Macrophyte Index for the Vasse-Wonnerup Wetlands

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August 2023

Final Report

Prepared for the Department of Water and Environmental Regulation

Government of Western Australia
Department of Water and Environmental Regulation

Revitalising Geographe Waterways
VASSE taskFORCE

Contents

Acknowledgements

This work was undertaken for the Department of Water and Environmental Regulation, as part of the Healthy Estuaries WA and Revitalising Geographe Waterways programs. The authors thank Department staff and members of the Science Advisory Group for their support and input, in particular Drs Kath Lynch, Linda Kalnejais and Sorcha Cronin-O'Reilly.

We acknowledge the Wadandi People as the traditional custodians of the Vasse-Wonnerup Wetlands and surrounding Country.

Summary

The Vasse-Wonnerup Wetland system is an internationally significant RAMSAR wetland and as such is the subject of focused management and monitoring. As part of this effort, aquatic plant communities have been monitored in this system since 2006. Aquatic plant communities are an excellent indicator of ecological health due to their significance in ecosystem processes and response to environmental conditions and anthropogenic impacts.

To facilitate communication of management outcomes, this report presents a **Macrophyte Index** which enables assessment of the four ecological regions of the Vasse-Wonnerup according to the condition and aquatic macrophyte communities and the extent of macroalgal growth. The Index is based on the condition of these communities during spring, when maximum biomass and diversity is present in the system, and is calculated using two metrics:

1. **Key species metric** - total density of key macrophyte species, specific to each region.
2. **Macrophyte dominance metric** - Proportion of macrophytes (including charophytes) as percentage of total PVI (macrophytes plus macroalgae).

The current 'percent volume inhabited' (PVI) monitoring methodology, combined with these indices, provides a simplified approach to communication of the current ecological status of aquatic plant communities in the system. This can be applied to the whole system or each ecological region to support different reporting requirements.

Testing of recent data against the index condition categories is considered representative of observed condition in the estuaries. Outcomes of testing across seventeen years of monitoring from 2006-2022 provides the following general assessment:

- Variation in results for all regions is high but no consistent decline in macrophyte community health is evident.
- Increased, consistent macroalgal growth has occurred in the upper Vasse in recent years, with some decline in macrophyte community health but with resilience of key macrophyte species.
- Generally poorer conditions occur in the lower Vasse, but with apparent recent improvement in macrophyte growth despite ongoing macroalgae co-dominance.
- Reduced macroalgal growth throughout the Wonnerup Estuary over the last ten years with good growth of key macrophyte species (especially charophytes) in most years.

Macrophyte Index condition categories and descriptions for the Vasse-Wonnerup Wetland system:

Condition Category		Score range	Description
A	Excellent	85-100	Healthy macrophyte community with key species dominant
B	Good	69-85	Healthy macrophyte community with some macroalgae present
C	Moderate	44-69	Macrophyte community density reduced or with macroalgae common
D	Poor	22-44	Low macrophyte density or risk of macroalgae dominance
E	Very poor	<22	Low extent of key species and macroalgae dominant

Introduction

The Vasse-Wonnerup Wetlands are a shallow estuarine system approximately 200km south of Perth in Western Australia. The wetlands have a highly developed, mainly agricultural, catchment and the hydrology has been modified by installation of surge barriers which are actively managed to control sea water exchange. The wetlands support tens of thousands of resident and migrant waterbirds of a wide variety of species and the largest regular breeding colony of Black Swan in south-western Australia, and as such are listed as under the Ramsar Convention as having international significance (Lane et al. 2007).

Aquatic plant communities in the Vasse-Wonnerup Wetland System include macrophytes (angiosperms), charophytes (specialised algae with a plant-like form) and macroalgae (multicellular algae). These plants are a critical element of the ecosystem, reflecting and influencing water quality and supporting aquatic invertebrates, fish, and birds. Herbivorous and omnivorous waterbirds such as swans and ducks consume aquatic flora directly; and by supporting higher diversity and abundance of aquatic invertebrates (Heck and Crowder 1991, Paice et al. 2016), which provide additional food resources. Aquatic plant species and extent in the wetlands have been monitored since 2006 through two separate programs: seasonal monitoring from 2017 to 2021 through the Integrated Ecological Monitoring (IEM) Program, and long-term spring monitoring from 2006 to 2021. For assessment purposes, the system is divided into four ecological regions: the upper and lower Vasse Estuary, and the upper and lower Wonnerup Estuary. The two programs provide a comprehensive data set for understanding aquatic plant communities.

The Integrated Ecological Monitoring Program (IEM), coordinated by the Department of Water and Environmental Regulation (DWER) aimed to better understand the relationships between water regime, macrophytes and the abundance of benthic macroinvertebrates, fish and birds utilising the range of habitats (regions) present in the Vasse-Wonnerup[1]. It was initiated in part to assess changes in ecological condition of the system that may be related to more active management of the Vasse Surge Barrier. This infrastructure enables managers to influence seawater exchange, which has potential to mitigate very poor water quality in the Vasse Estuary channel. Changes to the seawater inflow regime may also have ecological consequences for the broader estuary, and so it is critical to monitor for any associated changes. This active management of seawater exchange and the IEM program commenced in 2017.

The long-term monitoring program, initiated by Murdoch University, has helped to define the status of each ecological region in terms of characteristic macrophyte communities and relative dominance by macrophyte and macroalgae (Chambers et al, 2017). The IEM program has improved understanding of seasonal growth of macrophytes (including charophytes) and macroalgae and the relationship with seasonal water regime (water quality and water levels) (Paice and Chambers 2022). Results from the two monitoring programs have also enhanced understanding of environmental variables related to growth of particular aquatic plant species.

Spatial and temporal variation in aquatic plant communities reflect complex interacting processes and represent habitat and resource availability for aquatic fauna. Due to this foundation role in the system, macrophytes are a good candidate as an indicator of ecological health. The use of macrophytes to characterise ecological condition of lakes is common at a global scale, using metrics such as presence

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[1] https://rgw.dwer.wa.gov.au/applying-science/vasse-wonnerup-science/

of species sensitive to eutrophication, cover or percent volume inhabited (PVI) of macrophytes and charophytes or particular species, taxonomic diversity and trophic ranking (Brucet et al. 2013). However, much of this work is focused on freshwater systems and excludes consideration of macroalgae.

In coastal lagoons such as the Vasse-Wonnerup wetlands, transition to a phytoplankton-dominated regime often occurs via a pathway of macroalgal blooms (Viaroli et al. 2008, Pasqualini et al. 2017) and it is therefore critical to monitor growth of macroalgae. Nitrophilous seasonal macroalgae such as *Ulva* spp. restrict macrophyte growth by limiting light to regenerating macrophyte communities. Anoxic sediments from decomposition of macroalgae also limit macrophytes though the production of toxic sulphides and increased phosphorus release from sediment, competitively favouring algal growth (de Wit et al. 2001, Viaroli et al. 2008).

The presence of stable, submerged macrophyte communities is indicative of a healthy ecosystem, while the transition to macroalgal dominance reflects an undesirable shift in ecological state. This report presents development of an ecological index, the Macrophyte Index, based on the status of aquatic plant communities, to assist in tracking the health of the system and to simplify reporting for management and stakeholder communication.

Methodology

The methodology for index development was adapted from the approach outlined by Hering et al. (2006) and is summarised as follows:

1. Establish baseline condition.
2. Selection of appropriate metrics and calculation of metric values.
3. Calculation of metric scores to a unitless measure of condition out of 100.
4. Index calculation to combine metric scores.
5. Setting of category boundaries.

Seasonal growth of macrophytes commences with the onset of winter rains, rapidly reaching peak density in spring, followed by recession in summer as water levels drop. Established plant communities in spring provide the most informative data for understanding plant communities and identifying change over time. The maintenance of existing macrophyte communities is desirable and the extent of macrophytes in spring was therefore developed into a ***key species metric***. Macroalgal growth occurs in the system throughout most of the year when water is present. The extent of macroalgal growth in spring is an indicator of stress on macrophyte communities, as it reflects nutrient enrichment in the system, its presence has a negative impact on macrophyte growth and may indicate an undesirable shift from a macrophyte-dominated community to a macroalgae-dominated community. The relative proportion of macrophytes was therefore developed into a ***macrophyte dominance metric***. Scores for these two metrics were combined to provide the ***macrophyte index***, measured in spring.

The following sections provide further detail on the calculation of these metrics and indices, and the development of categories for testing and reporting.

1.1 Sampling methodology

Data used for development of the macrophyte indices was obtained through the two programs previously noted:

i. Long-term monitoring during spring annually from 2006 to 2021 by Murdoch University; and
ii. Seasonal monitoring of plant volume inhabited from 2017-2022 IEM Program coordinated by DWER.

There are 28 sampling sites established in the system for monitoring of aquatic plants (Figure 1). All sites were included for the long-term monitoring program, while a subset of 16 sites were included in the IEM Program.

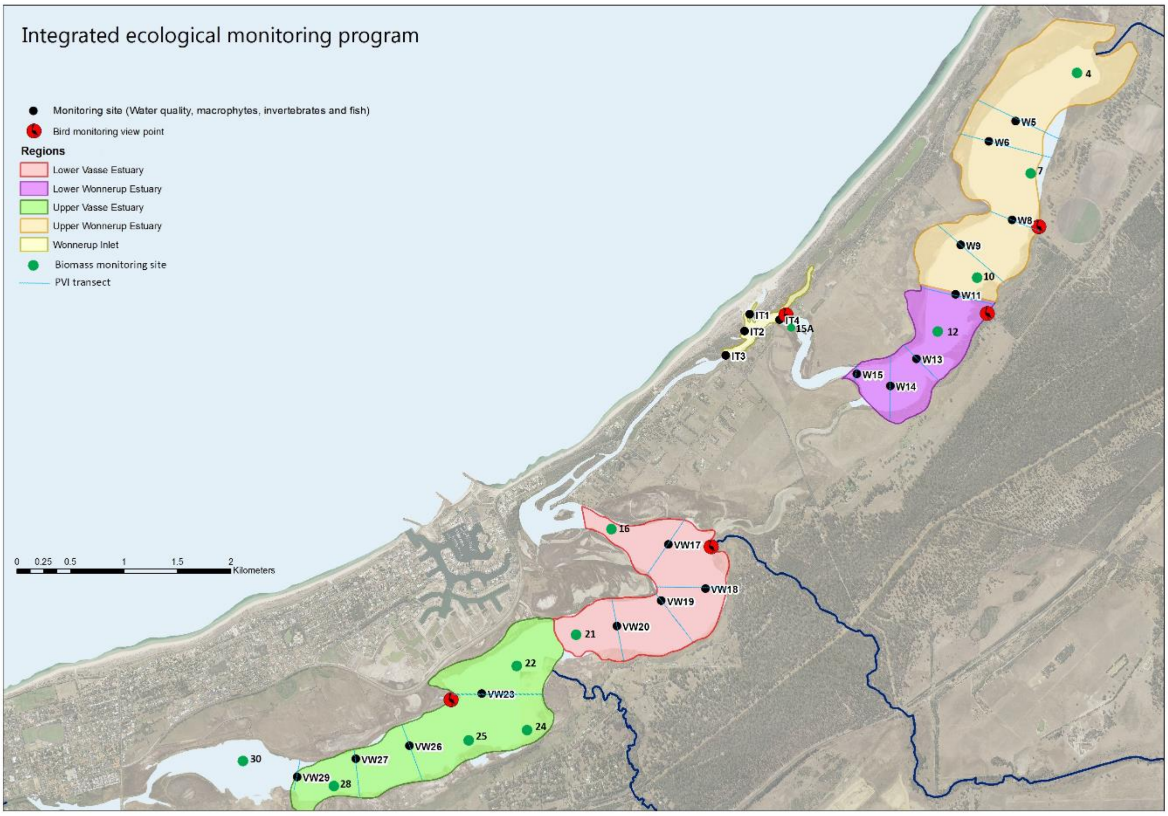

Figure 1. Sample site locations in the Vasse and Wonnerup Estuaries and the Wonnerup Inlet, showing a priori designated ecological regions. Black points are IEM sites, while long term monitoring included all sites.

1.1.1 Integrated Ecological Monitoring Program

Aquatic plants were sampled at 16 sites in the Vasse-Wonnerup System, four in each of five 'ecological regions' (Figure 1). These ecological regions were defined a priori for congruent sampling of multiple ecological indicators: aquatic plants, fish, macroinvertebrates, birds and water quality. These were:

1. Lower Vasse Estuary
2. Upper Vasse Estuary
3. Lower Wonnerup Estuary
4. Upper Wonnerup Estuary

To capture the seasonal changes in plant communities and density throughout the system, sampling was undertaken seasonally from March 2017 to March 2021, with additional monthly sampling from October to January in 2019-2020 and 2020-2021 (Table 1). The main growing season for aquatic plants is winter and spring with subsequent senescence in summer and autumn as water levels decline. Data is presented in this report to align with this growing season. March 2017 represents the end of the previous growing season, which was not sampled, and included some different sites, and is excluded from this analysis.

Table 1. Aquatic plant sampling dates during the IEM program.

Year	Winter	Spring	Summer	Autumn
2017-2018	24-25 Jul 2917	18-20 Oct 2017	17-18 Jan 2018	19-21 Mar 2018
2018-2019	30-31 Jul 2018	30 Oct – 1 Nov 2018	17 Jan 2019	20-21 Mar 2019
2019-2020	25-26 Jul 2019	29-31 Oct 2019	20-21 Dec 2019	26 Mar 2020
		26-28 Nov 2019	20-22 Jan 2020	
2020-2021		15-16 Oct 2020	21-22 Dec 2020	16-29 Mar 2021
		27 Nov – 1 Dec 2020	28 Jan 2021	

For seasonal sampling, plant density was assessed as ‘percent volume inhabited’ (PVI)[2]. This is a measure of plant density in terms of the proportion of a body of water taken up by plant material. In addition, biomass sampling was undertaken concurrently during spring from 2017-2021 to provide continuity of data with historic monitoring since 2006.

PVI was determined at five points along a transect from bank to bank across the estuary at four sites in each ecological region (Figure 1). These five transect points were located approximately equidistant along the each transect, with one of these points being the specific site location used for biomass sampling.

Each transect point consisted of a circular area 5m in diameter, determined using a stake with a 2.5m length of rope held to limit the area observed. At each transect point, PVI was determined using visual estimation of plant cover, combined with measurement of water depth and plant height. Due to the shallow nature of the Vasse-Wonnerup Wetlands, PVI was able to be determined for individual species, providing a clear indication of the extent and diversity of plant habitat relative to open water. This is valuable in an ecological sense as it describes how much of the body of water in the wetland is filled with plant material, both in total and for each species.

A bathyscope was used to observe plants and percentage cover was determined as total cover (up to 100%) and independently for each species (Figure 2a). Due to the growth of different species as layers, total of species’ cover may be greater than 100%. Cover was estimated as 1%, 5%, 10% increments to 90%, or 95%. Height for each species was measured directly by viewing a marked pole through the bathyscope (Figure 2b). The most common plant height for each species was measured to the nearest 5cm for most macrophytes and charophytes, and at 1cm intervals for very small plants and filamentous algae.

The following measurements were recorded for subsequent calculation of PVI for each species:

- D = water depth (m)
- C_{total} = total cover (%)
- $PC_{species}$ = proportion of total cover for each species (%)
- $H_{species}$ = height of each species (m)

For each species, cover $C_{species}$ was determined by $PC_{species}/100 \times C_{total}$. PVI was then calculated as:

$$PVI = \frac{C_{species} \times H}{D}$$

(Canfield *et al.*, 1984).

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[2] Also referred to in studies as ‘percent volume infested’, ’plant volume inhabited’, ‘plant volume index’.

The shallow nature of the system enabled accurate cover estimates from observations from above the water or using a bathyscope at most sites. Plant height was measured for the most common size plants of each species, using a measuring pole and bathyscope. For deeper and more turbid sites, five one-metre rake samples were pulled at each transect point. Cover for each species estimated based on the amount of rake teeth filled (i.e. all rake teeth filled on all rake pulls = 100%) and plant length measured to provide height. This approach was only required for the deeper transect points at sites 15 and 17.

1.1.2 Long-term Monitoring Program

Biomass samples were taken during spring in each year, with samples processed to determine dry weight per square metre for each species, as described in Chambers et al. (2017). Biomass sampling included additional sites (as sampled historically, Figure 1), with 5 replicate cores collected at a random location in close vicinity of each site. A perspex corer (9 cm diameter x 50 cm length) was pushed into the sediment over the benthic flora and sealed with a rubber stopper, allowing an intact core with plants and sediment to be extracted (Figure 2c). Extracted plant material was sieved to remove excess sediment and the samples bagged for transport to the laboratory, and frozen for later processing. In the laboratory each sample was sorted to separate species, and species samples then dried at 70 °C for 48 hours. Dry weights were determined to 0.0001g and species biomass was converted to grams per m^2 based on the area of the corer.

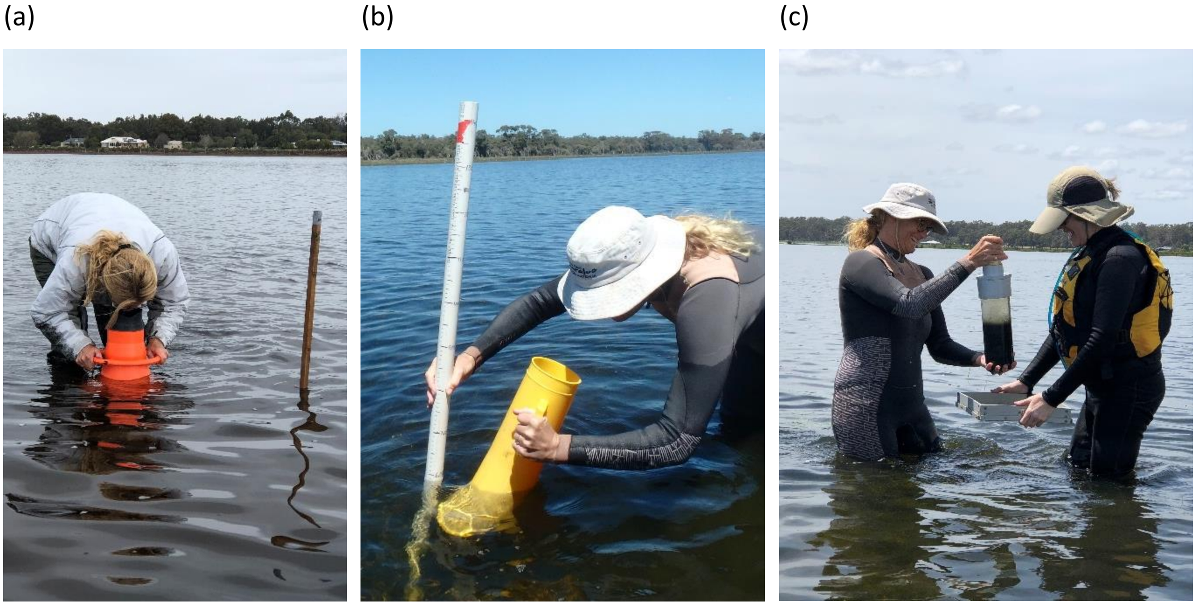

Figure 2. Sampling aquatic plants in the Vasse-Wonnerup Wetlands: (c) Estimating plant cover within a 2.5m radius; (b) Measuring plant height; (c) biomass core sampling.

1.2 Establishing baseline condition

Ecological indices are ideally developed with consideration of appropriate reference conditions, representing a near-natural state prior to anthropogenic impacts or least-disturbed conditions known (Brucet et al. 2013). For the Vasse-Wonnerup it was not practical to establish low disturbance reference conditions due to the long-term situation of altered hydrology and developed catchment. Use of alternative undisturbed wetlands as reference sites was also not appropriate due to the uniqueness of the system.

Long-term monitoring of macrophytes in spring found substantial variation in condition of aquatic plant communities throughout the Vasse-Wonnerup wetlands over time, reflecting a wide range of ecological condition in the system (Chambers et al. 2017). However, while the condition of the estuary varied year to year, there was high site fidelity, with each ecological region characterized by particular macrophyte and charophyte species as follows (Chambers et al. 2017):

- Upper Vasse Estuary: Ruppia polycarpa and Althenia cylindrocarpa dominance.
- Lower Vasse Estuary: *Ulva* dominance with *Ruppia megacarpa* and *Stuckenia pectinata* (since 2014) also present.
- Upper Wonnerup Estuary: *Lamprothamnium* and *Ruppia polycarpa* dominance.
- Lower Wonnerup Estuary: *Ruppia megacarpa* dominance in the very lower Wonnerup; consistent but small amounts of *Althenia*. Macroalgal growth in some years.

The historical extent (2006-2016) of these characteristic plant communities was considered an appropriate spring baseline for each ecological region, with a sufficiently broad sample distribution to allow development of categories reflecting a range of plant community condition. The ecological regions included the sites as shown in Figure 1, with site 11 categorised as part of the upper Wonnerup.

1.3 Selection and calculation of metric values

The management objective for the Vasse-Wonnerup Wetlands in regard to submerged macrophytes is to *maintain diversity and dominance of macrophytes*. This can be further refined into more specific objectives:

- Maintain key species dominance within each region.
- Maintain (or achieve) macrophyte dominance.

Appropriate metrics for these objectives were defined as:

- Total PVI of key macrophyte species, specific to each region, in spring (key species metric).
- Proportion of macrophytes as percentage of total PVI in spring (macrophyte dominance metric).

Due to variation in physical characteristics and key macrophyte species found in each ecological region, metric values were calculated separately. Values for these metrics were calculated according to Table 2.

Table 2. Description of metric values for use in calculating indices.

Region (sites)[1]	**Key species metric:** characteristic species in each region	**Macrophyte dominance metric**: proportion macrophytes of total plant density
Upper Vasse (16-22)	Sum of *Ruppia* spp.[2] and *Althenia cylindrocarpa* PVI	Sum of macrophytes PVI (including charophytes) as percentage of total PVI (macrophytes plus macroalgae) Calculated for each region
Lower Vasse (23-30)	Sum of *Ruppia* spp. and *Stuckenia pectinata*	
Upper Wonnerup (4-11)	Sum of *Ruppia* spp. and *Lamprothamnium macropogon*	
Lower Wonnerup (12-15)	Sum of *Ruppia* spp. PVI	

[1] This includes all historical monitoring sites. Fewer are used for IEM monitoring.

[2] *Ruppia* species can be difficult to distinguish in field assessments and biomass samples and are therefore combined.

1.3.1 Regression analysis for biomass and PVI data

The long-term and IEM monitoring programs used different sampling methods: core sampling for biomass (long-term); and field assessment of plant volume inhabited (PVI, IEM Program). Following five years of concurrent monitoring of biomass and PVI, it has been determined that future monitoring will implement the PVI method only. This is due to the following benefits in comparison to biomass sampling:

- lower cost due to no laboratory processing requirements;
- rapid availability of data, potentially within days of monitoring; and
- more understandable units of measurement.

Both monitoring programs and sampling methods occurred during spring from 2017-2021, therefore there is concurrent data for both methods from this five-year period. To enable the 2006-2016 historical biomass data to be used as a baseline for future assessment using the PVI method, linear regression modelling was used to predict PVI from biomass for this period. This was completed in SPSS with prior transformation of data [$\log_{10}(x+1)$] to improve normality.

1.3.2 Index calculation and boundary setting

Metric values were scaled into a unitless score out of 100 based on the distribution of the baseline data. This process provides for multiple metrics to be combined into a single index (Hering et al. 2006).

Key species metric scores were calculated separately for each ecological region using data for specified key species. Scaling was done using the 95 and 5 percentiles as the upper and lower ranges of ecological condition, respectively, and applying the following formula:

$$\text{Key species metric score} = \frac{\text{PVI key species} - 5^{\text{th}}\text{ percentile}}{95^{\text{th}}\text{ percentile} - 5^{\text{th}}\text{ percentile}} \text{ x } 100$$

(Hering et al. 2006)

Scores less than 0 or greater than 100 were manually bounded to 0 or 100 respectively.

For development of the macrophyte dominance metric, baseline (historical) data was pooled across the entire estuary to represent the full range of ecological condition and because regional macrophyte communities have potential to be impacted by macroalgae similarly. Although data ranges from zero to 100% macrophytes, this does not necessarily reflect a linear continuum of deteriorating condition, and so scaling based on percentiles was appropriate. As 100% macrophytes is the desired condition, this was set as the upper anchor. The 5th percentile was zero and was not appropriate, because poor condition is indicated by a low level of macrophyte dominance rather than complete loss. Therefore the 10th percentile was as the lower anchor for scaling. The following formula was applied to calculate the macrophyte dominance metric score:

$$\text{macrophyte dominance metric score} = \frac{\%\text{ macroalgae} - 90^{\text{th}}\text{ percentile}}{10^{\text{th}}\text{ percentile} - 90^{\text{th}}\text{ percentile}} \text{ x } 100$$

Scores less than 0 or greater than 100 were manually bounded to 0 or 100 respectively.

The average of the two metric scores provided the final index score out of 100, with higher scores representing better macrophyte community health.

To facilitate reporting, condition categories reflecting condition were established based on the distribution of the index scores. Various approaches to setting of category boundaries were tested (arbitrary, equal and unequal quintiles).

1.4 Testing

For the spring macrophyte index, PVI data (measured not modelled) from 2017 to 2022 was used to calculate metric values and metric scores according to the method described above.

The scaling approach to calculating metric scores from region-specific metric values provided one set of categories for the whole system. This allows testing of condition at different levels: ecological region, each estuary or the whole system. The steps for testing are:

1. Calculate metric scores transect point data, according to Table 2;
2. Calculate metric values according to equations in Section 1.3.2, ensuring key species metric scores use region-specific percentile values;
3. Determine the mean of the two metric scores to provide a final index score for each transect point;
4. Calculate mean values of metric and index scores for the region of interest;

5. Assess result against condition categories to determine outcomes as A=excellent, B=good, C=moderate, D=poor and E=very poor. Results should be rounded to whole numbers for assessment and when values are on the border of two categories, the decision should be the lower category.

Results

1.5 Modelled PVI from long-term biomass

Comparison of biomass and PVI results when sampled concurrently has found similar plant species composition in the defined ecological regions, but some differences in proportional contribution to total PVI and biomass (Paice and Chambers 2022). This is not surprising for two main reasons. Firstly, the methods use different spatial extents: with PVI sampling extending across transects the width of the estuary at each of 16 sites; and biomass replicates (5) at a greater number of site points (26) distributed longitudinally in the system. Secondly, plant species vary in water content and growth habit, hence dry weight does not equate to plant density similarly for different taxa. Despite differences in face-value comparison of proportional species composition, biomass and PVI data were significantly correlated for all species (Paice and Chambers 2022).

Regression analysis was performed using spring data from 2017-2021 to generate equations for the conversion of biomass data from 2006-2016 to PVI. This analysis found significant correlation between PVI and biomass for each species and for macroalgae as a group (*Ulva* spp., *Rhizoclonium* spp. and *Cladophora* spp.), and significant values for development of linear models to predict PVI from biomass data (Table 3). Due to intermittent occurrence of filamentous algae (*Rhizoclonium* and *Cladophora*), there was insufficient data for regression analysis.

Table 3. Results of correlation and regression analyses for PVI and biomass data from spring 2017 to 2021 (Dependent variable = PVI). Slope and intercept values were used to calculate PVI from historical biomass data.

Species	**R**	**R^2**	**P**	**Model parameter**	**Value**	**P**
Ruppia spp.	0.606	0.367	<0.001	Intercept	0.674	<0.001
				Slope	0.417	<0.001
Stuckenia. pectinata	0.683	0.467	<0.001	Intercept	0.560	<0.001
				Slope	0.617	<0.001
Althenia cylindrocarpa	0.549	0.301	0.003	Intercept	0.401	0.011
				Slope	0.432	0.003
Total macrophytes	0.647	0.419	<0.001	Intercept	0.859	<0.001
				Slope	0.414	<0.001
Lamprothamnium macropogon	0.751	0.564	<0.001	Intercept	0.230	0.003
				Slope	0.504	<0.001
Total macroalgae	0.576	0.332	<0.001	Intercept	0.260	<0.001
				Slope	0.428	<0.001

Modelled PVI 2006-2016 together with measured PVI 2017-2022 show variable but consistent occurrence of the key indicator species in each region (Figure 4, Figure 5). These results also show the increasing occurrence of *S. pectinata* in the system since 2014 contributing to higher total PVI. In addition, greater growth of macroalgae in the upper Vasse Estuary is notable in more recent years, as highlighted by Paice and Chambers (2022). The relative proportion of macrophyte to macroalgae in the system is highly variable (Figure 5). This is particularly evident in the lower Vasse Estuary from 2006 to 2016 when this region was considered to be in a transient state between macrophyte and macroalgae dominance (Chambers et al. (2017).

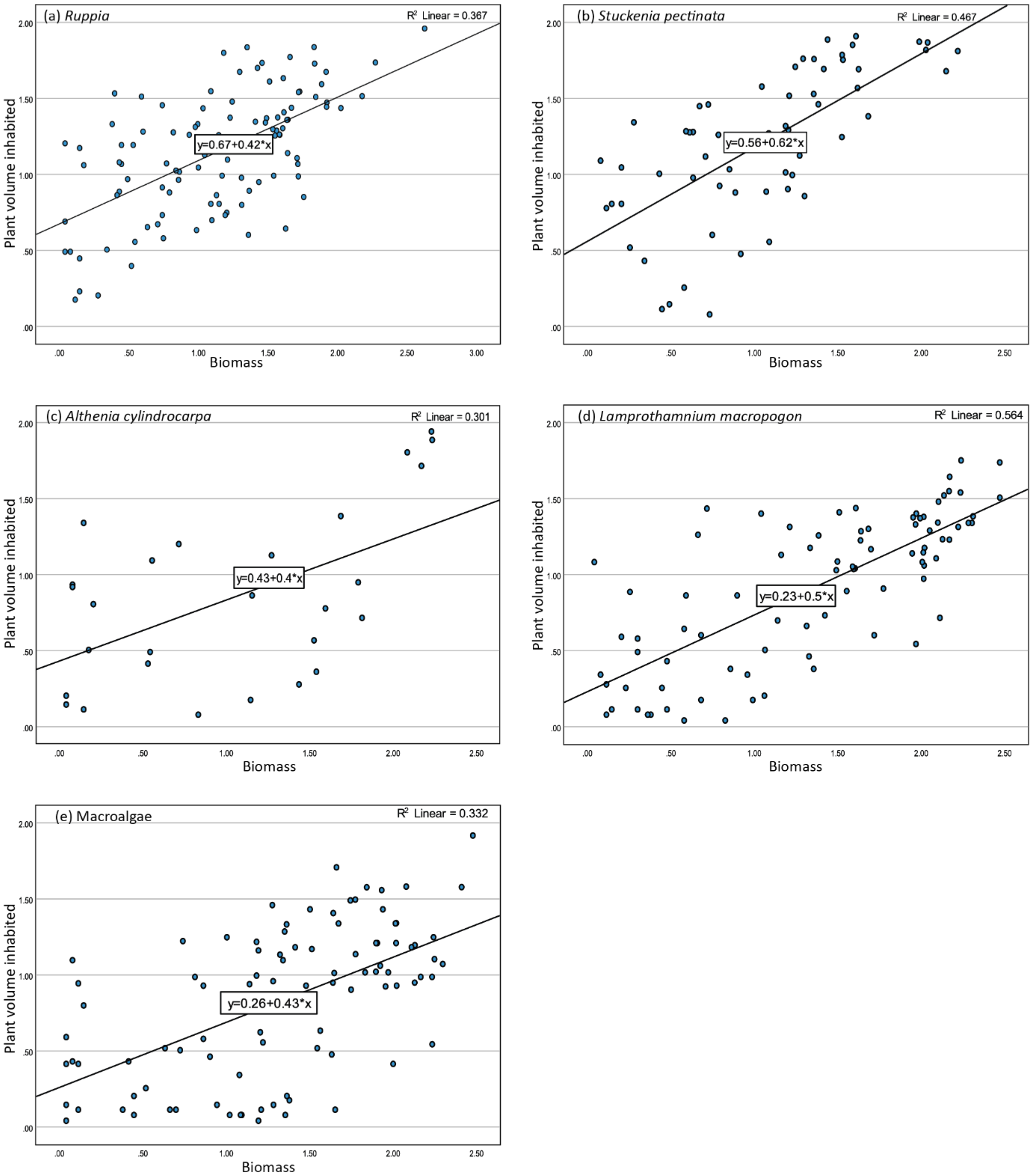

Figure 3. Scatterplots of percent volume inhabited against biomass for major plant species and groups in the Vasse Wonnerup system 2017-2021. Data shown is transformed data (log 10 [x+1]) used for regression analysis. Equations are regression equations subsequently used to convert historical biomass data to PVI to determine metric values.

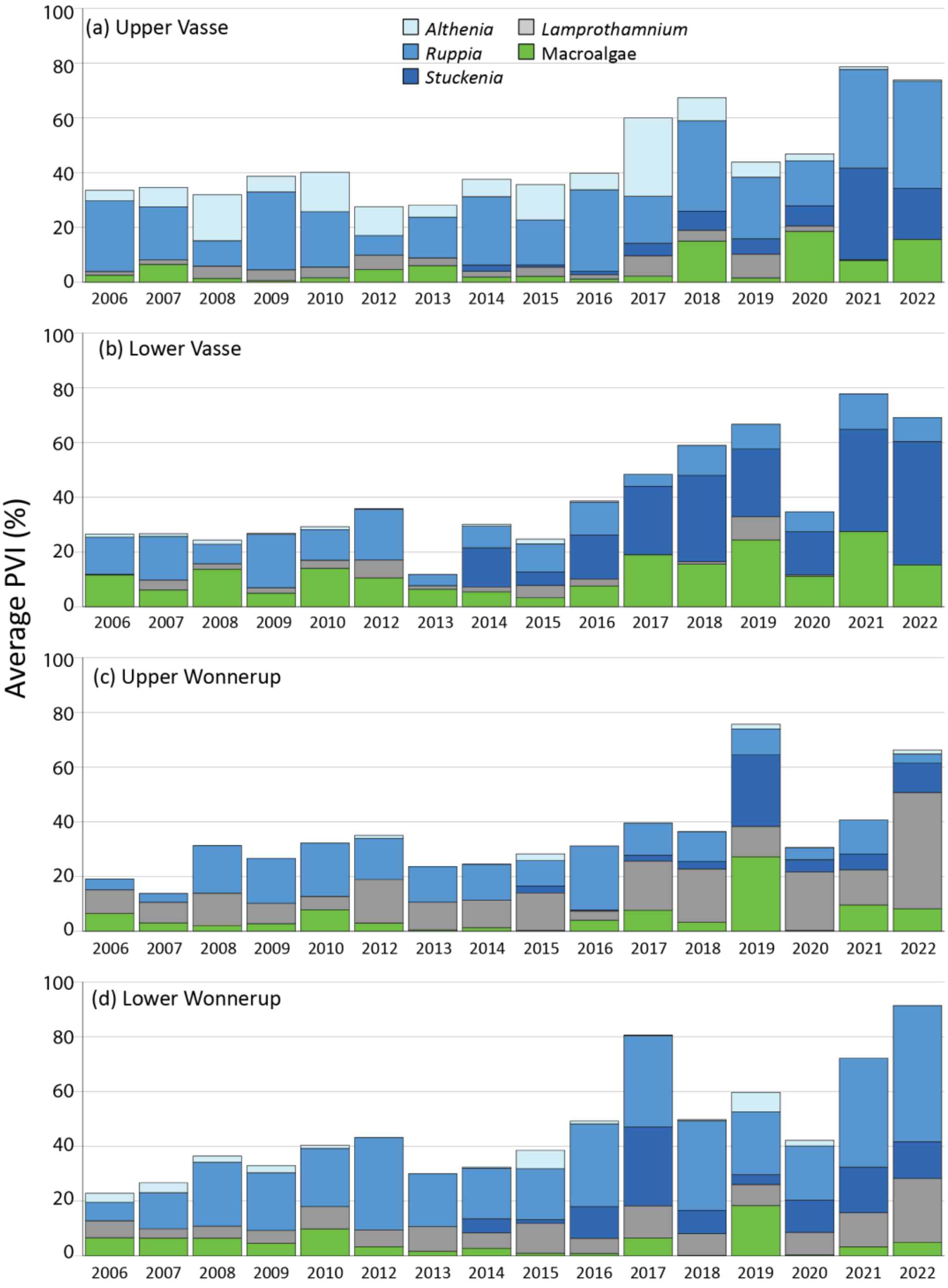

Figure 4. Modelled plant density (percent volume inhabited - PVI) from historical biomass data 2006-2016 and measured PVI from 2017-2022 in ecological regions of the Vasse-Wonnerup Wetland System in spring.

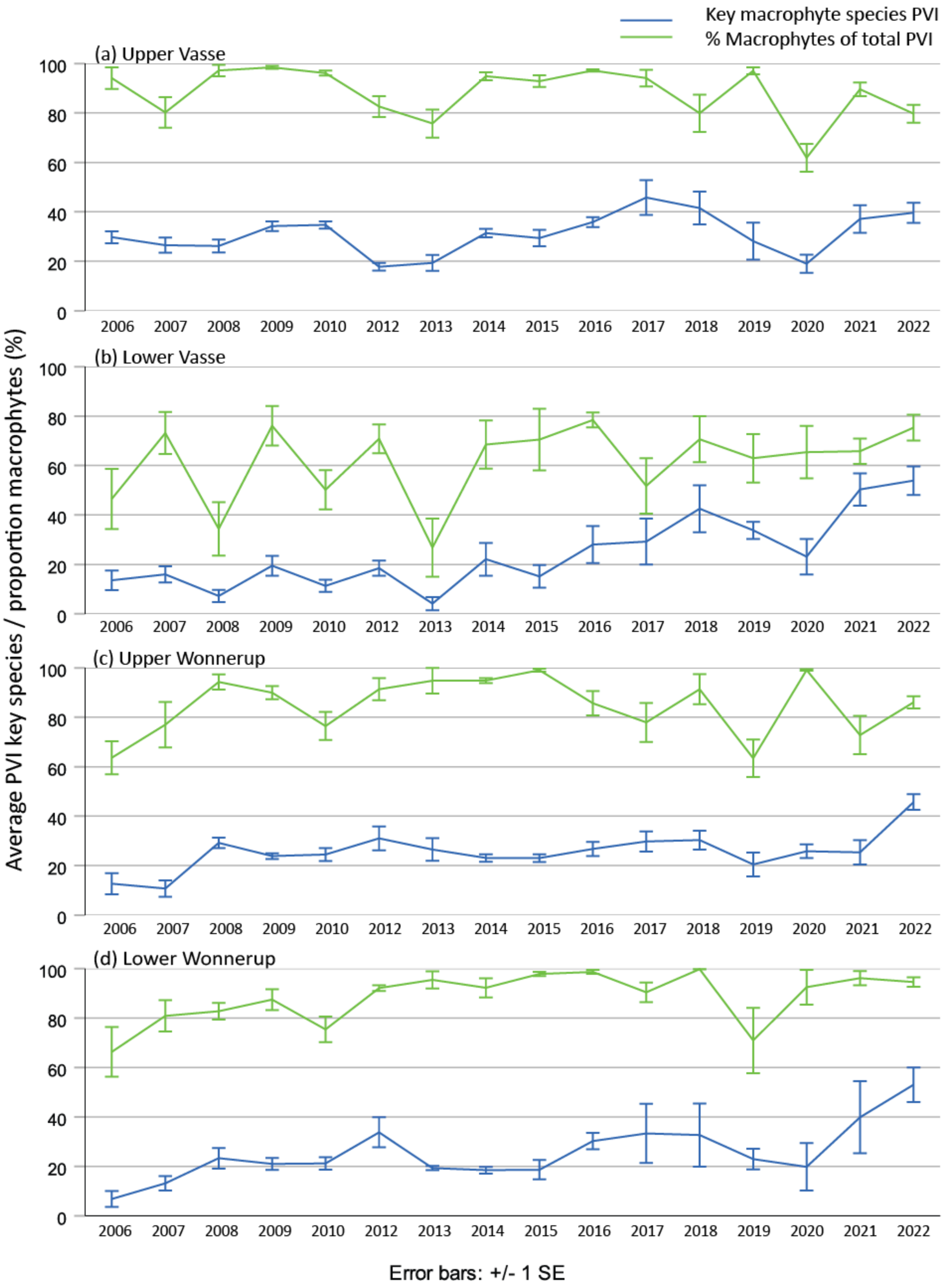

Figure 5. Metric values for the Vasse-Wonnerup Wetland system 2006-2022: key species PVI and macrophytes (including charophytes) as proportion of total PVI. Values are average of transect points in each region are shown ±SE. Values from 2006-2016 were used in metric formulae.

1.6 Index values and categories

For the key species metric, percentile-based upper anchors (95 percentiles) were relatively similar for the ecological regions: upper Vasse 40.2%, lower Vasse 34.9%, upper Wonnerup 39.6%, lower Wonnerup 32.6%. Lower anchors (5 percentiles) were quite different in the Vasse Estuary (upper 12.1%, lower 0.0%) and similar in the Wonnerup (upper 4.5%, lower 5.8%). The approach allowed the use of different key species characteristic of each region to be converted to a unitless metric score on an equivalent scale across the whole system.

For the spring macrophyte dominance metric (proportion of macrophytes relative to macroalgae), the upper anchor representing best condition was 0% macroalgae and the lower anchor representing worst condition, based on the lower Vasse 90 percentile was 64.9%. This lower anchor does reasonably reflect very poor condition as it represents of situation of macroalgae dominance.

The macrophyte index was calculated as the average of the key species and macrophyte dominance scores. Consideration of the distribution of metric and index scores and expert judgement regarding ecological condition found that unequal quintiles of 80, 50, 20 and 10 provided the most reasonable separation of index scores (Figure 6). In addition to the overall spring macrophyte index, this approach can also be applied to the individual metrics to allow more detailed assessment of the plant communities: for example, whether poor condition was due to low extent of key macrophyte species or excessive growth of macroalgae, or both. Based on these unequal quintiles, the A-E category ranges are provided in Table 4.

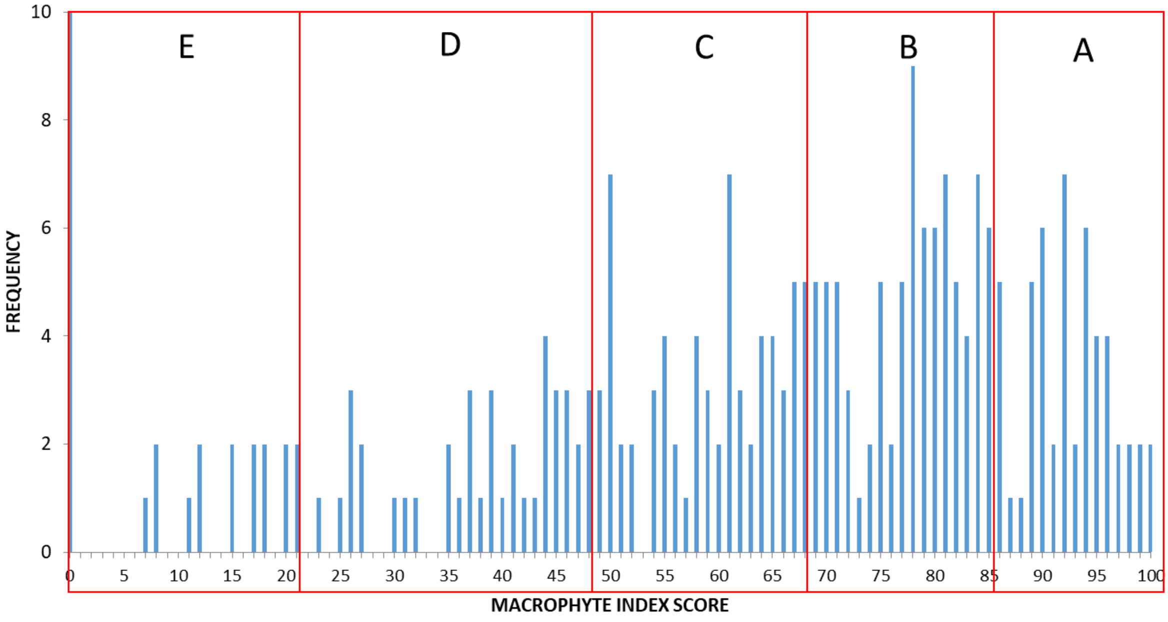

Figure 6. Distribution of spring macrophyte index scores for historical baseline data (2006-2016 modelled PVI) with condition categories equivalent to 80, 50, 20, and 10 percentile values of index scores.

Table 4. Ecological condition categories for the Macrophyte Index and Key Species and Macrophyte Dominance metrics.

Index / Metric	Condition Category		Score range	Description
Spring Macrophyte Index	A	Excellent	85-100	Healthy macrophyte community with key species dominant
	B	Good	69-85	Healthy macrophyte community with some macroalgae present
	C	Moderate	44-69	Macrophyte community density reduced or with macroalgae common
	D	Poor	22-44	Low macrophyte density or risk of macroalgae dominance
	E	Very poor	<22	Low extent of key species and macroalgae dominant
Key Species Metric	A	Excellent	79-100	Key species density very high
	B	Good	55-79	Key species density high
	C	Moderate	19-55	Key species density acceptable
	D	Poor	5-19	Key species density low
	E	Very poor	<5	Key species density very low
Macrophyte Dominance Metric	A	Excellent	98-100	Negligible macroalgae present
	B	Good	87-98	Macroalgae growth low
	C	Moderate	53-87	Macroalgae growth may impact macrophytes
	D	Poor	30-53	Substantial macroalgae, dominant in some parts
	E	Very poor	<30	Macroalgae dominant

1.7 Testing outcomes

Annual testing against the macrophyte index categories for 2017-2022 was possible using measured PVI data that were independent of the data used to develop the categories. Testing for this period was done at two levels: the whole system (Table 5), and the four ecological regions (Table 6 and Figure 7). In addition, historical data was tested to provide a longer term view of the aquatic plant community condition as indicated by the index (Table 7). Although this is a circular approach (testing data that was used to generate categories), the high variability of the system warrants assessment of the full extent of variation in condition rating for consideration by managers. This testing used historical biomass data converted to PVI for the period 2006-2016.

1.7.1 Whole-system assessment 2017-2022

Testing of the whole-system can be a useful reporting tool to provide a high-level overview assessment of the health of aquatic plant communities. In 2021 and 2022, plant communities overall were in good condition (B), indicating healthy macrophyte communities with some macroalgae present. This is an improvement on previous years, when a condition was consistently C. The metrics indicate that high to very high density of key species (A-B) in recent years have contributed to the better overall index result, despite ongoing growth of macroalgae with potential to impact macrophyte communities.

Table 5. Outcomes of macrophyte index testing for the Vasse-Wonnerup Wetlands at the whole system level (using all sites), 2017-2022.

Year	Macrophyte Index	Key Species	Macrophyte Dominance
2022	B	A	C
2021	B	B	C
2020	C	C	C
2019	C	B	C
2019	C	B	C
2017	C	C	C

1.7.2 Assessment of ecological regions 2017-2022

The macrophyte index B rating for the whole system in 2022 reflected consistent B results for all four ecological regions, while in 2021 the B rating for 2021 coincided with B ratings in three regions and C in the upper Wonnerup (Table 6). In 2018 and 2019, the C index rating for the whole system was a result of poorer conditions in the Vasse Estuary, while C or worse (E in lower Vasse) occurred throughout the system in 2017. The Vasse Estuary had consistently lower macrophyte index scores than the Wonnerup Estuary from 2017-2020, but more similar in 2021-22, while in the Wonnerup Estuary both regions have consistently scored high C to B (Figure 7). Metric scores were more variable and provide further insight to the condition of each region, as described below.

Results for the upper Vasse Estuary were variable over the 6-year period (Table 6), ranging from good (B) in 2018, 2021 and 2022 to moderate (C) in 2017 and 2019, and poor (D) in 2020. The metrics indicated moderate to good growth of key species, and a poor to moderate level of macrophyte dominance. Lower macrophyte dominance reflects observed increased growth of macroalgae since 2017 relative to historic data. It is encouraging that the macrophyte community has been in good condition for the past two years despite this occurrence of macroalgae. However, it is also of note that *Althenia cylindrocarpa* (a key species) has been almost absent from this region in 2021 and 2022.

The lower Vasse Estuary macrophyte community had a good condition rating in 2022 and a borderline C-B rating in 2021, indicating a healthier plant community compared to previous years (C-E). Key species of macrophyte in this region have exhibited excellent resilience despite ongoing moderate to high levels of macroalgae and dominance of macroalgae in some years. This reflects long term observations for this region that it is in a transient state between macrophyte and macroalgae dominance, although the last two years may indicate an improvement in this region.

The upper Wonnerup macrophyte community has been in mostly good condition (B with C in 2 years), primarily due to high density of the key species *Lamprothamnium macropogon* occurring extensively in this region. Lower condition (C) in 2017 was due to both lower key species density and higher macroalgal growth (lower macrophyte dominance), but mainly due to macroalgal growth in 2021. Variable levels of stress are apparent due to macroalgal growth. The lower level of macrophyte dominance in 2021 and 2022 is consistent with observed higher density of macroalgae in this region.

The lower Wonnerup region had good macrophyte index results from 2018-2022, due to persistent high density of *Ruppia megacarpa.* A moderate result in 2017 resulted from higher macroalgae growth with potential to impact macrophytes, however macroalgae levels have been consistently good in subsequent years.

Table 6. Spring macrophyte index results 2017-2022 for each ecological region in the Vasse-Wonnerup Wetlands.

Ecological region	**Index / Metric**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Upper Vasse	**Macrophyte Index**	C	B	C	D	B	B
	Key Species	C	B	C	C	B	B
	Macrophyte Dominance	C	C	C	D	C	C
Lower Vasse	**Macrophyte Index**	E	C	C	D	C	B
	Key Species	D	B	B	C	A	A
	Macrophyte Dominance	E	C	D	D	C	C
Upper Wonnerup	**Macrophyte Index**	C	B	B	B	C	B
	Key Species	C	B	B	B	B	A
	Macrophyte Dominance	C	B	A	A	C	C
Lower Wonnerup	**Macrophyte Index**	C	B	B	B	B	B
	Key Species	B	B	C	B	B	B
	Macrophyte Dominance	C	A	B	A	B	B

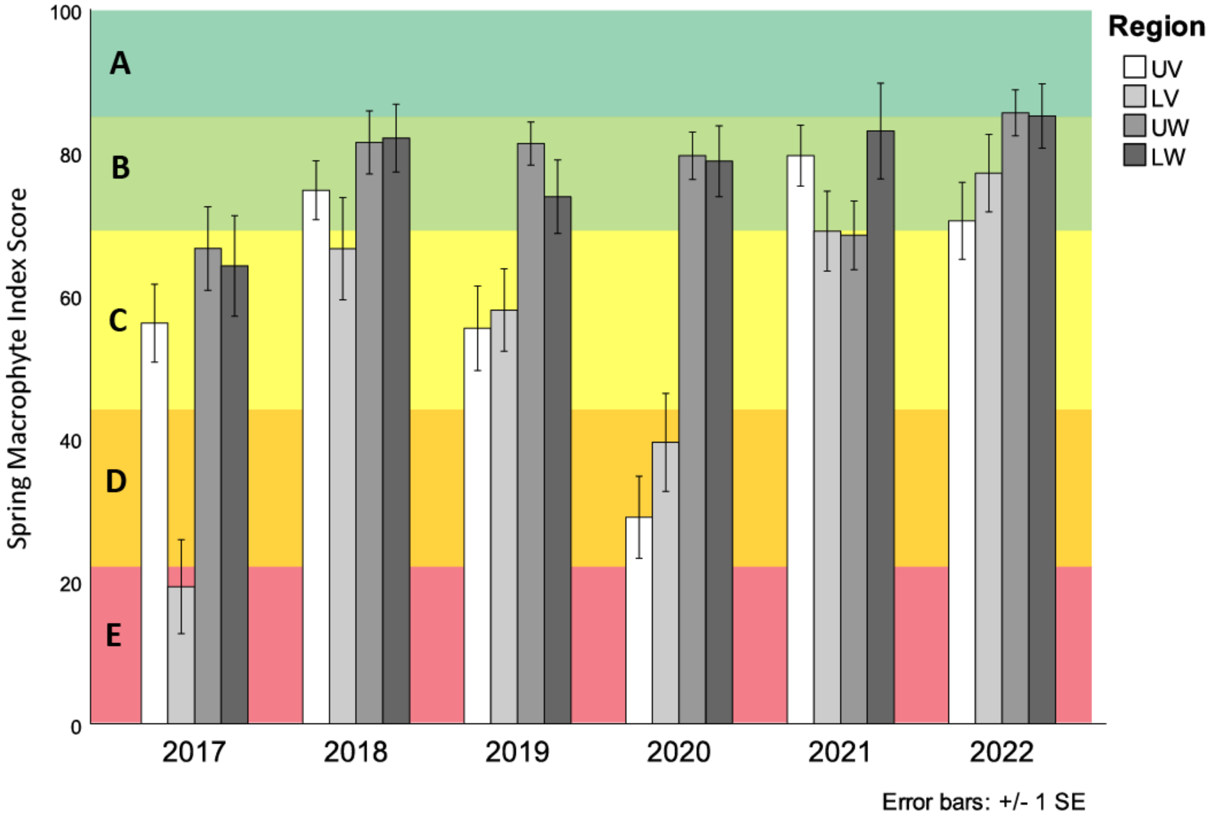

Figure 7. Spring macrophyte index scores relative to condition categories 2017-2022. Values are average of transect points in each region ±SE.

1.7.3 Historical assessment

Application of the Macrophyte Index and species and dominance metrics to historical data provides an overview of aquatic plant condition over seventeen years (Table 7). Annual testing better shows the extent of variation in condition, while testing of three-year rolling tends to mask this and is not considered as useful to annual reporting. Several observations can be made from this assessment, which are considered indicative of observed conditions in the system over this period:

- Variation in results for all regions is high but no consistent decline in macrophyte community health is evident.
- Increased, consistent macroalgal growth has occurred in the upper Vasse in recent years, with some decline in macrophyte community health but with resilience of key macrophyte species.
- Generally poorer conditions occur in the lower Vasse, but with apparent recent improvement in macrophyte growth despite ongoing macroalgae co-dominance.
- Reduced macroalgal growth throughout the Wonnerup Estuary over the last ten years with good growth of key macrophyte species (especially charophytes) in most years.

Table 7. Macrophyte Index and metric results for all available data. 2017-2022 is measured PVI and 2006-2016 is biomass converted to PVI. Annual and rolling 3-year averages are shown for each ecological region.

REGION	YEAR	Macrophyte Index	Key Species	Macrophyte dominance	Rolling averages	Macrophyte Index	Key Species	Macrophyte dominance
Upper Vasse	2022	B	B	C	2020-22	C	B	C
	2021	B	B	C	2019-21	C	C	C
	2020	D	C	D	2018-20	C	B	C
	2019	C	C	C	2017-19	B	B	C
	2018	B	B	C	2016-18	B	A	C
	2017	C	C	C	2015-17	B	B	B
	2016	A	A	B	2014-16	B	B	B
	2015	B	B	B	2013-15	C	C	C
	2014	B	B	B	2012-14	C	C	C
	2013	C	C	C	2010-13	C	C	C
	2012	C	C	C	2009-12	B	B	B
	2010	A	A	B	2008-10	B	B	B
	2009	A	B	B	2007-09	B	B	B
	2008	B	C	B	2006-08	B	C	C
	2007	C	C	C				
	2006	B	B	B				
Lower Vasse	2022	B	A	C	2020-22	B	A	C
	2021	B	A	C	2019-21	C	A	D
	2020	D	C	D	2018-20	C	B	C
	2019	C	B	D	2017-19	C	B	D
	2018	C	B	C	2016-18	C	B	C
	2017	E	D	E	2015-17	C	C	C
	2016	C	B	C	2014-16	C	B	C
	2015	C	C	C	2013-15	D	C	D
	2014	C	B	C	2012-14	D	C	D
	2013	E	D	E	2010-13	D	C	D
	2012	C	C	C	2009-12	C	C	D
	2010	D	C	D	2008-10	D	C	D
	2009	C	B	C	2007-09	C	C	D
	2008	E	C	E	2006-08	D	C	D
	2007	C	C	C				
	2006	D	C	D				
Upper Wonnerup	2022	B	A	C	2020-22	B	B	C
	2021	C	B	C	2019-21	C	C	C
	2020	B	B	B	2018-20	B	B	C
	2019	B	B	A	2017-19	C	B	C
	2018	B	B	B	2016-18	B	B	C
	2017	C	C	C	2015-17	B	B	C
	2016	B	B	C	2014-16	B	B	B
	2015	B	C	B	2013-15	B	B	B
	2014	B	C	B	2012-14	B	B	B
	2013	B	B	B	2010-13	B	B	C
	2012	B	B	B	2009-12	B	B	C
	2010	C	B	C	2008-10	B	B	C
	2009	B	C	C	2007-09	C	C	C
	2008	B	B	B	2006-08	C	C	C
	2007	C	C	C				
	2006	D	C	D				
Lower Wonnerup	2022	B	B	B	2020-22	B	B	B
	2021	B	B	B	2019-21	B	B	C
	2020	B	B	B	2018-20	B	B	C
	2019	B	C	B	2017-19	B	B	C
	2018	B	B	B	2016-18	B	B	B
	2017	C	B	C	2015-17	B	B	B
	2016	A	A	B	2014-16	B	B	B
	2015	B	C	B	2013-15	B	C	B
	2014	C	C	B	2012-14	B	B	B
	2013	B	C	B	2010-13	B	B	C
	2012	A	A	B	2009-12	B	B	C
	2010	C	B	C	2008-10	C	B	C
	2009	B	B	C	2007-09	C	C	C
	2008	B	B	C	2006-08	C	C	C
	2007	C	C	C				
	2006	D	D	C				

Conclusion and future monitoring

Aquatic plant communities are an essential component of ongoing monitoring of ecological health of the Vasse-Wonnerup Wetlands due to their significance in ecosystem processes and foundation role in supporting aquatic fauna, including waterbirds. Their response to environmental conditions and anthropogenic impacts makes these communities a useful indicator of ecological condition.

The Macrophyte Index presented in this report is based on a substantial (12-year) historical dataset and provides an intuitive, evidence-based solution to meeting the reporting requirements of management. The introduction of the PVI methodology for monitoring allows rapid assessment and provision of data to facilitate timely reporting. The index can be applied at the whole-system or ecological region level, depending on reporting objectives, and the key species and macrophyte dominance metrics used to generate the index allow for more detailed assessment of condition.

Ongoing annual monitoring using the PVI methodology is recommended during spring (November) for assessment using the approach outlined in this report. Site 11 should be included within the upper Wonnerup ecological region, and site 12 added to the lower Wonnerup to provide four sites in this region. Otherwise, sites should remain the same as for the IEM program. There is potential for development of a summer index reflecting macroalgal growth during this period when it is most problematic, and additional monitoring in January would be needed to inform this.

In addition to this index for aquatic plant communities, there is congruent work to develop indices for benthic invertebrates and fish, with potential to develop an integrative assessment of ecological condition. Management, research and monitoring for the Vasse-Wonnerup Wetlands continues to be a collaborative effort and it is hoped that enhanced reporting through these indices will leverage ongoing support for this important work.

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