The development and validation of an estuarine health index using fish community characteristics

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This thesis is presented for the degree of Doctor of Philosophy at Murdoch University

2010

Declaration

I declare that this thesis is my own account of my research and contains, as its main content, work which has not previously been submitted for a degree at any tertiary education institution.

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Sampling site in the upper reaches of the Swan Estuary

Abstract

The overall aim of this thesis was to develop an approach for constructing and validating a fish-based, multimetric index for assessing the ecological health of estuaries in south-western Australia, and to apply that approach to the large Swan Estuary, which has been subjected to substantial anthropogenic pressures. The indices developed for nearshore and offshore waters are the first to be produced for Western Australian estuaries. They deliver a reliable, practical and cost-effective method for quantifying the status of estuarine health, thus providing managers with a sound basis for preventative management actions and a means for communicating ecosystem health implications to the wider public.

An extensive range of potential fish community characteristics (metrics) were initially tested for their suitability for incorporation into the indices. These metrics included various measures of species composition, diversity and abundance, trophic and functional aspects of the assemblage, *i.e.* the contributions of different feeding and life-history guilds and, where relevant, sentinel species. An *a priori* hypothesis was formulated for each candidate metric, reflecting its predicted response to increasing ecosystem degradation.

Two different approaches were trialled to identify the subset of metrics that were most sensitive to changes in environmental integrity and thus most appropriate for inclusion in an index of ecosystem health. The first approach sought to identify those metrics that showed the strongest responses to spatial differences in the quality of physical habitat, as quantified using a novel and independent measure of habitat degradation. Habitat quality was thus assessed at 136 nearshore sites throughout the estuary in spring 2007, using rapid visual survey techniques to assign scores for each of six habitat quality metrics. Scores for all physical habitat metrics were then summed to produce an overall habitat quality index score for each site. The results of graphical screening and various multivariate statistical techniques (PERMANOVA, PCA and CCorA) demonstrated that this approach failed to confirm hypothesised responses of the

candidate fish metrics to physical habitat degradation and was thus unsuccessful in selecting appropriate metrics. This applied even to sites where water quality conditions were similar. Moreover, the compositions of the fish assemblages did not differ significantly among habitat quality categories, either across the whole estuary or within its various regions. It is thus suggested that habitat quality influences the fish communities of the Swan Estuary at a broader scale than that at which it was assessed.

As none of the candidate metrics were found to be sensitive to spatial differences in habitat quality at local scales, a novel alternative approach was employed to identify the metric subset that most consistently reflected temporal (inter-annual) changes at the ecosystem level, and was thus likely to be most sensitive to changes in ecosystem condition. This approach to metric selection relied on the assumption that the ecological condition of the Swan Estuary has varied over time in response to changes in the suite of stressors acting on the system. This assumption is supported by the fact that there has been considerable inter-annual variation in the severity of environmental perturbations affecting the estuary, including large phytoplankton blooms and hypoxic events, and consequently in their effects on ecological processes and biota including fish.

Given the above assumption, and the associated uncertainty surrounding the nature and magnitude of temporal changes in the ecological condition of the Swan Estuary over the last few decades, the second approach to metric selection employed a combination of multivariate (DISTLM and BEST) and information-theoretic statistical approaches to assess both metric sensitivity to inter-annual changes in ecosystem condition, and the extent of metric redundancy. This approach allowed inferences to be drawn from the weight of evidence derived from multiple analyses of fish data sets collected using divergent sampling techniques throughout the estuary between 1976 and 2009. Responsive and parsimonious subsets of 11 and seven candidate metrics were thus selected for subsequent incorporation into multimetric health indices for the nearshore waters (< 2 m depth) and offshore waters (> 2 m depth) of this system.

Reference conditions for each selected nearshore and offshore metric, representing the ‘best available’ values against which the previous, current and future

health of the Swan Estuary may be assessed and compared, were then established for each season and region of the estuary using 30 years of fish assemblage data recorded throughout that system. This included data collected during the current study, in which fish were sampled seasonally in the nearshore and offshore waters between 2007 and 2009, and in which the sampling locations, timing and net types employed replicated, as far as possible, those in all previous studies of fish assemblages in this system. However, prior to establishing the reference conditions for the nearshore metrics, the fish assemblage data recorded in those waters first required standardisation to minimise the effects of gear-induced bias that were attributable to the large differences in the characteristics of the seine nets used to sample the nearshore fish fauna of the Swan Estuary since the mid-1970s. A net selectivity study was thus conducted during spring 2008 and autumn 2009 in two main regions of the estuary to compare the compositions of fish samples collected using each of the different seine nets employed historically, *i.e.* 21.5, 41.5 and 133 m–long seines. The data from these samples were then subjected to generalised linear modelling techniques to derive net equivalence factors for quantitatively standardising fish species abundance data across all historical and current nearshore samples, and thereby minimise the effects of sampling biases.

Scoring thresholds were then determined statistically from the 5^{th} and 95^{th} percentiles of the composite nearshore and offshore fish assemblage data sets, enabling each metric in each sample to be scored according to the extent of its deviation from the relevant reference condition. Finally, index scores for both nearshore and offshore health indices were calculated by summing the scores for their component metrics and then adjusting the resultant value by the number of metrics in the index to produce a final, easily interpretable index score ranging from 0-100. Thresholds for establishing the qualitative health status of the estuary (*i.e.* good, fair, poor, very poor) were also determined by subdividing the possible range of index scores into four equal classes.

The trends exhibited by the mean index scores for nearshore waters of the Swan Estuary suggest that the health of those waters has remained relatively constant over the last three decades, with their health status being classified as fair throughout this time. It is important to recognise, however, that interpretation of these trends in mean scores is

hindered by differences in the spatial distribution, timing and intensity of sampling among studies, and most notably among those from the mid-1970s to the mid-1990s. Interpretations of trends in the index scores for nearshore waters from the mid-1990s to the present are more reliable, due to greater similarities in the sampling methodology throughout this period. Such trends suggest that the health of these waters has increased in recent years, with the mean health index score increasing from *ca* 58 in 2005/06 to 64 in 2008/09. In contrast, the mean offshore index score has decreased consistently from 56.5 in the late 1970s to 47 in 2008/09, resulting, for the first time in three decades, in the health status of the offshore waters being classified as poor.

The reliability of the nearshore and offshore indices was evaluated by quantifying the variability of index scores among replicate sites, within and between seasons and between consecutive years. The effects of random sampling variation on the precision of index scores were also determined using bootstrap resampling techniques. The sensitivity of the final nearshore and offshore indices to environmental degradation and other stressors was tested by determining the degree to which the health index scores for each replicate sample responded to three water quality parameters measured during sampling and, in the case of the nearshore index, to habitat quality metrics assessed in spring 2007. Although index responses to changes in specific stressors were not detected, the consistent decrease in offshore health index scores from 1978 to 2009 suggests that this index is capable of detecting the widely-perceived, long-term decline in the condition of offshore waters of the Swan Estuary. Moreover, the far greater inter-seasonal variability among offshore than nearshore index scores provides further evidence that the deeper waters of the estuary are in poorer health than the shallower waters, most notably in the upper reaches of this system.

The consistently lower spatial variability of nearshore and offshore index scores recorded in summer and autumn indicates that, dependent upon an appropriate examination of intra-seasonal index variability, these seasons represent a suitable index period for future monitoring of the ecological health of the Swan Estuary. Overall, validation of the indices developed during this study demonstrated that their spatial and temporal variability was comparable to that of existing multimetric indices employed in

the USA and Europe, and that classification of the health status of the estuary was fairly robust, despite the effects of both natural spatio-temporal variability and sampling error on index scores.

Given the relative lack of quantitative, biological indicators currently available to estuarine managers, there is considerable potential for multimetric, biotic indices to advance the field of estuarine health assessment in Australia. Several issues must be addressed if we are to understand the complex ways in which the condition of these estuarine systems responds to natural and anthropogenic pressures or to management actions designed to improve or maintain them, not least of which is the need for such indices to be integrated within a broader monitoring framework employing multiple indicators.

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List of acronyms

AIC	Akaike's Information Criterion
AIC_c	Version of Akaike's Information Criterion, modified for small samples
ANOVA	Analysis of Variance
AUSRIVAS	Australian Rivers Assessment Scheme
BA	Basin (region of Swan Estuary)
BIOENV	Biota-Environment matching
BVSTEP	Biota-Environment matching – Stepwise
CAP	Canonical Analysis of Principal Coordinates
CCorA	Canonical Correspondence Analysis
CDI	Community Degradation Index
CELCR	Canning Estuary and Lower Canning River (region/management zone)
CH	Channel (region of Swan Estuary)
CR	Canning River (region of Swan Estuary)
DISTLM	Distance-based Linear Modelling
DPSIR	Drivers, Pressures, Status, Impact, Response
EBI	Estuarine Biotic (Integrity) Index
EcoQ (EcoQS)	Ecological Quality Status
EFI	European Fish Index
EFCI	Estuarine Fish Community Index
EIBI	Estuarine Index of Biotic Integrity
EQUATION	Estuarine Quality and Condition Index
FAME	Fish-based Assessment Method for the Ecological Status of European Rivers
FCI	Fish Community Index
FRI	Fish Recruitment Index
GLM	Generalised Linear Model
HQC	Habitat Quality Category
HQI	Habitat Quality Index
IBI	Index of Biotic Integrity
IHAS	Integrated Habitat Assessment System
ISC	Index of Stream Condition
LS	Lower Swan River (region of Swan Estuary)
LSCE	Lower Swan/Canning Estuary (region/management zone)
MD	Middle-Downstream Swan River (region of Swan Estuary)
MDS	(Non-metric) Multi-Dimensional Scaling
MMI	Multi-Model Inference
MSE	Middle Swan Estuary (region/management zone)
MU	Middle-Upstream Swan River (region of Swan Estuary)
NEECAF	National Estuarine Environmental Condition Assessment Framework
NLWRA	National Land and Water Resources Audit
NSW	New South Wales
PC	Principal Component
PCA	Principal Components Analysis
PCO	Principal Coordinates Analysis
PERMANOVA	Permutational ANOVA and MANOVA
QHEI	Qualitative Habitat Evaluation Index
RBP	Rapid Bioassessment Protocol
RCE	Riparian, Channel and Environmental Inventory
RDA	(Distance-based) Redundancy Analysis
RHS	River Habitat Survey
RIVPACS	River Invertebrate Prediction and Classification System
SWR	Stream-Wetland-Riparian Index
TFCI	Transitional Fish Classification Index
TL	Total length
US	Upper Swan River (region of Swan Estuary)
USE	Upper Swan Estuary (region/management zone)
USEPA	United States Environmental Protection Agency
WA	Western Australia
WFD	Water Framework Directive

Acknowledgements

I wish to express my profound thanks to Fiona Valesini for her generous and dedicated supervision, endless advice, discussion and encouragement. My gratitude is expressed also to Ian Potter, for allowing me the opportunity to become part of 'the fish group' and for his enthusiasm and guidance throughout. Numerous friends and colleagues are thanked for their generous assistance with sampling and laboratory work, including Steeg Hoeksema, Ben Chuwen, James Tweedley, Alex Hesp, Bryn Farmer, Peter Coulson, Thea Linke, Emma Somerville and Jo Bannister. Particular thanks go to Alan Cottingham for his dedicated and tireless assistance in the field. I would like also to acknowledge the assistance of the many researchers from the Centre for Fish and Fisheries Research who have been involved in the collection of fish community data over several decades. Enormous thanks go to Norm Hall, Alex Hesp and Bob Clarke for their crucial statistical advice and problem solving, and for their patience in response to my constant questioning.

I thank Frances D'Souza and Naomi Hellriegel from the Department of Water for access to data and reports, and Rick Ellison of the Department of Fisheries for the loan of sampling equipment. Gratitude is expressed to the Swan River Trust, Department of Water, Department of Fisheries and Murdoch University for funding this project, and to the Western Australian Marine Science Institution (WAMSI) for financial support in the form of a top-up scholarship.

Above all else, I am immensely thankful to my beautiful wife Caitlin, whose patience and generosity continue to amaze me, for her ceaseless love and support throughout my studies.