable seed can be stored in the soil for a long period of time but, overall, little is known about the seed dispersion, recruitment , life span or strategies. It appears *M. horrida abdita* is tolerant to extended periods of drought and inundation for a number of years at a time and therefore may be well adapted to the hydrology of Lake Bryde and East Lake Bryde. When the plant is totally submerged the stem and branches go limp and soft, regaining its rigid structure when waters recede (N. Nicholson, pers. com. 2009). There are no published accounts of the hydrological habitat preference of *M. horrida abdita.*

Increases in salt loadings over a twenty-two year period have been associated with the decline in *M. horrida abdita* (Threatened Species Scientific Committee (TSSC), 2006). A survey in 2005 found that approximately 2000 plants were still extant in the wild. This number represented 4% of the original survey population (Threatened Species Scientific Committee (TSSC), 2006). As a result, *M. horrida abdita* met the four criteria of the EPBC Act (Section 178) and was listed as a critically endangered species. As a consequence of this Declared Rare Flora (DRF) categorisation and its geographic isolation the vegetation community comprised of *Muehlenbeckia horrida abdita* and *Tecticornia verrucosa* was declared a Threatened Ecological Community (TEC).

1.6. Tecticornia verrucosa

Tecticornia verrucosa is an herbaceous, short-lived annual that grows 20-60 centimetres high. The widespread distribution of the species suggests that it tolerates fresh to slightly saline water and soils and can survive in a variety of conditions from clay pans to coastal flats (Paczkowska, 1995). It flowers over a long period of time. Field monitoring carried out by the DEC (Lake Bryde Recovery Catchment) reports budding and flowering of individuals in both April and July. Periodic surveys of Lake Bryde carried out in 1987, 1993, and 1996 have shown a slow increase in abundance (Hamilton-Brown & Blyth, 1999). Observations by DEC field staff suggest that the species has steadily encroached into both Lake Bryde and East Lake Bryde. *T. verrucosa* may be a useful indicator of the changing state of the wetlands from freshwater to a more saline environment.

1.7 Contrasting sub-catchments

Over 64% of the Lake Bryde Catchment (14 000 ha) has been cleared for agriculture predominantly during the period from 1960 to 1970 (Sinclair Knight Merz, 2000). The catchment consists of a central valley system into which a number of sub-catchments drain (Farmer *et al.* 2002). The catchment was categorised into two sections, upper slope and valley floor. The upper slopes are the main shedding environment with slopes of 3-5%. The valley floor is the receiving environment with a slope of less than 1%. Significant shedding events from the upper slopes produce large volumes of surface run-off which flow onto the valley floor to a depth of 0.5 m or greater. The increase in flow from clearing has expanded the size of the lateral inundation and the frequency at which the surface run-off floods the valley floor (Sinclair Knight Merz, 2000).

While salt is a part of the natural system in the Lake Bryde Catchment, some areas are showing signs of degradation from secondary salinisation. In particular, grey clay soils are more susceptible to salinisation (Farmer *et al.* 2002). This may be the result of a number of contributing factors such as clay soils being found in low-lying areas prone to waterlogging coupled with high evaporation rates thus reducing the rate of export of salts down the soil profile and out of the terrestrial zone of influence (Farmer *et al.* 2002).

1.7.1 Lake Bryde sub-catchment

Lake Bryde itself, while in the Lake Bryde sub-catchment, is at the junction of two other sub-catchments, East Lake Bryde and South Lake Bryde (Figure 1.1). The majority of the inflow into Lake Bryde comes from the South Lake Bryde sub-catchment via a channel on the south-western corner of Lake Bryde. Before inflow can occur into Lake Bryde surface run-off must breach an artificial 0.6m levee. On the eastern side of Lake Bryde, two smaller inlets have been identified. These drain the eastern side of Lake Bryde sub-catchment (14 000ha). For this inlet to flow, natural vegetated levees of 0.5 m and 1 m need to be breached. Farmer *et al.* (2002) suggested that only during large rainfall events will the inlet connect with Lake Bryde. The South Lake Bryde sub-catchment was identified as the main source of salt loading to Lake Bryde. Salt stored in the soil behind the levee, combined with saline surface run off contributes to the inflow load into Lake Bryde. Monitoring of Lake Bryde since 1979 has shown increasing salinity levels.

1.7.1 East Lake Bryde sub-catchment

The East Lake Bryde sub-catchment is south-east of the Lake Bryde sub-catchment (Figure 1.1). Over 50% of the areal extent of the native vegetation of this sub-catchment has been cleared for agriculture (Hamilton-Brown & Blyth, 1999). East Lake Bryde is situated higher in the landscape than

Lake Bryde. Centrally located on the northern boundary, it receives inflow only from its own catchment. There are two significant nature reserves in the East Lake Bryde catchment, East Lake Bryde and Lake Magenta, covering around 10 000 ha. The remaining 6 000 ha of the catchment has largely been cleared for farming (Farmer *et al*, 2002). East Lake Bryde's southern inlet is not well defined and consequently significant volumes of surface run-off are required before water enters the lake from this source (Farmer *et al.* 2002). East Lake Bryde has a higher percentage of remnant native vegetation and therefore high rainfall events are required to produce significant inflows (Farmer *et al.* 2002). Such an event occurred in 2006 when wide-spread rainfall across the catchment was recorded. Rainfall greater than 70-80 mm across the catchment will produce run-off from Lake Magenta Nature Reserve. Since Lake Magenta Nature Reserve is a large portion of the East Lake Bryde sub-catchment, the run-off in 2006 had a significant impact on the inflow volume and subsequent water depths at East Lake Bryde (Farmer et al, 2002).

Due to the hydrology and the extent of native vegetation, salinity levels at East Lake Bryde are not as high as Lake Bryde. However, monitoring by the DEC suggests that salt loading in East Lake Bryde is increasing (DEC, 2009).

1.8 Outline and aims of the report

The conservation of *M. horrida abdita* will depend upon successful management of the two lakes described. To be effective, management must be informed by knowledge of the key environmental factors responsible for the observed decline in the TEC. These factors are hydrology, particularly the depth and frequency of inundation; and salinity of the wetland sediment during dry periods. This report aims to:

- Identify the recent hydrological history of Lake Bryde and East Lake Bryde and use this information to the hydrological habitat occupied by *M. horrida abdita* and *T. verrucosa* at the two lakes.
- Identify the distribution and condition of *M. horrida abdita* and *T. verrucosa* relative to the range in lake sediment salinity.

Observed hydrological regimes and salinity tolerances of *M. horrida abdita* and *T. verrucosa* at the two lakes will be outlined in order to assist the development of practical conservation measures for the Threatened Ecological Communities of Lake Bryde and East Lake Bryde.

2. METHODS

2.1 Experimental design

Micro-scale spatial changes and floristic responses in the *M. horrida abdita* and *T. verrucosa* community were measured along a number of environmental gradients at both lakes. Belt transects 200 m long and 5 m wide were established. Each was divided into forty 5 x 5 m sections (hereafter referred to as subplots). Transects extended from the riparian zone toward the centre of the lakebed. Transect 1 at Lake Bryde was extended to cover 240 m in order to better represent the topography of the lake. The location of the transects was chosen to coincide with previously installed DEC monitoring quadrats of which the exact datum was already known. These were therefore used as geo-reference points. The locations of transects at both Lake Bryde and East Lake Bryde are illustrated in Figures 2.1 and 2.2 respectively. The subplots, 128 at Lake Bryde and 120 at East Lake Bryde, were the locations for recording environmental parameters such as elevation, soil salinity and physical characteristics thereby providing a template of the current environmental conditions in which the two dominant species are found. Soil samples were taken to confirm similarity in soil physical characteristics. An elevation reading, at the junction of each subplot, combined with historical water depths (supplied by DEC), were used as a surrogate for water availability/flooding conditions at each subplot.

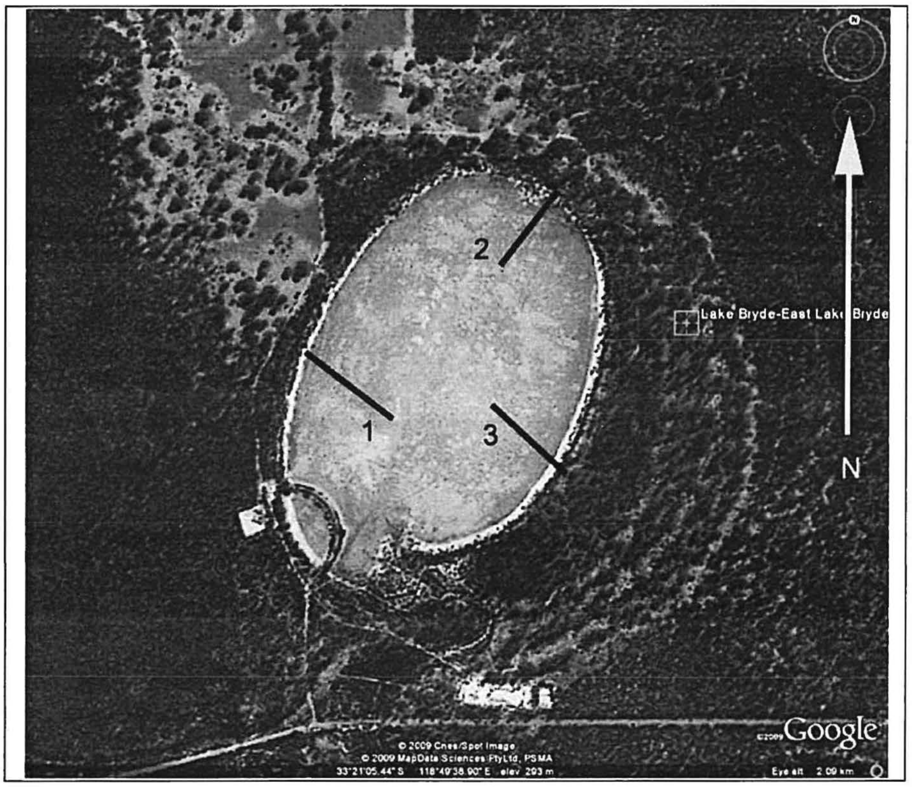

Figure 2.1. Satellite image of Lake Bryde showing the location of the three transects.

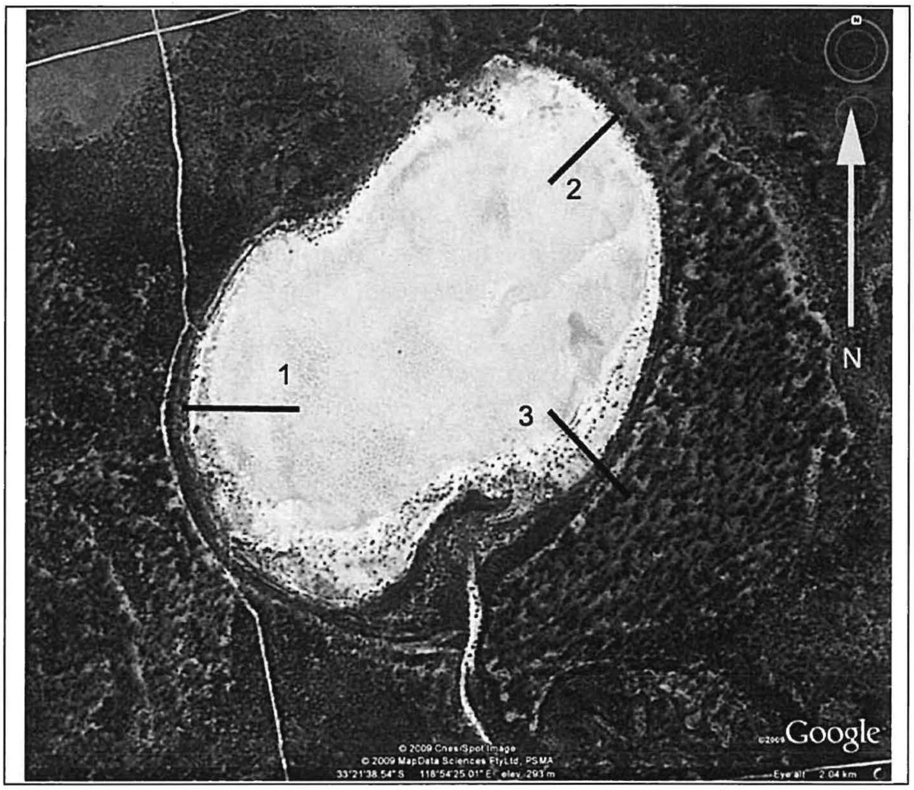

Figure 2.2. Satellite image of East Lake Bryde showing the location of the three transects.

2.2 Elevation and Inundation

Elevation measurements were taken in each subplot. A laser level was used to determine measurements in millimetre increments across the very subtle undulating lake-bed. Transect elevation data points were converted to Australian Height Datum (AHD) using the known datum of the DEC fixed monitoring quadrats along each transect. The laser level and tripod were positioned over a red quadrat marker (indicating a DEC monitoring quadrat) and the height was measured directly above the red marker and the DEC identification code recorded. If there were additional DEC fixed monitoring quadrats within the transect these readings were cross-referenced for greater accuracy. This was repeated across all transects on both wetlands.

Maximum water depth during 1999-2008 for both wetlands was calculated using the converted transect elevation and available water depth in metres AHD (mAHD). Duration of inundation was represented in days using the following methodology. Data from inflow events in 1997, 2000, and 2006 and surface wetting events in 2003 and 2005 were used to calculate periods of inundation for both wetlands. To be able to obtain resolution in days from monthly and/or yearly water depth records, extrapolation was performed between the official and/or inferred water depths. The resolution of the water depth was converted to mAHD where they were matched to the sub-plot elevation. The results were graphed to reflect the association between the duration of inundation and elevation on a subplot scale.

2.3 Soil Salinity

Electromagnetic induction surveys were carried out using a Geonics EM38 to measure the conductivity of the soil and hence the inferred stored salt level within the soil. Horizontal and vertical dipole readings were recorded in ECa mS/m (apparent conductivity) down to depths of 0-1.0

metres (horizontal) and 0-1.5m (vertical). This measurement was taken at the centre of each subplot to maximise representativeness. Calibrations of the EM38 were carried out daily.

2.4 Soil Samples

A soil sample was taken at the centre of each sub-plot using a steel corer. The corer was hammered into the sediment to a depth of 15 cms. The soil sampling sites were located at the same point as used for the EM38 salinity readings. Field texture was determined using two combined methods; the "Soil Texture by Feel" test adapted from Thien (cited in Tiner, 1999 p. 130); and, McDonald & Isbell (1984) bolus test and texture analysis.

2.5 Plant Characteristics

The following parameters were recorded for *M. horrida abdita* and *T. verrucosa* within each subplot:

1) Presence or absence of the species;

2) Total abundance of each species present;

3) Percentage of total foliage projective cover (TFPC) for each plant. This was calculated using two dimensions (at a 90° angle) taken across the canopy foliage. This value for all individuals of each species was tallied and related to the total area for each subplot. When a transect had a significant number of small *T. verrucosa* (e.g. >100) the plants were divided into a height/width class to make the procedure of measuring density cover more efficient. The four classes are as follows:

I. 15 cm high, 5cm x 2cm wide;
II. 25 cm high, 10cm x 2cm wide;
III. 35 cm high, 12cm x 7cm wide;
IV. 45 cm high, 17cm x 15cm wide;

4) Age class of *M. horrida abdita* using the scale described by Newland, Harding and Nicholson (2010). The three classes are as follows:

I. Seedlings (small less than 15cm tall, no hardwood, all softwood);
II. Juvenile (< 40% hardwood in their structure and softwood shoots with one or two stem and/or branches);
III. Mature (> 40% hardwood with softwood shoots); and

5) Condition class using the *M. horrida abdita* scale described by Newland *et al.* (2009). The three classes are as follows:

I. Live (tally seedling, juvenile & mature);
II. Senescent (predominately hardwood with little to no soft shoots. In addition to this assessment, senescent was further characterised as stems which have a combination of flaky or corky bark, in different tones of black, brown and grey (Phillimore *et al.*, 2003) with the occasional bleached stem and/or branch connected to the main body of the shrub); and
III. Dead (completely white and/or bleached stem and/or branches).

3. REGIONAL HYDROLOGY

Recent water regimes for Lake Bryde and East Lake Bryde compiled for this study are shown in Figure 3.1 and Figure 3.2 respectively. These were constructed from data supplied by the DEC and Lane *et al.* (2004 & 2009). It is assumed that these data are direct readings from staff gauges and are inclusive for the period 1979 to 2008 for Lake Bryde and 1980-1985 and 2000-2008 for East Lake Bryde. These data are largely from bi-annual monitoring which occurred in July and September from 1979-1985 and in September and November from 1986-2008.

To assist in filling the gaps in the data for both lakes, local catchment monitoring plans and research papers on Lake Bryde's catchment characteristics were reviewed. The sources of the data are given in Figure 3.1 and 3.2. This additional water depth information was synthesised with the officially recorded data. However, there remained an absence of data for East Lake Bryde during 1985-2000.

The water depth data for Lake Bryde and East Lake Bryde were combined into three phases, each characteristic of a different water regime. The phases were determined by the frequency and duration of wet and dry periods that the wetlands experienced, these were based mainly on Lake Bryde due to the more comprehensive dataset. The Phases were; (1) Dry Phase between 1979 and 1987, (2) Wet Phase between 1988 and 1995, and (3) Post-Wet Phase between 1996 and 2008. These phases are included in Figure.3.1 and 3.2.

3.1 Dry Phase (1979-1987)

During the dry phase Lake Bryde and East Lake Bryde were dry for 75% of the 9 years. This phase was characterised by the longest periods of drought with the highest frequency of seasonal wetting. No episodic events occurred but two subsequent seasonal inflows recorded in 1983 produced a combined maximum depth of 1.73 m resulting in a period of one and a half years of inundation. This was the shortest period of inundation with maximum water depths over 1.70 m.

3.2 Wet Phase (1988-1995)

The wet phase was characterised by up to 6 years of inundation at Lake Bryde or 94% waterlogging. The period of inundation was extended over this period because of frequent seasonal wetting. Four water depth peaks occurred over this period. These subsequent inflows aided in sustaining the water level above the lakebed and maintained saturated soils. East Lake Bryde was not monitored during this time but a similar pattern could be expected.

3.3 Post wet Phase (1996-2008)

The post wet phase was characterised by variation in dry periods. Approximately 50% of the period was wet without prolonged flooding but rather an increase in episodic frequency, as three of the four episodic events across all of the phases occurred in Phase 3. The last 6 years of the post wet phase appears to be very similar to the water regime experienced in the dry phase.

3.4 Lake Bryde

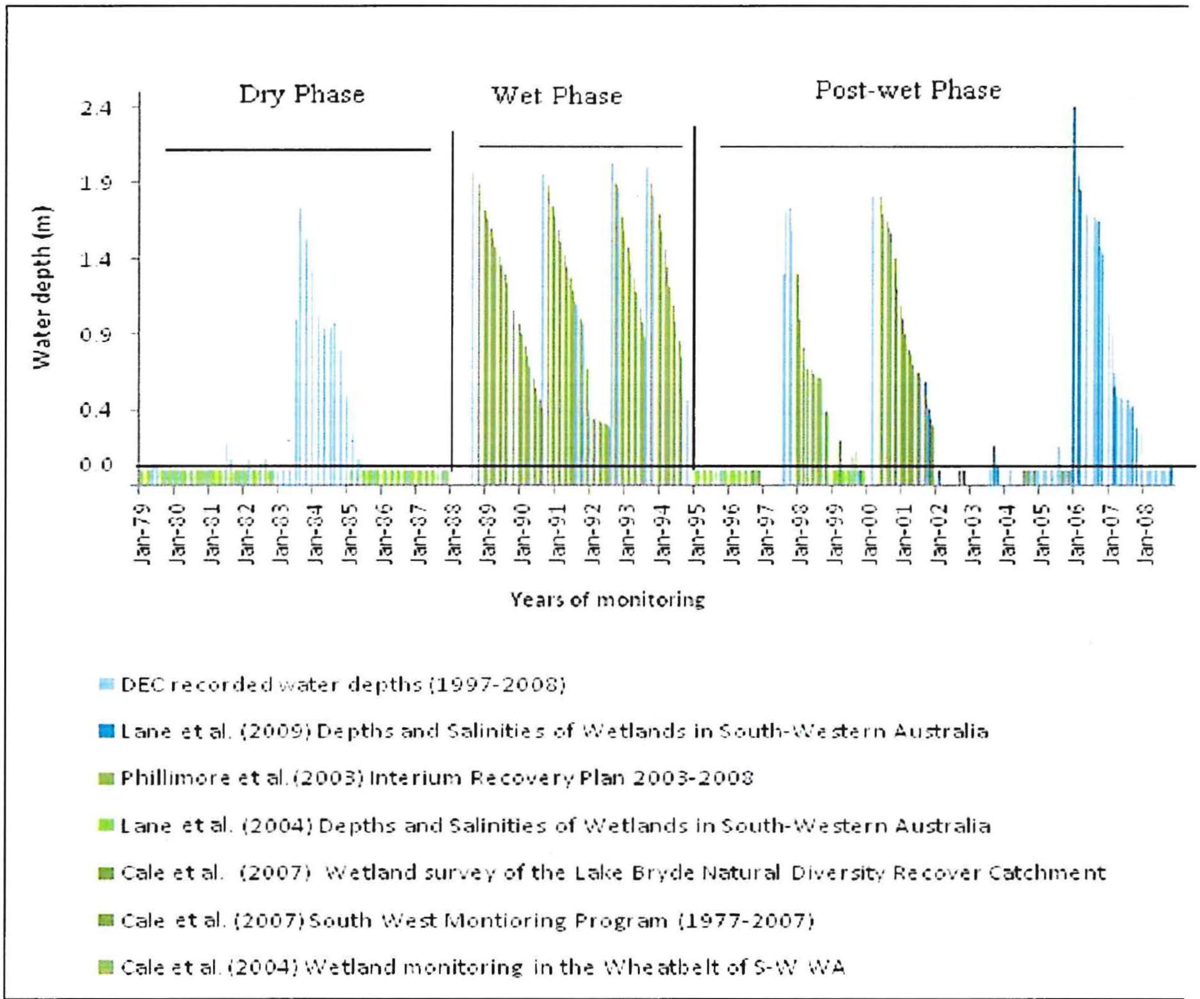

Figure 3.1. Composite hydrograph for Lake Bryde (1979-2009). Data are drawn from DEC observations (blue) and from the available literature (green). Three phases are identified; a dry phase (1979-1988), a wet phase (1989-1995); and a post wet phase (1995-2008) (Cale, 2007; Cale, Halse, & Walker, 2004; Lane *et al.*, 2009; Lane, Pearson, Clarke, Winchcombe, & Munro, 2004; Phillimore *et al.*, 2003).

Seasonal wetting (inundation by rainfall only with no inflow events) at Lake Bryde was found to increase water depth from dry to 17 cm deep. This occurred in the years 1979-1983, 1987, 2003 and 2005, compared to seasonal inflows which produced between 1 and 1.5 m increases in water depth. Seasonal inflows into a dry lakebed occurred only in 1983 and 1997. Both of these events had subsequent inflows during the following monitoring period and were the only years that two inflow events occurred in the same year. During 1991, 1993 and 1994 inflows into Lake Bryde increased the water depth. The frequency of seasonal inflows increased during 1991-1994 leading to a prolonged period of inundation. There were 3 episodic inflow events (1988, 2000 and 2006) where the lakebed went from dry to greater than 1.7 m water depth. Episodic events resulted in inundation of up to 2 years before the lakebed dried out. The maximum water depth (2.42 metres) occurred in 2006.

The longest recorded dry phase at Lake Bryde was 36 months during 1985-1987. A number of extended dry periods were recorded in 1979-1983, 1999, 2002 and 2004-5 which were only periodically interrupted with very shallow water depths recorded (Figure 3.1).

3.5 East Lake Bryde

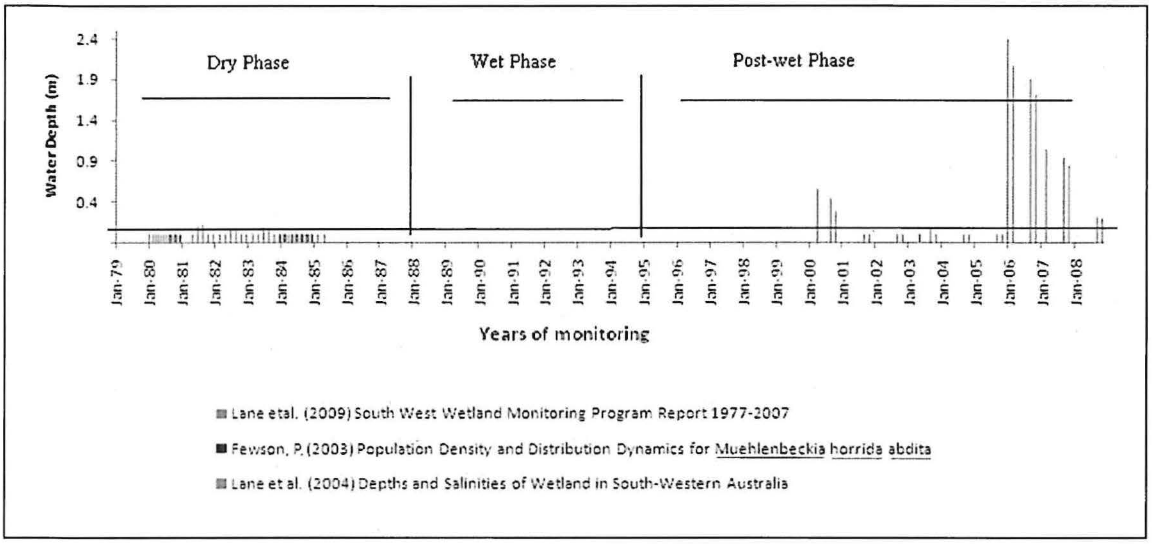

Figure 3.2. Composite hydrograph for East Lake Bryde (1979-2009). There are no recorded observations from the lake itself and therefore data are from the available literature. The three phases identified in Figure 3.1 have been superimposed here as well. These are a dry phase; (1979-1988), a wet phase (1989-1995) and a post wet phase (1995-2008) (Fewson, 2003; Lane *et al.*, 2004; Lane *et al.*, 2009).

East Lake Bryde shows seasonal wetting (inundation by rainfall only with no inflow events) with water depths up to 11 cm. This occurred during 1981-3, and 2003. Both Lake Bryde and East Lake Bryde data show that seasonal duration of inundation typically lasts for one to two months before drying out. The only recorded seasonal inflow into East Lake Bryde occurred in 2000 with a hydro-period of around 265 days. One episodic event in 2006 attained a maximum water depth of 2.4 m. The lake remained inundated for 1073 days or nearly 3 years. East Lake Bryde also recorded extended dry periods in 1984-5, 2001-2 and 2004-5.

4. WATER LEVELS AND RETENTION TIMES

4.1. Wetland profiles

Water levels are obviously a function of the wetland lake bed topography. Figure 4.1 shows the three transects from each wetland plotted on a common scale. Water depth data for both Lake Bryde and East Lake Bryde was used as a surrogate for inflow events into the wetlands. This helped determine the hydrological characteristics such as periodicity and episodic inflows, seasonality, frequency and duration of inundation and drought periods.

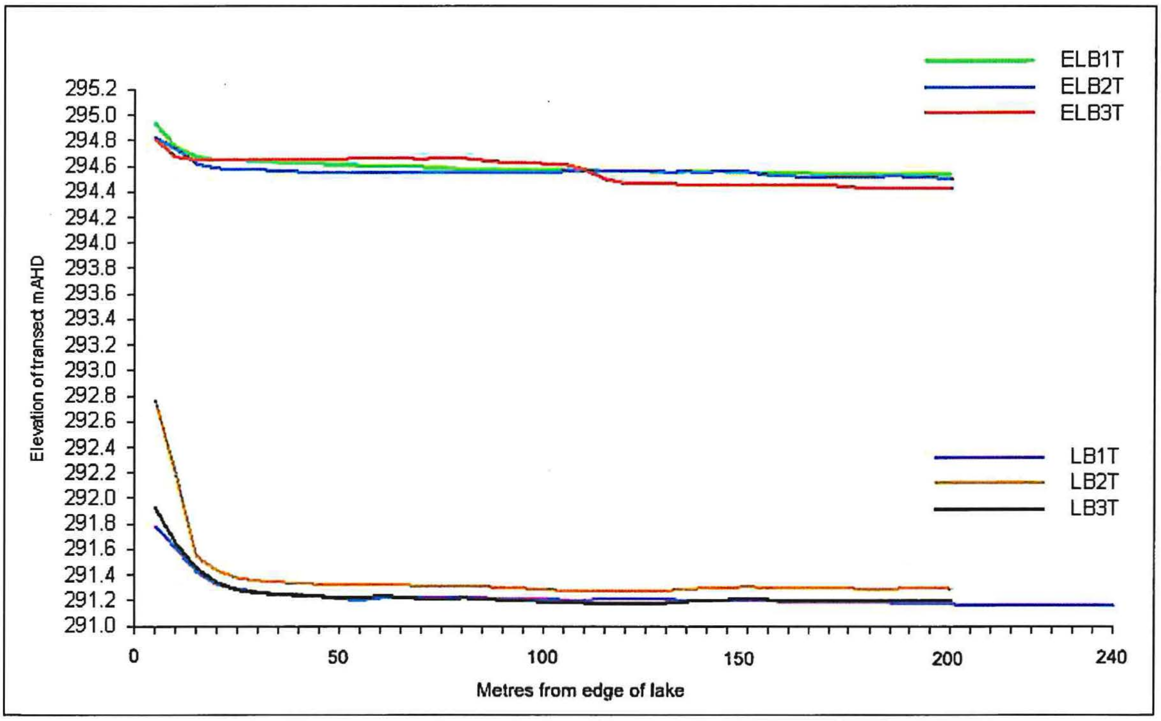

Figure 4.1. Profiles of Lake Bryde (LB) and East Lake Bryde (ELB) showing each of the three transects.

Figure 4.1 shows East Lake Bryde to be higher in the landscape than Lake Bryde. Both lakes have an embankment at the perimeter but this is noticeably steeper at Lake Bryde. The wetland floor is relatively flat across both wetlands, however, transect three at Lake Bryde has a dip of about 2 cm. The third transect in East Lake Bryde showed a distinct shoreline with a drop in elevation of 10 cm over the first 10 m.

4.2 Significant inflow events

Figure 4.2 and 4.3 show the profiles of the two wetlands illustrated in Figure 4.1 together with the maximum water levels of the significant inflow events during the post wet phase identified in Figure 3.1. At Lake Bryde the extent of the two inflow events in 2000 and 2006 are clearly shown. These correspond with peaks shown in the post-wet phase defined in Figure 3.1. These events both resulted in complete inundation of the wetland for extended periods with the maximum water depth recorded at Lake Bryde and East Lake Bryde of 293.46 and 296.86 mAHD respectively. Smaller rainfall-derived seasonal wettings occurred in 2003 and 2005. These seasonal events were similar in their water levels and did not inundate the whole basin. It is notable that at Lake Bryde, Transect 2 is not inundated by this type of filling. These are two distinctly different hydrological regimes. The two inflow events (2000 and 2006) are also shown on Figure 4.3 for East Lake Bryde. These events inundated the wetland for an extended period. In contrast to Lake Bryde seasonal wetting by rainfall occurred only in 2003.

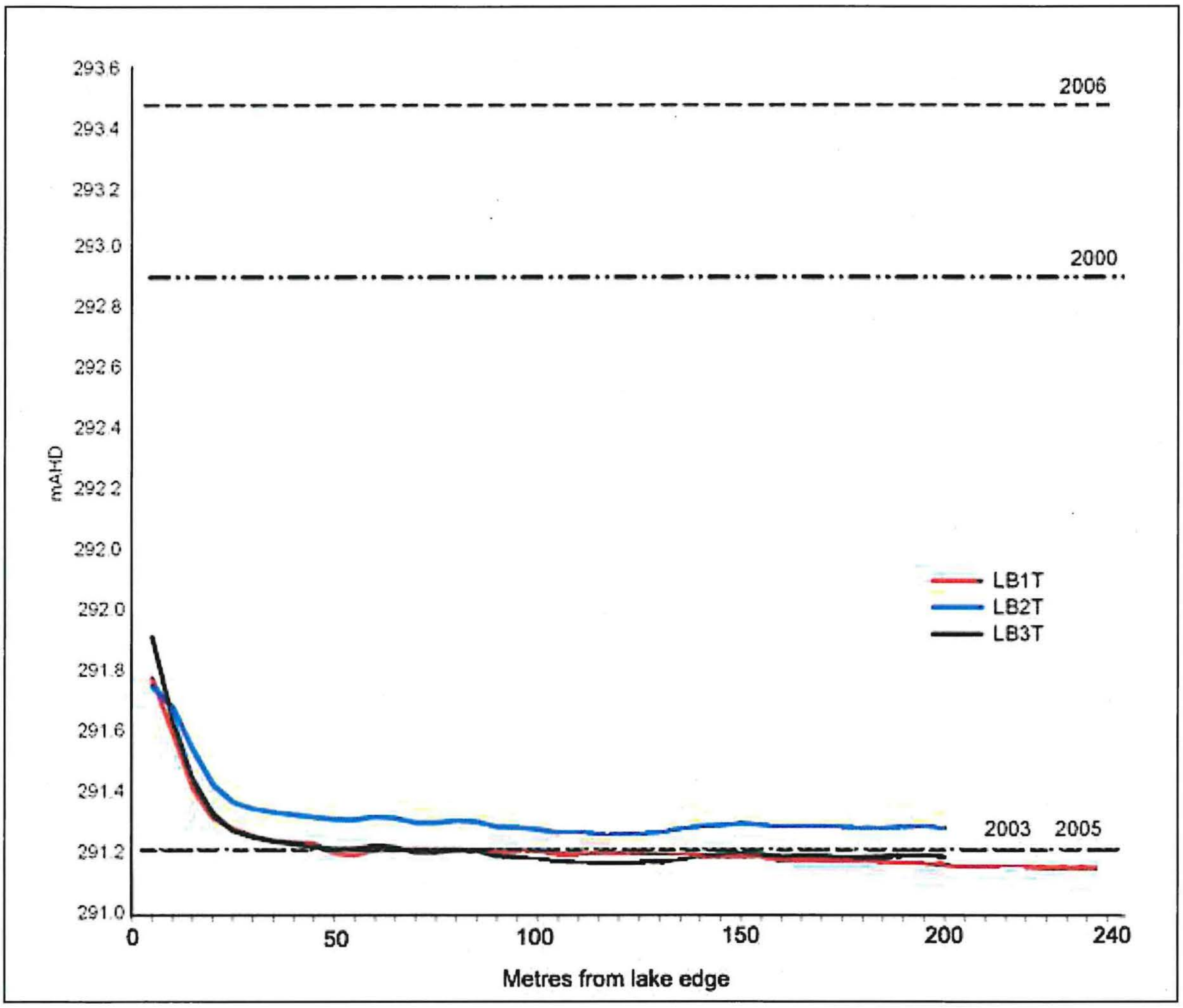

Figure 4.2 Profile of Lake Bryde showing the maximum water levels for 2000, 2003, 2005 and 2006

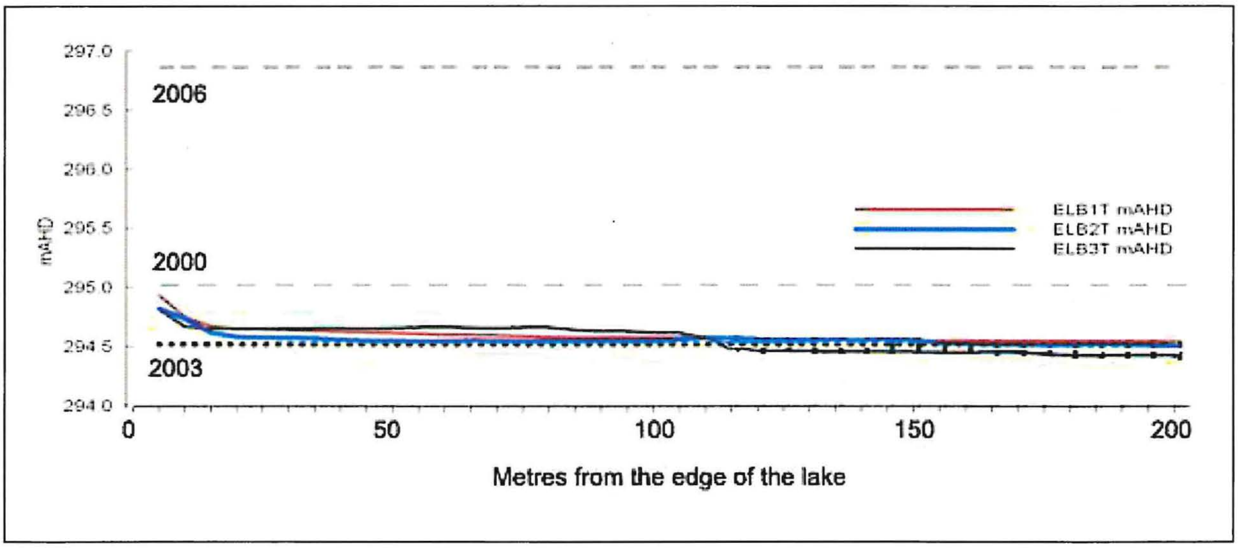

Figure 4.3 Profile of East Lake Bryde showing the maximum water levels for 2000, 2003 and 2006

4.3 Duration of inundation 1997-2008

The average drying time for each lake was determined using the official records for water depth taken in September of each year for the monitored periods and provided by DEC. Where a declining water depth was evident from one year to the next, the difference in depth (each September) was averaged. The average reduction in water depth (m) over a single calendar year (September-September) is represented in Table 3.1 for Lake Bryde (1979-2008) and East Lake Bryde (1980-1985, 2000-2008).

Table 3.1 Average decline in water depth (metres) at Lake Bryde and East Lake Bryde for a September to September year during the monitored period 1979-2008.

Monitoring Date	Lake Bryde		East Lake Bryde	
	Depth (m)	Change (m)	Depth (m)	Change (m)
Sep-1983	1.73	-		
Sep-1984	0.98	0.75		
Sep-1988	1.97	-		
Sep-1989	1.16	0.81		
Sep-1990	1.96	-		
Sep-1991	1.1	0.86		
Sep-1993	2	-		
Sep-1994	0.7	1.3		
Sep-1997	1.72	-		
Sep-1998	0.6	1.12		
Sep-2000	1.57	-		
Sep-2001	0.59	0.98		
Sep-2006	1.65	-	1.90	
Sep-2007	0.41	1.24	0.95	0.95
Sep-2008	-	-	0.21	0.74
Average depth decline		**1.0**		**0.85**

Note: Data for East Lake Bryde are incomplete

Having calculated the average loss of water over the monitoring period, expected water retention times of the subplots of a known elevation were calculated. For both lakes the duration of inundation for each of the inundation events shown in Figures 4.2 and 4.3 were calculated and are presented in Figures 4.4 (Lake Bryde) and 4.5 (East Lake Bryde).

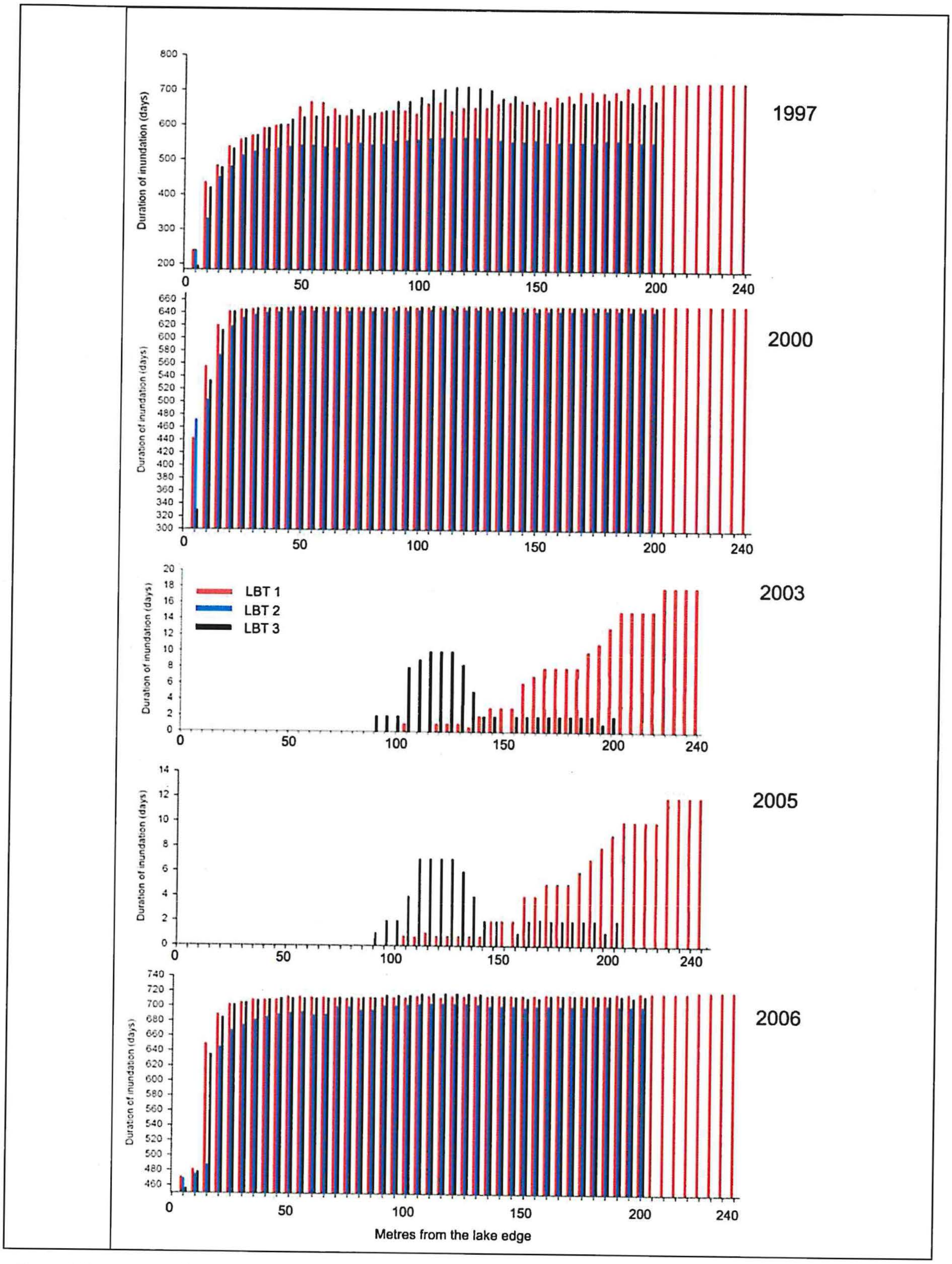

Figure 4.4 A series of bar charts showing the calculated duration of inundation at Lake Bryde for the each of the inflow events identified in the post-wet phase of Figure 3.1. Each transect is plotted individually.

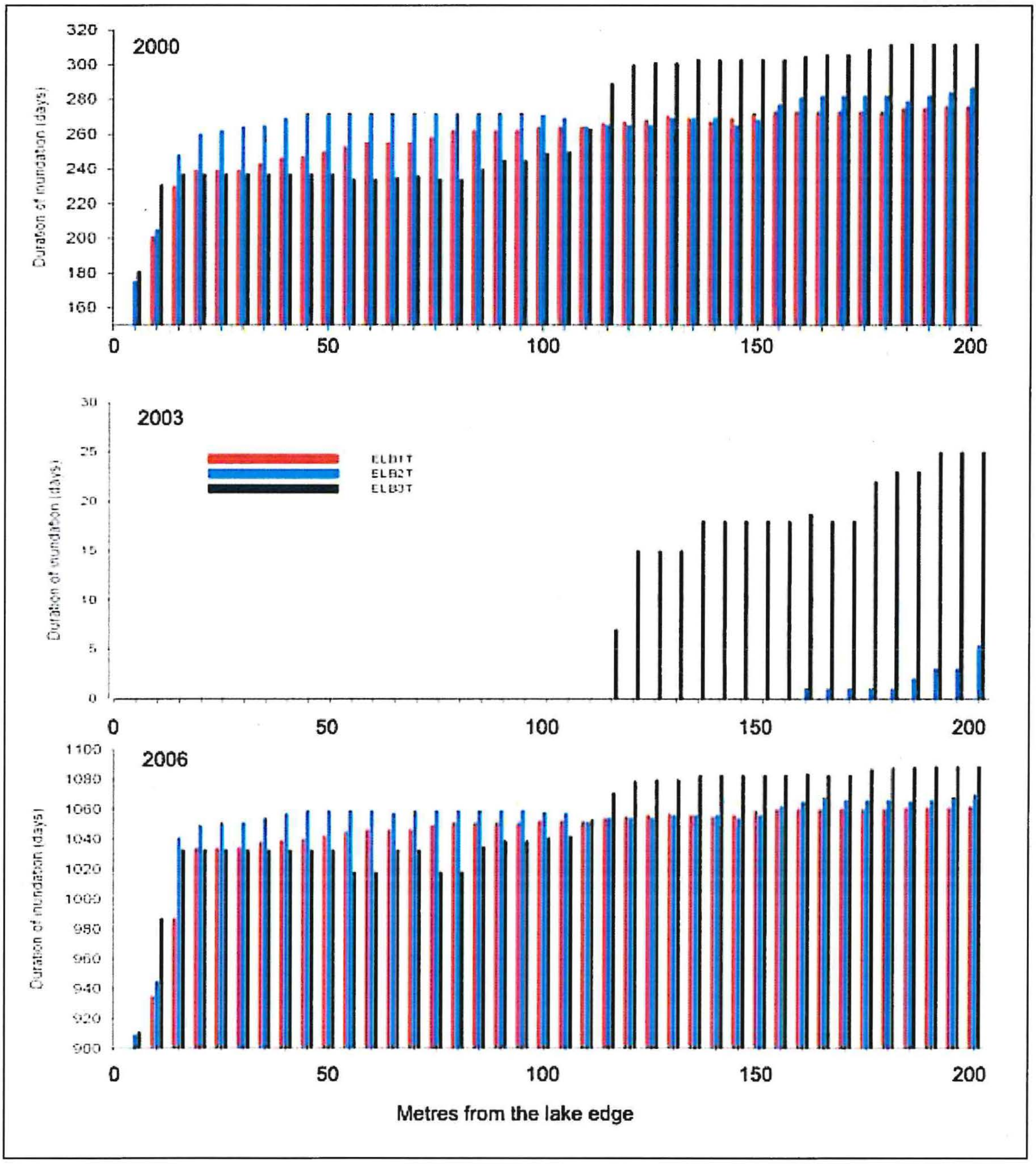

Figure 4.5. A series of bar charts showing the calculated duration of inundation at East Lake Bryde for each of the inflow events identified in the post-wet phase of Figure 3.2. Each transect is plotted individually.

One of the most remarkable features of Figures 4.4 and 4.5 is the long hydroperiods (periods of inundated sediment) evident along the elevational gradients at both wetlands following a surface inflow event. Surface inflow produces much longer periods of inundation than seasonal wetting (direct rainfall). Hydroperiods vary between lakes and inflow events. For example, for the 2000 inflow event Lake Bryde showed a maximum inundation period of approximately 650 days while at East Lake Bryde this was only 180-323 days. By contrast in 2006 Lake Bryde had a hydroperiod of 701-721 days while East Lake Bryde was much longer with 1062-1089 days. As expected, the duration of inundation generally increased toward the centre of each lake.

5. SOIL SALINITY

The horizontal (surface, up to 1 m) and vertical (subsurface, 1-1.5 m) soil salinity readings (ECa mS/m) represent the conductivity of soil salt stores and are presented Figures 5.1 and 5.2. Lake Bryde had higher salt levels than East Lake Bryde. Mean soil salinity at Lake Bryde was more than twice that of East Lake Bryde. The salinity range at Lake Bryde was 198 – 877 mS/m with a mean of 583 mS/m and standard deviation 117 mS/m. At East Lake Bryde salinity ranged from 10 – 527 mS/m with a mean of 200 mS/m and standard deviation 121 mS/m. Overall, East Lake Bryde had lower and more variable soil salinity.

Lake Bryde's soil salinity (Figure 5.1) profile showed that the deeper soils had a higher salt content than surface soils. At East Lake Bryde (Figure 5.2) this was reversed. However, there were a few notable exceptions at both lakes. There were a few notable drops in salinity at Lake Bryde. Transect 1 showed two significant drops in soil salinity both at the surface and at depth. Transect 3 showed an extended trough of lower soil salinity levels only to rise sharply again towards the end of the transect. There was no relationship between salinity levels and distance from the edge of the lake. At both lakes, salinity levels were similar at the edges of the lake to those at the centre. Only Transect 3 at East Lake Bryde showed any relationship at all with elevation.

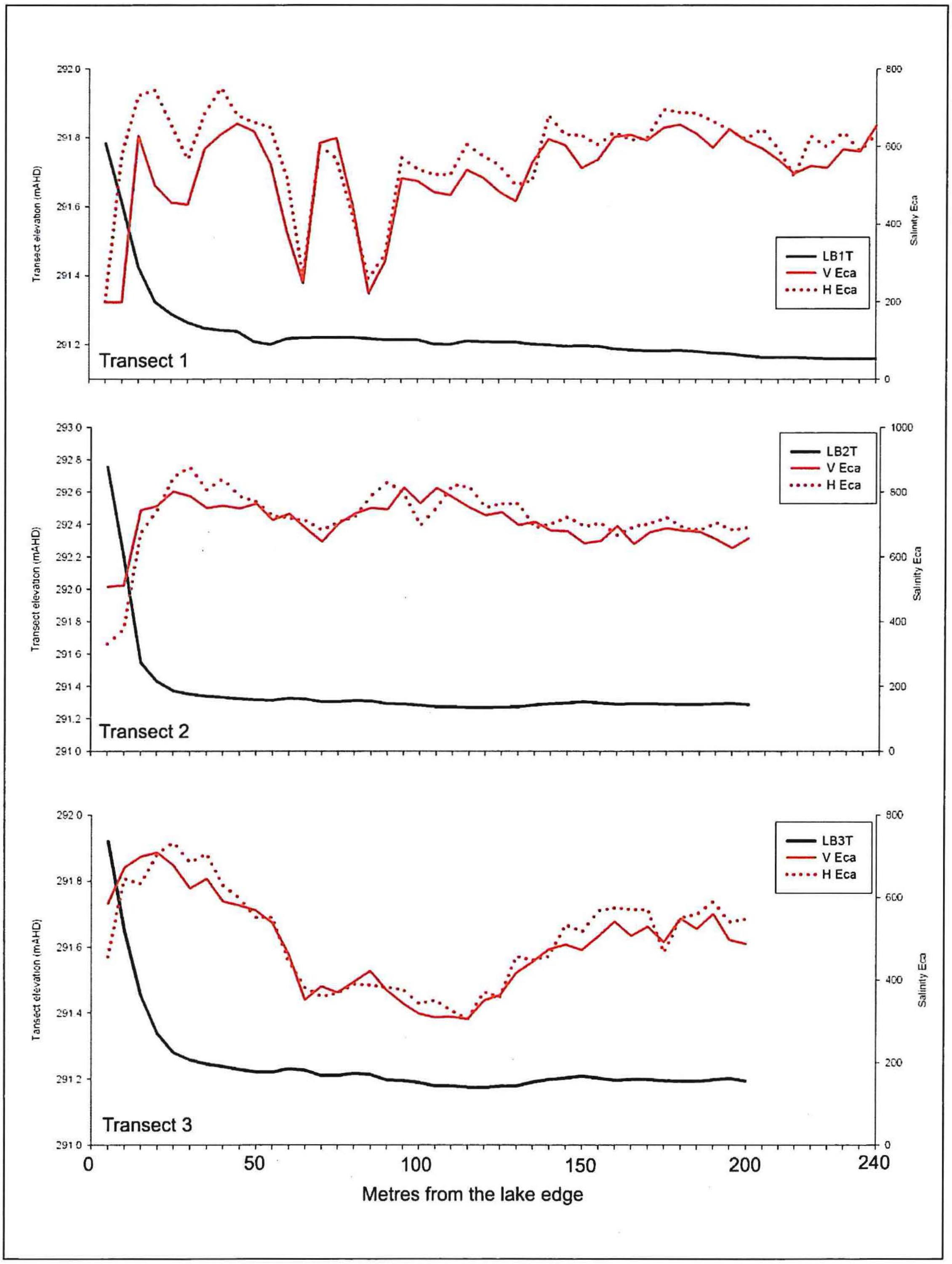

Figure 5.1. Salinity profiles for the three transects at Lake Bryde. Salinity range was 198 – 877 mS/m, mean 583 mS/m and standard deviation 117 mS/m.

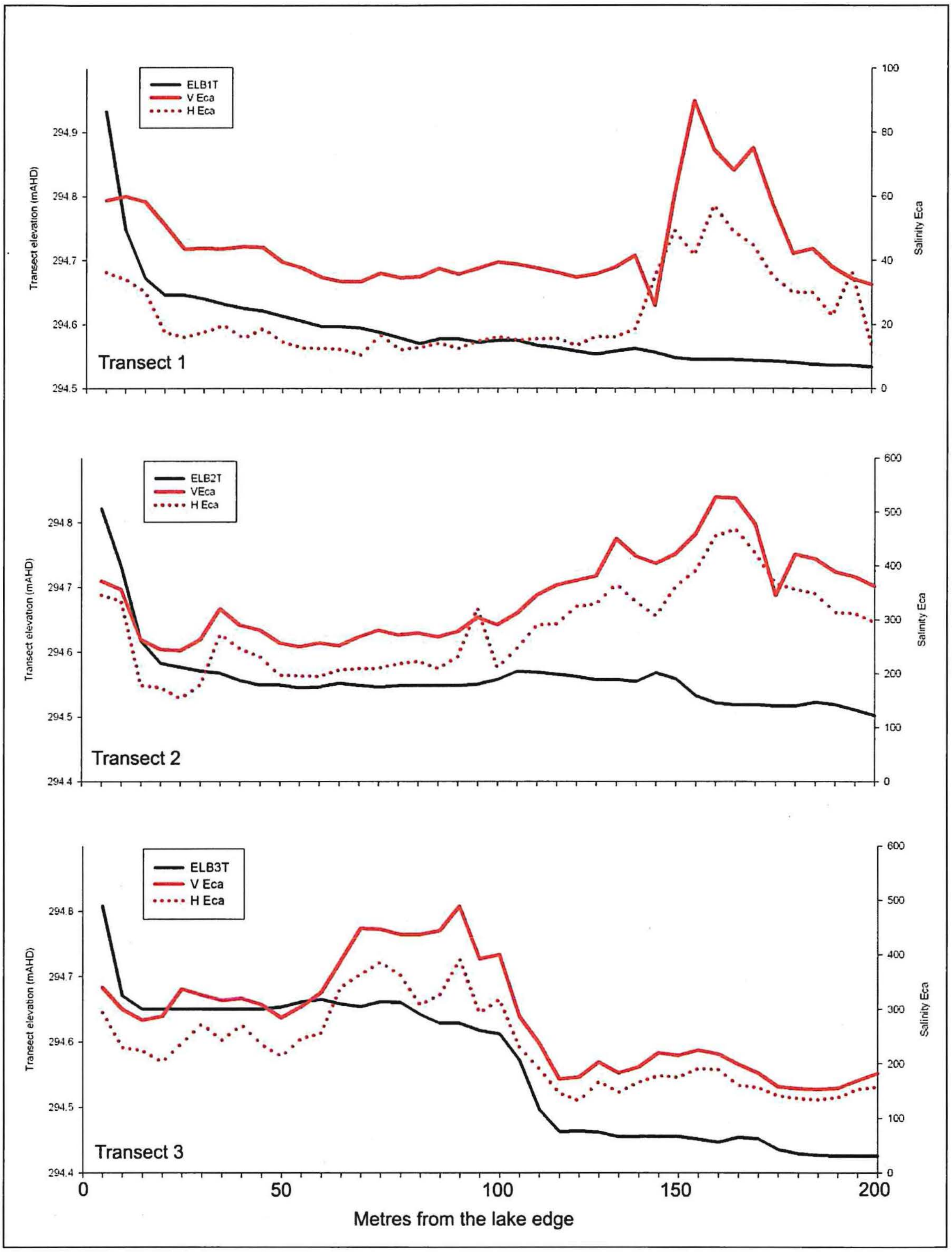

Figure 5.2. Salinity profiles for the three transects at East Lake Bryde. Salinity range was 10 – 527 mS/m, mean 200 mS/m and standard deviation 121 mS/m.

5.1 Soil physical properties

The purpose of determining soil properties was to detect any significant variation between the lakes or within the lakes that might influence plant root penetration, sediment water retention and sediment salt storage. Both lakes had similar soil types and only small variations were found within and between subplots and transects lakes. At Lake Bryde the field texture was predominantly clay-loam-sand (CLS) while a sand-clay-loam (SCL) texture was dominant at East Lake Bryde. Clay content at Lake Bryde was approximately 30-35% which was slightly higher than East Lake Bryde (20-30%). Soil at the perimeter of Lake Bryde tended to be sandier than elsewhere in the lake. At East Lake Bryde soil at the perimeter of the lake were more variable in texture than elsewhere. Overall the variability of the physical properties of the soil was thought to be of little importance in determining the characteristics of the populations of the two plants studied.

6. SUMMARY OF ENVIRONMENTAL GRADIENTS

Figures 4.4 and 4.5 showed that the hydrological habitats of both lakes are neither uniform nor predictable. Subtle variations in lakebed topography combined with unpredictable seasonal and episodic inflows create a range of hydrological conditions across the lake bed. Salinity patterns are not uniform either, with Figures 5.1 and 5.2 showing heterogeneous patterns across both lakes. Salinity gradients do not match elevation gradients at all transects nor do they necessarily reflect water depth. It would be expected that populations of both *M. horrida abdita* and *T. verrucosa* will show distributional and population structure differences and varying 'condition' responses to these variations.

Two key environmental parameters were found to be associated with population distribution and health of the two plant species. These are duration of inundation and soil salinity. Duration of inundation also acts as a surrogate measure for water depth. While only duration of inundation is illustrated, corresponding water depths are included in the text where appropriate. Duration of inundation however is only relevant to the recent hydrological history of the two lakes (1996-2008) and it should be stated that observations made at East Lake Bryde are from very few data.

7. RESPONSES OF PLANT POPULATIONS TO ENVIRONMENTAL GRADIENTS

7.1 General observations

7.1.1 Muehlenbeckia horrida abdita

Total abundance generally declined with distance from the lake edge at both Lake Bryde and East Lake Bryde. The exceptions are Transect 2 at Lake Bryde where abundance declined in the middle of the transect only to increase again toward the centre of the wetland and at East Lake Bryde where Transect 2 showed a peak total abundance in the middle of the transect.

There was a notable difference in the health of the plants between transects and lakes. *M. horrida abdita* at Lake Bryde recorded only 30% of plants alive along Transect 1 while transect 2 and 3 recorded 70% and 90% respectively. This suggests considerable spatial variation in the health of the species at Lake Bryde. At East Lake Bryde there was close to 100% of plants alive across all transects.

Seedlings were found predominantly at East Lake Bryde and were concentrated in the centre of Transect 1. Juvenile plants were found at both wetlands with greater numbers occurring along Transect 1 at East Lake Bryde. Seedlings at Lake Bryde were scarce and only found scattered along Transect 3, with a small cohort toward the centre of the lake at the end of Transect 2. Mature plants were by far the most abundant age class at both wetlands. They were generally found in most sub-plots at Lake Bryde.

7.1.2 Tecticornia verrucosa

At Lake Bryde, and in contrast to *M. horrida abdita,* there was a general increase in total abundance as transects extended into the wetland. However, a similar trend at East Lake Bryde was not evident. Transect 1 showed low abundance, Transect 3 showed abundance peaking in the middle and Transect 2 near the centre of the lake. *T. verrucosa* appeared healthy at both lakes. Close to 100% of the plants encountered were alive across all transects, with a minor exception at Lake Bryde transect 3.

7.2 Responses to environmental gradients

7.2.1 *M. horrida abdita*

7.2.1.1 Lake Bryde

Lake Bryde plants were found over a range of inundation duration from 1835 to 2080 days associated with maximum water depths in the order of 1.66-1.86 m (Figure 7.1). The highest population densities occurred at around 1990-2070 days inundation and a corresponding maximum depth of 1.8-1.86 m. Senescent plants appeared to more abundant at the lower end of the range of inundation period (1835-1884 days) although maximum water depth would have been only slightly lower (1.67-1.75 m) at these subplots.

There were high numbers of dead plants at Lake Bryde and these were also were spread throughout the observed range of inundation, with a slight concentration of dead plants within the inundation period of 1835-2130 days with a maximum water depth of 1.66-1.86 m. There was a tight cluster of dead plants (with very few live plants) between 1990-2050 days of inundation and a maximum water depth of 1.78-1.85 m.

Live plants occurred in soil salinity ranging between 305 and 830 mS/m (Figure 7.2). The overall range for all sites at the lake was 198 – 877 mS/m, with a mean of 583 mS/m and standard deviation of 117 mS/m. However, Figure 7.2 clearly shows that live plants are found in greater abundance in areas of lower soil salinity. A higher abundance of senescent plants was generally found at the higher salinity levels but occurred throughout the range. Dead plants experienced a board range of soil salinities 437-800 ECa mS/m but, like the senescent plants, they also were predominantly found above 500 mS/m.

Duration of inundation was significantly correlated (negative) with the number of senescent (r_s = -0.486, $p < 0.001$) and dead plants ($r_s = -0.201$, $p < 0.05$). This suggests that *M. horrida abdita* may survive better through longer periods of inundation particularly if it results in lower soil salinity. However, duration of inundation was not correlated with age of healthy plants. Salinity was significantly correlated with the number of senescent plants ($r_s = 0.438$, $p < 0.001$).

7.2.1.2 East Lake Bryde

Live plants were found across the entire range of inundation periods (Figure 7.1) of 1218-1426 days of inundation with maximum water depths of 1.26-1.52 m. The highest abundance of live plants was found in the inundation range of 1273-1426 days at a maximum water depth of 1.26-1.41 m.

There were far fewer senescent plants at East Lake Bryde and they were found across the entire duration of inundation range from 1273 to 1426 days with a maximum water depth of 1.29-1.52 m. Unlike Lake Bryde, there were no well defined areas with high abundances of senescent plants. There was also a surprising absence of dead plants. In fact, there was only one recorded across all transects at a duration of inundation of 1331 days and a corresponding water depth of 1.39 m.

Soil salinity was generally lower than Lake Bryde and the range narrower (10 – 527 mS/m with a mean of 200 mS/m and standard deviation 121 mS/m) but still as inherently variable (Figure 7.2). Live plants were found in a soil salinity range of 47-491 mS/m. As illustrated by Figure 7.2 this is much lower in comparison to Lake Bryde. Senescent plants were found across a similar range of soil salinity (47-328 mS/m) as at Lake Bryde.

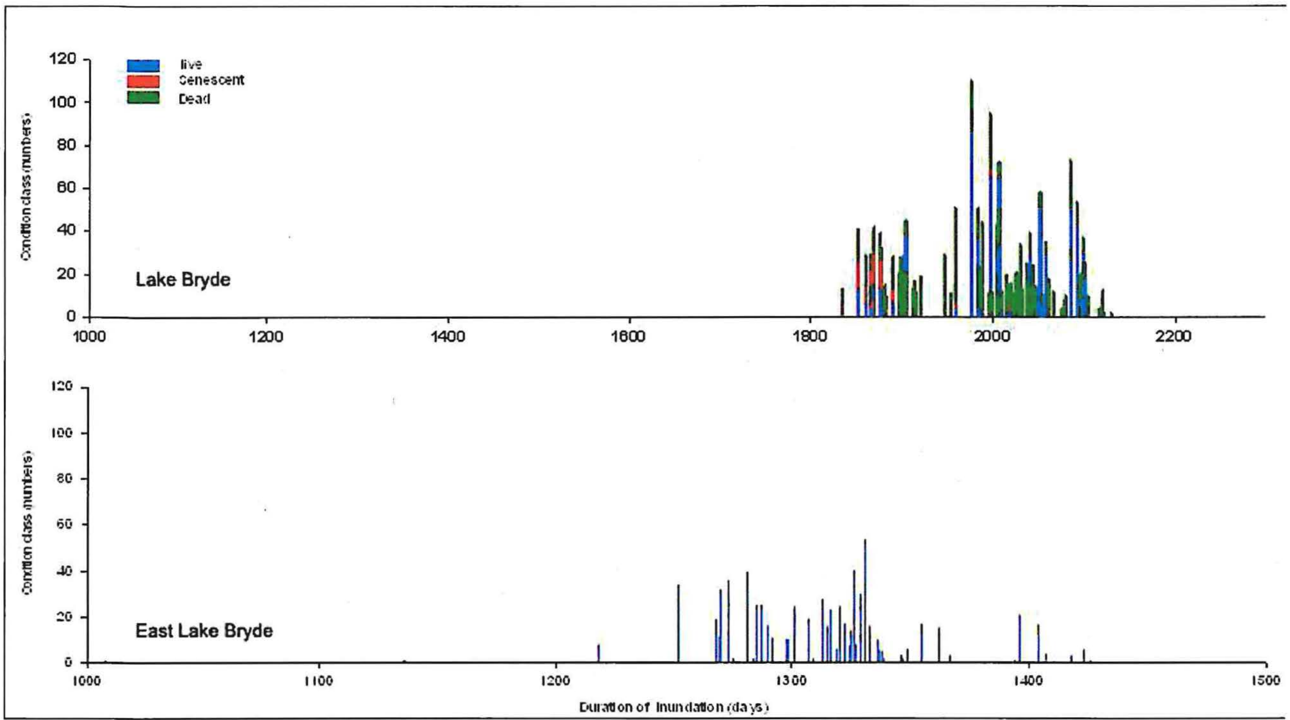

Figure 7.1 Histogram showing the condition of *Muehlenbeckia horrida abdita* plants in relation to the duration of inundation calculated for each of the subplots at both Lake Bryde and East Lake Bryde

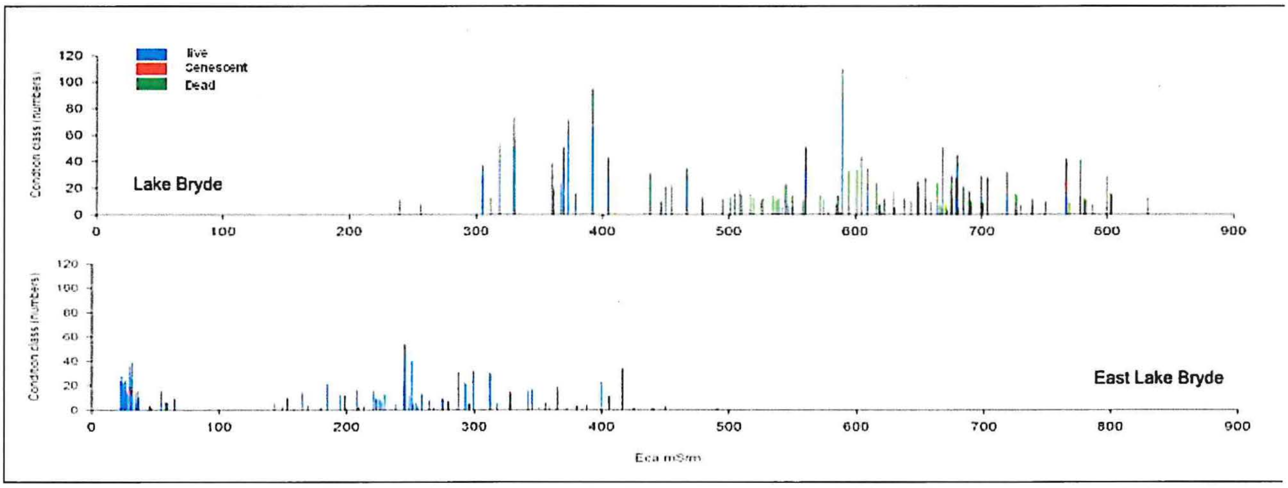

Figure 7.2 Histogram showing the condition of *Muehlenbeckia horrida abdita* plants in relation to averaged salinity values at both Lake Bryde and East Lake Bryde. Lake Bryde salinity range was 198 – 877 mS/m, mean 583 mS/m and standard deviation 117 mS/m. East Lake Bryde salinity range was 10 – 527 mS/m, mean 200 mS/m and standard deviation 121 mS/m.

Duration of inundation was negatively correlated with the number of mature plants ($r_s = -0.362$, $p < 0.001$) and positively correlated with the number of senescent plants ($r_s = 0.300$, $p < 0.01$). There was a less significant correlation with the combined number of seedlings and juveniles ($r_s = -0.234$, $p < 0.05$). Salinity did not show a significant relationship other than a correlation with the combined number of seedlings and juveniles ($r_s = -0.431$, $p < 0.001$).

7.2.2 *Tecticornia verrucosa*

7.2.2.1 Lake Bryde

Live plants occurred in a range of 1900-2140 days of inundation with a corresponding maximum water depth of 1.72-1.85 m (Figure 7.3). This was a slightly longer period of inundation but a similar depth than *M. horrida abdita*. The highest abundance of live plants within these categories showed a narrow range of 2040-2080 days of inundation and a maximum depth of 1.80-1.85 m. There were very low abundances of dead plants. The highest abundance of dead plants were found at a range of 1990-2040 days of inundation at a maximum water depth of 1.80-1.85 m.

The soil salinity range at Lake Bryde was 198 – 877 mS/m with a mean of 583 mS/m and standard deviation of 117 mS/m (Figure 7.4). Live plants were found in a narrow range from 500-680 mS/m. In contrast to *M. horrida abdita*, this is toward the higher end of the range of soil salinity observed at the lake.

There were fewer significant plant-habitat relationships evident for *T. verrucosa* at Lake Bryde than were evident for *M. horrida abdita*. However, both the number of live ($r_s = 0.360$ $p < 0.01$) and dead plants ($r_s = 0.365$, $p < 0.01$) were correlated with the duration of inundation. There were no clear relationships with salinity.

7.2.2.2 East Lake Bryde

Live plants occurred in areas where inundation ranged between 1250 and 1360 days. This was similar to the pattern displayed by *M. horrida abdita* (Figure 7.3). There was higher abundance at an inundation duration of 1320-1350 days. This equates to a maximum water depth of 1.42-1.45 m, which is slightly less than the peak abundance of *M. horrida abdita*.

The soil salinity range at East Lake Bryde was 10 – 527 mS/m with a mean of 200 mS/m and standard deviation 121 mS/m (Figure 7.4). Live plants were found in areas with ECa between 230-510 mS/m. This is toward the higher end of the salinity range and again is in contrast to *M. horrida abdita*. There were few dead *T. verrucosa* plants and these generally occurred at a soil salinity range of 145-210 mS/m. As was the case at Lake Bryde, the abundance of live plants showed a statistically significant, positive correlation ($r_s = 0.823$, $p < 0.001$) with salinity.

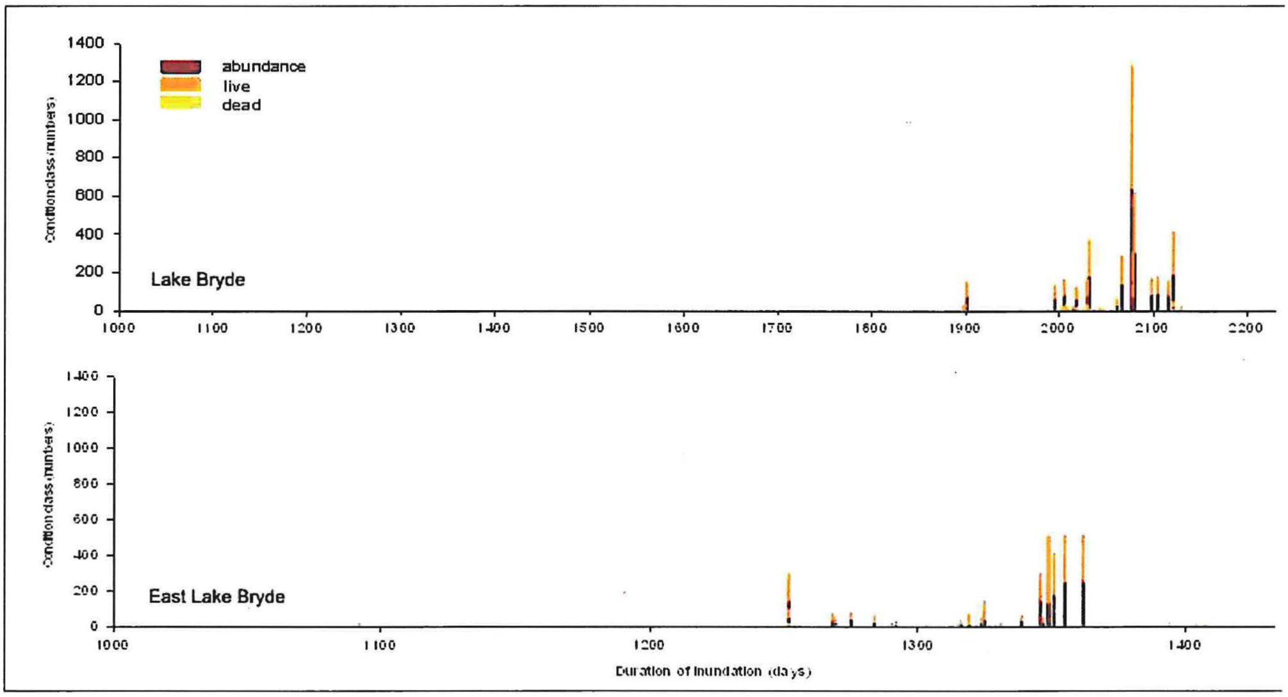

Figure 7.3 Histogram showing the condition of *Tecticornia verrucosa* plants in relation to the duration of inundation calculated for each of the subplots at both Lake Bryde and East Lake Bryde.

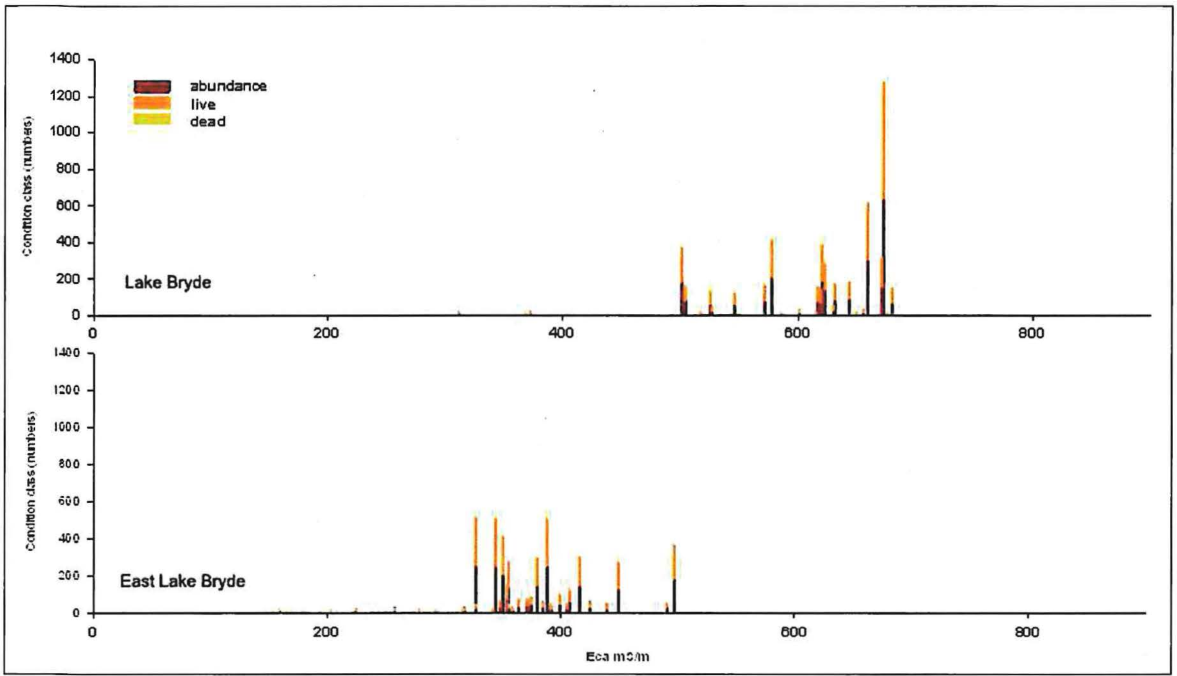

Figure 7.4. Histogram showing the condition of *Tecticornia verrucosa* plants in relation to averaged salinity values at both Lake Bryde and East Lake Bryde. Lake Bryde salinity range was 198 – 877 mS/m, mean 583 mS/m and standard deviation 117. East Lake Bryde salinity range was 10 – 527 mS/m, mean 200 mS/m and standard deviation 121 mS/m.

8. DISCUSSION – IMPLICATIONS FOR MANAGEMENT.

Lake Bryde and East Lake Bryde are both ephemeral wetlands which experience highly variable water regimes. Two types of regimes predominate. The first is wetting/filling from seasonal rainfall directly onto the lake bed which creates a shallow seasonal wetland, and the second occurs when heavy rainfall in the catchments creates surface inflow. These surface flows yield large volumes of (saline) water and the lakes can remain inundated for a period of years. During the historic hydrological record, the temporal variability of rainfall produced periodic inflows and subsequently a range of maximum water depths. The lake-bed topography creates a subtle mosaic of hydrological conditions at both lakes.

Drought is also a significant part of the water regime and records show that periods of up to 3 years may occur between recorded inflow events. As well as intermittent dry periods both wetlands experienced three episodic flooding events (1997, 2000 & 2006) over a ten-year period. Lake Bryde experienced 200-400 days of total inundation and East Lake Bryde experienced up to 900 days before the wetland's perimeters began to be exposed. The pattern of drying within the lakes reflects the lake-bed topography, with the central, deepest points in the wetland being exposed last, and is where we observe the lowest abundance of both the TEC species.

Micro-scale variation in elevation (observed across the transects) of the wetland bed are important as pools are created, and salt accumulates, as the main body of water evaporates. These pockets of water become disconnected and isolated and have different evaporation rates from the main body of water. The duration of drying of both wetlands also varies. For example, the drying time (from the wetland's edge) in Lake Bryde for the 1997, 2000 and 2006 episodic events, ranged from 500, 420 to 383 days respectively (Fig. 3.10) and in East Lake Bryde (for the 2000 and 2006 episodic events) the drying time was 140 and 170 days. This spatial heterogeneity in the hydrological regime is critical to the ecology of both lakes because it provides a range of soil moisture and salinity conditions.

Episodic and seasonal inflows deliver saline water into Lake Bryde and East Lake Bryde at varying concentrations (Hamilton-Brown & Blyth, 1999; Farmer et al., 2003). This saline surface water run-off has been directly linked to the clearing of perennial vegetation within the catchment. Farmer et al (2002) identified that the South Lake Bryde sub-catchment was the main source of water and salt into Lake Bryde, whilst East Lake Bryde's catchment delivered water with lower salt concentrations. The 30 years of monitoring records show that both salt concentrations received during inflow events and those recorded during the drying phase of the wetlands vary. In 2003, a low flow event inundated portions of both wetlands. The salt concentration from this event was higher than the 2006 event. In 2006 salt concentration was diluted due to the volume of water received during the inflow. This relationship between lower levels of salt at higher inflow volume concurs with Hart *et al.* (2003).

Table 8.1. Summary table showing the range and 'optimum' (as indicated by plant distribution and condition) inundation and salinity tolerances for *Muehlenbeckia horrid abdita* and *Tecticornia verrucosa* extrapolated from observations at Lake Bryde and East Lake Bryde. The data are a summary of Figures 7.1 -7.4. Age and condition class are calculated from all three transects at each wetland. Salinity is the mean ECa mS/m from the vertical and horizontal readings within each subplot.

Plant species	*Muehlenbeckia horrida abdita*				*Tecticornia verrucosa*	
	Lake Bryde		East Lake Bryde		Lake Bryde	East Lake Bryde
	Optimum	Range	Optimum	Range	Range	Range
Duration of Inundation (Days)						
Condition Class						
Live	1835-2080	-	1252-1396	1218-1426	1900-2140	1250-1360
Senescent	1835-1884	1835-2080	1273-1426	-	No Data	No Data
Dead	1835-2130	-	1331*	-	1960-2050	~1400
Age Class						
Seedlings	1984-2004	1901-2004	1270-1316	1312-1332	No Data	No Data
Juveniles	1898-2007	1905-2085	1270-1336	-	No Data	No Data
Mature	1899-2058	1905-2058	1273-1426	1008-1429	No Data	No Data
Salinity (ECa mS/m)						
Condition Class						
Live	305-676	367-680	31-299	-	360-680	230-510
Senescent	655-803	239-832	47-249	47-328	No Data	No Data
Dead	437-800	239-832	55*	-	300-660	145-210
Age Class						
Seedlings	367-454	367-680	31-299	-	No Data	No Data
Juvenile Plants	367-609	367-690	22-279	22-279	No Data	No Data
Mature plants	305-609	305-680	34-328	22-440	No Data	No Data

* Note: Only one value recorded

Table 8.1 represents a summary of the observed range and suggested 'optimum' in inundation and salinity tolerances for *Muehlenbeckia horrid abdita* and *Tecticornia verrucosa* at both lakes. Given the short term dataset and the lack of data at East Lake Bryde this study could determine only a narrow range of duration of inundation. What is shown is that both species are capable of surviving the hydrological regimes of the wetlands over the period studied (historical record). This included both lengthy periods of inundation and drought. A longer term study would be needed to assess recruitment in relation to the frequency and duration of inundation. There is also a relationship between the volume of water received during an inflow event and resultant soil salinity. It may be that the relationship between the hydrological regime, particularly the periodicity and volume of water entering the wetland, and soil salinity is more important to the persistence of *M. horrida abdita* than the hydrological regime alone.

The results of this study strongly suggest that salinity is the key factor influencing the health of *M. horrida abdita*. The population at East Lake Bryde, where salinity is demonstrably lower, is much healthier and is the only place where recruitment has been observed. Results for *M. horrida abdita* show a clear localised relationship between salinity and health of the plants at Lake Bryde. The majority of healthy plants were found growing in soil with salinity less than ECa 500 mS/m. At East Lake Bryde this corresponds to the maximum level of soil salinity measured.

T. verrucosa is clearly capable of surviving in the higher salinity levels at Lake Bryde. It appears tolerant of the higher salinity and the population is healthy. The likely outcome is that *T. verrucosa* will displace *M. horrida abdita* at Lake Bryde if salinity levels remain high. This is supported by the fact that at East Lake Bryde, where both populations are healthy, *T. verrucosa* is found in a significantly higher salinity range than *M. horrida abdita*.

East Lake Bryde gives us the best snapshot of the threatened ecological community in a healthy state. Given that there are clear differences between the populations at both lakes, it would appear that *M .horrida abdita* prefers lower salinity, and at Lake Bryde it is possible that *T. verrucosa* may be encroaching as salinities increase. While *M. horrida abdita* is clearly able to tolerate the conditions at East Lake Bryde, recruitment may be impaired if salinities rise. Continued monitoring of the relative abundance and recruitment of the two species at East Lake Bryde would help inform on-going management.

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