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Seed Bank Assessment of Managed River Murray Wetlands

Jason Nicol and Kate Frahn

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

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EXECUTIVE SUMMARY

The seed bank provides an important mechanism for the survival of species during unfavorable conditions and a pool of propagules for establishment of plant communities during favorable conditions in wetland ecosystems. Unregulated arid and semi-arid Australian wetlands are subject to highly variable hydrology, with both drought and flooding making survival of asexual propagules often unfeasible; hence, the seed bank is the major source of propagules for establishment of plant communities following disturbance. The lower River Murray is a highly regulated system, with largely stable water levels and wetlands that were historically temporary now connected to the main river channel at pool level and permanently inundated. To reinstate drying cycles (lost due to river regulation) in lower River Murray wetlands, structures that can isolate the wetland from the main channel are constructed.

Previous vegetation monitoring of wetlands where drying cycles have been reinstated often showed a lack of response in the vegetation and it was proposed that this was due to a depauperate seed bank, the probable legacy of nearly 100 years of permanent inundation due to river regulation. The primary aims of this study were to determine whether the poor response of the vegetation was due to depauperate seed banks in the managed wetlands and assess the seed banks of wetlands where new structures are being built.

The seed banks of 15 lower River Murray wetlands between the New South Wales border and Mannum were assessed using the seedling emergence technique. At the end of the seedling emergence trial, 30 samples (six sediment samples from five wetlands) from wetlands where no germination occurred were further assessed using seed separation. Sediment samples were collected from below normal pool level (the area permanently inundated due to river regulation) at ten sites with managed wetting and drying cycles (Lake Merreti, Lake Woolpolool, Yatco Lagoon, Beldora, Spectacle Lakes, Loveday (Mussel Lagoons), Brenda Park, Morgans Lagoon, Sugar Shack and Silver Lea) and five sites where structures were under construction (unmanaged sites: Pyap Horseshoe (two sites), Big Bend, Teal Flat Hut and Teal Flat).

All except for three managed wetlands (Yatco Lagoon, Brenda Park and Sugar Shack), had depauperate seed banks with seed densities <10,000 seeds m^{-2} and two or fewer species detected. No germination was observed in Morgans Lagoon, Beldora, Teal Flat, Silver Lea and Pyap Horseshoe-northern section. Furthermore, seed separation detected no seed in the sediment of these wetlands. All of the unmanaged wetlands had a depauperate seed bank and despite three managed wetlands having seed densities >10,000 seeds m^{-2} and species richness

≥8, there were no significant differences between seed density, species richness (overall and native) and seed bank composition between the managed and unmanaged wetlands. Whilst there was no statistically significant difference between the seed banks of managed and unmanaged wetlands, the overall variation between wetlands is likely to be ecologically significant as all unmanaged wetlands had depauperate seed banks.

Data from this study showed that the observed poor response of the vegetation in managed wetlands is likely due to a depauperate seed bank, and suggest that the unmanaged wetlands will respond in a similar manner when drying cycles are reinstated. Nevertheless, seed banks dominated by native species have developed in three of the managed wetlands albeit with lower species richness and often lower seed densities compared to other Australian arid and semi-arid wetlands. Numerous species commonly recorded in River Murray wetlands and floodplains that are known to form soil seed banks were not recorded in the seed banks of either managed or unmanaged wetlands.

Whilst data from this study suggested that nearly all the managed and unmanaged wetlands had depauperate seed banks, the seedling emergence technique does not detect all seeds and may not detect all species present; therefore, these assessments are probably an underestimate of seed density. However, seed separation may miss small seeded species, non-viable seeds may be included, seeds are more difficult to identify to species than growing plants and when used in this instance, did not detect any viable seed. Furthermore, it is possible that there are localised areas of higher seed density and species richness that were not detected by the sampling due to spatial heterogeneity.

It is unlikely that reinstating wetting and drying cycles will result in the development of diverse plant communities in lower River Murray wetlands in the short or even medium-term; however, reinstatement of a more “natural” hydrological regime is still fundamental in wetland restoration. Without the appropriate hydrology, many floodplain and amphibious species will not recruit and a diverse seed bank will not develop. Many of the amphibious and floodplain species that require a drying cycle to recruit are prolific seed producers and may only require one individual to complete its life cycle to provide a seed bank “hot spot” for that species that may contribute significantly to the regenerating plant community through time. The most important management action after hydrological manipulation is to implement a spatially and temporally appropriate monitoring program to detect changes in the vegetation through time and protect areas in wetlands where the vegetation has responded positively.

If the vegetation does not respond to hydrological manipulation through time, active revegetation may be required. This can involve mixed planting, planting of keystone or nurse species that facilitate recruitment of other species, direct seeding of desirable species or sediment transplant.

Keywords: Seed banks, managed wetlands, South Australian River Murray.

1. INTRODUCTION

1.1. Background

The soil seed bank is defined as the reserve of viable seed present in and on the soil surface (Roberts 1981) and associated litter (Simpson et al. 1989), capable of replacing adult plants (Baker 1989) and is an important component of the vegetation. Not all species form a soil seed bank; for example, some *Melaleuca* (e.g. Holliday 2004, Hamilton-Brown et al. 2009) and *Eucalyptus* (e.g. Colloff 2014) species rely on seed held in their canopies for regeneration. Furthermore, many aquatic and amphibious species have cosmopolitan distributions, which implies they are capable of long-distance dispersal by wind (anemochory) (e.g. Finlayson et al. 1983, Hocking et al. 1983, Soomers et al. 2013), water (hydrochory) (e.g. Nilsson et al. 1991, Nilsson et al. 2002, Chambert and James 2009, Favre-Bac et al. 2017) and animals (zoochory) (e.g. Pollux 2011, Raulings et al. 2011, Flaherty et al. 2018). Despite the evolution of canopy seed banks for some long-lived species and the ability of aquatic and amphibious species to disperse into areas, the sediment seed bank is an important mechanism for species to persist through periods of unfavorable conditions by regeneration of vegetation when conditions become favorable (e.g. van der Valk and Davis 1976, Brock and Casanova 1997, Casanova and Brock 1999). In unmodified Australian arid and semi-arid wetlands, hydrological regimes are highly variable and subject to both drought and flooding (Walker et al. 1995, Puckridge et al. 1998, 2000). These extreme conditions have an adverse effect on vegetative propagules such that they are not a reliable means of persistence for the majority of wetland species (Thompson 1992). This leaves the seed bank as the only resident source of propagules for regeneration after disturbance. Human-induced pressures (such as river regulation) that modify the seed bank also change the capacity of the system to regenerate after disturbance.

The lower River Murray (downstream of the Darling River junction) is a highly modified system with a series of ten low level (approximately 3 m head differential) weirs and tidal barrages that control water levels over 90% of the time (e.g. Walker 1985). This has resulted in largely stable water levels resulting in wetlands connected at normal pool level being permanently inundated and wetlands and floodplains above normal pool level being drier for longer periods compared to before regulation (Maheshwari et al. 1995).

In order to reintroduce drying cycles to permanently inundated wetlands connected at pool level on the lower River Murray, structures that allow the temporary disconnection of the wetland from the main river channel have been built on numerous wetlands. The reintroduction of drying cycles lost as the result of river regulation, provides an opportunity to increase the diversity of wetland types at the reach and landscape scales. At the individual wetland scale, the drying cycle (either full or partial) provides an opportunity for species that require a dry phase for recruitment (e.g. Brock and Casanova 1997, Brock et al. 2000, Nicol et al. 2003) and in turn increase regional biodiversity as different species are present in these wetlands compared to those in permanently inundated wetlands (sensu Sabo et al. 2005). Furthermore, numerous studies from Australia (e.g. Nielsen and Chick 1997, Siebentritt 2003) and overseas (e.g. van Geest et al. 2005, Katz et al. 2012) have shown that wetlands with fluctuating hydrological regimes have greater plant diversity compared to wetlands with largely static hydrological regimes.

Despite considerable evidence to suggest that the reintroduction of wetting and drying cycles will increase vegetation diversity in wetlands (e.g. Nielsen and Chick 1997, Siebentritt 2003), a review by Muller et al. (2017) of monitoring data collected by the Riverine Recovery Project (RRP) of wetlands where the drying cycle was reinstated found that diverse plant communities did not establish on the exposed wetland beds. A depauperate soil seed bank, with low seed density and/or species richness, (a potential legacy of nearly 100 years of permanent inundation due to river regulation) was one hypothesis put forward to explain the lack of vegetation response on the exposed wetland beds to hydrological management. The collection of information regarding the seed banks of managed wetlands will determine whether the poor vegetation response observed in some cases is due to the wetland having a depauperate seed bank. If this is the case, other interventions such as revegetation, seeding of desirable species or sediment transplant from a donor wetland (or other area within the same wetland) with a healthy seed bank may be required to achieve the desired response. Conversely, if a healthy seed bank is present, managers will not waste resources on the aforementioned interventions and investigate other causes for the poor vegetation response.

Furthermore, information regarding the seed bank of wetlands that will undergo hydrological management in the future, prior to management being undertaken, is important as it provides an indication of the likely response of the plant community and informs complementary management actions such as weed control.

1.2. Objectives

The project has six objectives:

1. To determine whether the poor vegetation response to hydrological manipulation in managed wetlands is due to a depauperate seed bank;
2. To provide an indication of the vegetation response of wetlands that will be managed in the future (sites where structures were being built at the time of writing);
3. To compare the composition of the seed banks between managed and unmanaged wetlands;
4. To compare the seed bank at different elevations within wetlands to determine whether there were any spatial patterns in seed bank composition within individual wetlands.
5. To provide management advice regarding hydrological regimes and complementary actions to feed into Wetland Management Plans (WMP) as part of their review cycle.
6. To provide information to underpin recommendations for improved management outcomes in order to improve seed bank condition.

2. METHODS

2.1. Study sites

A total of 15 wetlands were sampled on the River Murray Floodplain between the New South Wales border and Mannum (Figure 1). Ten of these were managed wetlands (managed hydrological regimes): Lake Merreti, Lake Woolpolool, Yatco Lagoon, Beldora, Spectacle Lakes, Loveday (Mussel Lagoons), Brenda Park, Morgans Lagoon, Sugar Shack and Silver Lea (Figure 1). The remaining five (referred hereafter as unmanaged wetlands) were: Pyap Horseshoe (two sites were sampled in Pyap Horseshoe due to differences in land management, with cattle grazing present in the northern section of the complex) (Department of Environment, Water and Natural Resources 2014b), Big Bend, Teal Flat Hut and Teal Flat. These were all sites where control structures were being built to enable future hydrological management (Figure 1).

Managed wetlands

Lake Merreti

Lake Merreti is a shallow freshwater lake located on the northern side of the River Murray (Figure 1). The lake covers an area of 379 ha when full at normal pool level and is connected to the River Murray via Ral Ral Creek (Jensen et al. 1996). Historically, Lake Merreti was a temporary wetland, even after the construction of Lock and Weir number 5, and it is thought that the construction of a bank between Hunchee and Ral Ral creeks in 1960 to maintain flow in Ral Ral Creek led to it becoming permanently inundated (Steggles and Tucker 2003). Fluctuating water levels were reintroduced in 1991, and wetting and drying regimes in 1995, and since then it has been managed as a temporary freshwater wetland (Steggles and Tucker 2003). When sampled in July 2018, the regulator was closed with a residual pool in the centre of the lake and the sediment at all elevations was damp.

Lake Woolpolool

Lake Woolpolool is a shallow (maximum depth of 0.7 m when connected at normal pool level) saline, temporary wetland located on the northern side of the River Murray (Figure 1). The lake covers an area of 296 ha and is connected to the River Murray via Ral Ral Creek (Jensen et al. 1996). Historically, Lake Woolpolool was used for cropping, and in 1953 a 2 km long levee was constructed to around 20 m AHD to prevent water entering the lake, ultimately leading to the lakebed becoming salinised in 1956. The lake remained separated from Ral Ral Creek until 1983, when a regulator was constructed to allow managed wetting and drying. Since then the inlet structure has been upgraded, an additional inlet added and the inlet channel widened to improve flow. There is a strong salinity gradient in the lake, with surface water electrical conductivity ranging from 200 to 300 $\mu S.cm^{-1}$ at the inlet to >20,000 $\mu S.cm^{-1}$ on the northern shoreline as the lake dries (Harper 2003). When sampled in July 2018, the regulator was closed with a residual pool in the centre of the lake and the sediment at all elevations was damp.

Yatco Lagoon

Yatco Lagoon is a shallow wetland located on the western side of the River Murray, upstream of the township of Moorook (Figure 1). It runs parallel to the river and covers an area of 346 ha when connected at normal pool level (Jensen et al. 1996). Following construction of Lock and Weir number 3, it was permanently inundated until 2007, when an earth bank and flow control structure was constructed on the inlet allowing wetting and drying to be implemented. When sampled in July 2018, the regulator was closed, the wetland was dry and the sediment at all elevations was dry.

Beldora Wetland and Spectacle Lakes

Beldora Wetland and Spectacle Lakes are located on the eastern side of the Murray River opposite Yatco Lagoon (Figure 1). Beldora Wetland runs parallel to the river and covers an area 157 ha and Spectacle Lakes 94 ha when inundated at pool level (Jensen et al. 1996). Beldora Wetland consists of two lagoons; the Beldora North Wetland, which until the Riverine Recovery Project (herein referred to as RRP) was permanently connected to the River Murray, and which feeds the Beldora South Wetland and Spectacle Lakes (Willis and Muller 2015). In 2003, regulators were constructed between Beldora North and Beldora South and Beldora North and Spectacle Lakes, which allowed the wetlands to be operated independently (Robertson 2006). This allowed wetting and drying to be reinstated to Spectacle Lakes, but complete drying could not be achieved in Beldora South because the regulator between Beldora North and Beldora South leaked through the stop logs; however, a partial drying was achieved (Robertson 2006). In September 2014, two flow control structures were constructed on the inlet to Beldora North, which now allows hydrological management in Beldora North Wetland (Willis and Muller 2015). When sampled in July 2018, all regulators were open and all wetlands inundated.

Loveday (Mussel Lagoons)

Mussel Lagoons are part of the Loveday Complex, located on the eastern side of the River Murray near the township of Cobdogla (Figure 1). Mussel Lagoons covers an area of 147 ha when inundated at pool level (Jensen et al. 1996). Following construction of Lock and Weir number 3, they were permanently inundated until 1995, when structures were completed on the feeder creeks allowing the wetland to be dried for the first time since 1925 (Jensen et al. 1996, Wegener 2012), and they have been hydrologically managed since. When sampled in July 2018, all regulators were open and the wetland inundated.

Brenda Park

Brenda Park is located on the western side of the River Murray between the townships of Morgan and Blanchetown (Figure 1). Brenda Park wetland runs parallel to the river and covers an area of 99 ha when inundated at pool level (Jensen et al. 1996). Historically, the wetland was temporary, but in 1906 a levee was constructed around the wetland and banks in the up and downstream flow paths that prevented water entering the wetland until flows in the river exceeded 70,000 ML day^{-1} (Turner 2012). In 1976 a pipe was installed in the upstream embankment and in 2001 a flow control structure was installed in the downstream embankment, allowing the wetland to be filled at pool level with managed wetting and drying cycles. When sampled in July 2018, the regulator was closed with a residual pool in the centre of the wetland and the sediment at all elevations was damp.

Morgans Lagoon

Morgans Lagoon is part of the Moorundi Complex, located on the western side of the River Murray between the townships of Swan Reach and Blanchetown (Figure 1). Morgans Lagoon is a shallow linear wetland that runs parallel to the river, and covers an area of 35 ha when inundated at pool level (Jensen et al. 1996). Since the completion of the Barrages, the wetland was permanently inundated until flow control structures were completed on the two inlets in 2001, allowing hydrological management (Bjornsson 2005, Tesoriero et al. 2013). When sampled in August 2018, all regulators were open and the wetland inundated.

Sugar Shack

Sugar Shack Wetland is located on the eastern side of the River Murray near the township of Swan Reach (Figure 1). The wetland covers an area of 26 ha when inundated at pool level, with a maximum depth of 75 cm and is connected to the River Murray by Yatco Creek (Bjornsson 2006, Tesoriero and Mason 2012). Since the completion of the Barrages the wetland was permanently inundated until a flow control structure was completed on the inlet in 2007 allowing managed wetting and drying (Tesoriero and Mason 2012). When sampled in August 2018, the regulator was closed, the wetland was dry and the sediment at all elevations dry.

Silver Lea

Silver Lea is located on the western side of the River Murray adjacent to the township of Swan Reach (Figure 1). The wetland covers an area of 68 ha when inundated at pool level (Jensen et al. 1996), with a maximum depth of 100 cm (Department of Environment, Water and Natural Resources 2013). The wetland was permanently inundated after the completion of the Barrages in 1940, but in the 1950s and 1960s embankments were placed in the river connections and the wetland used for cropping, although the wetland would periodically fill when high river flows removed the embankments (Department of Environment, Water and Natural Resources 2013). After cropping on the wetland bed ceased in the late 1960s, the wetland was permanently inundated until 2007 when all wetlands downstream of Lock 1 dried due to low flows. The wetland was refilled in spring 2010 when flows increased, and was permanently inundated until construction of the flow control structures commenced and construction activities required the river connections to be blocked. The structures were completed in October 2018 allowing for managed wetting and drying cycles in the future. When sampled in August 2018, the wetland was predominantly dry with a residual pool in the centre of the wetland, and the sediment at all elevations was damp.

Unmanaged wetlands

Pyap Horseshoe

Pyap Horseshoe is located on the north west side of the River Murray between the townships of Loxton and Moorook (Figure 1). The wetland covers an area of 66 ha when inundated at pool level (Jensen et al. 1996), and since the construction of Lock and Weir number 3 has been permanently inundated (Department of Environment, Water and Natural Resources 2014b). Two sites were sampled in Pyap Horseshoe as there is cattle grazing in the northern section of the wetland complex (Department of Environment, Water and Natural Resources 2014b). When sampled in July 2018 the regulators were under construction and the wetland was inundated.

Big Bend

Big Bend is located on the eastern side of the River Murray between the townships of Swan Reach and Walker Flat (Figure 1). The wetland covers an area of 48 ha when inundated at pool level (Jensen et al. 1996) to a depth of 1.45 m, and since the construction of the Barrages has been permanently inundated, except between 2007 and spring 2010 when it dried due to low flows over Lock 1 (Department of Environment, Water and Natural Resources. 2014a). When sampled in August 2018, the regulators were under construction, the wetland was predominantly dry with a residual pool in the centre of the wetland, and the sediment at all elevations was damp.

Teal Flat Hut

Teal Flat Hut is located on the north-western side of the River Murray between the townships of Walker Flat and Mannum (Figure 1). The wetland covers an area of 20 ha when inundated at pool level (Jensen et al. 1996) to a depth of 1.05 m, and since the construction of the Barrages has been permanently inundated, except between 2007 and spring 2010 when it dried due to low flows over Lock 1 (Department of Environment, Water and Natural Resources 2014c). When sampled in August 2018, the regulator was under construction and the wetland was inundated.

Teal Flat

Teal Flat is located on the north-western side of the River Murray between the townships of Walker Flat and Mannum (Figure 1). The wetland covers an area of 82 ha when inundated at pool level (Jensen et al. 1996) to a depth of 90 cm, and since the construction of the Barrages has been permanently inundated, except between 2007 and spring 2010 when it dried due to low flows over Lock 1 (Department of Environment, Water and Natural Resources 2014d). When sampled in August 2018, the regulator was under construction and the wetland was inundated.

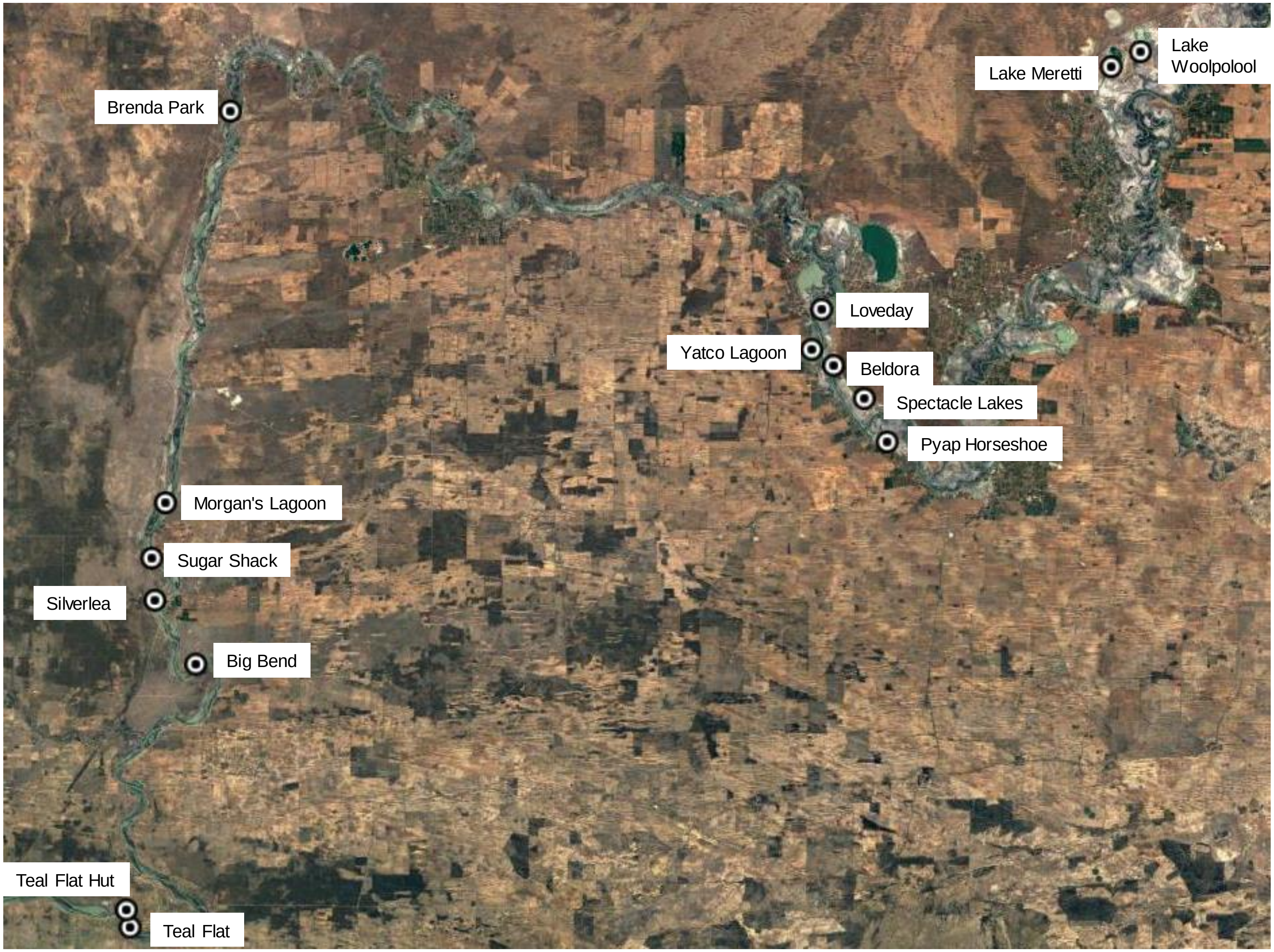


Figure 1: Satellite image of the Lower Murray from the New South Wales border to Teal Flat, showing the location of the sampled wetlands.

2.2. Sediment sampling protocol

Sediment samples to a depth of 5 cm were collected from all wetlands, with four locations (evenly spaced around the wetland edge) sampled within each wetland. At each location single soil samples at 10, 30 and 60 cm below normal pool level (the area permanently inundated due to river regulation) were collected (hereafter referred to as -10 cm, -30 cm and -60 cm). Samples were collected using a spade and typically covered an area of around 0.04 m^2. Samples were transported to the South Australian Aquatic Sciences Centre, dried at 40º C to a constant weight, and soil bulk density measured to enable number of germinants to be converted into seeds m^{-2} using the formula in Nicol *et al.* (2003).

2.3. Seed bank assessment

Samples were divided into two sub-samples of 250 g of dried sediment (providing sufficient soil was collected, if not the mass of each sub-sample was recorded) and spread onto a base of 15 cm deep 80:20 sandy loam (80% sand, 20% clay) contained in 20 cm diameter potting bags. One sub-sample was subjected to continuous damp conditions and the other continuously submerged to a depth of 20 cm (from the soil surface) for 18 weeks (August 6th to December 10th 2018) to maximise the chance for species that require submergence or exposure to be detected (sensu Nicol et al. 2007). To take local seed input and contamination of the sandy loam soil into consideration, 10 blanks (pots containing only the sandy loam) were randomly placed amongst the samples in each of the treatments.

The germinable seed bank was assessed using the seedling emergence technique (sensu Gross 1990, Brown 1992). Seedlings were removed at regular intervals when they could be identified. After 18 weeks, numbers of germinants and species from both treatments were collated and converted to germinants m^{-2} using the following formula (Nicol et al. 2003):

No. germinants m^{-2} = (No. germinants x mass of soil to a depth of 5 cm m^{-2})/sample mass

Plants were identified using keys in Jessop and Tolken (1986) and Jessop *et al.* (2006), and from photographs in Cunningham et al. (1992) and Sainty and Jacobs (2003). Plants that could not initially be identified were grown to a stage when they could; however, in the case of *Medicago* spp. plants were identified to genus due to lack of floral structures. Nomenclature follows the South Australian Herbarium Plant Census (2018). A list of all species recorded, life history strategy and conservation status are presented in Appendix 1.

Six samples from the damp treatment from each of the wetlands where no germination was observed (30 samples in total) were further assessed using seed separation (sensu Gross 1990, Mesgaran et al. 2007, Mcfarland and Shafer 2011). The top 5 cm of soil from the pot was removed and sieved through a 250 µm sieve to remove the fine soil fraction with the remaining coarse and organic fraction dried at 40º C and sorted using a magnifying lamp and dissecting microscope.

2.4. Data analysis

Multivariate and univariate statistical analyses were used to compare the germinable seed banks between managed and unmanaged wetlands, with data from the different elevations and transects pooled for each wetland. Univariate PERMANOVA (using Euclidian distances to calculate the similarity matrices) (Anderson and Ter Braak 2003) was used to compare seed density and species richness between managed and unmanaged wetlands. Multivariate PERMANOVA (Anderson and Ter Braak 2003) and Nonmetric Multidimensional Scaling (NMS) ordination (both using Bray-Curtis (1957) similarities to calculate the similarity matrix) were used to compare germinable seed bank composition between managed and unmanaged wetlands and between elevations within Yatco Lagoon, Brenda Park and Sugar Shack (wetlands where a species rich and abundant seed bank was detected). Species with a Pearson Correlation Coefficient >0.5 were overlaid as vectors on the ordination comparing the seed banks of the different wetlands. The package PRIMER version 7.0.12 (Clarke and Gorley 2015) with the PERMANOVA add on (Anderson et al. 2008) was used for all statistical analyses.

3. RESULTS

3.1. Germinable Seed Bank Density

The seed banks of the sampled wetlands typically had very low seed densities, except Brenda Park, Yatco Lagoon and Sugar Shack (Figure 2). No seed was detected at Beldora, Morgans Lagoon, Silverlea, Pyap Horseshoe-north section and Teal Flat (Figure 2). Despite high seed densities at Brenda Park, Sugar Shack and Yatco Lagoon, there was no significant difference in seed density between managed and unmanaged wetlands (PERMANOVA *Pseudo* $F_{1,14}$=2.08; P=0.17).

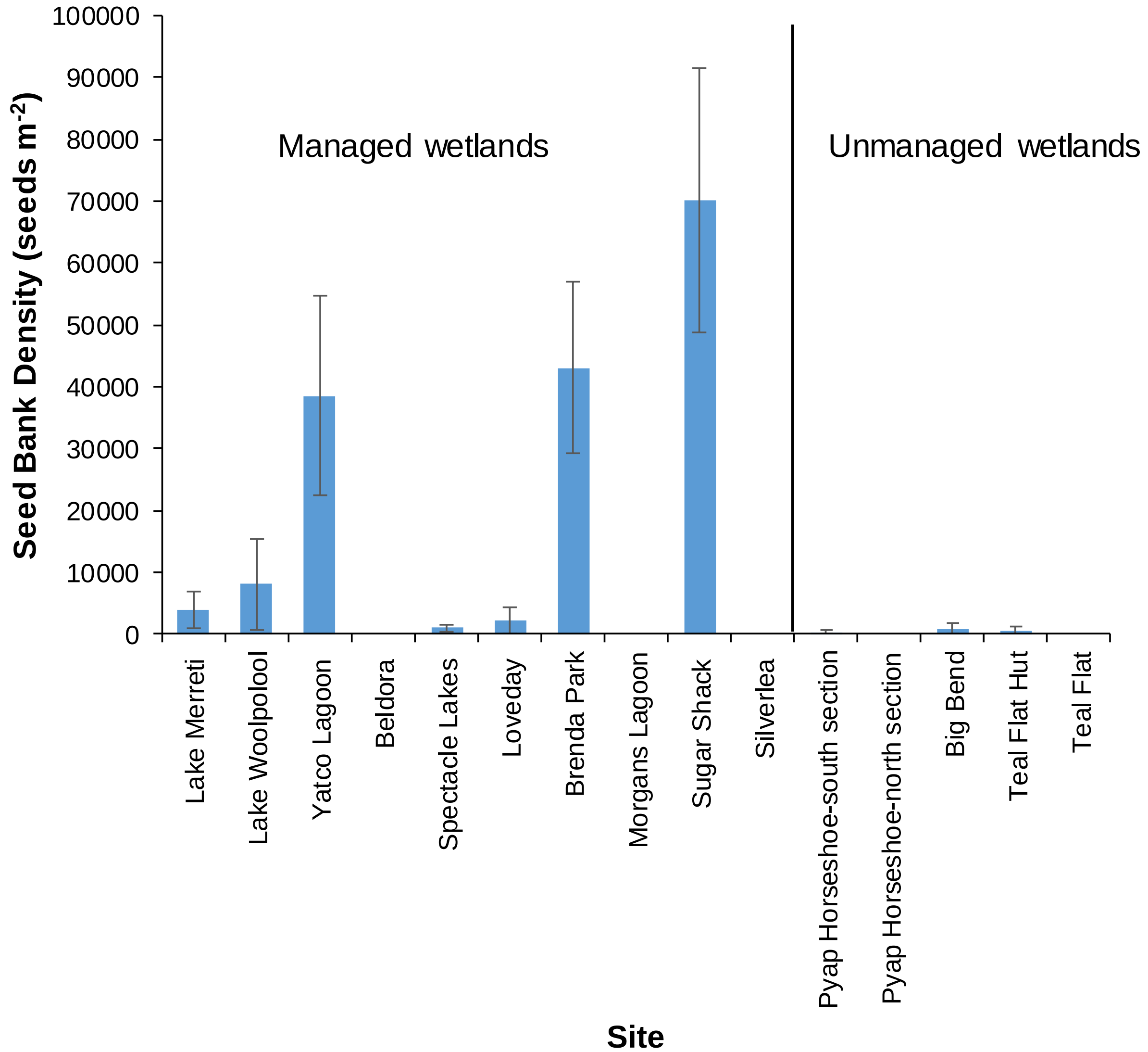


Figure 2: Mean germinable seed bank density for each sampled site (error bars = ±1 S.E.).

3.2. Germinable Seed Bank Species Richness

Germinable seed bank species richness followed similar patterns to seed density, with the highest species richness (Figure 3) in wetlands with the highest seed densities (Figure 2). The highest number of species were detected in Brenda Park (14 species), followed by Sugar Shack (nine species) and Yatco Lagoon (eight species) (Figure 3). The germinable seed bank was dominated by native species in Brenda Park and Sugar Shack (13 and eight species respectively), but half the species detected in Yatco Lagoon were exotic (Figure 3). Two native species were detected in Lake Meretti, Lake Woolpolool and Spectacle Lakes, and one in Big Bend Wetland and Teal Flat (Figure 3). One exotic species was detected in Loveday and Pyap Horseshoe-southern section (Figure 3). Despite greater species richness at Brenda Park, Sugar Shack and Yatco Lagoon, there was no significant difference in overall species richness (PERMANOVA *Pseudo* $F_{1,14}$=2.03; P=0.23) and native species richness (PERMANOVA *Pseudo* $F_{1,14}$=1.82; P=0.23) between managed and unmanaged wetlands.

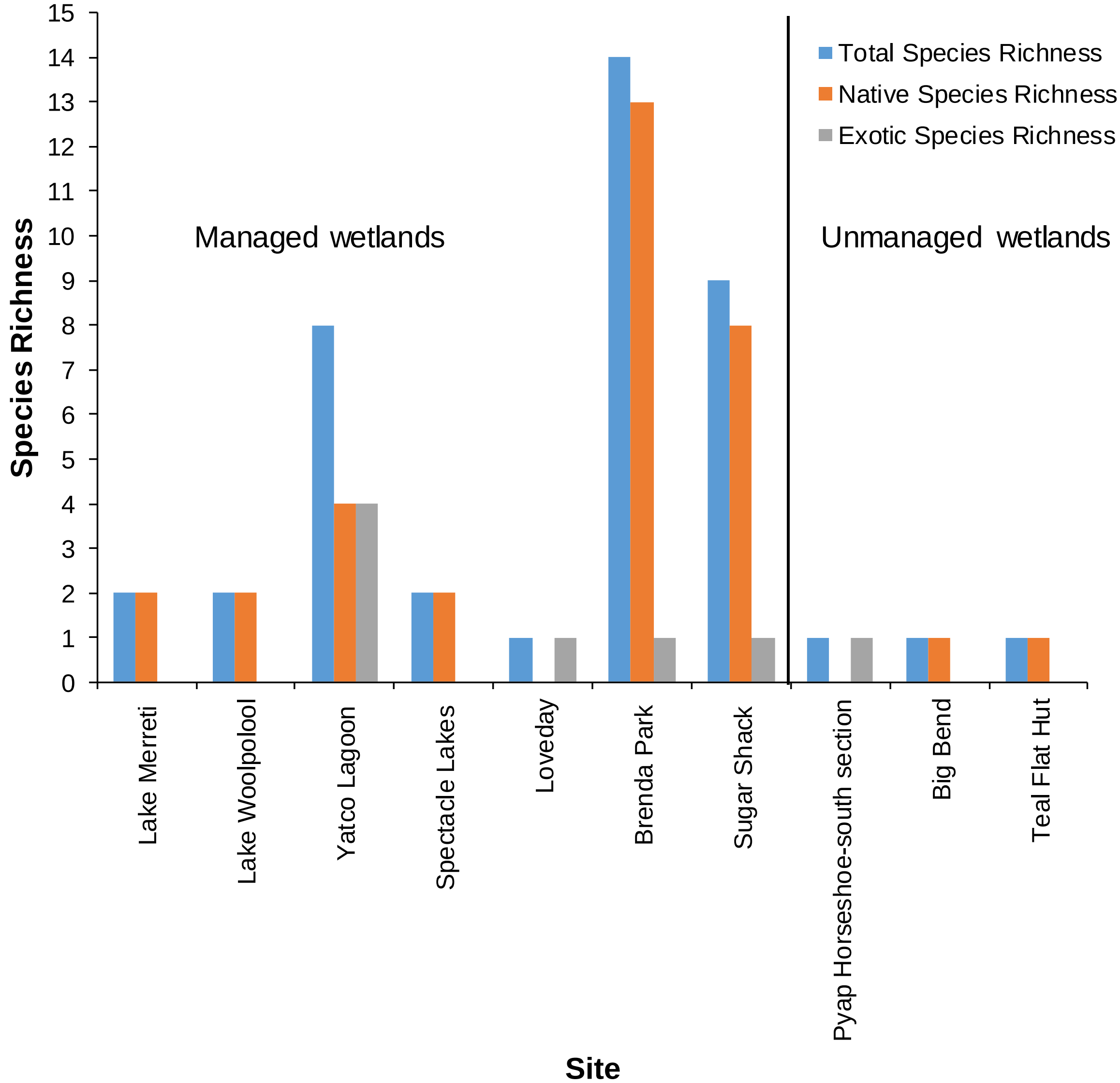


Figure 3: Germinable seed bank species richness (total, native and exotic) of each wetland where germinants were recorded.

3.3. Germinable Seed Bank Composition

Similar to seed density and species richness there was no significant difference in species composition between the seed banks of the managed and unmanaged wetlands (PERMANOVA *Pseudo* $F_{1,14}$=2.03; P=0.23). However, the NMS ordination did show separation between the managed wetlands with high seed density and species richness (Brenda Park, Yatco Lagoon, Woolpolool and Sugar Shack), and those with low density and species richness, driven by high densities at the former of the common species represented by the vectors (Figure 4). The group of points on the right hand side of the ordination (Morgans Lagoon, Beldora, Teal Flat, Silver Lea and Pyap Horseshoe-northern section) are the wetlands where no germination was recorded (Figure 4).

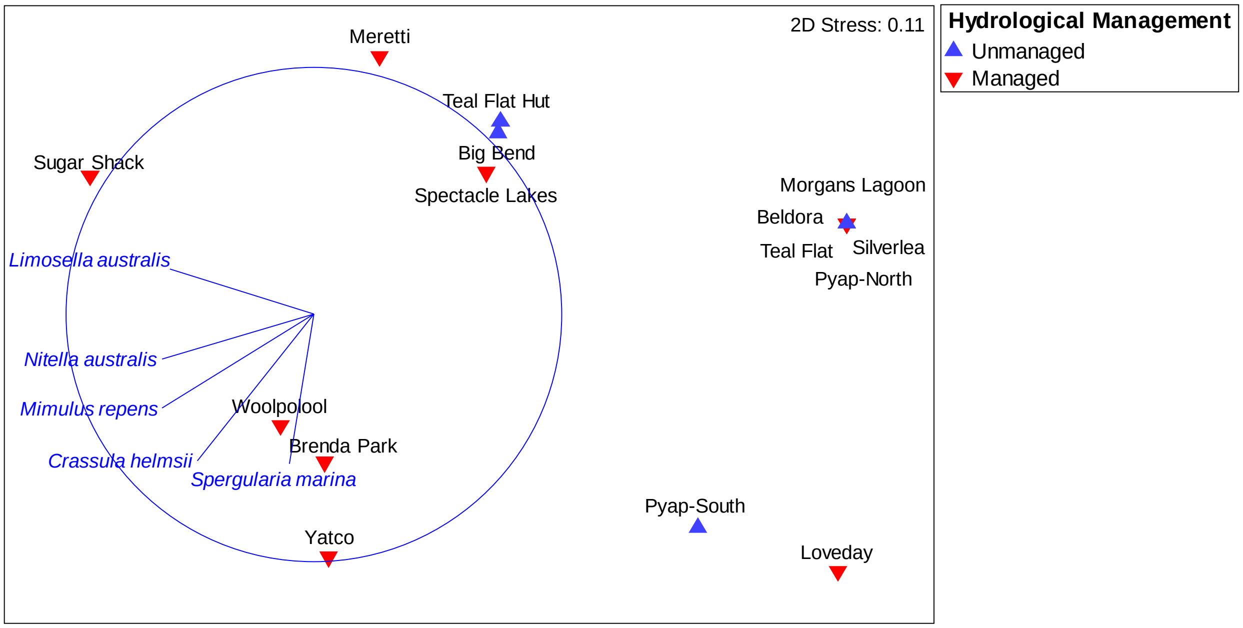


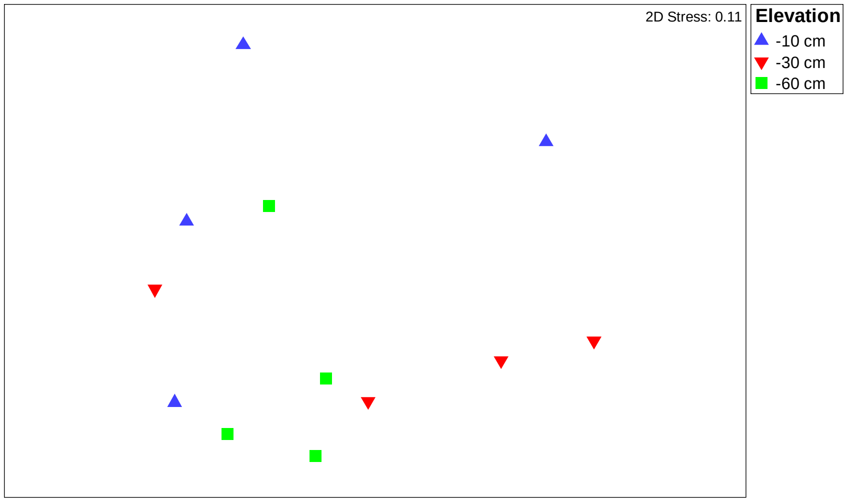
Figure 4: NMS ordination comparing the species composition (combined elevations and transects) of the germinable seed bank of each wetland (the circle represents the length of a vector that has a Pearson Correlation Coefficient of one with the axes and is included for scale).

There was no evidence of seed bank zonation with respect to elevation and hence no clear spatial patterns in Brenda Park, Yatco Lagoon and Sugar Shack Wetland (wetlands with the greatest species richness and seed densities) (Table 1, Figure 5).

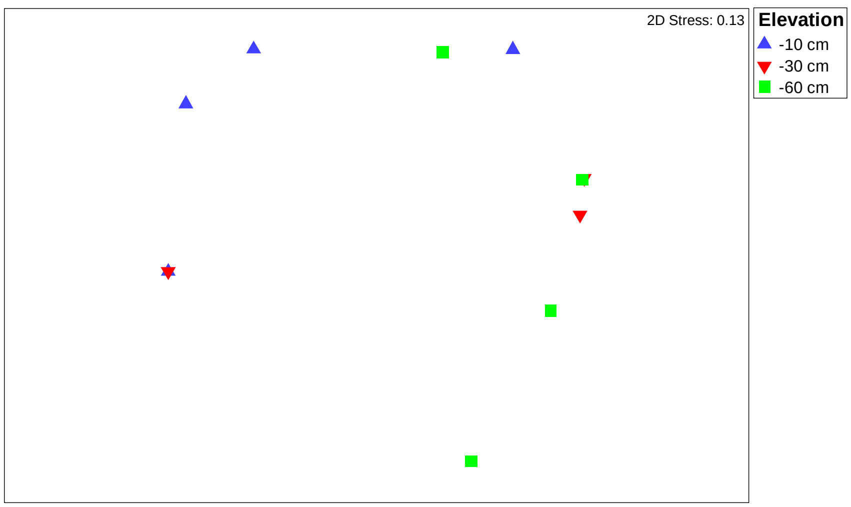
Table 1: PERMANOVA results comparing the seed bank composition at different elevations in Yatco Lagoon, Benda Park and Sugar Shack Wetland.

Wetland	*Pseudo F*	*df*	*P*
Yatco Lagoon	1.63	2,11	0.12
Brenda Park	1.29	2,11	0.15
Sugar Shack	1.34	2,11	0.22

a.



b.



c.

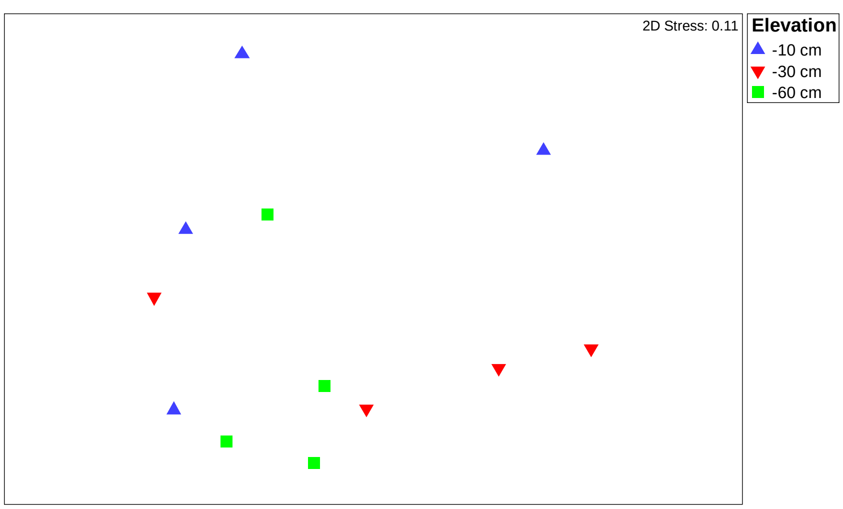


Figure 5: NMS ordination comparing the species composition of the seed bank in a. Yatco Lagoon, b. Brenda Park and c. Sugar Shack Wetland at different elevations.

3.4. Seed Separation

Seed separation detected no seed in any samples tested from the sites with no germination. All of the samples consisted of predominantly mineral clay (except Teal Flat, which had sandier sediment) with very little particulate organic matter. The small amount of particulate organic matter retained in the sieve was clearly not seed and disintegrated when pushed against the sieve mesh.

4. DISCUSSION

This study provides evidence that the previously observed poor vegetation response in many of the hydrologically managed wetlands in the Lower River Murray (Muller et al. 2017) may be due to a depauperate seed bank. Furthermore, it is also likely that the response of the vegetation will be poor when wetting and drying cycles are introduced in the unmanaged wetlands after the structures are completed, as all of these wetlands had a very limited seed bank. The only wetlands with mean seed densities over 10,000 seeds m^{-2} were Brenda Park, Yatco Lagoon and Sugar Shack (Figure 2), which have been subject to managed wetting and drying cycles for over 10 years (over 15 years in the case of Brenda Park). However, Lake Meretti, Lake Woolpolool, Loveday and Spectacle Lakes have been subject to managed wetting and drying cycles for over 10 years and their seed banks were depauperate and it is unclear why these wetlands have depauperate seed banks compared to Brenda Park, Yatco Lagoon and Sugar Shack.

Seed densities of permanently inundated or managed River Murray wetlands in South Australia are not known; however, results from this study suggest that they are highly variable between wetlands and many may have depauperate seed banks. With the exception of Yatco, Benda Park and Sugar Shack, seed densities and species richness (although species richness is often related to sampling effort) are typically lower than other arid/semi-arid wetlands in eastern Australia (Table 2).

Table 2: Maximum seed density (to 5 cm depth) and species richness reported for arid/semi-arid wetlands in eastern Australia (*wetlands sampled from the Lower Lakes were historically permanent but dry when sampled due to low water levels between 2007 and 2010).

Wetland	Region	Hydrological regime	Maximum recorded seed density (seeds m^{-2})	Species Richness	Reference
Menindee Lakes	Lower Darling River	Temporary	75,000	59	Nicol 2004
Thegoa Lagoon	Lower River Murray	Temporary	37,683	21	Nicol *et al.* 2007
Goolwa Channel, lower Finniss River and lower Currency Creek	Lower Lakes	Permanent*	14,182	57	Nicol and Ward 2010)
Chowilla Floodplain	Lower River Murray	Ephemeral	102,000	61	J. Nicol unpublished data, Kelly 2017, Skinner 2017
Bool Lagoon	South East of South Australia	Temporary	78,000	31	Nicol *et al.* 2003
Channel Country, Cooper Creek	Lake Eyre Basin	Temporary	23,000	56	Capon and Brock 2006
Narran Lakes	Lower Balonne Floodplain	Temporary	16,000	77	James *et al.* 2007
Goulburn River Tibutaries	Goulburn Catchment	Temporary/ Permanent	27,000	55	Williams *et al.* 2008
Wannon River	Western Victoria	Temporary	Not recorded	69	Casanova 2015

The absence of germinants in five wetlands does not necessarily mean that there is no seed bank present in these wetlands, as the seedling emergence technique typically underestimates the total seed density (and possibly species richness), compared to seed separation techniques (Gross 1990, Brown 1992, Nielsen et al. 2018). Nielsen et al. (2018) reported that only 5% of the viable seed pool from River Murray wetlands germinated under damp conditions; however, they counted the number of plants present after 12 weeks and did not remove seedlings during the experiment. In this study, no viable seed was detected using seed separation in a sub-sample of the wetlands where no germination was observed. Small seeded species (e.g. *Typha* spp.) may have been missed by passing through the sieve (Mcfarland and Shafer 2011) but it is likely that no seeds were present in these samples.

Despite generally underestimating seed density and species richness, the seedling emergence technique has several advantages over seed separation. Seeds that are not viable are not included in seed bank estimates, and seeds are more difficult to identify than actively growing plants (Roberts 1981, Gross 1990, Brown 1992, Baskin and Baskin 1998, Mcfarland and Shafer 2011). Subjecting the seed bank to damp and submerged conditions also improved the seed bank estimate, especially with regard to species richness (sensu Nicol et al. 2007). In this study, the submergent species *Nitella australis*, and amphibious species *Myriophyllum verrucosum* and *Crassula helmsii,* were only detected in the submerged treatment and would not have been detected if only a damp treatment was used. *Typha domingensis* was the only species recorded in both treatments.

In addition to the seedling emergence technique not detecting all of the seed present in the soil, seed banks are highly spatially heterogeneous (e.g. Bigwood and Inouye 1988, Brock et al. 1994) and it is practical to only sample a very small amount of soil in a large area of wetland (for example, the largest wetland sampled was Lake Meretti at 379 ha (Jensen et al. 1996)). Brock et al. (1994) suggested sampling a minimum of 0.016 m^2 of soil to gain an accurate estimate of species richness for wetlands in the New England Tablelands. Based on the sampling technique; a total of 0.48 m^2 was collected from each wetland and based on the mass of soil used in the germination trial; 0.22 m^2 was assessed in each of the damp and submerged treatments, which is more than an order of magnitude greater than Brock et al. (1994). However, similar to most seed bank studies, a species-area relationship was not determined prior to sampling. Therefore, it is possible that there are localised areas of higher seed density and species richness (e.g. strandlines) (Nicol 2004) that were missed by the sampling. Furthermore, many species found in arid/semi-arid wetlands are prolific seed producers (e.g. Cunningham et al. 1981) and it may only require one individual to complete its life cycle to provide a seed bank "hot spot" for that species. Hence, it is conceivable that very few individuals (given hydrological conditions that enable life cycles to be completed) could contribute significantly to the regenerating plant community in the early stages of wetland management.

Nevertheless, the seed bank studies presented in Table 2 all used similar soil sampling protocols, assessing seed bank density and species richness using the seedling emergence technique and (with the exception of Thegoa Lagoon) were larger systems. Hence, it is highly probable that the seed banks are depauperate (the likely legacy of nearly 100 years of river regulation and increased permanency) in the sampled wetlands except Brenda Park, Sugar Shack and Yatco Lagoon (although native species richness was low in Yatco Lagoon) (Figure 3).

Numerous common lower River Murray temporary wetland and floodplain species were absent from the seed banks of the sampled wetlands. Species known to form soil seed banks such as *Juncus usitatus, Juncus aridicola, Ludwigia peploides, Glinus lotoides, Dysphania pumilio, Helichrysum luteo-album, Isolepis australiensis, Isolepis producta, Rumex bidens, Marselia* *drummondii, Iseotopsis graminifolia, Euphorbia drummondii, Stemodia florulenta* and *Wahlenbergia fluminalis* (Nicol 2004, Nicol et al. 2007, Nicol and Ward 2010) were not recorded. All of these species germinate on the drying cycle or when floodwaters recede (Nicol 2004, Nicol et al. 2018), and many are common in the seed bank of the lower River Murray Floodplain in areas above pool level (J. Nicol unpublished data, Kelly 2017, Skinner 2017) and temporary wetlands (Nicol 2004). Without a drying cycle, these species cannot colonise wetlands, although it is likely they will eventually colonise given appropriate hydrology is maintained.

There was no significant difference in seed density, species richness or species composition between the managed and unmanaged wetlands despite three of the managed wetlands having seed densities and species richness comparable to other wetlands in arid/semi-arid eastern Australia (Table 2). The seven remaining managed wetlands had depauperate seed banks and were similar to the unmanaged wetlands. The large amount of variability between the managed wetlands is probably the reason there was no significant difference (probably resulting in a type II error) in the seed banks between the managed and unmanaged wetlands.

5. CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

Results from this study suggest that reinstating drying cycles to the unmanaged wetlands sampled in this study will not result in diverse plant communities in the short-term or possibly the medium-term, if the soil seed bank is the primary means of recruitment. Whilst three of the managed wetlands have comparable seed banks to other arid/semi-arid wetlands in eastern Australia (Table 2), the majority have depauperate seed banks. Furthermore, wetlands that have been subjected to managed wetting and drying cycles for over 20 years such as lakes Merreti and Woolpolool had depauperate seed banks. However, reinstating a more “natural” hydrological regime is fundamental in wetland restoration as hydrology is the most important factor in determining plant communities in wetland ecosystems (Mitsch and Gosselink 1993). The wetting and drying cycles proposed in wetland management plans produced by RRP are based on the pre-regulation hydrograph of the lower River Murray and information from existing sites (e.g. Willis and Muller 2015). Rate of draw down, which is the most important component of the hydrograph for amphibious species recruitment, follows evaporation and provides sufficiently slow water level recession for survival to reproduction and replenishment of the seed bank (Nicol et al. 2003). Partial drying provides similar benefit to complete drying; however, less area is available for species that require a drying cycle to recruit but soil moisture is higher in the exposed areas giving greater chances of survival. Therefore, the hydrographs proposed by RRP wetland management plans provide conditions conducive to the recruitment of amphibious species not present in unmanaged wetlands and do not require modification.

The depauperate seed banks observed in most of the wetlands in this study are probably a legacy of nearly 100 years of regulation and permanent inundation as altered hydrological regimes changed the habitat template and the biological character changed accordingly (Walker and Thoms 1993) including the soil seed bank. Under the new managed hydrological regime, it is likely the seed bank will change through time as amphibious and floodplain species have the opportunity to colonise new areas and contribute to the seed bank, but that may take years to decades. Information gained by this study cannot give an indication of the time required for wetlands to develop an abundant and species rich seed bank.

Seed bank assessments can give an indication of the vegetation response to reinstatement of drying cycles; however, these are no substitute for a well-designed monitoring program. Monitoring at an appropriate spatial and temporal scale is required to assess impacts of management, and will detect changes through time and assess the vegetation at a greater spatial scale than a seed bank assessment. Greater spatial coverage of the wetland by monitoring the vegetation through time will determine if there are localised areas where the vegetation has responded positively to management, allowing these areas to be protected (e.g. grazing exclosures) to ensure plants reach maturity and contribute to the seed bank during the drying cycle and expand their distribution. Monitoring programs designed to detect change through time in vegetation typically employ two broad techniques; quadrat based surveys or belt transect/point intercept surveys. Quadrat based surveys using fixed areas and locations detect changes in abundance and species composition at patches through time and (providing sufficient area is surveyed) give an estimate of species richness. Belt transect and point intercept surveys (when transects are positioned perpendicular to elevation contours) detect changes in distribution of species within a wetland through time. The type of survey used depends on the objectives of the monitoring program but the timing of surveys is probably more important. Surveys should be undertaken more frequently when the wetland is being drawn down compared to when it is inundated.

If monitoring detects no increase in the extent or diversity of vegetation through time, active measures to introduce species or communities into the wetland may be required. These include active revegetation of adults or juveniles (e.g. Pezeshki et al. 2007, Riis et al. 2009, Quistberg and Stringham 2010), direct seeding of desirable species (e.g. Marion and Orth 2010) or sediment transplant from a donor wetland (or other area in the wetland) to introduce propagules (e.g. Brown and Bedford 1997). Active revegetation can involve mixed plantings or planting of keystone (e.g. Jellinek et al. 2016) or nurse (e.g. Hengst et al. 2010, James et al. 2015) species that provide suitable habitat for other species to recruit. Sediment transplant can be an efficient method of propagule introduction into degraded wetlands; however, disturbance to the donor wetland and the possibility of introduction of undesirable species need to be considered (Brown and Bedford 1997).

Non-hydrological management actions (revegetation, exclosures, sediment transplant) have not been undertaken in lower River Murray wetlands below pool level with the exception being planting of *Schoenoplectus tabernaemontani* in the Lower Lakes to control shoreline erosion (Jellinek et al. 2016). This resulted in planted shorelines being more diverse than unplanted shorelines due to the breakwater effect provided by *Schoenoplectus tabernaemontani* (Jellinek et al. 2016). However, this is not an appropriate management action for wetlands undergoing managed wetting and drying cycles as *Schoenoplectus tabernaemontani* is an emergent species adapted to permanent water and would not provide conditions to enhance recruitment of other species. As active management is largely untested in wetlands below pool level in the lower River

Murray, a pilot study to compare the effectiveness of the different management actions (and the timing of those management actions in relation to the hydrograph) should be undertaken before any large-scale interventions are undertaken.

REFERENCES

Anderson, M.J., Gorley, R.N. and Clarke, K.R. (2008). PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods, PRIMER-E, Plymouth, UK.

Anderson, M.J. and Ter Braak, C.J.F. (2003). Permutation tests for multi-factorial analysis of variance. *Journal of Statistical Computation and Simulation* **73**: 85-113.

Baker, H.G. (1989). Some aspects of the natural history of seed banks. In Leck, M.A., Parker, V.T. and Simpson, R.L. (eds). Ecology of Soil Seed Banks. pp. 9-21. Academic Press, San Diego.

Baskin, C.C. and Baskin, J.M. (1998). Seeds. Ecology, Biogeography, and Evolution of Dormancy and Germination, Academic Press, San Diego.

Bigwood, D.W. and Inouye, D.W. (1988). Spatial pattern analysis of seed banks: an improved method and optimized sampling. *Ecology* **69**: 497-507.

Bjornsson, K.T. (2005). Morgan's Lagoon (Moorundi Wetland Complex) Wetland Management Plan. Mid Murray Local Action Planning Committee Inc., Cambrai.

Bjornsson, K.T. (2006). Sugar Shack Lagoon Wetland Management Plan. Mid Murray Local Action Planning Committee Inc., Cambrai.

Bray, J.R. and Curtis, J.T. (1957). An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs* **27**: 325-349.

Brock, M.A. and Casanova, M.T. (1997). Plant life at the edge of wetlands: ecological responses to wetting and drying patterns. In Klomp, N. and Lunt, I. (eds), Frontiers in Ecology: Building the Links. pp. 181-192. Elsevier Science, Oxford.

Brock, M.A., Casanova, M.T. and Berridge, S.M. (2000). Does your wetland flood and dry? Water regime and wetland plants. Land and Water Resources Research and Development Corporation, University of New England, New South Wales Department of Land and Water Conservation and Environment Australia, Canberra.

Brock, M.A., Theodore, K. and O'Donnell, L. (1994). Seed-bank methods for Australian wetlands. *Australian Journal of Marine and Freshwater Research* **45**: 483-493.

Brown, D. (1992). Estimating the composition of a forest seed bank:a comparison of the seed extraction and emergence methods. *Canadian Journal of Botany* **70**: 1603-1612.

Brown, S.C. and Bedford, B.L. (1997). Restoration of wetland vegetation with transplanted wetland soil: an experimental study. *Wetlands* **17**: 424-437.

Capon, S.J. and Brock, M.A. (2006). Flooding, soil seed bank dynamics and vegetation resilience of a hydrologically variable desert floodplain. *Freshwater Biology* **51**: 206-223.

Casanova, M.T. (2015). The seed bank as a mechanism for resilience and connectivity in a seasonal unregulated river. *Aquatic Botany* **124**: 63-69.

Casanova, M.T. and Brock, M.A. (1999). Life histories of charophytes from permanent and temporary wetlands in eastern Australia. *Australian Journal of Botany* **47**: 383-397.

Chambert, S. and James, C.S. (2009). Sorting of seeds by hydrochory. *River Research and Applications* **25**: 48-61.

Clarke, K.R. and Gorley, R.N. (2015). PRIMER Version 7.0.12: User Manual/Tutorial. PRIMER-E, Plymouth.

Colloff, M.J. (2014). Flooded forest and desert creek: ecology and history of the river red gum, CSIRO Publishing, Collingwood.

Cunningham, G.M., Mulham, W.E., Milthorpe, P.L. and Leigh, J.H. (1992). Plants of Western New South Wales, CSIRO Publishing, Collingwood.

Department of Environment, Water and Natural Resources (2013). Riverine Recovery. Silver Lea Wetland Management Plan. Department of Environment, Water and Natural Resources, Adelaide.

Department of Environment, Water and Natural Resources (2014a). Riverine Recovery. Big Bend Management Plan. Department of Environment, Water and Natural Resources, Adelaide.

Department of Environment, Water and Natural Resources (2014b). Riverine Recovery. Pyap Horseshoe Wetland Management Plan. Department of Environment, Water and Natural Resources, Adelaide.

Department of Environment, Water and Natural Resources (2014c). Riverine Recovery. Teal Flat Hut Wetland Management Plan. Department of Environment, Water and Natural Resources, Adelaide.

Department of Environment, Water and Natural Resources (2014d). Riverine Recovery. Teal Flat Wetland Management Plan. Department of Environment, Water and Natural Resources, Adelaide.

Favre-Bac, L., Lamberti-Raverot, B., Puijalon, S., Ernoult, A., Burel, F., Guillard, L. and Mony, C. (2017). Plant dispersal traits determine hydrochorous species tolerance to connectivity loss at the landscape scale. *Journal of Vegetation Science* **28**: 605-615.

Finlayson, C.M., Roberts, J., Chick, A.J. and Sale, P.J.M. (1983). The biology of Australian weeds 11. *Typha domingensis* Pers. and *Typha orientalis* Presl. *Journal of the Australian Institute of Agricultural Science* **41**: 3-10.

Flaherty, K.L., Rentch, J.S. and Anderson, J.T. (2018). Wetland seed dispersal by white-tailed deer in a large freshwater wetland complex. *AoB Plants* **10**: plx074.

Gross, K.L. (1990). A comparison of methods for estimating seed numbers in the soil. *Journal of Ecology* **78**: 1079-1093.

Hamilton-Brown, S., Boon, P.I., Raulings, E., Morris, K. and Robinson, R. (2009). Aerial seed storage in *Melaleuca ericifolia* Sm. (Swamp Paperbark): environmental triggers for seed release. *Hydrobiologia* **620**: 121-133.

Harper, M. (2003). Management and restoration plan, Lake Woolpolool. Australian Landscape Trust, Renmark.

Hengst, A., Melton, J. and Murray, L. (2010). Estuarine restoration of submersed aquatic vegetation: the nursery bed effect. *Restoration Ecology* **18**: 605-614.

Hocking, P.J., Finlayson, C.M. and Chick, A.J. (1983). The biology of Australian weeds. 12. *Phragmites Australis* (Cav.) Trin. ex Steud. *The Journal of the Australian Institute of Agricultural Science* **40**: 123-132.

Holliday, I. (2004). Melaleucas: a field and garden guide, Reed New Holland, Sydney.

James, C., Capon, S.J., White, M., Rayburg, S. and Thoms, M.C. (2007). Spatial variability of the soil seed bank in a heterogeneous ephemeral wetland system in semi-arid Australia. *Plant Ecology* **190**: 205-217.

James, C.S., Capon, S.J. and Quinn, G.P. (2015). Nurse plant effects of a dominant shrub (*Duma florulenta*) on understorey vegetation in a large, semi-arid wetland in relation to flood frequency and drying. *Journal of Vegetation Science* **26**: 985-994.

Jellinek, S., Te, T., Gehrig, S.L., Stewart, H. and Nicol, J.M. (2016). Facilitating the restoration of aquatic plant communities in a Ramsar wetland. *Restoration Ecology* **24**: 528-537.

Jensen, A., Paton, P., Mowbray, T., Simpson, D., Kinnear, S. and Nichols, S. (1996). Wetlands atlas of the South Australian Murray Valley. South Australian Department of Environment and Natural Resources, Adelaide.

Jessop, J., Dashorst, G.R.M. and James, F.R. (2006). Grasses of South Australia. An illustrated guide to the native and naturalised species, Wakefield Press, Adelaide.

Jessop, J.P. and Tolken, H.R. (1986). The Flora of South Australia, Government of South Australia Printer, Adelaide.

Katz, G.L., Denslow, M.W. and Stromberg, J.C. (2012). The Goldilocks effect: intermittent streams sustain more plant species than those with perennial or ephemeral flow. *Freshwater Biology* **57**: 467-480.

Kelly, D. (2017) Seed bank responses to flow bands in an arid wetland. Honours Thesis, Flinders University, Adelaide.

Maheshwari, B.L., Walker, K.F. and McMahon, T.A. (1995). Effects of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers Research and Management* **10**: 15-38.

Marion, S.R. and Orth, R.J. (2010). Innovative techniques for large-scale seagrass restoration using *Zostera marina* (eelgrass) seeds. *Restoration Ecology* **18**: 514-526.

Mcfarland, D.G. and Shafer, D.J. (2011). Protocol considerations for aquatic plant seed bank assessment. *Journal of Aquatic Plant Management* **49**: 9-19.

Mesgaran, M.B., Mashhadi, H.R., Zand, E. and Alizadeh, H.M. (2007). Comparison of three methodologies for efficient seed extraction in studies of soil weed seedbanks. *Weed Research* **47**: 472-478.

Mitsch, W.J. and Gosselink, J.G. (1993). Wetlands, Van Nostrand Reinhold, New York.

Muller, K.L., Cheshire, A. and Westphalen, G. (2017). Riverine Recovery: Review of RRP Monitoring and Evaluation Program: Conceptual understanding of the ecological response to water level manipulation including initial assessment of vegetation response. A report for Riverine Recovery Program, Department for Environment, Water and Natural Resources (DEWNR), Adelaide.

Nicol, J., Muston, S., D'Santos, P., McCarthy, B. and Zukowski, S. (2007). The impact of sheep grazing on the soil seed bank of a managed ephemeral wetland: implications for management *Australian Journal of Botany* **55**: 103-109.

Nicol, J. and Ward, R. (2010). Seed bank assessment of Goolwa Channel, Lower Finniss River and Lower Currency Creek, South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Nicol, J.M. (2004) Vegetation Dynamics of the Menindee Lakes with Reference to the Seed Bank. PhD Thesis, The University of Adelaide, Adelaide.

Nicol, J.M., Ganf, G.G. and Pelton, G.A. (2003). Seed banks of a southern Australian wetland: the influence of water regime on final species composition. *Plant Ecology* **168**: 191-205.

Nicol, J.M., Ganf, G.G., Walker, K.F. and Gawne, B. (2018). Response of three arid zone floodplain plant species to inundation. *Plant Ecology* **219**: 57-67.

Nielsen, D.L., Campbell, C., Rees, G.N., Durant, R., Littler, R. and Petrie, R. (2018). Seed bank dynamics in wetland complexes associated with a lowland river. *Aquatic Sciences* **80**: 23.

Nielsen, D.L. and Chick, A.J. (1997). Flood-mediated changes in aquatic macrophyte community structure. *Marine and Freshwater Research* **48**: 153-157.

Nilsson, C., Andersson, E., Merritt, D.M. and Johansson, M.E. (2002). Difference in riparian flora between riverbanks and lakeshores explained by dispersal traits. *Ecology* **83**: 2878-2887.

Nilsson, C., Gardfjell, M. and Grelsson, G. (1991). Importance of hydrochory in structuring plant communities along rivers. *Canadian Journal of Botany* **69**: 2631-2633.

Pezeshki, S.R., Li, S., Shields, F.D. and Martin, L.T. (2007). Factors governing survival of black willow (*Salix nigra*) cuttings in a streambank restoration project. *Ecological Engineering* **29**: 56-65.

Pollux, B.J.A. (2011). The experimental study of seed dispersal by fish (ichthyochory). *Freshwater Biology* **56**: 197-212.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. (1998). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* **49**: 55-72.

Puckridge, J.T., Walker, K.F. and Costelloe, J.F. (2000). Hydrological persistence and the ecology of dryland rivers. *Regulated Rivers Research and Management* **16**: 385-402.

Quistberg, S.E. and Stringham, T.K. (2010). Sedge transplant survival in a reconstructed channel: influences of planting location, erosion, and invasive species. *Restoration Ecology* **18**: 401-408.

Raulings, E., Morris, K., Thompson, R. and MacNally, R. (2011). Do birds of a feather disperse plants together? *Freshwater Biology* **56**: 1390-1402.

Riis, T., Schultz, R., Olsen, H. and Katborg, C. (2009). Transplanting macrophytes to rehabilitate streams: experience and recommendations. *Aquatic Ecology* **43**: 935-942.

Roberts, H.A. (1981). Seed banks in soils. *Advances in Applied Biology* **6**: 1-55.

Robertson, H.A. (2006). Spectacle Lakes-Beldora Wetland Management Plan. Berri Barmera Local Action Planning Committee, Berri.

Sabo, J.L., Sponseller, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C., Watts, J. and Weltera, J. (2005). Riparian zones increase regional species richness by harboring different, not more, species. *Ecology* **86**: 56–62.

Sainty, G.R. and Jacobs, S.W.L. (2003). Waterplants in Australia, Sainty and Associates, Darlinghurst, N.S.W., Australia.

Siebentritt, M.A. (2003) The influence of water regime on the floristic composition of Lower River Murray wetlands. PhD Thesis, The University of Adelaide, Adelaide.

Simpson, R.L., Leck, M.A. and Parker, V.T. (1989). Seed banks: general concepts and methodological issues. In Leck, M.A., Parker, V.T. and Simpson, R.L. (eds). The Ecology of Soil Seed Banks. pp. 3-8, Academic Press Inc., San Diego, California.

Skinner, M. (2017) Effect of livestock grazing on seed banks of an arid floodplain in south-eastern Australia. Honours Thesis, FLinders University, Bedford Park.

Soomers, H., Karssenberg, D., Soons, M.B., Verweij, P.A., Verhoeven, J.T.A. and Wassen, M.J. (2013). Wind and water dispersal of wetland plants across fragmented landscapes. *Ecosystems* **16**: 434-451.

South Australian Herbarium (2018). South Australian Plant Census, http://www.flora.sa.gov.au/census.shtml.

Steggles, T. and Tucker, P. (2003). The management of Lake Merreti: using past experiences to guide future practices. Australian Landscape Trust, Renmark.

Tesoriero, J. and Mason, K. (2012). Sugar Shack Pangki Wetland Management Plan Update 2012. Department of Environment, Water and Natural Resources, Murray Bridge.

Tesoriero, J., Mason, K. and Tucker, M. (2013). Morgan's Lagoon Wetland Management Plan Update 2012. Department of Environment, Water and Natural Resources, Murray Bridge.

Thompson, K. (1992). The functional ecology of seed banks. In Fenner, M. (ed). Seeds: The Ecology of Regeneration in Plant Communities. pp. 231-258, C.A.B. International, Wallingford.

Turner, R.J. (2012). Brenda Park Lagoon / Scotts Creek Wetland Management Plan Review and Update 2012, Department of Environment, Water and Natural Resources, Berri.

van der Valk, A.G. and Davis, C.B. (1976). The seed banks of prairie glacial marshes. *Canadian Journal of Botany* **54**: 1832-1838.

van Geest, G.J., Coops, H., Roijackers, R.M.M., Buijse, A.D. and Scheffer, M. (2005). Succession of aquatic vegetation driven by reduced water-level fluctuations in floodplain lakes. *Journal of Applied Ecology* **42**: 251-260.

Walker, K.F. (1985). A review of the ecological effects of river regulation in Australia. *Hydrobiologia* **125**: 111-129.

Walker, K.F., Sheldon, F. and Puckridge, J.T. (1995). A perspective on dryland river ecosystems. *Regulated Rivers Research and Management* **11**: 85-104.

Walker, K.F. and Thoms, M.C. (1993). Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers: Research and Management* **8**: 103-119.

Wegener, I.K. (2012). Loveday Mussels Lagoons Wetland Complex Management Plan Review and Update 2012. Natural Resources – SA Murray-Darling Basin: Department of Environment, Water and Natural Resources, Berri.

Williams, L., Reich, P., Capon, S.J. and Raulings, E. (2008). Soil seed banks of degraded riparian zones in southeastern Australia and their potential contribution to the restoration of understorey vegetation. *River Research and Applications* **24**: 1002-1017.

Willis, D. and Muller, K. (2015). Riverine Recovery Beldora - Spectacle Lakes Wetland Management Plan. Version 1.4. Department of Environment, Water and Natural Resources, Adelaide.

APPENDICES

Appendix 1: List of species recorded, including life history strategy and conservation status in South Australia (*denotes exotic species, [#]*Sphaeromorphaea australis* was formerly named *Epaltes australis* and ^*Thyridia repens* was formerly *Mimulus repens*).

			Managed wetlands							Unmanaged wetlands		
Taxon	**Life History Strategy**	**Conservation Status**	**Lake Merreti**	**Lake Woolpolool**	**Yatco Lagoon**	**Spectacle Lakes**	**Mussel Lagoons**	**Brenda Park**	**Sugar Shack**	**Pyap Horseshoe-south section**	**Big Bend**	**Teal Flat Hut**
Alternanthera denticulata	Annual	Least Concern						■				
*Atriplex prostrata**	Annual				■							
Atriplex suberecta	Annual	Least Concern						■				
Centipeda minima	Annual	Least Concern						■				
Crassula helmsii	Perennial	Least Concern		■	■			■				
Crassula sieberana	Annual	Endangered						■	■			
Cyperus gymnocaulos	Perennial	Least Concern						■				
*Heliotropium curassavicum**	Annual				■							
Limosella australis	Perennial	Least Concern	■					■	■			
Medicago spp.*	Annual						■	■				
Myriophyllum verrucosum	Perennial	Least Concern						■	■			
Nitella australis	Perennial	Least Concern			■	■		■	■			
Persicaria lapathifolia	Perennial	Least Concern						■				
*Polygonum aviculare**	Annual				■							
Polygonum plebium	Annual	Least Concern						■	■			
Sarcocornia quinqueflora	Perennial	Least Concern			■							
*Sonchus oleraceus**	Annual								■			
*Spergularia marina**	Annual				■					■		
Sphaeromorphaea australis[#]	Annual	Least Concern						■				
Sporobolus mitchellii	Perennial	Least Concern							■			
Thyridia repens^	Perennial	Least Concern			■			■	■			
Typha domingensis	Perennial	Least Concern	■	■		■		■	■		■	■