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Water allocation to River Murray wetlands: a basin-wide modeling approach

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Introduction

The primary aim of this project was to relate the water regime preferences of wetland plants to hydrology throughout the Murray River Basin and to predict the volume of additional water required to achieve optimal plant species diversity. This report details the methods and key findings of the project which examined the impact of regulation and changes in water allocation on the community composition of wetland plants through the Murray River basin. Due to a lack of primary data, it deals only with a subset of wetlands. The study includes 2,746 wetlands with a total area of 53,303 hectares, spanning 16 hydrologically distinct reaches (Table 1). Geographically, these wetlands are restricted to areas of NSW and Victoria because no commence to fill (CTF) (sill height) data were available for wetlands in South Australia. This subset is approximately one-third of the wetlands spread through the NSW-Victorian portion of the river. A statistical modeling approach was used to analyse the relationship between discharge, CTF, wetland connectivity and the probability of occurrence of wetland plant species. This approached enabled a basin wide analysis. A key assumption was that the amount of water required for wetlands is that which optimizes plant species diversity at the regional spatial scale (here the 16 defined reaches).

This report explains the methods used to model hydrology and community composition through the Murray River basin (section 2), a description of the effect of changing discharge on plant community indicators through the basin (section 3), identification of wetlands within each reach which have a unique flora (section 4), and concluding remarks.

Table 1: Area and number of wetlands from the 16 reaches of the River Murray included in the study.

Reach	Gauging station ID	Number of wetlands	Area (hectares)
Edwards River at Deniliquin	409003	186	8,554.8
Wakool River at Stoney Crossing	409013	122	638.5
Edwards River at Moulamien	409014	91	1,179.2
Wakool River DS offtake regulator	409019	32	489
Yallakool Creek DS offtake regulator	409020	50	307.2
Edward's River DS Steven's Weir	409023	145	1,544.6
Colligen Creek DS offtake regulator	409024	23	506.1
River Murray DS Yarrawonga Weir	409025	137	643.9
Edward River at Liewah	409035	3	5.3
Murray River at Tocumwal	409202	485	8,521.1
River Murray at Swan Hill	409204	575	13,321.1
Murray River at Torrunbarry	409207	65	2,518
Murray River below Wakool Junction	414200	183	7,249.8
Murray River at Euston	414203	631	7,520.4
Rufus River at Lake Victoria outlet	426502	1	5.1
Murray River DS Lock 6	426510	17	298.9

Sum	2,746	53,303

2. Methods and procedures

2.1. Wetland-river connectivity

The basis for the modeling of plant communities was wetland water regime. This was estimated as the wetland-river connectivity which is the number of days out of each year a wetland receives water from the river expressed as a fraction. To illustrate this concept the connectivity of two wetlands in the Swan Hill Reach (#409204) with Commence To Fill (CTF) of 10 and 20 thousand ML day^{-1} are shown in Fig 1 alongside the average connectivity for the years 1992 to 1996. The 575 wetlands in the Swan Hill Reach (Table 2) have CTF between 0 and 68,300 ML day^{-1}. The hydrograph (Figure 2) for that period shows that only wetlands with a CTF of < 35.000 ML day^{-1} received water from the main channel and the variation in the annual hydrograph influenced their connectivity (Fig. 3).

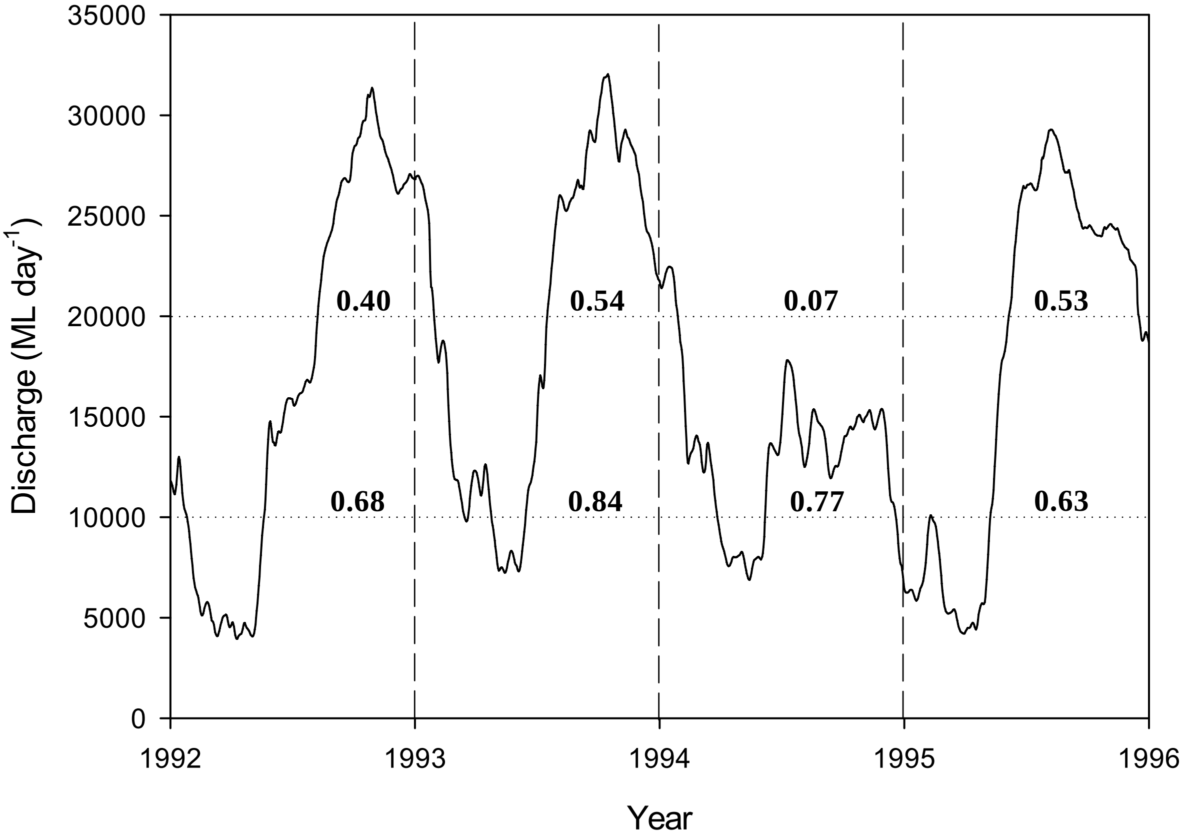

Figure 1: Annual hydrograph (expressed as discharge; ML day^{-1}) and the attendant measurement of wetland-river connectivity for two wetlands In the Swan Hill Reach with commence to fill values (or sill heights) of 10000 and

20000 ML day^{-1}. The connectivity of each wetland is presented above each dotted line. The averages for the two wetlands are 0.31 and 0.58.

CTF (ML day-1)	Number of wetlands	Cumulative number of wetlands	Area of wetlands (hectares)	Cumulative area of wetlands
0	8	8	444	444
6,000	11	19	6,983.6	7,427.6
6,800	1	20	0.6	7,428.2
7,590	2	22	25.7	7,453.9
11,000	1	23	1	7,454.9
12,500	1	24	24.3	7,479.2
13,700	6	30	47	7,526.2
16,000	31	61	290.8	7,817
17,000	1	62	3	7,820
17,280	10	72	1,422.1	9,242.1
19,000	3	75	16.6	9,258.7
22,100	1	76	9.6	9,268.3
49,100	360	436	3,353.4	12,621.7
58,700	138	574	698.9	13,320.6
68,300	1	575	0.5	13,321.1

Table 2: The number and area of wetlands and their CTF for 575 wetlands in the Swan Hill Reach.

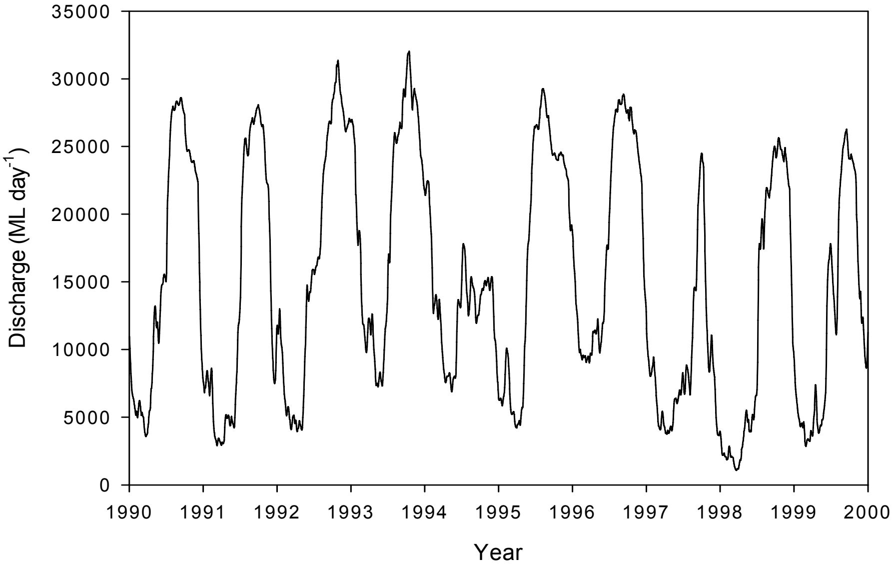

Figure 2: The annual hydrograph for the Swan Hill Reach 1990 to 2000.

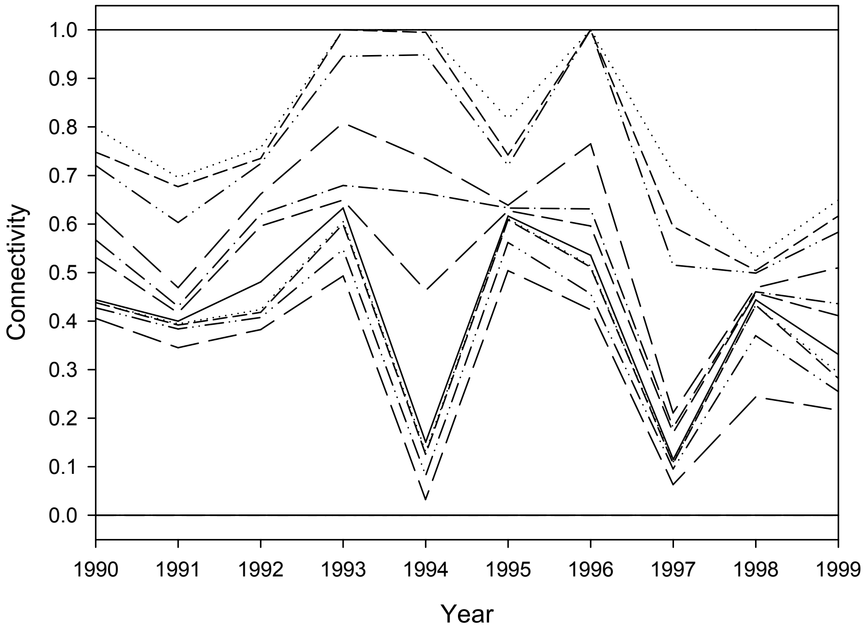

Figure 3: Annual variation in the connectivity of the wetlands in the Swan Hill Reach that received water from the main channel during the period 1990 to 2000.

At the basin wide scale wetland CTF connectivity decreases with increasing wetland commence to fill (Figure 4). The exact relationship differs among river reaches reflecting the differences in the annual hydrographs of different reaches, but the relationship is commonly described by a logarithmic decrease in connectivity with increasing commence to fill.

Two comparative sets of data were used in estimating connectivity (courtesy MDBC): i) natural conditions - data modeled without water extraction or regulatory structures impeding flow through the river, and ii) current conditions - data modeled to include the effects on discharge of water extraction and regulatory structures. The two sets of hydrological data, hereafter termed simply "natural" and "current", span the period 1891 -2001. A subset of these data covering the decade 1990 to 2000 was used in estimating wetland-river connectivity. This period was selected for being reasonably constant (no major flood or drought events) while still providing a robust average estimate of connectivity. The connectivity was averaged over the decade for each wetland under natural and current conditions.

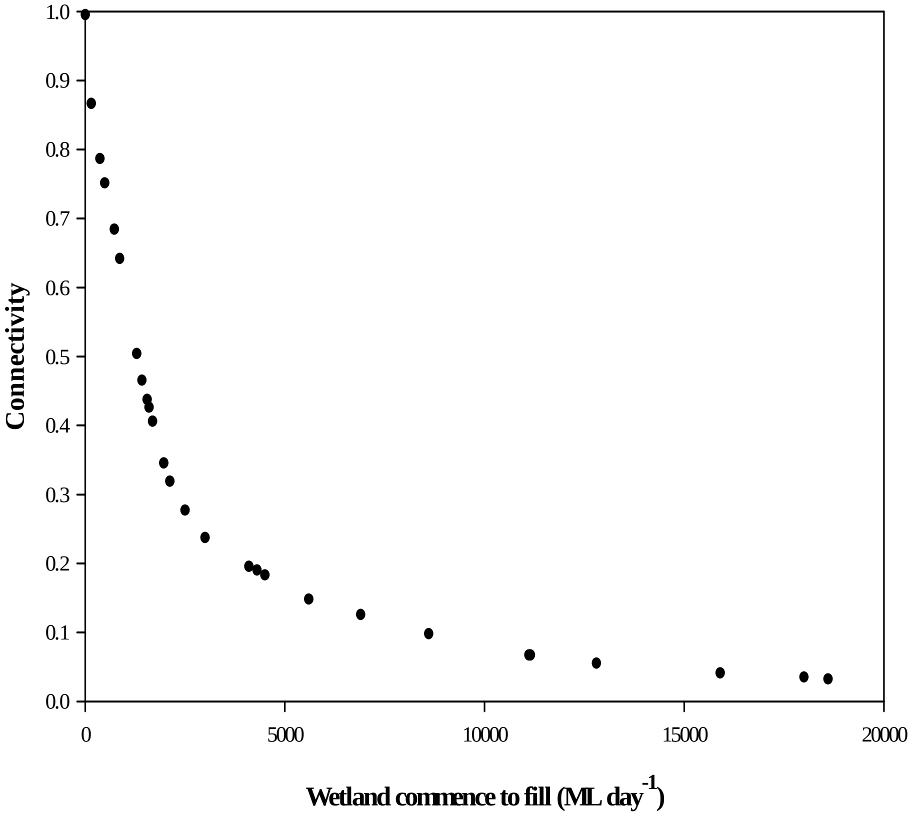

Figure 4: Relationship between wetland commence to fill and the wetland-river connectivity.

Analysis of pre- and post-regulation

Three 20 year periods (1900-1920, 1957-1977, 1979-1999) were investigated and 3773 wetlands allocated to 10 connectivity categories. The influence of river regulation (Figure 5 and Table 2) is that the number of wetlands falling into each of the connectivity categories 0.1 to 1.0 has either fallen or remained static, the only exceptions are those wetlands with a connectivity of 0.8. The most significant change is the number of wetlands that never or only rarely receive water from the main channel which have increased from 1372 to 2248. The number of wetlands falling into the categories 0.4 to 1.0 has fallen from 688 to 455. This is of particular concern because it is these wetlands that harbor the greatest functional group diversity (Figure 8).

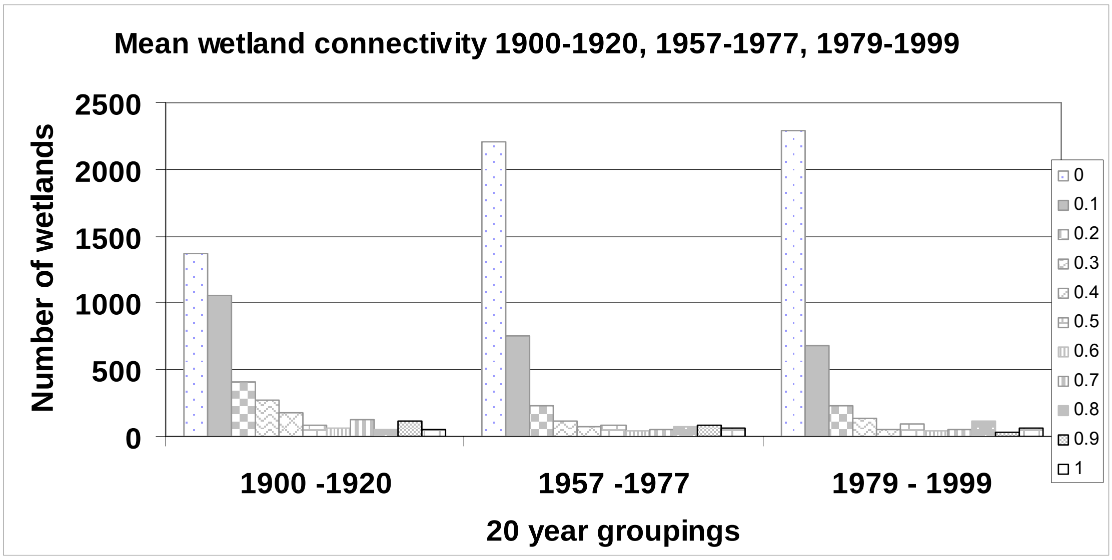

Figure 5. The number of wetlands falling into 10 connectivity categories pre-regulation 1900–1920 and post-regulation, 1957-1977 and 1979-1999.

2.2. Species models

Species models were constructed from field survey data drawn from four sources (Ward, 1994; Blanch *et al*., 1999; Siebentritt, 2002; South Australian Baseline Wetland Survey). The data was collated and used to construct Gaussian models

# Wetlands	**Mean connectivity**										
	0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
1900 -1920	**1372**	**1059**	**406**	**268**	**178**	**87**	**59**	**124**	**50**	**116**	**54**
1957 -1977	**2204**	**757**	**225**	**110**	**70**	**87**	**41**	**55**	**77**	**81**	**66**
1979 - 1999	**2293**	**680**	**232**	**135**	**51**	**89**	**37**	**52**	**115**	**30**	**59**

describing the probability of presence of 36 species of wetland species (Table 3) across a gradient of wetland-river connectivity (see Figure 6 for an example of the distribution curves). Although implicit to the species distribution models, the effects of stress (e.g. salinity), resource availability (e.g. nutrients), and biotic interactions (e.g. competition) are not explicitly delineated in the species models.

Table 2. The number of wetlands falling into 10 connectivity categories pre-regulation 1900 – 1920 and post-regulation, 1957-1977 and 1979-1999.

The 36 species included submerged macrophytes, emergent macrophytes, and floodplain species from 17 families. Most of the species have a wide distribution through Australia (Table 3). Each of the species can be allocated to a functional group which describes the species' tolerance to aspects of water regime – flooding, exposure and so on. Blanch *et al*. (1999; 2000) identified five functional groups in mature wetland plants (although more exist for germinants): *widespread tolerant*, *common floodplain*, *permanently flooded*, *uncommon floodplain*, and *infrequently flooded*.

Table 3: Model species. Authority, life history and distribution from Black, 1986. Functional group based on Blanch *et al*. (1999).

Species	**Family**	**Functional group**	**Flowering time**	**Distribution (*=naturalised, ^=introduced)**
Azolla filiculoides Lam.	Azollaceae	Permanently flooded	-	NSW,SA,Tas,Qld,Vic
Bolboschoenus caldwellii (V.J.Cook) Soják	Cyperaceae	Infrequent flooded	spring-summer	Qld,NSW,Vic,Tas,WA,SA,NT
Bolboschoenus medianus (V.J.Cook) Soják	Cyperaceae	Widespread tolerant	spring-summer	NSW,Vic,Tas,SA
Brachyscome basaltica F.Muell.	Asteraceae	Infrequent flooded	year round	NSW,Qld,Vic,SA,Tas
Carex tereticaulis F.Muell.	Cyperaceae	Common floodplain	spring-summer	NSW,Vic,Tas,WA,SA
Centipeda cunninghamii (DC.) A. Braun & Asch.	Asteraceae	Widespread tolerant	spring-autumn	Qld,NSW,Tas,WA,SA,NT
Cotula coronopifolia L.	Asteraceae	Common floodplain	winter-spring	Qld^,Vic^,NSW^,Tas^,WA^,SA^
Cynodon dactylon (L.) Pers.	Poaceae	Widespread tolerant	summer	NSW,Vic,Tas,WA,SA,NT
Cyperus bulbosus Vahl	Cyperaceae	Infrequent flooded	spring-summer	Qld,WA,SA,NT,NSW
Cyperus exaltatus Retz.	Cyperaceae	Widespread tolerant	spring-summer	Qld,Vic,WA,SA,NT
Cyperus gymnocaulos Steudel	Cyperaceae	Widespread tolerant	spring-summer	Qld,Vic,WA,SA,NT
Eleocharis acuta R.Br.	Cyperaceae	Uncommon floodplain	spring-summer	Qld,Vic,WA,SA,NT

Species	Family	Functional group	Flowering time	Distribution (*=naturalised, ^=introduced)
Glycyrrhiza acanthocarpa (Lindley) J. Black	Fabaceae-Faboideae	Widespread tolerant	spring-summer	Qld,Vic,NSW,WA,SA
Juncus aridicola L. Johnson	Juncaginaceae	Permanently flooded	spring-summer	Qld,Vic,WA,SA,NT,NSW
Juncus usitatus L. Johnson	Juncaginaceae	Common floodplain	spring-summer	Qld,Vic,WA*,SA*
Lemna minor L.	Lemnaceae	Permanently flooded	-	
Ludwigia peploides subsp. *montevidensis* (Sprengel) Raven	Onagraceae	Permanently flooded	spring-autumn	NSW,Qld,Vic,SA
Muehlenbeckia florulenta Meissner	Polygonaceae	Common floodplain	spring-summer	Qld,Vic,NSW,SA,NT
Myriophyllum salsugineum Orch.	Haloragaceae	Permanently flooded	spring-summer	Vic,Tas,WA,SA,NSW
Paspalidium jubiflorum (Trin.) Hughes	Poaceae	Common floodplain	spring-summer	
Paspalum distichum L.	Poaceae	Widespread tolerant	summer	Qld,Vic,Tas,WA,SA,NT
Persicaria prostratum R.Br.	Polygonaceae	Widespread tolerant		Qld,Vic,Tas,WA,SA,NT,NSW
Phragmites australis (Cav.) Trin. ex Steudel	Poaceae	Widespread tolerant	autumn	Qld,Vic,Tas,SA,WA,NT,NSW
Phyla canescens (L.) Greene	Verbanaceae	Infrequent flooded	spring-autumn	Qld*,Vic*,WA*,SA*,NSW
Potamogeton crispus L.	Potamogetonaceae	Permanently flooded	spring	Qld,Vic,WA,SA,NT,NSW
Pratia concolor (R.Br.) Druce	Lobeliaceae	Common floodplain	summer-autumn	Qld,Vic,WA,SA,NT,NSW
Pseudoraphis spinescens (R.Br.) Vick.	Poaceae	Uncommon floodplain	summer	Qld,Vic,NSW,WA,SA,NT
Rorippa nasturtium-aquaticum (L.) Hayek	Brassicaceae	Common floodplain		Qld*,Vic*,Tas*,WA*,SA*,NT*,NSW*
Rumex bidens R.Br.	Polygonaceae	Widespread tolerant		Vic,Tas,SA
Schoenoplectus validus (Vahl) Á. Löve & D. Löve	Cyperaceae	Permanently flooded	spring-summer	Qld,Vic,Tas,WA,SA,NSW
Senecio cunninghamii DC.	Asteraceae	Widespread tolerant	spring-summer	Qld,Vic,NSW,SA
Sporobolus mitchellii (Trin.) C.E. Hubb ex. S.T. Blake	Poaceae	Common floodplain	following rain	Qld,Vic,WA,SA,NT,NSW
Stemodia florulenta W.R. Barker	Scrophulariaceae	Common floodplain	spring-summer	Qld,Vic,WA,SA,NT,NSW
Triglochin procerum R.Br.	Juncaginaceae	Permanently flooded	spring-summer	NSW,Qld,Vic,SA

Species	**Family**	**Functional group**	**Flowering time**	**Distribution (*=naturalised, ^=introduced)**
Typha domingensis (Pers.) Steudel	Typhaceae	Permanently flooded	autumn	Qld,Vic,Tas,WA, SA,NT,NSW
Vallisneria americana Graebner	Hydrochartaceae	Permanently flooded	spring-summer	Qld,Vic,Tas,WA, SA,NT,NSW

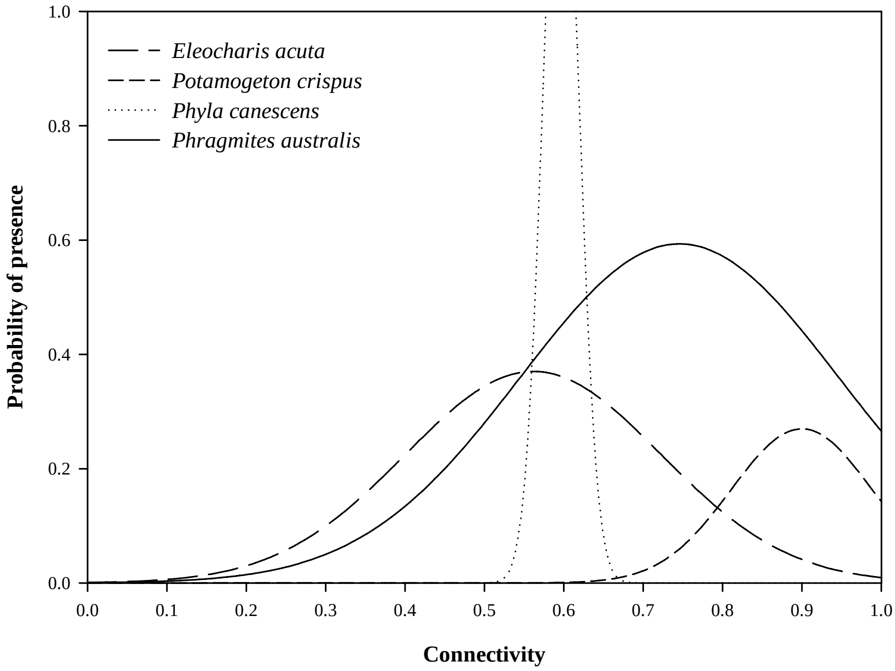

Figure 6: Gaussian distribution curves describing the probability of presence for four species across a gradient in wetland-river connectivity.

2.3. Changes in community with changes in connectivity

Community richness (species, family, and functional group) varies across the connectivity gradient (Fig. 7). The highest richness occurs at connectivities of around 0.7. Because of the exclusive distribution of some species, no single connectivity value can support all of the 36 modeled species. For example, a wetland cannot support both *Phyla canescens* and *Potamogeton crispus* (Fig. 6).

Maximum diversity is therefore only achieved within a reach by having wetlands with a range of complimentary connectivity values.

Across the gradient in connectivity there is a transition from a permanently flooded system to an ephemeral system which corresponds to a transition in the habitat specialisation and lifecycle of the flora. The permanently flooded community is dominated by perennial species such as *Vallisneria americana*, *Azolla filiculoides*, and *Typha domingensis*. These species commonly rely heavily on vegetative reproduction as the primary means of spread and temporal persistence. The intermediate wetland has a strong seasonal change in water level, and contains annual species which can complete their lifecycle during drawdown (eg, *Cynodon dactylon*), terrestrial invaders (eg, *Rumex bidens*), and floodplain species which require occasional wetting (eg, *Muehlenbeckia florulenta*). Species from intermediate wetland type include a number of annual species which rely on seed banks as a means of year to year persistence. Seed longevity is often short (<5 years) in the expectation that flooding will occur regularly. The ephemeral wetland community contains species which have adaptations to periods (years) of dry conditions such as *Carex tereticaulis*, *Pratia concolor*, *Paspalidum jubiflorum* and *Brachyscome basaltica*. These species often have long-lived seeds which can persist in the sediment for years until conditions conducive to germination occur. This transition is reflected in a change in the prevalence of the functional groups (Fig. 8). The groups *widespread tolerant* (eg, *Phragmites australis*) and *common floodplain* (eg, *Juncus usitatus*) are present across the whole gradient in wetland-river connectivity. Species from the *permanently flooded* (eg, *Potamogeton crispus*) functional group are most prevalent at connectivities of >0.7 and are not found at connectivities of below 0.5. The functional groups *uncommon floodplain* (eg, *Eleocharis acuta*) and *infrequently flooded* (eg, *Brachyscome basaltica*) are most prevalent at connectivities of 0.4 to 0.6. All functional groups are supported by connectivity values between 0.5 and 0.9.

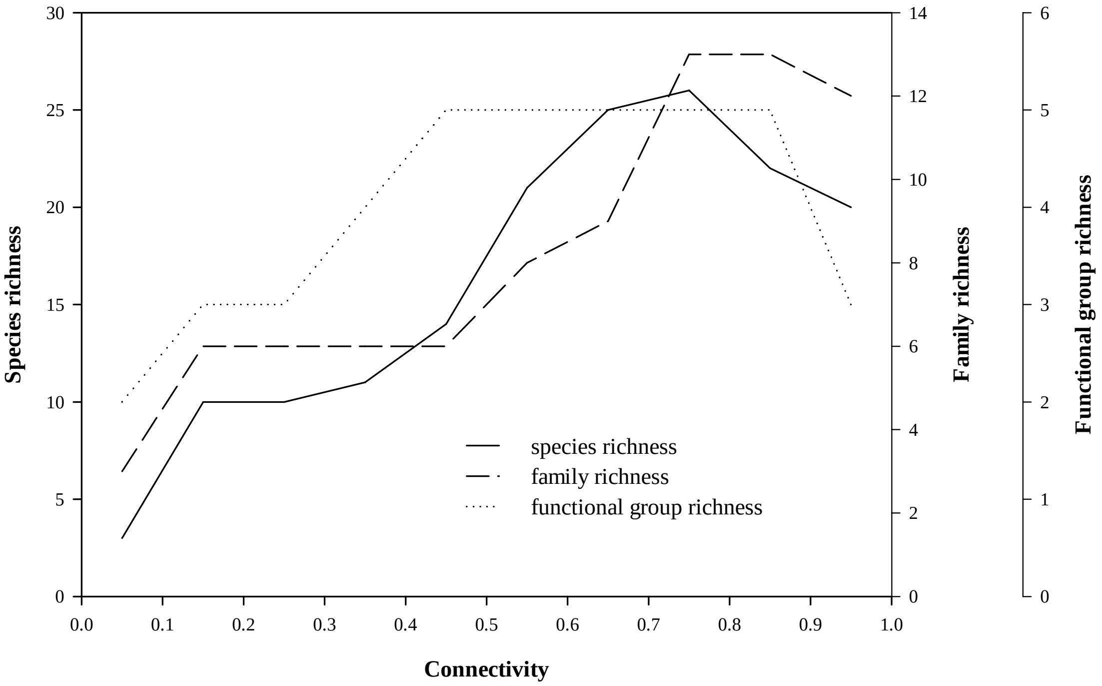

Figure 7: Effect of wetland-river connectivity on species richness, family richness, and functional group richness.

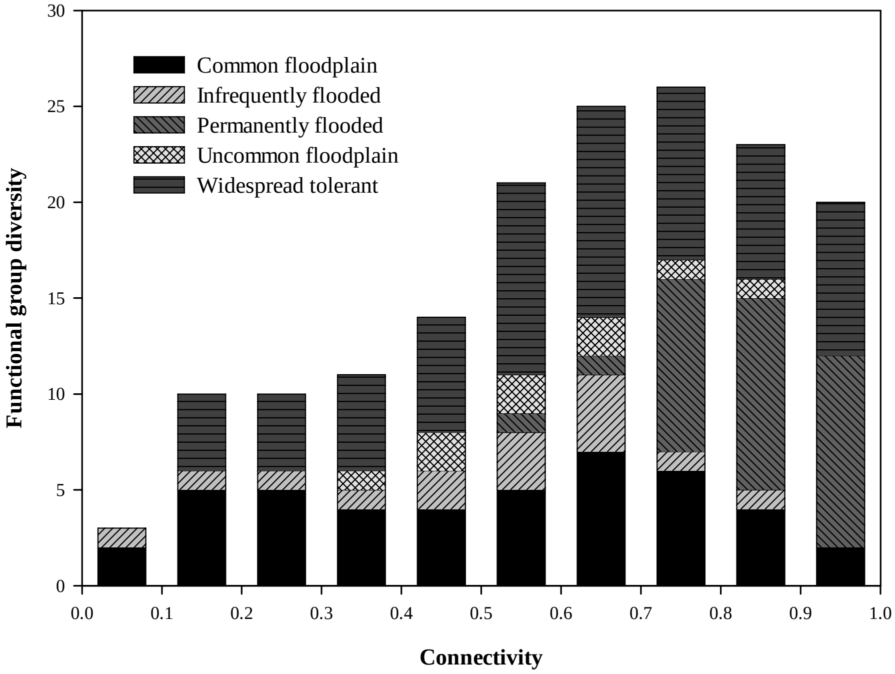

Figure 8: Effect of wetland-river connectivity on functional group prevalence.

3. The effect of changing discharge on community composition through the Murray River basin

3.1. Methods

The presence of each of the 36 species was predicted in each wetland commence to fill for each reach. To examine how changes in discharge might affect this, the daily hydrograph for each reach (averaged over the ten year period 1990-2000) was multiplied by factors ranging from 0.5 (simulating drought) to 1.5 (simulating flood) at intervals of 0.1 (Figure 9). This approach maintained the annual pattern in discharge but allowed for a summary change to be made in the annual discharge specific to each reach (Table 4). The connectivity was estimated for each hydrograph and the presence of each of the 36 model species predicted within each wetland commence to fill value for each reach under natural and current conditions.

A number of community indicators were chosen to describe the community based on the prediction of the presence of the 36 model species. These were species richness, family richness, functional group richness, species diversity index (Simpson's Diversity Index), species equitability, and sum species areal cover. Species equitability quantifies how evenly territory is shared among different species whilst Simpson's Diversity Index expresses both the species richness and how evenly territory is shared among those species. The sum species areal cover is the total territory of each species within a reach summed across all of the species found within a reach. The maximum value for this indicator is the maximum number of species multiplied by the total area of the reach. The indicators can be divided into two groups: richness-related indices (species, family, and functional group) and evenness- or spread-related indices (diversity index, equitability, and sum areal cover).

Community indicators were estimated for the each discharge interval from 0.5 to 1.5 to investigate how changes in discharge would affect the wetland plant community (Fig. 10). The minimum discharge required to support maximum richness was collated for each reach and summed across the whole study area under natural and current conditions. The results were ranked by discharge and plotted against the cumulative number or area of wetlands in which the indicator has been maximised (see section 3). The water return from flooded wetlands was arbitrarily set at 100 %.

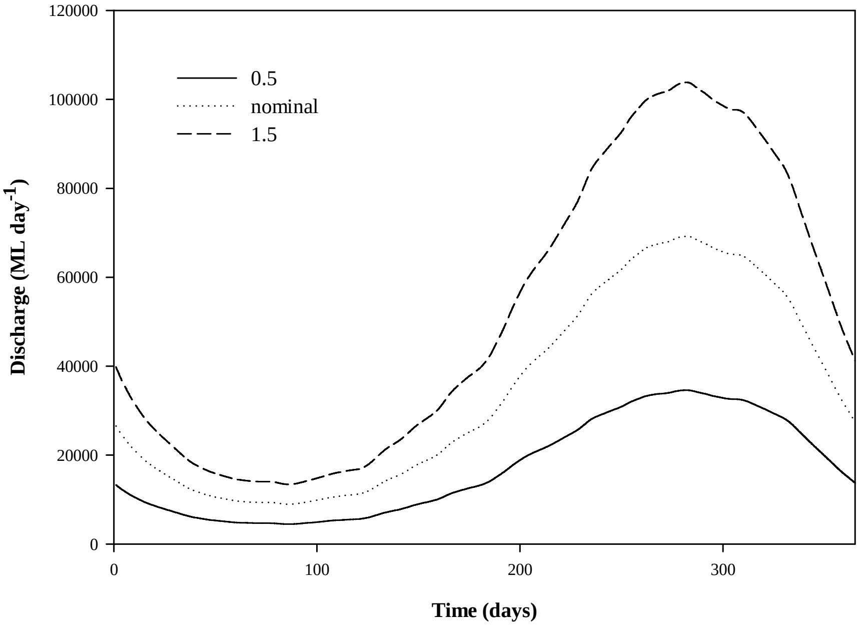

Figure 9: Example of hydrograph with nominal discharge, and discharge multipliers 0.5 and 1.5.

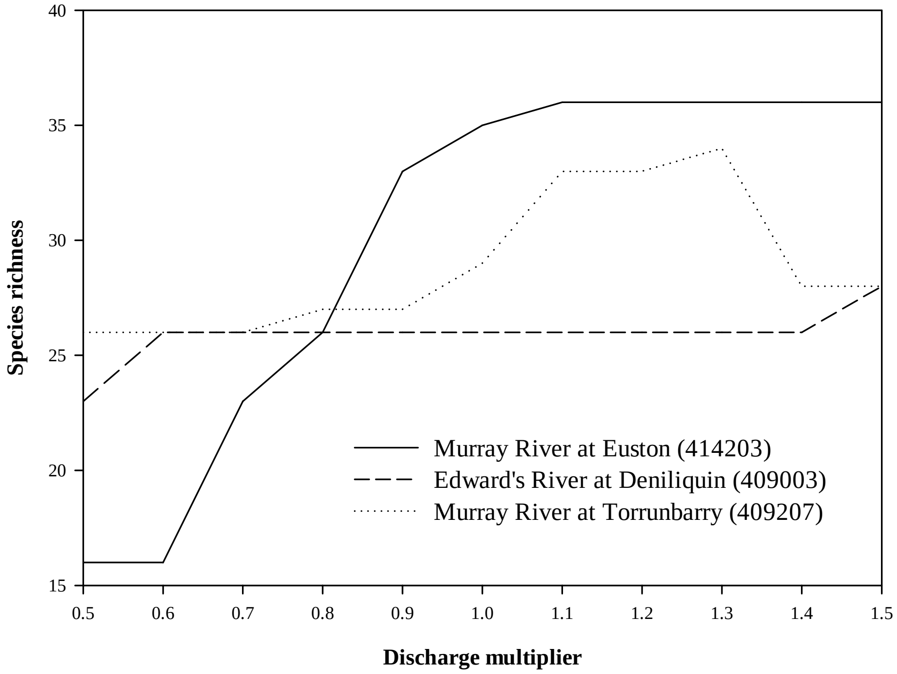

Figure 10: Effect of discharge (indicated as a discharge multiplier) on species richness at three example reaches. Nominal discharge through the Euston reach is 19651.6 ML day^{-1} (Table 2). Species richness is maximised across the reach at 1.1 times the nominal discharge or 21,616 ML day^{-1}. Thus, maximum species richness is achieved within the Euston reach by the addition of 1,965.2 ML day^{-1}.

Table 4: Average daily discharges for various reaches with minimum and maximum discharge values used in modeling.

	Average discharge (ML day^{-1})		
Reach	**lower (**×0.5)	**nominal**	**upper (**×1.5)
409003	2769.1	5538.3	8307.4
409013	9825.8	19651.6	29477.4
409014	1345.0	2690.1	4035.1
409019	122.4	244.8	367.2
409020	205.9	411.8	617.7
409023	1667.2	3334.5	5001.7
409024	627.8	1255.6	1883.4
409025	7637.3	15274.6	22911.9
409035	1248.4	2496.9	3745.3
409202	7610.4	15220.9	22831.3
409204	4754.7	9509.5	14264.25
409207	5886	11772.0	1765

414200	8107.5	16215.0	24322.5
414203	9825.8	19651.6	29477.4
426502	2023.8	4047.7	6071.5
426510	9978.3	19956.7	29935.0

3.2. Effect of discharge across the whole basin

The basin-wide impact of changing discharge was assessed by six community indicators under two hydrological conditions - natural and current. This allowed an examination of the impact of regulation and water extraction on the system. To provide a context for the results, the discharge required to restore natural wetland-river connectivity was estimated (Fig. 11). These data suggest up to 4,000 GL yr^{-1} (10,959 ML day^{-1}) would be needed to restore all wetlands in the study area to natural levels of wetland-river connectivity.

Under current conditions, species richness was maximised in only a small proportion of the wetlands studied (Fig. 12A). Out of the 2,746 wetlands, species richness was only maximised in approximately 700 under nominal discharge suggesting sub-optimal conditions reduced species richness in the remaining 2,046 wetlands. Incremental increases in discharge through the system would lead to proportional increases in the area and number of wetlands in which species richness was maximised. An additional 2,100 GL yr^{-1} (5,753 ML day^{-1}) would maximise species richness in the majority of wetlands. Further increases in the discharge would have little benefit.

Under natural conditions, species richness was maximised in almost 2,300 wetlands under nominal discharge (Fig. 12A). Indeed, the only benefit to increasing discharge was in a single reach which increased the number of wetlands by approximately 200. Discharge could be reduced by up to 3,000 GL yr^{-1} (8,219 ML day^{-1}) before any drop in the area or number of wetlands was detected. Moreover, the slope of the drop in wetland area or number with incremental decreases in discharge was lower than for the current system. Overall, this suggests the natural system is more resilient to change in discharge. The reason for the difference between the current and natural systems is unclear and warrants further investigation.

Similar results were obtained for family richness (Fig. 12B) and functional group richness (Fig. 12C). Under current conditions with nominal discharge, family richness was maximised in *ca* 1,100 wetlands and functional group richness was maximised in all 2,746 wetlands. The difference in the three richness indicators (species, family, and functional group) is likely due to the different number of members each of these indicators included. Species richness is measured out of 36, family richness out of 17, and functional group richness out of 5. Species richness will therefore be the most sensitive indicator and the most difficult to maximise, and functional group the least sensitive.

All three evenness indicators (Fig. 12D-E) showed much less difference between natural and current conditions than species richness (especially the Species Diversity Index). Under current conditions with nominal discharge, species equitability was maximised in *ca* 750 wetlands, Simpson's Diversity Index in *ca* 250 wetlands, and sum areal cover maximised in *ca* 80 wetlands.

At nominal discharge, the number of wetlands in which a given indicator was maximised was consistently smaller under current conditions than natural conditions (with the exception of functional group richness). The difference in terms of species richness, for example, was *ca*. 1,400 wetlands (Fig. 11). In order to close this gap, the current system would need an additional 1,200 GL yr^{-1}. To close the gap for the other indicators would require the addition of between 800 GL yr^{-1} (2,304 ML day^{-1}; sum areal cover) and 1,800 GL yr^{-1} (4,932 ML day^{-1}; family richness). To maximise the indicators across the whole basin would require the addition of between 1,800 to 3,600 GL yr^{-1} (4,932 to 9,863 ML day^{-1}; *cf* Fig. 12).

The number of wetlands in which indicators were maximised would reach zero with losses of discharge from the system of between 500 GL yr^{-1} (1,370 ML day^{-1}; sum areal cover) and 3,800 GL yr^{-1} (10,411 ML day^{-1}; functional group richness) below nominal.

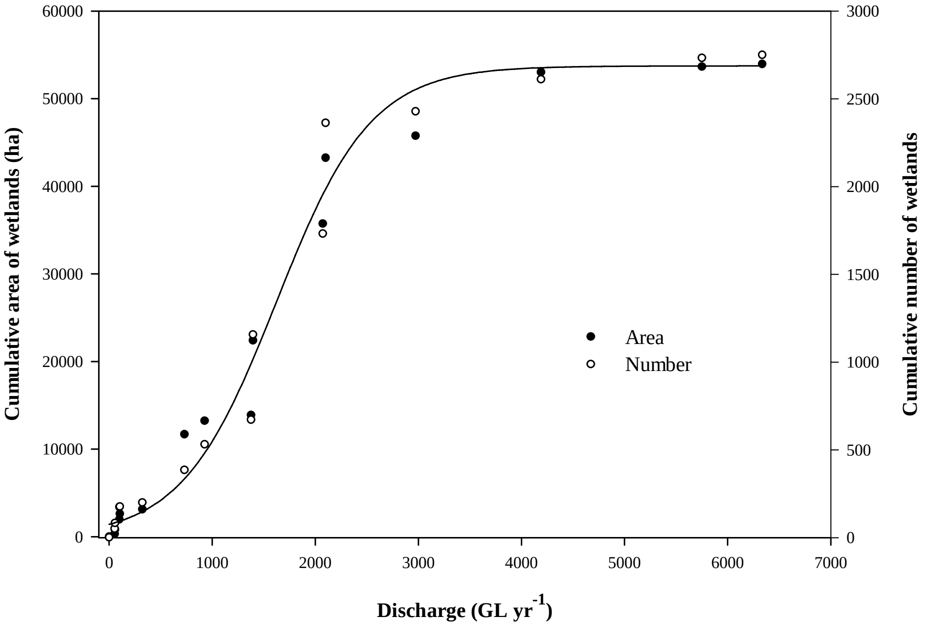

Figure 11: Discharge (GL yr^{-1}) required to restore pre-regulation wetland-river connectivity through reaches of the Murray River.

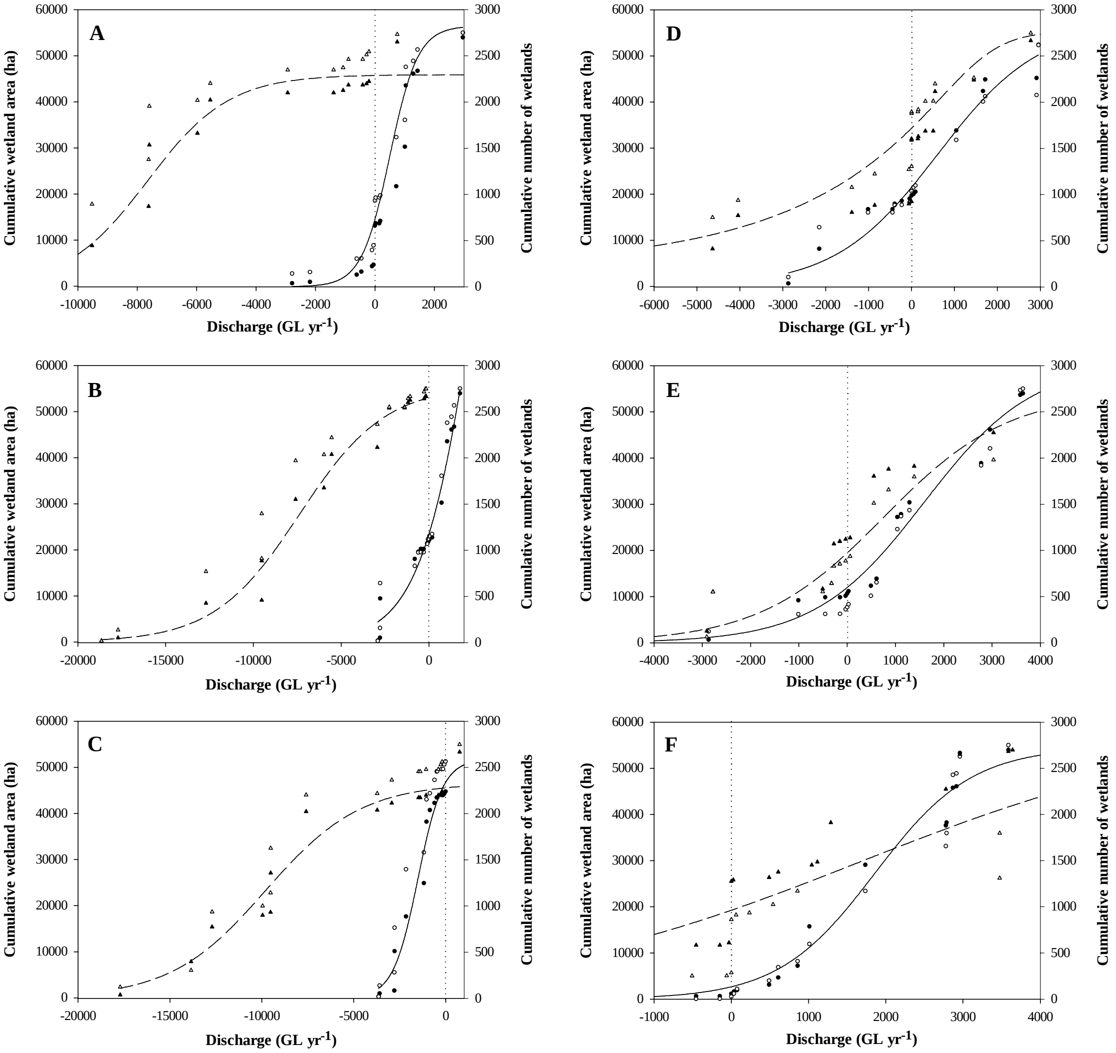

Figure 12: Effect of changing discharge (GL yr^{-1}; zero is nominal discharge) on the cumulative area (ha) and number of wetlands in which the following indicator is maximised: A) species richness, B) family richness, C) functional group richness, D) species equitability (estimated as *D/S* where *D* is Simpson's Diversity Index and *S* the maximum number of observed species in a system), E) species diversity index

(Simpson's Diversity Index)(estimated as $1/\Sigma p_i^2$ where p_i equals the areal proportion of species *i* within the community), and F) sum areal cover. Natural conditions - triangle and dashed regression line; current conditions - circle and solid regression line. Wetland area - closed symbols; wetland number - open symbols. Sigmoidal regressions describe the relationship between discharge and wetland area. Calculations of discharge assume the water return from wetlands equals 100 %. Note the different *x*-axis scales - the dotted vertical line in each figure marks nominal discharge.

3.3. Concordance (correlation) among indicators and reaches

Data from the preceding section can be analysed to test for concordance or correlation among reaches and indicators. To illustrate this we can consider the relationship between discharge and the area/number of wetlands in which species richness is maximised (Fig. 12A). For this indicator, there is a particular ranking of reaches from those that respond (have the indicator maximised) at low discharges to those that respond at high discharges. This is the same as the order in which reaches are plotted from left to right along the *x*-axis. This analysis asks how similar this ranking is to the ranking of another of the community indicators. The data can also be weighted so as to test more specifically for concordance amongst the uppermost rankings (top down concordance) or the bottommost rankings (bottom up concordance). This tests the concordance at low levels of additional discharge (or negative levels, as the case may be) or high levels of additional discharge, respectively.

A significant concordance was found among indicators in the natural system (W=0.32; Table 4) suggesting that a response in one indicator was likely to be associated with a response in the other indicators. The overall concordance was mainly the result of a high correlation (C_B =0.38) at low (or negative) levels of additional discharge. The response of reaches was also significantly correlated (W=0.21) in the natural system. Concordance was significant at both ends of the discharge spectrum but a higher correlation occurred at low levels of additional discharge (C_B=0.58).

No significant concordance among reaches or indicators was found in the current system (P>0.05). To illustrate what this means, consider the ranking of reaches that respond to changing discharge in terms of species richness (Fig. 12A). In the natural system there is significant concordance among the reaches meaning that the ranking or order in which the different reaches respond to changing discharge is similar whether the response is measured by species richness or by some other indicator. In the current system, the order or rank in which the different reaches respond to changing discharge varies among the indicators. Hence, under current conditions a reach might require a small amount of additional discharge to maximise species richness but a large amount to maximise species equitability whereas under natural conditions the reach would require roughly the same amount of additional discharge to maximise both indicators. The lack of concordance among reaches suggests that regulation and water extraction has segmented the river community, creating a number of discrete community units that respond discordantly (i.e. in different indicators) to changes in discharge.

The reciprocal, that of concordance among indicators, can be similarly interpreted. Where there is concordance among the indicators, as there is in the natural system, it suggests the ranking in which the various indicators are maximised with changing discharge is similar among the different reaches; that is, with incremental increases in discharge a given indicator, for example species richness, is most often maximised first and another indicator, say species equitability, is maximised last. This allows prediction of a hierarchy of community indicators from the indicator which requires the smallest amount of additional water to the indicator that requires the most additional water (Table 6). While there is a predictable order in the ranking of indicators in the natural system, there is no similar concordance for the current system suggesting the ranking of indicators is reach-specific.

Table 5: Concordance among indicators and reaches (based on Kendall's χ^2 test) under current and natural conditions. Top down and bottom up concordance was tested on data after substitution of rank for Savage score.

		Concordance	
	overall	top down	bottom up
Among indicators			
natural	**W=0.3248***	C_T=0.2688	**C_B=0.3780****
current	W=0.2721	C_T=0.2599	C_B=0.2544
Among reaches			
natural	**W=0.2064***	**C_T=0.1763****	**C_B=0.5813*****
current	W=0.0923	C_T=0.1537	C_B=0.0056

Significance: $P \le 0.05$ *, $P \le 0.01$ **, $P \le 0.001$ ***.

Table 6: Ordinal ranking, weighted ranking and expected (ideal) ranking of reaches and indicators in the natural system in response to changing discharge. Expected weighting assumes perfect correlation and is calculated as the rank multiplied by six (the number of indicators) or 16 (the number of reaches). The ranking of reaches and indicators in the current system were discordant and so are not listed.

	Reach			**Community indicator**		
Rank	**Ordinal ranking**	**Weighted ranking**	**Expected ranking**	**Ordinal ranking**	**Weighted ranking**	**Expected ranking**
1	409013	17	6	Functional group richness	20	16
2	409207	34	12	Family richness	22	32
3	409202	35	18	Species richness	30	48
4	414203	38	24	Species equitability	45	64
5	409025	40	30	Diversity Index	46	80
6	409204	40	36	Sum areal cover	52	96
7	414200	46	42			
8	409035	50	48			

9	409023	53	54
10	409024	59	60
11	426502	61	66
12	409020	63	72
13	409019	65	78
14	426510	66	84
15	409003	74	90
16	409014	75	96

3.4. Summary

Under current conditions, wetlands of the Murray River system are characterised by low species richness, low species evenness (measured as either Equitability or Species Diversity Index), and low areal cover but high functional group richness. Wetland community richness shows comparatively low resilience to changing discharge. Reciprocally, the system would benefit from any additional disbursement of water. The various indicators suggest the Murray River would benefit from at most an additional 1,800 to 3,600 GL yr^{-1} (4,932 to 9,863 ML day^{-1}; *cf* Fig. 11).

Regulation has more strongly affected richness indicators (species, family, and functional group) than evenness (equitability, Simpson's Diversity Index) or area indicators (sum areal cover). To compensate for the effect of extraction and regulation on community indicators would require the addition of between 800 GL yr^{-1} and 1,800 GL yr^{-1} (2,304 to 4,932 ML day^{-1}; *cf*. Fig. 11).

Overall concordance was only found to occur in the natural system suggesting that water extraction and, more especially, regulation, has segmented the river system into a number of discreet systems (reaches) which respond discordantly to changes in discharge (Table 5).

4. Wetland elimination study

4.1. Methods

A study was undertaken into the importance of individual wetlands in supporting reach-level community richness. Richness indicators were estimated for the whole reach with each wetland commence to fill removed in turn (see Table 7 for an example). Any drop in reach-level richness indicated a wetland which supports a suite of species (or families or functional groups) unique to the reach, and as such deserves priority preservation. On the other hand, wetland commence to fill which, when excluded, had no obvious impact on reach-level indicators were to some degree redundant.

Table 7: Example of the procedure for the elimination study. The total number of species found within this hypothetical reach is four (*Azolla filiculoides*, *Bolboschoenus caldwellii*, *Bolboschoenus medianus*, and *Brachyscome basaltica*). When the first wetland commence to fill value is excluded (0 ML day^{-1}), richness drops to 3 (*Azolla* is missing). On the other hand, excluding any other single commence to fill does not affect the reach-level richness.

		Area of distribution (ha)			
Commence to fill (ML day^{-1})	Wetland-river connectivity	*Azolla filiculoides*	*Bolboschoenus caldwellii*	*Bolboschoenus medianus*	*Brachyscome basaltica*
0	1.00	7.1	0	7.1	0
6,000	0.84	0	5.3	5.3	0
10,400	0.51	0	58.3	58.3	0
15,770	0.28	0	4.2	4.2	4.2
23,000	0.13	0	129.9	0	129.9

4.2. List of wetlands making a unique contribution to reach-level diversity

Wetlands which support a unique flora had commence to fill values of 8,000 ML day^{-1} (2,920 GL yr^{-1}) or less (Table 8). Under current conditions, only 15 wetland commence to fill values, spread among 11 reaches, were found to make a unique contribution to the reach-level community. In contrast, only nine wetlands were found to be unique under natural conditions suggesting a greater degree of overlap or redundancy of wetland type in the natural condition than in the current condition. Seven wetland commence to fill values were common to both natural and current conditions.

There was general agreement among the richness indicators: species, family, and functional group. Species richness quantifies the presence of 36 species and as such is the most sensitive to changes in the reach. Next is the family richness, which includes only 17 groups and functional group was the least sensitive indicators with only five groups. Thus, the loss of a single functional group was likely to be accompanied by a loss of 3-4 families and 6-7 species. Correlation coefficients among the three indicators were greater than 0.9 suggesting the three indicators were responding in a similar fashion (autocorrelation).

Table 8: Details of wetlands which contribute a unique suite of species to reach-level richness (species, family, and functional group).

Reach	**Number of wetlands**	**CTF (ML day^{-1})**	**Species richness**		**Family richness**		**Functional group richness**	
			current	natural	current	natural	current	natural
409003	64	0	15	15	8	9	2	2
409003	4	6000		2				
409013	1	8000	4	8	1	1		1
409014	1	1100	8					
409019	20	0	12		8		1	
409019	1	50	11		2			

Reach	**Number of wetlands**	**CTF (ML day^{-1})**	**Species richness**		**Family richness**		**Functional group richness**	
			current	natural	current	natural	current	natural
409020	6	0		8		1		1
409020	1	152	4		1			
409024	1	275	1					
409204	8	0	14	1	8	1	1	
409204	11	6000	1					
409207	20	0	2	11	7			1
409207	45	6000	8	14	1		1	1
414200	1	0	15	1	8	1	2	
414203	2	5000	12		7		1	
414203	3	8000	2		1			
426501	1	6000	12	3	6	3	2	2

4.3. Hydrological explanation

The hydrological basis for this can be explained on the basis of the relationship between commence to fill and wetland connectivity. Commonly, the relationship between commence to fill and connectivity is non-linear but can be approximately described by a transformed regression (*x*-axis log.-transformed)(Fig. 13). For demonstration purposes, let us consider two connectivity categories: 0.1-0.2 and 0.6-0.7. Hypothetically, each of these categories support one or more species not found at any other connectivity. To maximise reach-level species diversity it is therefore desirable to have a wetland within each of these two connectivity categories. If we first consider the low connectivity category (0.1-0.2), a wetland must have a commence to fill value between 3,937 and 8,208 ML day^{-1} (1,437 and 2,996 GL yr^{-1}) - a wide range. On the other hand, for a wetland to have a connectivity of between 0.6-0.7 it must have a commence to fill value of between 657 and 935 ML day^{-1} (239 and 341 GL yr^{-1}) - a much narrower range, and therefore less likely.

The spread of commence to fill values is shown in Figure 14 where, despite the even spacing of wetlands across the commence to fill gradient, obvious redundancy occurs at low connectivity categories while a number of higher categories are missed. Within the category of 0-0.1 there are six wetlands groups whereas there is only a single wetland with a connectivity above 0.5. Within this particular reach, this wetland would be of particular importance in supporting a unique suite of species; loss of the wetland will have a significant impact on the reach-level species richness.

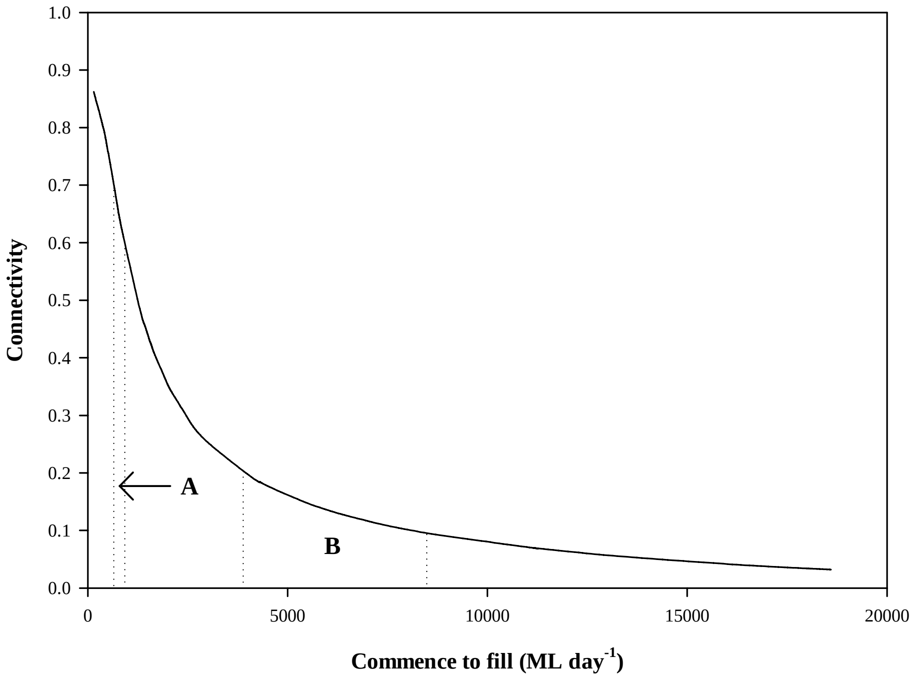

Figure 13: A hypothetical relationship between wetland commence to fill (ML day^{-1}) and connectivity. A) for a wetland to fall within the 0.6-0.7 connectivity category it must be within a very narrow commence to fill range of *ca.* 278 ML day^{-1}. B) for a wetland to fall within the 0.1-0.2 connectivity category it must fall within a wide commence to fill range of *ca.* 4,271 ML day^{-1}.

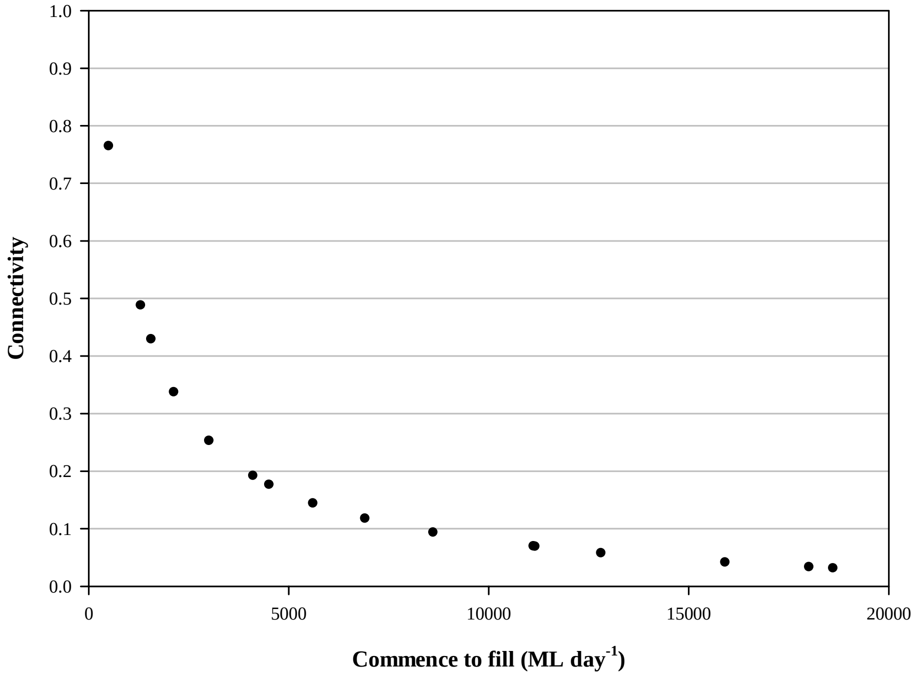

Figure 14: A hypothetical relationship between wetland commence to fill and connectivity demonstrating the differential spread of wetlands to categories of connectivity. There is a high degree of redundancy of wetlands in low connectivity categories but low redundancy in high connectivity categories.

4.4. Summary

Only a small number of wetlands (190 out of 2,750) make a unique contribution to reach-level richness, but these wetlands contribute as many as 15 unique species to reach-level richness. The wetlands are spread among different reaches and have commence to fill values of no more than 8,000 ML day^{-1} (2,920 GL yr^{-1}). Despite having low commence to fill values, the connectivity of these wetlands ranges from 0.37 to 1.0 indicating that some management of the wetlands may be possible (necessary) to preserve reach-level community richness.

5. Concluding remarks

Regulation and water extraction has had a significant and multifarious impact on the wetlands of the River Murray. Firstly, five out of six community indicators showed a negative effect by regulation and/or water extraction at nominal discharge, affecting the community in *ca*. 400 to 1,750 out of the 2,746 wetlands studied (Fig. 12). Secondly, the way in which the indicators respond to changes in water allocation has been altered as a result of regulation, with five of the six indicators showing decreased resilience to dropping discharge (Fig. 12). Thirdly, regulation has segmented the river into a number of discreet community units (reaches) which have discordant community responses to incremental changes in water allocation (Table 5), departing from the predictable response heirarchy (Table 6), a heirarchy that might have otherwise guided restoration and management.

To be effective, restoration or management of the Murray River system must occur at the scale of the reach. This conclusion is based on three observations. Firstly, due to the exclusive distribution of some species along the wetland-river connectivity gradient, no single wetland (or commence to fill group) can support all of the modeled species. Secondly, remarkably few individual wetlands (190 out of 2,746) support a unique suite of species (Table 8). It is in the range of wetlands, spread through the landscape, that maximum community richness is attained. Thirdly, that flow regulation has affected the manner in which the wetland community responds to incremental increases in discharge. In the unregulated river system, there was a predictably ordered response by the indicators to increasing discharge within a reach: first functional group richness was maximised, then family richness, species richness, equitability, diversity index, and finally sum areal cover (Table 6). By adding enough water to a reach to maximise sum areal cover, it was likely the other indicators were also maximised, and the whole river basin could be managed with reference to a single community indicator. Regulation has abolished this concordance (Table 5) such that different indicators are ultimately more important in different reaches. Management must therefore be reach-specific.

A system-wide restoration of community indicators to pre-regulation levels would require an additional 800 to 1,800 GL yr^{-1} (2,192 to 4932 ML day^{-1}; Table 9). The addition of any discharge less than this would have a proportional but reach-level benefit to the system that could potentially be measured in all community indicators except functional group richness. A more ambitious goal would be to maximise community indicators across the whole basin, a goal that would require the addition of between 1,800 and 3,600 GL yr^{-1} (4,932 and 9,863 ML day^{-1}; Table 9). These data can be placed in the context of the need for an additional 4,000 GL yr^{-1} to restore pre-regulation levels of wetland-river connectivity (Fig. 12A).

Further losses in community indicators are possible. For indicators to reach zero in *all* reaches would only require a drop in discharge of between 500 and 3,800 GL yr^{-1} (1,370 to 10,411 ML day^{-1}; Fig. 10) below nominal. At this point it is likely that groups, starting with species, then families and finally functional groups, will be permanently lost from the River Murray system.

Table 9: Summary of the additional discharge (GL yr^{-1}) required to i) restore wetland community indicators to pre-regulation levels, and ii) maximise community indicators across the whole basin, under current conditions.

	Discharge (GL yr^{-1})	
Community indicator	Pre-regulation	Maximise across basin
Species richness	1,200	2,100
Family richness	1,800	1,800
Functional group richness	0	0
Species equitability	1,200	3,000
Species diversity index	800	3,500
Sum areal cover	1,600	3,600

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