Novel approach for the classification of habitats in tropical estuaries exposed to urban and industrial development

Thesis submitted by

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“Sorry, sorry! No monkey!”

Kinabatangan River Guide, Malaysia 1993

Abstract

In response to the increasing rate of coastal development in tropical regions managers are calling for ecosystem-based management strategies to assist with decisions regarding further urban and industrial expansion. Knowledge on the composition, status, and function of the ecosystems exposed to development is necessary and helps to ensure the conservation/restoration of natural habitat and the ecological services and functions they provide. Such information however is often not available at the scale at which managers perform their work, does not include artificial features as components of the ecosystem, and its acquisition is frequently limited by timelines and budgets. Additionally, the patterns of change and cumulative effects of incremental development in coastal ecosystems – particularly in tropical regions – are far from having been fully characterised and are still being investigated.

To address these gaps in methodology and information I have developed a rapid assessment tool specific to intertidal foreshore mapping that can assist in gathering information on the structural complexity and status of an ecosystem at a scale applicable to managers and ecological researchers. Such information is not only essential as a baseline for effective planning of new developments but is also applicable for restoration of impacted areas. This novel approach to the classification of coastal ecosystems is achieved by assessing structural attributes (vegetation, sediment type, and artificial features) which can be combined in easily identifiable units called 'structural habitats', a factor essential for mapping, quantification, and planning. This classification scheme for structural habitats can be applied to a variety of coastal ecosystems and has the advantage of being rapid, inexpensive, and versatile enough to align to other existing classifications or to be integrated in environmental impact assessment protocols.

I tested and applied this classification scheme to the assessment of the habitat composition and mosaic configuration of four tropical estuaries located in Townsville and the broader region surrounding the city (Queensland, Australia). I chose these estuaries as they represent varying levels of urban development, with a mix of natural and hard engineering structures distributed along their linear length. Their location in the Great Barrier Reef World Heritage Area makes this research particularly relevant and essential for the broader context of GBR reef resilience as well, being part of a complex larger seascape. The protection and restoration of the GBR and the connected coastal ecosystems are in fact key targets in the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan) prepared by the Australian government. The results obtained indicate estuaries that are largely modified by urban and industrial expansion have a higher level of habitat

complexity compared to those less exposed to development. I identified over seventy-nine different structural habitats across the four estuaries. Most habitats (81%) are characterised by the presence of one or more artificial features (*e.g.* rock walls, stormwater drains) and found predominantly in the more urbanised areas. This high variability in habitat composition is linked to the progressive development carried out in these ecosystems, and probably in coastal tropical regions more broadly. The distribution and extent of the different habitats across the estuaries revealed how incremental urban development has likely contributed to the formation of a complex and varied shoreline mosaic, particularly so in the more urbanised estuaries compared to the low-development estuaries that still have much natural shoreline vegetation present.

Next, I assessed the species composition of the macrofauna present in each type of structural habitat and determined patterns of spatial distribution in three of the four estuaries. Using data collected over two years, I ran classification trees which revealed how the presence of non-transient species across the different estuaries is influenced by the structural components selected for the classification scheme and utilised for structural habitat mapping: vegetation, sediment type and artificial features. Further investigation identified trends in association and preferences of species for certain structural elements, such as the presence of vegetation for terrestrial species and the preference of several gastropods for soft sediment. Understanding the relationship between the species inhabiting an ecosystem and its structural components provides essential information for the management and conservation of the local biotic communities. It also has the potential to facilitate the prediction of consequences on species composition and community assemblages associated with changes occurring with development, be that in the form of vegetation/substratum alteration or introduction of artificial features. Moreover, the trends identified on the importance of sediment and vegetation for species assemblages have also highlighted how the (re)introduction of mangrove vegetation and soft sediment in front of hard artificial structures could assist in achieving the balance between having a structure which provides a service to humans and ensuring the presence of a natural section of the ecosystem, with its native biotic communities and many ecological services.

Overall, this thesis presents the development and application of a classification scheme for managers to rapidly perform habitat assessment along coastal estuaries. This simple and effective tool has the major advantage of quickly providing information on the habitat composition and configuration of coastal ecosystems, including an evaluation of the type and extent of structural changes linked to previous development works. Such information can be used to determine the status and condition of the ecosystem and thus assist in selecting the best course of action for management in the face of development based on the objectives and outcomes desired. The classification approach presented here can be integrated as a standard tool in environmental impact assessment, monitoring programs, or ecological mapping, particularly when assessing extent of modification, and its influence on the local faunal communities, a fundamental starting point to plan restoration efforts. In addition, it provides a broadly applicable and standardised method that allows for the comparison of different ecosystems in the same area. This simple and rapid assessment tool can assist researchers in expanding on the current knowledge of coastal ecosystems exposed to anthropogenic development while also allowing managers to be in a stronger position to adequately plan for future development, avoiding unnecessary efforts, resources and time, and increasing the success of conservation/restoration of important coastal ecosystems.

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1.1 Background information: Ecosystem-Based Management in coastal development

The rate of development has increased concurrently with global population growth (Cohen 2006; McDonald 2008; Neumann *et al.* 2015), a phenomenon particularly evident along coastlines where the access to water transport, rich alluvial coastal land, fisheries and recreational resources favor urban or industrial expansion (Ehrenfeld 2000; Small and Nicholls 2003; Turner *et al.* 1996; Yeung 2001). Extensive structural modifications of coastal areas are linked also to armouring against sea level rise and erosion (Davis *et al.* 2002; Ghazali 2006). Human development results in a suite of environmental changes that range from local alterations to radical transformations in an ecosystems' geomorphology (El Banna and Frihy 2009; Gregory 2006; Hapke *et al.* 2013), structure (Alberti 2005; Coverdale *et al.* 2013; Fischer and Lindenmayer 2007), resilience (Folke *et al.* 2004), and functioning (Airoldi and Beck 2007). Such changes can lead to declines in native species' composition/abundance and variations in habitat connectivity (Li *et al.* 2010; Lindenmayer and Fischer 2013). The concept of 'sustainable development', which focuses on minimising negative effects on the environment while allowing for development to take place (Dernbach 1998; Emas 2015), has become a priority for managers, planners and scientists (Foley *et al.* 2010; Harding 2006; Lele 1991; Yeung 2001). Integrated approaches such as ecosystem-based management (EBM) (Foley *et al.* 2010; Foley *et al.* 2013; Rosenberg and McLeod 2005) align the ecological objective of preserving natural resources with the societal needs for spatial, economic, and social growth. This is particularly relevant in tropical regions, given they include some of the most biologically diverse and productive ecosystems on the planet (Burt 2014; Costanza 1998; Spalding *et al.* 2001), many of which have been negatively affected by human actions (Airoldi and Beck 2007; Laurance *et al.* 2011; Lee *et al.* 2006; Polidoro *et al.* 2010). EBM relies on clearly defining the appropriate strategy based, among other things, on the characteristics of the ecosystem involved. Thorough understanding of the ecological composition, status, functions, and services of the ecosystem exposed to human expansion and how these are affected by the development works is essential for planning and implementing appropriate EBM strategies (Airoldi and Beck 2007; Moberg and Rönnbäck 2003; Morrissey *et al.* 2012; Wegscheidl *et al.* 2017).

1.2 Ecosystem assessment and mapping tools

A primary step in the acquisition of information to effectively manage an ecosystem is the characterisation of the biological, physical and chemical variables at a spatial scale relevant for the assessment of ecological characteristics and processes and/or for planning specific anthropogenic interventions (Busch 2018; De Groot *et al.* 2002; Mann and Lazier 2013; Zajac 1999). There are many different methodologies and criteria available to collect such data, ranging from remote sensing to ground-truthing as part of field sampling (Borja and Dauer 2008; Brandmeyer and Karimi 2000; Diaz *et al.* 2004; Singh *et al.* 2012). While remote sensing has the advantage of providing consistent and long-term data on large areas at low/minimal labour cost (Wang *et al.* 2010), it often lacks small-scale or horizontal perspectives (Sabins 2007). On-ground data collection assists in complementing the information collected remotely by providing a higher resolution at smaller scales, even though in this case costs can increase due to supplemental labour. This can be achieved through visual or photographic surveys, sediment/water sampling, or the collection of biota (Davis *et al.* 2016; Vermeiren and Sheaves 2015a). Regardless of whether data are collected remotely or on-ground, a classification scheme is needed to provide a clear and precise evaluation of the ecosystem and its components. Numerous classification schemes have been developed for the characterisation and mapping of coastal ecosystems (Table 1; Appendix 1a-b). These schemes aim to provide a standardised way of classifying natural ecosystems based on a series of pre-established parameters (predominantly physical and chemical), and to clearly define ecological units necessary for the mapping process.

Table 1. Existing classification schemes for marine and/or coastal ecosystems around the world.

Country	Classification scheme	Reference	Application	Scale
Australia	Interim Marine and Coastal Regionalisation for Australia (IMCRA) (V3.3)	IMCRA 1998	National & Regional	100 km to 1000s km
Australia	Interim Marine Classification Scheme (MHC) Stage 3 (V.2)	Ferns and Hough 2000	Regional	100 km to 1000s km
Australia	National Marine Bioregionalisation of Australia (NMB)	Commonwealth of Australia 2005	National & Regional	<1000 km^2 to >100,000 km^2
Australia	Wetland Mapping and Classification Methodology (V1.2)	EPA Queensland 2005	Regional	1:50,000 to 1:100,000
Australia	Integrated Marine and Coastal Regionalisation for Australia (IMCRA) (V4.0)	Commonwealth of Australia 2006	National & Regional	100 km to 1000s km
Australia	CSIRO Marine Research hierarchical scheme for habitat mapping and classification	Lyne *et al.* 2006	Regional	1 m^2 to 100 km^2
Australia	National Intertidal/Subtidal Benthic habitat classification scheme (NISB) (V.01)	Mount *et al.* 2007	National	n.c.d.
Australia	Primary Shallow Habitat Classification Scheme (Victoria)	Ball *et al.* 2006	Regional	n.c.d.
Australia	GIS Mapping Classification Scheme (Victoria)	Ball *et al.* 2006	Regional	n.c.d.
Australia	Seamap Australia benthic habitat classification scheme (SEAMAP)	Butler *et al.* 2017	National	n.c.d.
Australia	Queensland Intertidal and Subtidal Ecosystem Classification Scheme (V1.0)	DEHP 2017	Regional	1:5000 to 1:2,500,000
Canada	Hierarchical classification of marine environment	Roff and Taylor 2000	National	10s km to 1000s km
Canada	British Columbia Marine Ecological Classification	Howes *et al.* 2002	Regional	1:250,000 to 1:2,000,000
Caribbean	Systematic classification scheme of marine habitats	Mumby and Harborne 1999	International	10s m to 100s m
Europe	European Nature Information System (EUNIS)	Davies *et al.* 2004	International	1 m to >100 m^2
N/A	Marine Ecoregions of the World (MEOW)	Spalding *et al.* 2007	International	n.c.d.
New Zealand	The New Zealand Marine Environment Classification	Snelder *et al.* 2005	National	1:250,000 or >1:4,000,000

New Zealand	Coastal Marine Classification	MFDC 2008	National	100s m to 1000s km
UK and Ireland	Marine Habitat Classification for Britain and Ireland (MHC) (V04.05)	Connor *et al.* 2004	National	>1 m
USA	Classification of Wetlands and Deepwater Habitats of the United States	Cowardin *et al.* 1979	National	n.c.d.
USA	Hydrogeomorphic Classification for Wetlands	Brinson 1993	National	n.c.d.
USA	Classification of wetlands of the central and southern California coast and coastal watersheds	Ferren *et al.* 1996	Regional	n.c.d.
USA	U.S. Marine and Estuarine Ecosystems Classification System	Allee *et al.* 2000	National	>10m
USA	Classification of benthic estuarine habitats in Mid-Atlantic USA	Llansó *et al.* 2002	Regional	n.c.d.
USA	System for Classification of Habitats in Estuarine and Marine Environments (SCHEME) for Florida	Madley *et al.* 2002	Regional	1:12,000 to 1:48,000
USA	Coastal and Marine Ecological Classification Standard (CMECS) (V.2)	Madden *et al.* 2005	National	1 m^2 to 1000s km^2
USA	Classification of Marine Sublittoral Habitats	Valentine *et al.* 2005	National & International	1:25,000 to 1:100,000
USA	National Estuarine Research Reserve System (NERRS)	Kutcher *et al.* 2005; Kutcher 2008	National	1:12,000
USA	Habitat Classification Scheme	Auster *et al.* 2009	Regional	1:5,000 to 1:100,000
USA	Marine Habitat Classification	Guarinello *et al.* 2010	National	n.c.d.
USA	Coastal and Marine Ecological Classification Standard (CMECS) (V.6)	FGDC 2012	National	>10m
USA	Classification of Wetlands and Deepwater Habitats of the United States	FGDC 2013	National	n.c.d.
USA	Estuarine Habitat Classification for a Complex Fjordal Island Archipelago (Alaska)	Schoch *et al.* 2014	Regional	1 km^2 to 1000s km^2

n.c.d. = not clearly defined

All classification schemes presented in Table 1 focus on large-scale assessment of physical and biological parameters, such as bathymetry, geomorphology, granulometry, water chemistry, and broadly classified sessile biotic communities (e.g. Ball et al. 2006; Commonwealth of Australia 2006; IMCRA 1998). Many classification schemes however tend to not include vegetation or present it merely as 'presence/absence' rather than providing individual classes focusing on different types of vegetation. Moreover, in some cases vegetation and sediment are treated as mutually exclusive classes within the scheme. Structural elements such as sediment type and vegetation are fundamental ecological parameters to be included in classification schemes, particularly in the context of ecological assessment for coastal development and EBM (Zajac 1999). Sediment and vegetation represent the major structural components of coastal ecosystems and are directly affected/modified by development works in the form of removal, reduction, or substitution (Benfield *et al.* 2005; Hamilton and Gehrke 2005; Polidoro *et al.* 2010; Zajac 1999). Knowledge of the presence, type, and distribution of these structural elements in an ecosystem, as well as the changes occurred related to urban and/or industrial expansion, would therefore assist in providing a thorough evaluation of the structural composition of the ecosystem, including spatial heterogeneity. Moreover, sediment and vegetation are known to influence the presence and distribution of faunal communities in an ecosystem (Gray 1974; Martin *et al.* 2005; McKee

1993; Wallace 2011). This is another factor of relevance for environmental assessments and decision-making related to coastal development (be it past, current, or future) that is not considered or included in the range of available classification schemes.

1.3 Issues identified in existing ecosystem assessment tools

The classification schemes currently available present many advantages for mapping and assessment of coastal ecosystems, including simple and clear language for end users, repeatable environmental units, and applicability to a variety of ecosystems (Appendix 1a). However, these classification schemes also present issues and/or conceptual gaps that need to be addressed to ensure the validity, relevance, and applicability of the assessment tools and information collected (Appendix 1b). Some issues are particularly relevant for the context of EBM and local-scale coastal construction, and the most prominent are described in the sections below:

1.3.1 Spatial scale

Most standardised classification schemes are aimed to be applicable at national (if not international) scale to ensure the comparability of information across different temporal and spatial ranges. Examples of such schemes can be found in Europe (*e.g.* EUNIS), in the USA (*e.g.* Classification of Wetlands and Deepwater Habitats of the United States), and Australia (*e.g.* SEAMAP) (Table 1). While these large-scale classifications encompass a wide range of ecosystems and geographical areas, the resolution is coarse and thus frequently unsuitable for local management decisions (*e.g.* a council addressing the management of a single estuary or a small coastal section within their district). Urbanisation and industrial development usually occur at small/local scales (*e.g.* city, suburb, or neighbourhood); sometimes with works or modifications happening in specific sections of an ecosystem ranging from a few meters (*e.g.* stormwater drains, boat ramps, pontoons) to hundreds of meters (*e.g.* armouring of the banks, complex constructions, port developments for shipping goods and services overseas) (Figure 1).

Figure 1. Examples of coastal development works and their spatial extent: a) stormwater drain that intersects a stretch of mangrove shoreline, b) bridge that also intersects a mangrove shoreline, and c) armouring of the banks.

The level of detail and up-to-date information on the composition of an ecosystem that is required to address the ecological implications of any development work (Wegscheidl *et al.* 2017) cannot be achieved using large-scale classification schemes solely, such as those developed for national or even regional use. Such classifications operate at scales that may be too large to detect variability in composition within individual ecosystems (Table 1). This is particularly relevant for classifications where the minimum mapping unit, representing the smallest areal entity to be mapped as a discrete entity (Lillesand and Kiefer 1995), corresponds to a few hundred meters or a kilometre (*e.g.* Butler *et al.* 2017; Davies *et al.* 2004; Howes *et al.* 2002; Spalding *et al.* 2007).

1.3.2 Lack of inclusion of anthropogenic features

A further complication in the application of the available classification schemes to coastal management is the lack of inclusion of anthropogenic features or modifications present in coastal ecosystems (Appendix 1b). In Australia examples can be seen with classifications such as the Primary Shallow Habitat Classification Scheme (Ball *et al.* 2006), CSIRO Marine Research hierarchical scheme for habitat mapping and classification (Lyne *et al.* 2006), or the National Intertidal/Subtidal Benthic habitat classification scheme (Mount *et al.* 2007). The SEAMAP Australia (Butler *et al.* 2017) system, for instance, provides maps for coastal ecosystems across Australia but often lacks information on several ecosystems located in urbanised or developed areas, such as cities or residential areas. The lack of focus or integration of anthropogenic features represents a substantial gap in information that is likely to affect the suitability of these classifications in the context of coastal development and ecosystem restoration projects. Many coastal ecosystems have been subjected to structural modifications associated with urban expansion, industrialisation, and farming (Airoldi and Bulleri 2011; Davis *et al.* 2002).

Anthropogenic modifications, particularly when (semi)permanent or present for years/decades, should be considered as integrated components of the ecosystem, and thus included in classification and mapping protocols to ensure a thorough descriptions of physical and structural characteristics. The presence of artificial structures can also impact species composition and utilisation of the area, with potential repercussions in the functioning and services of the ecosystem (Bulleri and Chapman 2010; Connell and Glasby 1999; Firth *et al.* 2016a; Hanlon *et al.* 2018; Mayer-Pinto et al. 2018). Moreover, most classification schemes do not include a way to assess the nature and extent of structural modification linked to coastal expansion, nor do they provide a way to rapidly and consistently measure further additions or changes occurring over time with new urban developments.

1.3.3 Time and costs

A further practical issue/limitation of many existing classification schemes is that their application can be costly and/or lengthy. In many cases this is not related to the classification scheme itself, but rather to the large-scale at which the assessments are carried out. Mapping whole regions and states, in fact, requires considerable resources and time (*e.g.* Bell *et al.* 2006; Ferns and Hough 2000; Commonwealth of Australia 2005). However, there are instances where the timescales and costs are associated to the classification schemes themselves. The inclusion of many different biological and physical parameters (*e.g.* Guarinello *et al.* 2010; Madden *et al.* 2005) can require different assessment techniques, sometimes with the use of expensive instrumentation/analyses (*e.g.* Roob 2000) (Appendix 1b). In the context of coastal development, time and financial budgets are important factors that influence planning and decision-making. As such, given a target quality for any ecosystem assessment related to landscape management, achieving results/information in a more cost-effective way and/or in a shorter period of time is a competitive advantage.

1.4 Thesis structure

Considering the limitations of current ecosystem assessment tools that are available to managers, a standardised classification scheme that supports science-based decision-making and addresses the gaps highlighted in the sections above is needed for sustainable coastal development and management.

This thesis aims to develop a rapid and cost-effective assessment tool to classify and map tropical coastal ecosystems to assist ecosystem-based management decisions, and to then use the tool to evaluate habitat complexity and related faunal communities in a range of estuaries exposed to different extents of development. The integration of the proposed assessment tool with existing protocols for the characterisation of coastal wetland ecosystems would provide high-resolution data on the structural composition and configuration of target study areas (selected on a case-by-case basis) and allow to determine the effect of different natural and anthropogenic structural features on local biodiversity. This information can be used to evaluate the potential resilience or vulnerability of coastal areas to development works, with detailed understanding of the role/impact of the different structural features assessed on local ecological processes, functioning, and services. Such information can be readily applied to ecological restoration of modified areas, by identifying natural structural features to be protected/restored and assist in the selection of locations to prioritise for intervention. Moreover, understanding of the effects that different artificial structures and modifications have on local biodiversity can be applied during the planning phase of future development to identify the most suitable strategy or the least impactful structure/modification to be introduced.

The development, testing, and application of this rapid assessment tool have been achieved by:

1) Developing a standardised classification scheme to define and map the structural habitat features of coastal ecosystems. (Chapter 2)
2) Apply the classification scheme to assess habitat complexity in tropical estuaries that have been subjected to urban/industrial development. (Chapter 3)
3) Determine the influence of structural attributes (sediment, vegetation, artificial features) on faunal communities. (Chapter 4)
4) Present new resources and information for ecosystem assessment and landscape management in face of coastal development. (Chapter 5)

Chapters of the thesis follow the general structure and format required for publication to facilitate their conversion to peer reviewed scientific articles.

The thesis structure is therefore as follows:

Chapter 1. Urban expansion in tropical coastal wetlands: blending management with conservation.

This introductory chapter analyses different classification schemes available to assess and characterise coastal ecosystems, and highlights key gaps and issues to be addressed in the context of their applicability for ecosystem-based management.

Chapter 2. Mapping the structural complexity of tropical coastal wetlands: development of a standardised classification scheme.

This chapter describes the development and testing of a broadly applicable classification scheme that focuses on the structural components, both natural and artificial, of tropical coastal wetlands to provide information useful for managers challenged with approving new development, while also protecting and enhancing coastal ecosystems.

Chapter 3. Structural habitat configuration of estuaries exposed to different extent of urban development.

This chapter investigates the habitat composition and distribution of tropical estuaries exposed to different types and extent of development over time. Focus is given to measuring the extent and distribution of structural modifications in each estuary as well as identifying the presence of dominant structural elements representing a shared or common composition between the different estuaries.

Chapter 4. Influence of structural attributes on species assemblages in urbanised estuaries.

This chapter analyses the influence of different structural elements of intertidal habitats in tropical estuaries with different amounts of development on the occurrence of faunal assemblages, with particular focus on non-transient species.

Chapter 5. Analysing tropical coastal ecosystems in face of development: a new understanding of structural changes with implications for ecology and management.

In the final chapter the information and new understanding presented in this thesis is expanded and discussed within the context of sustainable development techniques for tropical coastal ecosystems characterised by soft sediment and vegetation. New perspectives for ecosystem conservation and restoration of such ecosystems are presented.

Chapter 2

Mapping the structural complexity of tropical coastal wetlands: Development of a standardised classification scheme

2.1 Introduction

Tropical coastal wetlands are highly dynamic and complex ecosystems located in transition areas between land and sea (Queensland EPA 1999). They support a wide range of plants and animals, both resident and transient (Gopal and Junk 2000; Milton *et al.* 2018), and provide numerous ecological services that benefit humans (Mitsch and Gosselink 2000). The high ecological value of wetlands and numerous functions and services provided (Barbier *et al.* 2011; Queensland EPA 1999) make these ecosystems a priority for conservation and management of tropical coastal areas. At all levels of government, strategies are implemented and continuously updated to safeguard the ecological values of coastal wetlands (Barbier *et al.* 2011; Rogers *et al.* 2016) and promote restoration of areas affected by development (Bayraktarov *et al.* 2016; Moberg and Rönnbäck 2003). This is particularly relevant considering that coastal wetlands are among some of the ecosystems most heavily impacted by urban/agricultural/industrial development (Gardner *et al.* 2015; Milton *et al.* 2018). Extensive land reclamation to make space for residential housing and urban/coastal infrastructures are the leading cause of wetland reduction and degradation (Department of Environment and Energy 2016; Gardner *et al.* 2015). With an increasing rate of development expansion in tropical coastal areas (Barragán and de Andrés 2015) there is a pressing need for effective ecosystem-based management (EBM) to minimise and reverse further degradation of coastal wetlands (Foley *et al.* 2010; Temmerman *et al.* 2013). The aim is to achieve a balance between the need for coastal expansion and the conservation of the ecosystems where such works take place. The selection of appropriate strategies for the conservation and/or restoration of coastal wetlands exposed to development requires comprehensive understanding of the ecosystems' composition, dynamics, and functions, as well as how these are affected by human expansion (Airoldi and Beck 2007; Moberg and Rönnbäck 2003; Morrissey *et al.* 2012). Such information is essential to managers and stakeholders to avoid wasted effort, resources, and time, and to adequately plan future development footprints while maximising conservation of natural resources. Most of the existing assessment tools available for the characterisation of coastal ecosystems, however, present limitations that affect their applicability in the context of coastal development, including coarse resolution, lack of inclusion of artificial features as structural elements of an ecosystem, and non-competitive timescales or costs (see Chapter 1). As such there is need for a rapid, standardised, comprehensive, and easy to apply assessment tool that provides data on the status and composition of coastal wetlands at a local scale. These protocols for ecosystem characterisation, mapping, and quantification need to focus on the acquisition of information at a scale relevant for location-specific decision-making while also being broadly applicable to ensure comparability of data across different regions and times.

To address this gap, I have developed and tested a broadly applicable classification scheme that focuses on the structural components, both natural and artificial, of tropical coastal wetlands, which is far more applicable in contemporary times given increasing development expansion in coastal areas. This simple and rapid assessment tool provides information useful for managers challenged with approving new development, while at the same time protecting and enhancing coastal ecosystems.

To do so, the classification scheme incorporates the following characteristics:

1) Be broad enough for application and generalisation to a wide range of coastal wetland ecosystems.
2) Provide local-scale information on the structural composition and attributes of an ecosystem in a specific spatial level and tidal zone.
3) Incorporate both natural and artificial elements in the scheme.
4) Be adaptable to include new classes and/or hierarchical levels and able to be updated, so that location-specific variants can be included in the scheme.
5) Permit the rapid assessment of a large range of coastal wetland ecosystems and the production of detailed maps of their structural composition.
6) Provide a standardised way to assess type and extent of structural modification linked to coastal expansion.
7) Use clear definitions and consistent terminology to reduce risk of ambiguity.
8) Provide easily identifiable and homogenous ecological units to describe and map the structural composition of the ecosystem. In this classification such units are called "Structural Habitats", abbreviated as "HABs".
9) Provide information in a format relevant and applicable to a wide range of stakeholders, regardless of their level of scientific knowledge.
10) Be structured to allow consistency and repeatability to other ecosystems/regions.
11) Provide location-specific information that value-adds to broader classification schemes.
12) Focus on components that can be linked to ecosystem connectivity, processes, and services.

2.2 Materials and methods

2.2.1 Procedural steps for the development of the classification scheme

The sequential steps followed to develop, test, and validate the classification scheme are listed below and visualised in Figure 2.

1) Review of existing classification schemes at national (Australia) and international level.
2) Identification of the biological and physical attributes to be included in the proposed classification scheme. Since this classification scheme focuses only on the structural components of an ecosystem, chemical attributes were not included.
3) Selection of the individual classes to be used to categorise each attribute, and the metrics used to measure them.
4) Definition of scale, resolution, and spatial parameters for application of the classification scheme.
5) Field-test the classification in a model urbanised wetland ecosystem (Ross Creek, Townsville) to test the feasibility, consistency, and meaningfulness of the classification scheme.
6) Presentation of the classification scheme to experts from different relevant backgrounds (*i.e.* researchers, managers, city council members, and representatives of the community) to obtain feedback on applicability and relevance.
7) Integration of the results and feedback obtained to adjust and improve the scheme.

Finalisation of the classification scheme based on field tests and expert review.

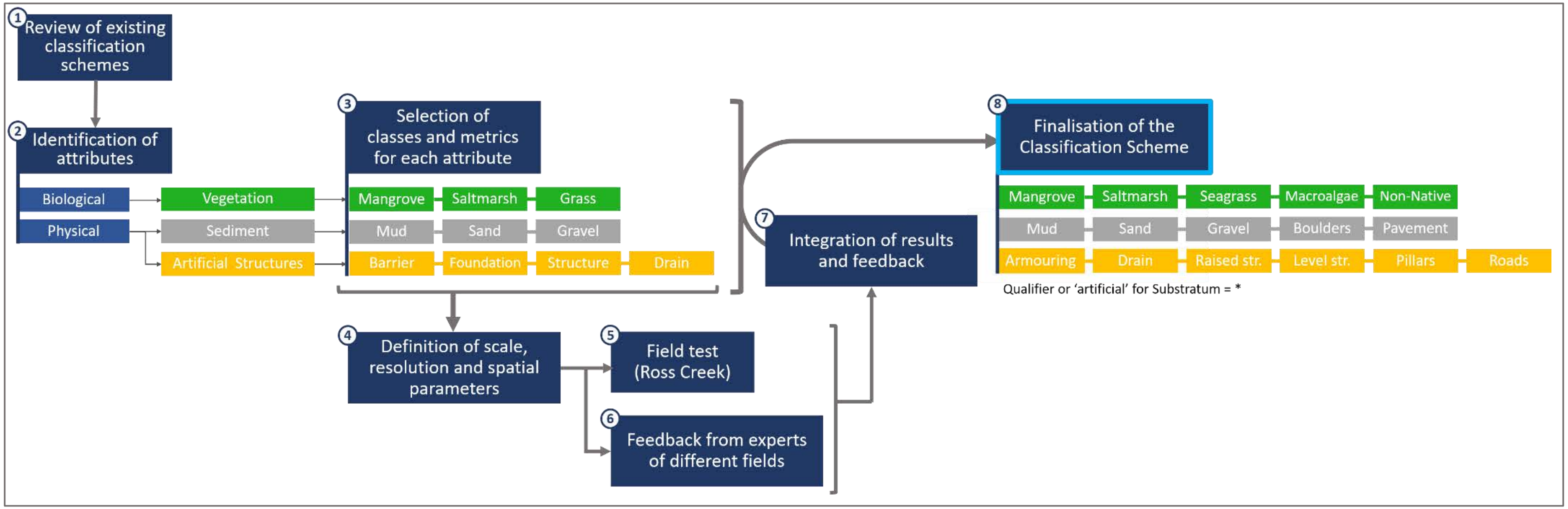


Figure 2. Conceptual flowchart of the process followed to develop and finalise the proposed classification scheme.

A detailed description of each of the sequential steps followed for the development, testing, and finalisation of the proposed classification scheme is presented in the sections below (sections 2.2.2 to 2.2.6).

2.2.2 Step 1: Review of existing classification schemes

A review of existing classification schemes from around the world was carried out to explore the current knowledge and tools available for the classification of coastal ecosystems and to identify relevant features to be integrated in this work. Web search engines Google, Google Scholar, Web of Science, and Science Direct were used to access peer reviewed publications and available technical reports on classification schemes developed for coastal and/or marine ecosystems. The keywords “classification scheme”, “scheme”, “marine”, “coastal”, “wetland”, “mapping”, “ecosystem”, “habitat”, “ecology”, “national”, and “international” were used individually and combined to perform a first selection of the literature. The following four criteria were used to select the publications/reports to be analysed: a) the document should describe a classification scheme for marine and/or coastal ecosystems, b) the classification must be aimed at describing or categorising ecosystems based on measurable physical, chemical and/or biological parameters, c) details on the scope, scale, parameters used, and hierarchical layers of the classification must be described, and d) the document should not consist solely of a case study where the classification scheme was applied, but rather describe in detail the development and wide applicability of the method.

The 33 publications resulting from this selection (Table 1) were examined to obtain information on the process and criteria used to develop each scheme. Objectives, scope, geographical location, scale, parameters used, and classes developed were recorded for each scheme. Conceptual and practical gaps of individual classification schemes were also recorded (Appendix 1b). The information collected was then used as a frame of reference for the development of the structural classification scheme presented in this study.

2.2.3 Steps 2-3: Identification and selection of attributes and classes

The selection of appropriate ecological parameters to focus on and their subdivisions (or ‘classes’) was the first step undertaken for the development of a consistent, detailed, and scientifically complete classification scheme.

Structural elements were chosen among the different biological, physical, and chemical attributes of an ecosystem as the core parameters of this classification scheme. Knowledge of the structural composition is essential for the characterisation and mapping of an ecosystem. Structural elements are also directly impacted by development works for urban, industrial, and agricultural purposes (Benfield *et al.* 2005; Hamilton and Gehrke 2005; Polidoro *et al.* 2010; Thrush *et al.* 2004). The most common structural alterations caused by development are introduction/removal of sediment, vegetation clearing or thinning, and introduction of artificial features and structures. Structural elements, such as vegetation, sediment type, and artificial features, also play an important role in influencing the presence and distribution of biota in an ecosystem (Gray 1974; Martin *et al.* 2005; McKee 1993; Wallace 2011). Inclusion of structural elements in assessment protocols is therefore relevant also for the evaluation of the status, composition, and distribution of the biotic communities of an ecosystem (Pihl 1986; Zajac 1999). As such, the structural classification scheme presented here focuses on three physical attributes: sediment, vegetation, and artificial structures or modifiers.

2.2.3.1 Sediment

Sediment is the primary structural element of most ecosystems (Thornton *et al.* 1995). Natural coastal wetlands in tropical regions are primarily characterised by small-particle sediments such as mud, clay and sand (Badarudeen et al. 1996). Hard sediments and rock formations can be found as well, albeit less frequently. In modified ecosystems larger sediment size fractions such as cobbles and boulders can be used as armouring structures to assist with bank stability and prevent erosion (Smith and Chapman 1982).

Particle size of unconsolidated substrates was used to categorise the different classes of the attribute 'Sediment'. A modified version of the Wentworth (1922) particle size chart was used. Sediment was grouped in three major classes to be used as subdivisions or layers for the classification scheme: mud (particle size <0.063mm), sand (between 0.063mm and 2mm), and gravel (>2mm) (Table 2). Silt and mud were grouped together under 'mud' since their difference in particle size may be considered negligible for a structural classification at an ecosystem scale. The class 'gravel' included substrates ranging from granules (2-4mm) to boulders (>256mm) and combined all unconsolidated hard substrate types that can be found in an ecosystem (*e.g.* an estuary). Where man-made hard structures (*e.g.* cement slopes and brick inclines) fully replaced unconsolidated substratum (mud/sand/gravel), the sediment type was marked as 'absent' and replaced by the artificial feature 'foundation' (see section 2.4.3).

Table 2. Sediment classes selected for the structural classification criteria based on particle size

SEDIMENT		
Mud	**Sand**	**Gravel**
<0.063mm	0.063mm-2mm	>2mm

2.2.3.2 Vegetation

Vegetation cover and plant diversity are factors frequently used in landscape planning and management as important indicators of ecosystem status and composition (Lindenmayer *et al.* 2008). Native vegetation is also often a core element for many ecological restoration projects of areas impacted by development (Lindenmayer *et al.* 2008). In this classification wetland vegetation was grouped in three major classes (mangrove, saltmarsh, and terrestrial grass) following the information available in literature and from the Department of Environment and Heritage Protection (DEHP) 2017 (Table 3). Since this classification scheme focuses solely on the structural role/characteristic of vegetation, taxonomical differentiations such as information on genus and species of plants were not considered.

Table 3. Vegetation classes selected based on the type of flora commonly found in tropical wetlands.

VEGETATION		
Mangrove	**Saltmarsh**	**Grass**

2.2.3.3 Artificial structures or modifiers

A review of existing literature on developed/urbanised wetlands was carried out to create a list of artificial structures and modifiers commonly found in these ecosystems. Relevant peer reviewed publications were identified using the following keywords and their combinations: "urbanised wetland", "estuaries", "piers", "pontoons", "boat ramps", "weirs", "storm-water drains", "artificial structures", "bank armouring", and "coastal construction".

Based on the data generated in this literature search, the following four classes were created (Table 4):

- Barriers: any continuous structure that impedes the settlement or landward movement of vegetation (*e.g.* brick walls, concrete slopes, boulder breakwaters, weirs);
- Foundations: any man-made structure/element replacing or functioning as substratum (*e.g.* cement slopes, boulder inclines, rubble, walkways, roads);

- <u>Structures</u>: bridges, pontoons, floating piers, ramps and pillars. All smaller objects were recorded as 'garbage' (*e.g.* abandoned shopping trolleys, chains, anchors, nets), and thus excluded from the results; and

- <u>Stormwater drains and pipes</u>: these were considered separately from the other structures, being permanent features that discharge surface waters that potentially would transfer nutrients/pollutants from the land to adjacent estuaries.

Table 4. Artificial structure and/or modifier classes grouping the different anthropogenic features that can be found in a wetland ecosystem.

ARTIFICIAL STRUCTURES/MODIFIERS			
Barrier	**Foundation**	**Structure**	**Stormwater drain**
breakwaters	armouring	bridges	drains
cement slopes	breakwaters	piers	outlets
fences	cement slopes	pillars	
walls	ramps	platforms	
weir	rubble	pontoons	

Once the structural attributes to be used in the classification scheme (*i.e.* sediment, vegetation, and artificial structures/modifiers) and their classes were defined, the next step was to determine the measurement criteria to be used in assessing their presence. Each attribute listed is measured in the form of 'presence/absence' of the different classes. This allows for equal assessment of the three attributes as well as a clear-cut subdivision of an ecosystem in standard and repeatable structural habitats. In the context of this thesis a 'structural habitat' is defined as a continuous spatial unit characterised by the presence of one or more of the ten classes (3 sediment, 3 vegetation, and 4 artificial structures/modifiers) recorded in a specific tidal range. Each distinct combination of classes observed corresponds to an individual habitat type and is labelled with a unique code formed by the prefix 'HAB-' followed by a number (in order of appearance during the first field assessment): *e.g.* the fourth combination of classes identified would be labelled as HAB#04.

Additionally, habitats without plants were labelled as 'unvegetated' (UNVEG), while habitats with at least one plant type present were labelled as 'vegetated' (VEG). Such classification is often used in landscape management as an indicator of ecosystem status and composition (Lindenmayer *et al.* 2008). The presence of artificial structures or modifications was used as an indicator of human development and alteration. Thus, habitats without artificial features were labelled as 'natural' (NAT), while habitats with at least one artificial feature were labelled as 'modified' (MOD).

A ‘habitat patch’ is defined as a continuous spatial unit with clearly defined boundaries that is occupied by a single structural habitat (Figure 3). The combination and distribution of all habitat patches in a study area represents the ‘habitat configuration’. The extent of each habitat patch (*i.e.* ‘habitat patch extent’) is defined as the measurement in meters (m) of the linear distance from end to end (lengthwise) of the patch (Figure 3). For habitats that occur more than once in the same study area, their overall habitat extent (*i.e.* ‘habitat extent’) is calculated by summing the values of the individual habitat patch extents for that particular habitat type mapped in the study area.

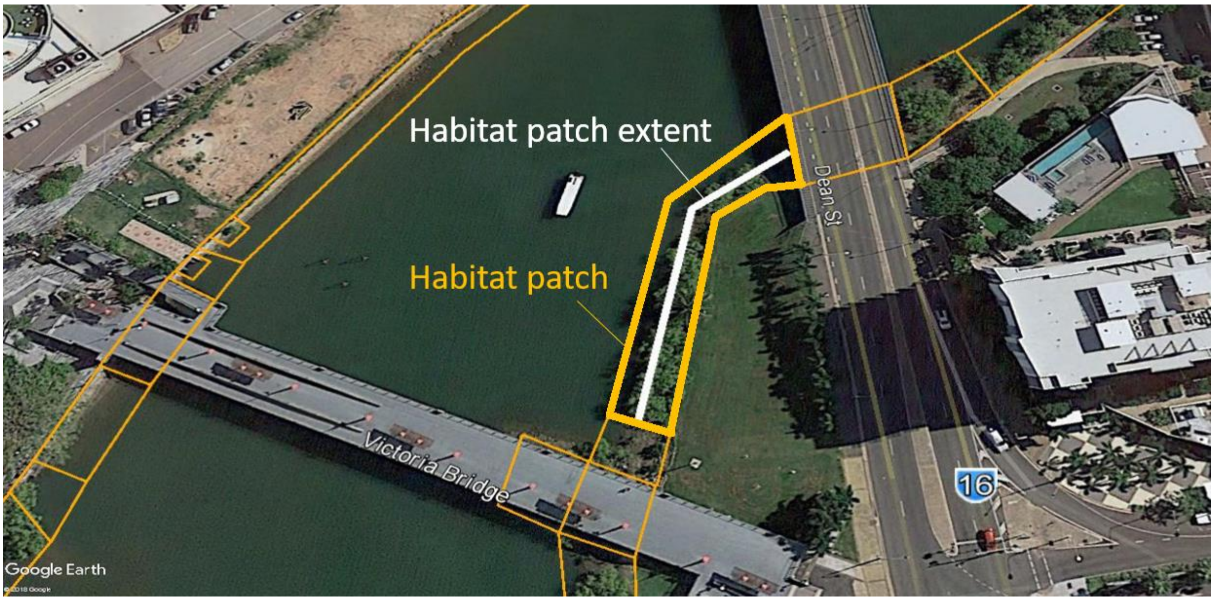


Figure 3. Example of habitat patch (in orange) and habitat patch extent (in white) in an estuary.

2.2.4 Step 4: Scale, resolution and spatial parameters

The classes chosen for each attribute were selected considering the scale at which the classification criteria would be applied. The spatial levels described in the Australian National Aquatic Ecosystem Classification Framework (ANAE) (AETG 2012) were used to determine spatial scale (Figure 4).

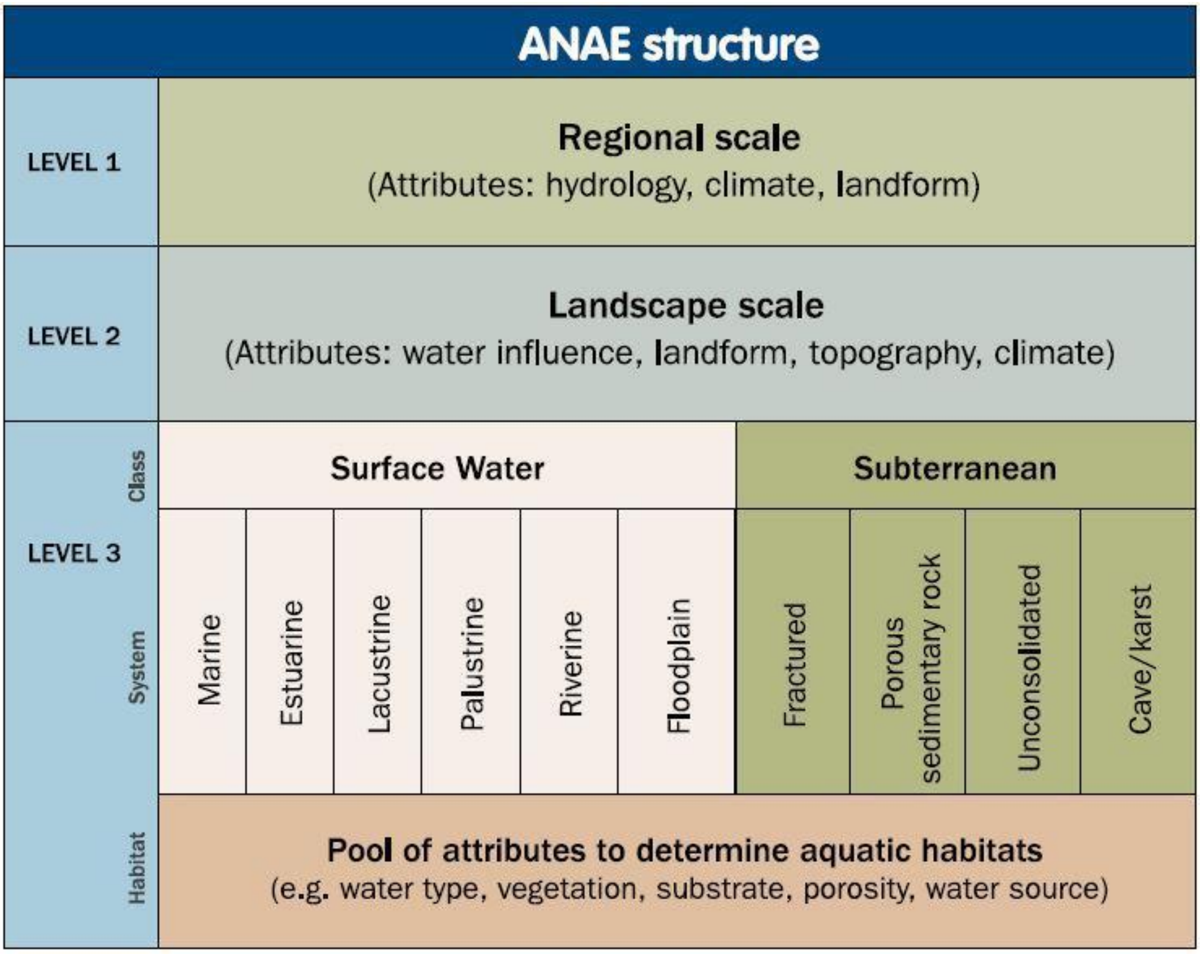


Figure 4. Structure and levels of the Interim Australian National Aquatic Ecosystems Classification. Adapted from: Aquatic Ecosystems Task Group (2012). Aquatic Ecosystems Toolkit. Module 2. Interim Australian National Aquatic Ecosystem Classification Framework.

Level 3 (system) was determined to be the most suitable scale to characterise the structural components of an ecosystem. This scale was also deemed relevant for coastal management and development planning. Several artificial structures and modifiers such as boat ramps, pontoons and storm-water drains are in fact relatively small (ranging from 1 m – 10 m) and visible only at small-scale resolutions. Another factor that influenced scale for the application of this model is the spatial range of movement, and distribution of several faunal species typical of wetlands. Most of the species inhabiting wetlands are invertebrates with a relatively small range of movement throughout their adult lives (Batzer and Boix 2016; Gopal and Junk 2000). Faunal communities in these ecosystems can therefore vary greatly in composition and abundance between areas of small size. Ecological assessments focusing on habitat utilisation and species assemblages need to be conducted at a scale relevant for the local biota. The classification scheme described in this work should therefore be applied at a within-ecosystem scale: optimal at 1:5000, but extendable to 1:10000, and has a minimum mapping unit of 1 m^2.

The intertidal zone (undifferentiated between lower-mid-high) was selected as the target for the application of this classification scheme. The supratidal zone was excluded since this classification scheme focuses on coastal wetland ecosystems. The subtidal zone was excluded due to practical issues such as poor water visibility and the presence of crocodiles in this region. Additionally, the intertidal zone of tropical estuaries is characterised by high distribution and richness of macro-benthic fauna which play an essential role in the ecological functioning and services of these ecosystems (Sheaves *et al.* 2016).

2.2.5 Steps 5-6: Testing of the model and expert feedback

To assess the feasibility, consistency and meaningfulness of the classification scheme described above, a field test was conducted in a model urbanised estuary: Ross Creek (Townsville, Australia) (Figure 5). This tropical estuary, while relatively small in size with its 5 km length, runs through the most populated city in northern Australia (approximately 190,000 people; Townsville City Council 2018a). Ross Creek is classified as the most modified ecosystem in the Great Barrier Reef World Heritage Area (Waltham and Sheaves 2015) and represents an exemplary case study of the interface between urbanisation and ecological processes. Ross Creek has had over 150 years of urban modification and intensification, manifested through alterations of riverbank morphology, changes in hydrology, removal of vegetation, and introduction of artificial features. Despite such extensive modifications, several areas along this creek are fringed with thick patches of mangroves and saltmarsh, and past surveys have determined the presence of numerous invertebrate, bird, and fish species (Webb 1999), including a subset of fish species with life cycle linkages with the Great Barrier Reef (Sheaves and Johnston 2010). Considering these characteristics, the availability of historical records and data, and the plans for further development along the foreshore area of Ross Creek (Waltham 2016), this estuary represents a suitable ecosystem to test the applicability of the structural habitat classification scheme proposed in this study.

Figure 5. Map of the Townsville region with highlighted field test area of Ross Creek.

Fieldwork was carried out along both banks of the creek starting from the furthest reach inland at Queens Road (19°16'S, 146°48'E) and ending at the Breakwater Marina (19°15'S, 146°49'E) at the mouth of the estuary. The combined length of Ross Creek riverbanks measured 8.8 km: 7.8 km were directly accessed from land, while 1 km could not be accessed directly due to private land access limitations and was thus examined from a distance (5 m – 100 m). Visual and photographic data were recorded along the intertidal zone at low tide every three months in the period August 2016 – March 2017 to record the composition and configuration of the different habitats found in Ross Creek. Assessments were performed individually by four different observers to verify the consistency in the application of the classification scheme. No differences in the identification of the structural habitats resulted from the individual assessments. Habitat composition was evaluated by listing the different habitats present in the intertidal zone of both riverbanks. The spatial configuration of structural habitats along the riverbanks was mapped by using landmarks and photographic evidence. A GPS was initially used during a test run to mark coordinates of each structural habitat edge, however the margin of error of a few meters associated with the GPS devices resulted too great to allow for accurate mapping, particularly considering that several structural habitat patches were smaller than 5 meters from edge to edge. A map of the distribution and extent of the habitats identified was then prepared using a combination of aerial mapping (source: Google Earth) and ground-truthing (photographic evidence and landmarks recorded in the field).

Fifty-five different structural habitats were identified in Ross Creek. All ten classes belonging to the three structural attributes were observed throughout the estuary. Mud and gravel were the most common sediment types, present in 34 and 35 of the habitats, respectively, while sand occurred in 19 only. Mangrove trees, although the prominent feature of Ross Creek vegetation, were present in 21 habitats, often as narrow bands (<5 m thickness landward) along the riverbank. Saltmarsh succulents were found in 12 habitats, and wetland grass was found in 9 habitats.

Thirty-one habitats exhibited at least one artificial structure, the most common type being stormwater drains. Artificial structures of the 'foundation' group – *i.e.* cement slopes and boulder inclines – were found in 19 habitats. Structures such as bridges, pontoons, boat ramps and floating piers were present in 11 habitats. Physical barriers such as vertical walls and brick embankments where the least common artificial structure, observed in 5 habitats of the 55 identified.

The use of the classification scheme described in sections 2.2 and 2.3 led to simple, straightforward, and rapidly generated data relating to the habitat composition and mosaic configuration of the ecosystem assessed. Nevertheless, observations during the field testing and after analysing the data highlighted the need for alterations to improve the methodology.

The classification scheme was also presented and described in detail to several experts from different fields and backgrounds to obtain feedback on its applicability and relevance. These people were identified as the 'pilot test group'. The preliminary model was presented at the 2017 scientific conference of the Australian Marine Sciences Association (Darwin, Australia), during lectures and special topic events at different institutions around Australia (James Cook University, University of New South Wales, Manly Hydraulics Laboratories, NQ Dry Tropics, TropWATER, CSIRO), at a city council meeting (Townsville), and during meetings with representatives of the public in Townsville. Overall, the classification scheme was received with high interest and considered to be both adequate and suitable for application in research and management. Feedback and comments provided was used to further refine the classification methodology. The changes are detailed in the section below.

2.2.6 Steps 7-8: Finalisation of the classification scheme

After the field test and feedback provided by the pilot test group consulted (see section 2.2.5), the following definitions and adjustments were made (Tables 5-6-7):

- The 'sediment' attribute was renamed as 'substratum'.
- The difference in size between boulders and the other unconsolidated hard substrates was considered too great for a single common class. Boulders were therefore separated and introduced as a class separately.
- A 'pavement' class was introduced to represent undifferentiated consolidated substrates such as bedrock and cement.

Table 5. Updated sediment classes selected for the structural classification criteria based on particle size and consolidation.

SUBSTRATUM				
Mud	**Sand**	**Gravel**	**Boulder**	**Pavement**
<0.063mm	0.063mm-2mm	2.1mm-256mm	>256mm	consolidated

- In the 'vegetation' attribute the class 'grass' was removed due to its substantial absence in intertidal and subtidal zones.
- 'Seagrass' and 'macroalgae' classes were added to the vegetation attribute.
- The class 'non-native' was introduced to represent any form of exotic or non-native vegetation intentionally introduced in the intertidal zone of wetlands (e.g. ornamental plants, exotic trees, or artificial forests/gardens).

Table 6. Updated vegetation classes selected based on the type of flora commonly found in tropical wetlands.

VEGETATION				
Mangrove	**Saltmarsh**	**Seagrass**	**Macroalgae**	**Non-Native**

- The 'artificial structures/modifications' attribute was renamed as 'artificial features'.
- Due to the overlap between some of the classes within the artificial features attribute (*e.g.* brick wall being both a 'barrier' and a 'substratum') as well as with some of the substratum classes (*e.g.* boulders introduced as bank armouring being both 'gravel' and 'substratum'), the classification of the attribute 'artificial features' was changed to the following classes:
  - Armouring: this class indicates whether one or more of the substratum classes have been artificially introduced to prevent erosion or to strengthen the riverbank.

- Drain: this class remains unchanged and represents the presence of any pipe, drain or outlet that introduces (uninterruptedly, periodically or just following flooding events) water into the ecosystem.
- Raised (structure): any artificial structure that extends over the water and is supported by pylons or columns. It includes bridges, piers, docks, and other permanent raised structures.
- Level (structure): any artificial structure built fully in contact with water that serves the purpose of a landing stage for vessels. It includes boat ramps, jetties, pontoons, and other permanent floating platforms.
- Pillars: any permanent supportive structure in use or abandoned.
- Roads: pathways, roads and tracks caused by or laid for vehicle transit.

- The qualifier symbol '*' was introduced to indicate whether the individual substratum classes recorded in a habitat are natural in origin or have been artificially introduced or are a result of the degradation of artificial structures. Its role is to help distinguish between 'natural' and 'artificial' substratum (*e.g.* natural rocks vs. armouring boulders; natural bedrock vs. pavement or cemented slopes) and facilitate the distinction and labelling of individual habitats as either NAT or MOD. This symbol is to be placed immediately after the acronym of each artificial substratum class. Modified (MOD) habitats are defined as habitats that have at least one artificial feature or one class of substratum that has been artificially introduced (marked by the qualifier '*'). Natural (NAT) habitats are defined as habitats without any artificial feature or artificially introduced substratum.

Table 7. Updated artificial feature classes grouping the different anthropogenic elements that can be found in a wetland ecosystem.

ARTIFICIAL FEATURES					
Armouring	**Drain**	**Raised**	**Level**	**Pillars**	**Road**

- Habitat nomenclature was also changed from the numerical 'HAB#n' naming to a descriptive and sequential one that expresses more clearly and in detail the different classes found in a given habitat. All classes were given an abbreviation or acronym as symbol to be used in the nomenclature process of the different habitats, as shown in Table 8.

Table 8. List of the sixteen different classes belonging to the three structural attributes, and their corresponding abbreviation in the scheme.

	SUBSTRATUM					
Class	**Mud**	**Sand**	**Gravel**	**Boulder**	**Pavement**	
Symbol	MUD	SAN	GRV	BLD	PAV	
	VEGETATION					
Class	**Mangrove**	**Saltmarsh**	**Seagrass**	**Macroalgae**	**Non-Native**	
Symbol	MG	SM	SG	MA	(NN)	
	ARTIFICIAL FEATURES					
Class	**Armouring**	**Drain**	**Raised**	**Level**	**Pillars**	**Roads**
Symbol	(A)	(D)	(R)	(L)	(P)	(RD)

* = Qualifier of 'artificial' substratum

Habitat names are created by concatenating in the following sequential order the symbols of the different classes found in each individual habitat: substratum-vegetation-artificial features. The symbol '*' is to be placed after the acronym of the relevant substratum class when it is artificial in origin.

Example:
A habitat having a combination of mud and gravel (the latter originated from construction rubble) with mangroves and a pier will therefore be named: MUD-GRV*-MG-(R).

Such nomenclature not only permits the immediate identification of the structural components of a habitat in absence of photographic and/or map material, but also assists with the assessment of potential structural connections among habitats. Moreover, this nomenclature allows for the hierarchical placement of structural habitats based on their characteristics and potential identification of patterns of change and levels of modification (Figure 6).

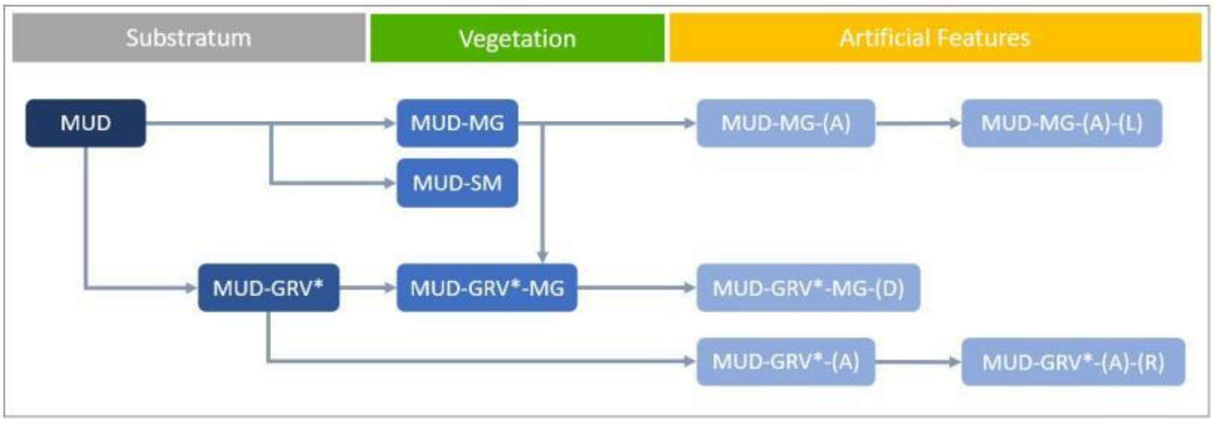


Figure 6. Example of hierarchical placement of structural habitat types based on their structural characteristics and added features/modifications. The base habitat 'MUD' can generate or change into several different habitat types with the addition of one or more other structural elements.

The option of creating hierarchical connections between different habitat types is a useful tool to hypothesise patterns of change in the structural composition of an ecosystem. The information can then be complemented with data collected on the influence of different structural features/habitats on species assemblages to evaluate effects over time of development works on local biodiversity. Knowledge of how different structural modifications affect the ecosystem and change over time would be useful in ecological restoration to prioritise areas for intervention and in further development plans to identify strategies to minimise impacts on the ecosystem connectivity, processes, and functioning. For instance, a habitat having artificial gravel (GRV*) located downstream of a habitat characterised by artificial pavement (PAV*-(A)) could be the result of an ongoing, progressive degradation process. The deterioration of the pavement with time could contribute to the formation of cobbles and rocks that have been gradually transported downstream during high water flow, and then deposited in a different habitat on an accretion bank. Alternatively, a large section characterised with bare mud (MUD) with a small habitat patch of mud with mangrove plants (MUD-MG) located at the seaward fringe could indicate the beginning of a (re)colonisation or recruitment response.

The newly updated classification scheme was then submitted again for evaluation by a subset of the original reviewers and deemed simple in its application as well as relevant in generating data outputs for both research and management. Once finalised, the scheme was then applied for the assessment of the habitat composition and configuration of four estuaries in the Townsville region subjected to different levels of urban development. The assessment was carried out to further test the ability of this classification to rapidly and accurately assess different estuaries regardless of their size or their extent of modification.

2.3 Discussion

The increasing rate of development in coastal regions, particularly in tropical areas, means that more effective plans for the conservation of existing resources and restoration of affected areas at a local scale are critically needed (Foley *et al.* 2010; Moberg and Rönnbäck 2003; Rogers *et al.* 2016). In-depth knowledge on the composition, status, functioning, and services of an ecosystem will assist managers in making informed decisions with respect to ecosystem-based management (Airoldi and Beck 2007; Moberg and Rönnbäck 2003; Morrissey *et al.* 2012). Such information is often not available or applicable at a local scale, does not include artificial features as components of an ecosystem, and its acquisition requires extensive work with timelines and budgets that are in conflict with those available for development and landscape management. Many existing ecological assessment tools such as classification schemes and mapping protocols have been developed for scales coarser than those at which urban and industrial development take place and present several issues that still need to be addressed (Appendix 1b). High variability in scale, resolution, and parameters are often contributing problems that lead to the development of many different approaches for the classification of the same ecosystem. Additionally, the variety in methodologies employed for the collection of data (as well as sampling size/frequency) increase the likelihood of limitations and further obstacles to the comparability of the data collected. Alongside the lack of standardised rapid assessment protocols that provide information relevant at a local scale, there is also an overall lack of integration of anthropogenic features as detailed 'classes' or 'layers' of these classification systems (see sections 1.2 and 1.3). Complete and thorough description of the physical and structural characteristics of an ecosystem is required for proper assessment and planning. Considering the prevalence of human structures and modifications along coastlines and their effect on the environment (Barwick *et al.* 2004; Becker *et al.* 2013; Bulleri and Chapman 2010; Dugan *et al*. 2011; Mayer-Pinto *et al.* 2018), the integration of such factors in classification schemes is essential for the objective of management and conservation. As such, standardised schemes for the classification of all structural components present in an ecosystem provide information to be applied for the prevention of adverse impacts in future development and for restoration of areas already affected (Baker and Harris 2020; Davidson-Arnott *et al.* 2019; Guarinello *et al.* 2010).

The classification scheme for structural habitats of tropical coastal wetlands presented in this study was developed with the intention of complementing existing classification schemes at a finer scale and providing a template applicable to other ecosystems (*e.g.* freshwater or beaches) and geographical areas (*e.g.* temperate and polar). This classification is a simple, cost-effective and rapid assessment tool for mapping and acquisition of information on the structural composition of tropical coastal wetlands. The information collected is presented in a way that quickly provides standard ecological units (*i.e.* structural habitats) that can be investigated further either individually or as a mosaic to suit the requirements and objectives of end-users. Information on chemical or other environmental variables can be easily integrated to this scheme. Combining information on the composition, distribution and potential relationship among habitats of an ecosystem with historical data and/or other environmental parameters will assist in developing an in-depth understanding of the status of an ecosystem. Additionally, the use of ecological units allows for the linking of structural elements with faunal communities, ecosystem processes, and services. Knowledge of the ecological composition, status, functioning, and services of coastal ecosystems that are directly or indirectly affected by human presence/expansion can then be easily applied by different end users (*e.g.* researchers, managers, and officials) to achieve objectives and outcomes set.

This classification scheme can be easily applied to other coastal ecosystems and locations thanks to its simple framework and flexibility, thus providing a standard template that would increase the comparability of information collected in different areas. New structural classes can be added accordingly based on the characteristics of other coastal ecosystems around the world without compromising the core structure, applicability, and type of information provided by this classification scheme. The language and standard ecological units also ensure that the classification can be used by stakeholders from different areas of expertise, thus contributing to bridging the communication gap between research, management, and development.

This classification scheme also addresses several gaps currently present in most existing assessment tools (see Chapter 1): 1) It focuses on a scale and resolution suitable for local management decisions with the possibility to assess structural habitats ranging from a few meters to several kilometres. This can be applied in the context of small-scale management (*e.g.* a city council addressing the introduction/change of a stormwater drain) as well as large scale development (*e.g.* the armouring of a long stretch of riverbank against erosion); 2) It includes artificial features as structural elements of an ecosystem, thus allowing the comprehensive evaluation of the type and extent of structural modification present in an ecosystem as consequence of progressive development; 3) It provides a standardised and user-friendly method to rapidly assess the structural composition of an ecosystem.

This basic and rapid assessment tool allows managers and stakeholders to be in a stronger position to make informed decisions, adequately plan for development while maximising the conservation of natural resources or the restoration of affected areas at a local scale. Integrated approaches for landscape management and ecosystem-based management are essential to balance the need for human expansion with the duty to preserve or restore as much as possible the ecological resources available and related services (Foley *et al.* 2010; Foley *et al.* 2013; Moberg and Rönnbäck 2003; Morrissey *et al.* 2012; Rosenberg and McLeod 2005). The integration of this classification as a standard for development planning and restoration efforts would facilitate the prioritisation of intervention and potentially increase the successful achievement of set environmental goals.

The next step in this research is to apply the newly developed classification scheme to four tropical estuaries exposed to different types and extents of development over the decades. The composition and configuration of structural habitats in the different estuaries was mapped and then used to assess the influence of presence and change in structural elements on local faunal assemblages.

Chapter 3

Structural habitat configuration of estuaries exposed to different extent of urban development.

3.1 Introduction

Throughout history, coastal wetlands and estuaries have been modified by urban expansion and land conversion for agricultural or fisheries use (Diegues 1999; Ehrenfeld 2000; Wolanski and Elliott 2015; Yeung 2001; Zhang *et al.* 2013). The geomorphological and ecological composition of these ecosystems are modified by development (McKinney 2008; Wolanski and Elliott 2015), with changes ranging from minor local alterations to radical transformations (*e.g.* El Banna and Frihy 2009; Surian and Rinaldi 2003). Changes to the geomorphology of wetlands and estuaries include: alteration of the shape of channels, riverbanks, or shorelines (Dallas and Barnard 2011; Isik *et al.* 2008; Surian and Rinaldi 2003), removal or substitution of natural sediment (Isik *et al.* 2008; Jia *et al.* 2006; Wienberg and Bartholomä 2005), and introduction of artificial features (French 2002; Isik *et al.* 2008). Geomorphological changes can lead to alterations in the hydrology and erosion/accretion patterns of an ecosystem – particularly in areas comprising fine-grained sediments (El Banna and Frihy 2009; Hapke *et al.* 2013; Richter *et al.* 2003). Bank armouring and the engineering of permanent artificial structures reduce the natural lateral migration of waterways and coastlines (Gregory 2006; Hohensinner *et al.* 2004; Richter *et al.* 2003), and the ability of these ecosystems to evolve over time (Hapke *et al.* 2013). This results in a loss of resilience and the ability to adapt to changing or extreme environmental conditions such as flooding events, droughts, or geological phenomena (Biron *et al.* 2014; El Banna and Frihy 2009). The reduction of vegetation occurring with development and urban expansion also contributes to overall loss of resilience to flooding events and sea level rise (El Banna and Frihy 2009; Lee *et al.* 2006). Changes in vegetation cover (*i.e.* patching, thinning, clearing), landscape modifications, and the introduction of artificial features can result in the loss or fragmentation of natural habitats (Lindenmayer and Fisher 2013), as well as changes to biogeochemical processes; most notably carbon, nitrogen, and sulphur cycles (Lal 2015). Such alterations not only affect the composition of natural ecosystems, but also the diversity of plant and animal species supported by different habitats (Airoldi and Beck 2007; McKinney 2008).

Coastal wetlands and estuaries that have been progressively modified by development – in some cases even over hundreds of years – are likely to have a different structural composition and configuration (*i.e.* types and spatial distribution of substratum, vegetation, and artificial features) when compared to less developed or ‘natural’ ecosystems (Airoldi and Beck 2007; Lee *et al.* 2006; Lindenmayer and Fisher 2013). Such differences in structural composition can equate to changes in the presence, abundance, and distribution of local biota (Alberti 2005; Bulleri and Chapman 2010; Connell and Glasby 1999; Mayer-Pinto *et al.* 2018), in some cases even shifting and becoming novel ecosystems (Hobbs *et al.* 2013). It is important to note however that changes observed in the biotic communities do not necessarily correspond to loss in species richness. Anthropogenic alterations and artificial features can provide new conditions for different species to colonise the area (*e.g.* Bulleri and Chapman 2010; Cermak 2002; Connell 2001). This is a concept also used in ecological restoration and enhancement, such as artificial reefs (Charbonnel *et al.* 2002; Gratwicke and Speight 2005) and ecological engineering (or "eco-engineering") (Browne and Chapman 2011; Dyson and Yocom 2015; Paalvast *et al.* 2012; Strain *et al.* 2018; Todd *et al.* 2019).

Conservation and/or restoration of tropical wetlands and estuaries facing development sprawl requires a clear and thorough understanding of the structural composition and configuration of these ecosystems. As a result, information on the composition and role of different structural habitats of the target ecosystem is essential for the prioritisation of efforts and rapid decision-making.

In this part of my research I selected four model estuaries and used the classification scheme for structural habitats (HABs) (see Chapter 2) as a rapid assessment tool to:

a) Determine the structural habitat complexity of each estuary by assessing their structural habitat composition (*i.e.* list of the types of structural habitats in the area assessed) and structural habitat configuration (*i.e.* the spatial distribution of the different structural habitats in the area assessed).

b) Compare the structural habitat complexity and extent of structural modification of four estuaries exposed to different extents of development.

c) Compare patterns of distribution of structural modification in the four estuaries.

d) Identify the 'dominant' habitats (*i.e.* habitats with the highest measure of habitat extent in the area assessed) for each estuary.

e) Evaluate the differences in proportion of natural-modified habitats and vegetated-unvegetated habitats to examine the role of vegetation and modifications as indicators of ecosystem status.

f) Test the adequacy of the rapid assessment tool in evaluating the structural composition and complexity of a range of estuaries exposed to different extents of development.

3.2 Materials and methods

3.2.1 Study areas

The tropical estuaries examined in this study are located in the Townsville province (-19°15'13.80' S ; 146°49'3.59' E) adjacent to the Great Barrier Reef World Heritage Area (GBRWHA) in North Queensland, Australia. The highly diverse coastal and marine ecosystems characteristic of Queensland are physically and functionally connected in a complex network and provide numerous essential ecological functions and services (Paice and Chambers 2016). In view of the development planned for northern Australia (The State of Queensland 2017), including within and adjacent to the GBRWHA, research focusing on understanding the composition of different estuaries and providing data essential for the development of appropriate management strategies is essential. Management of estuaries along the Queensland coast is relevant also for the broader context of the GBR, particularly when considering that several reef species spend part of their lifecycle in estuaries and nearby coastal ecosystems (Bradley *et al.* 2017). The study area was designed to test the rapid assessment tool for mapping the structural habitat composition of coastal estuaries established in Chapter 2. The Townsville area is characterised by several waterways subjected to different extents of urban/industrial development. Since one of the goals of this study was to assess the impact of anthropogenic development on the structural habitat composition of tropical estuaries, attempts were made to account for and minimise the impact of potential biases caused by naturally occurring differences, as much as possible. Environmental factors that could influence structural composition, such as climatic, water quality, and geomorphic conditions, were thus considered when choosing the estuaries for this study. For this reason, only estuaries characterised by similar geomorphological composition/structure and exposed to the same meteorological events typical of the dry tropics were selected. Four estuaries were chosen for this study (Figure 7).

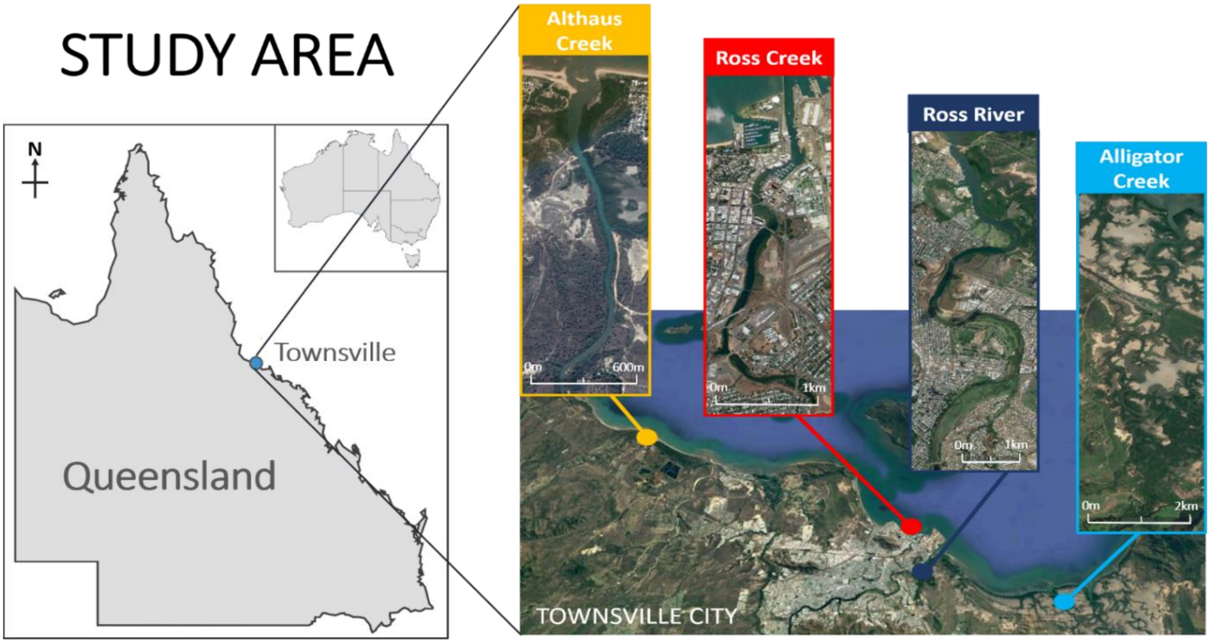


Figure 7. Map of the study area highlighting the four estuaries assessed in this study: Althaus Creek, Ross Creek, Ross River, and Alligator Creek.

<u>1) Ross Creek (RCk)</u> [5 km linear length]

This tropical estuary, while relatively small with its 5 km length, runs through the most populated city in northern Australia (approximately 190,000 people; Townsville City Council 2018a) and is classified as the most modified estuary in the GBRWHA (Waltham and Sheaves 2015). Ross Creek is an exemplary case study of the interface between urbanisation and ecological processes, and how development can progressively shape and change the structure and composition of an estuary. Ross Creek was originally a tributary of Ross River, but its connection with the main river was gradually cut off due to land reclamation and development works carried out in the 50's and 60's for Townsville's expansion (The State of Queensland 2007; The State of Queensland 2011). This estuary could represent what future coastal seascapes might look like given expanding tropical coastal urban and industrial development (State of the Tropics, 2014; The State of Queensland 2017). Ross Creek has been exposed to over 150 years of urban modification and intensification, manifested through alterations of riverbank morphology, changes in hydrology and water quality, removal of natural vegetation along the creek margins, and introduction of infrastructure and artificial features (Browne *et al.* 1994). Despite this, several areas along the creek still support mangrove vegetation, and past surveys have recorded many invertebrate, bird and fish species that utilise this creek (Webb 1999). This includes also a subset of marine fish species with life cycle linkages with the Great Barrier Reef (Sheaves and Johnston 2010).

2) Ross River (RR) [49 km linear length]

Ross River is the major river flowing through Townsville, representing the primary source of freshwater for the city as well as providing several social, environmental and economic services (EPPD 2013). The estuarine section of this river extends from the mouth up to Aplins weir, the first of several built concrete barrages that have been introduced to regulate freshwater flow (Townsville City Council 2018b). Similar to Ross Creek, this estuary supports several sections of continuous wetland along its banks despite having been subjected to decades of urbanisation and port development. As such, Ross River still supports conditions suitable for many vertebrate and invertebrate species typical of local coastal wetlands (Sheaves *et al.* 2012).

3) Alligator Creek (AlCk) [52.5 km linear length]

This estuary is located 12 km South-East of Townsville within the western border of the Bowling Green Bay National Park, a wetland area of international importance and protected under the Ramsar Convention (WetlandInfo 2018a). Alligator Creek has been exposed to limited development on the riverbank due to its location in a national park and in a rural area with low population density (Google Earth 2017a; WetlandInfo 2016). The only visible development along the riverbank is located around the boat ramp of the Cleveland Palms Private Estate community, on the western bank.

4) Althaus Creek (AtCk) [21 km linear length]

This estuary is located near the Saunders Beach community, a sub-urban area 25 km North-West of Townsville, within the Black catchment (WetlandInfo 2018b). Flowing through a rural area, most of the riverbanks of Althaus Creek have remained structurally unmodified, with only few locations downstream, closer to the mouth, that have been cleared to provide direct access to the water for recreational purposes(Google Earth 2017b).

Side channels and tributaries were not included in this survey.

3.2.2 Habitat composition investigation

In the context of this research, ‘habitat composition’ is defined as the list of different types of structural habitats identified in a spatially defined area. The classification scheme presented in this thesis can be applied to assess the habitat composition of areas of different sizes based on the scale and spatial boundaries defined a priori by managers or end-users. Such scales can range from a few meters to entire ecosystems (ANAE level 3 or below) (AETG 2012). The habitat composition of each estuary was assessed by recording the different types of structural habitat present in the intertidal zone of both riverbanks, using the standardised classification scheme for structural habitats of tropical coastal wetland ecosystems (see Chapter 2). In brief, a 'structural habitat' is defined as the combination of one or more of sixteen classes belonging to the structural attributes 'substratum', 'vegetation', and 'artificial features' (Table 9).

Table 9. List of the different structural classes (and their corresponding acronym) to be used for the classification of individual habitats found in natural and modified wetland/coastal areas.

	SUBSTRATUM					
Class	Mud	Sand	Gravel	Boulders	Pavement	
Symbol	MUD	SAN	GRV/GRV*	BLD/BLD*	PAV/PAV*	
Grain size	<0.063mm	0.063mm-2mm	2.1mm-256mm	>256mm	consolidated	
	VEGETATION					
Class	Mangrove	Saltmarsh	Seagrass	Macroalgae	Non-Native	
Symbol	MG	SM	SG	MA	(NN)	
	ARTIFICIAL FEATURES					
Class	Armouring	Drain	Raised structure	Level structure	Pillars	Roads
Symbol	(A)	(D)	(R)	(L)	(P)	(RD)

Qualifier of 'artificial' for Substratum = *

The intertidal zone (mean low water spring tide to mean high water spring tide) was selected as the target section to be mapped since most artificial structures are set in this range. Additionally, physical alterations of the banks such as armouring, land reclamation and vegetation clearing are usually performed in intertidal areas (Chen et al. 2016; Dugan *et al.* 2011; Richards et al. 2016). All surveys were carried out during low spring tides to allow full access to the intertidal zone of each estuary for a complete and thorough mapping of its structural habitats.

The sectors of each estuary characterised and mapped in this survey are the following:

RCk (4 km assessed of 5 km total): from the ferry terminal located at the mouth of the creek until the furthest reach upstream (delimited by Queens Road).

RR (10.9 km assessed of 49 km total): from the mouth of the river (delimited by Southern Port Road) until Aplins weir, the first barrage from downstream that separates the estuarine section of the river from the freshwater section.

AlCk (14 km assessed of 52.5 km total): from the mouth of the creek until the first weir located upstream.

AtCk (2.5 km assessed of 21 km total): only the first 2.5 km measured from the mouth of the creek could be assessed due to limitations in the accessibility of the estuarine sections bordered by private properties. The water in the creek at low tide was too shallow to allow the use of a vessel to access the intertidal zone, but deep enough in some sections to represent a danger for the surveyors to wade in the water (due to the presence of estuarine crocodiles in the region).

It is understood that due to the difference in length of each sector assessed for the four estuaries (as they represent the estuarine section of each of these waterways), careful consideration has to be applied when interpreting the data and results obtained.

The surveys were carried out by walking in the intertidal zone of each riverbank moving from the mouth of the estuary to the highest reach upstream (or otherwise defined limit of the estuarine area). On some occasions, due to sufficient water depth at low tide, a vessel was used to assist in reaching remote or hard-to-access locations. Surveys were repeated periodically from October 2016 to March 2018 to ascertain the consistency of results through the different meteorological events, which could have affected the presence, composition and distribution of sediment and vegetation (*e.g.* heavy rains, flooding, and cyclones). Surveys for the four estuaries were conducted during spring tides as follow:
Round 1: Oct-Nov 2016
Round 2: May-June 2017
Round 3: Aug-Sept 2017
Round 4: Feb-March 2018

Visual/photographic assessments and granulometric analysis were employed to determine the presence of each structural class at a given location:

- Substratum classes were assessed by sieving three subsamples of sediment (500 mL) collected from the top 5 cm horizon, where possible, for particle size fractionation of the finer sediments. A tape measure was used for the classification of gravel and boulders. Locations with consolidated sediment were marked as 'pavement'. A further visual analysis and comparison with historical records was carried out to determine whether the sediment classes at each location were of natural or anthropogenic origin (*e.g.* armouring, rubble, detritus). The symbol '*' was added after the acronym of each sediment class deemed 'of artificial origin'.

- Vegetation classes were determined by identifying the plants observed at each location as either mangrove trees or saltmarsh plants (no seagrass or macroalgae were observed in this survey). Following the classification scheme for structural habitat of intertidal wetlands, vegetation observed in the field were as such classified as 'Mangrove' (MG) or 'Saltmarsh' (SM). No taxonomic identification was carried out.

- Artificial features were classified based on the structural characteristics and position of man-made elements located in the intertidal zone. Photographic evidence was used to record artificial features.

Each habitat type identified was labelled with a unique name created by concatenating the acronyms and symbols of the structural classes it is formed of, in order of appearance left to right and top to bottom as shown in Table 6. Example: a habitat formed by mud, artificial gravel, and mangroves would be recorded as 'MUD-GRV*-MG'. The position and extent of each habitat along the banks of the estuary was recorded on a paper map in the field using photographic evidence and landmarks to record the exact position and later digitised. GPS devices were not used due to their margin of error of a few meters that prevents accurate recording of the edges of the individual structural habitats.

3.2.3 Habitat extent and mosaic configuration

A 'habitat patch' was defined as the section of the intertidal zone occupied by a single type of structural habitat (or 'habitat type'). A map of the location, size and characteristics of all habitat patches identified was created for each estuary assessed. Once the different structural habitats were identified along the creek, the information on the individual habitat patches collected through a combination of aerial mapping (source: Google Earth) and ground-truthing was used to prepare a habitat mosaic map for each estuary using a geographic information system (GIS) software. The distance from edge to edge lengthwise of each patch (following the bank meandering) corresponded to the measure of 'habitat patch extent'. The overall combined extent of each habitat type (or 'habitat extent') was calculated by summing the extent of all the patches mapped in the estuary belonging to that habitat type. Calculations were made both in km and as % of the combined length of both riverbanks. The total number of patches of each habitat identified in an estuary was used to represent the frequency of occurrence (or 'patch frequency') for that habitat.

The data on habitat composition and extent permitted the calculation of the overall extent and distribution of each habitat type, as well as of the individual sixteen structural classes. Additionally, the data collected allowed determination of the 'natural-modified' and 'vegetated-unvegetated' ratio of each estuary. The presence/absence of vegetation and/or anthropogenic features is often used in landscape management as an indicator of ecosystem status and composition (Lindenmayer *et al.* 2008), and applied in the planning of further development, restoration, or conservation works.

In the context of this research, habitats without plants were classified as ‘unvegetated’ (UNVEG), while habitats with one or more vegetation classes were classified as ‘vegetated’ (VEG). The presence of artificial structures or artificially introduced substratum/non-native vegetation were used as an indicator of human development and alteration. Thus, habitats without any artificial structures, non-native vegetation or artificial substratum (marked by the symbol '*') were classified as ‘natural’ (NAT), while habitats with at least one artificial structure/substratum/non-native vegetation were classified as ‘modified’ (MOD). The combined extent of all MOD habitats identified in an estuary was used as the total measure of extent of structural modification.

The data collected were used to prepare aerial maps of the structural habitat composition of all four estuaries using the program QGIS 2.18. Each map was fitted with nineteen individual layers highlighting the presence and distribution of the following:

- Structural habitats (habitat mosaic map)
- The 16 different structural classes recorded (one per layer)
- Natural-modified sections (‘NAT-MOD’)
- Vegetated-unvegetated sections (‘VEG-UNVEG’)

3.3 Results

3.3.1 Extent and patterns of structural modification

The four estuaries analysed exhibited a wide range of values of the extent of structural modifications in the intertidal zone. Ross Creek and Ross River were the estuaries with the highest proportion of modification, with respectively 52.2% and 30.9% of MOD habitat extent (Figure 8a-b; Appendix 2a-b). Given their history and location in a highly urbanised centre, it was expected that these two estuaries would have the most structurally altered shoreline. Alligator Creek and Althaus Creek on the other hand had little structural modification along their riverbanks, with only 4.5% and 1.9% of the total habitat extent modified, respectively (Figure 8c-d; Appendix 2c-d).

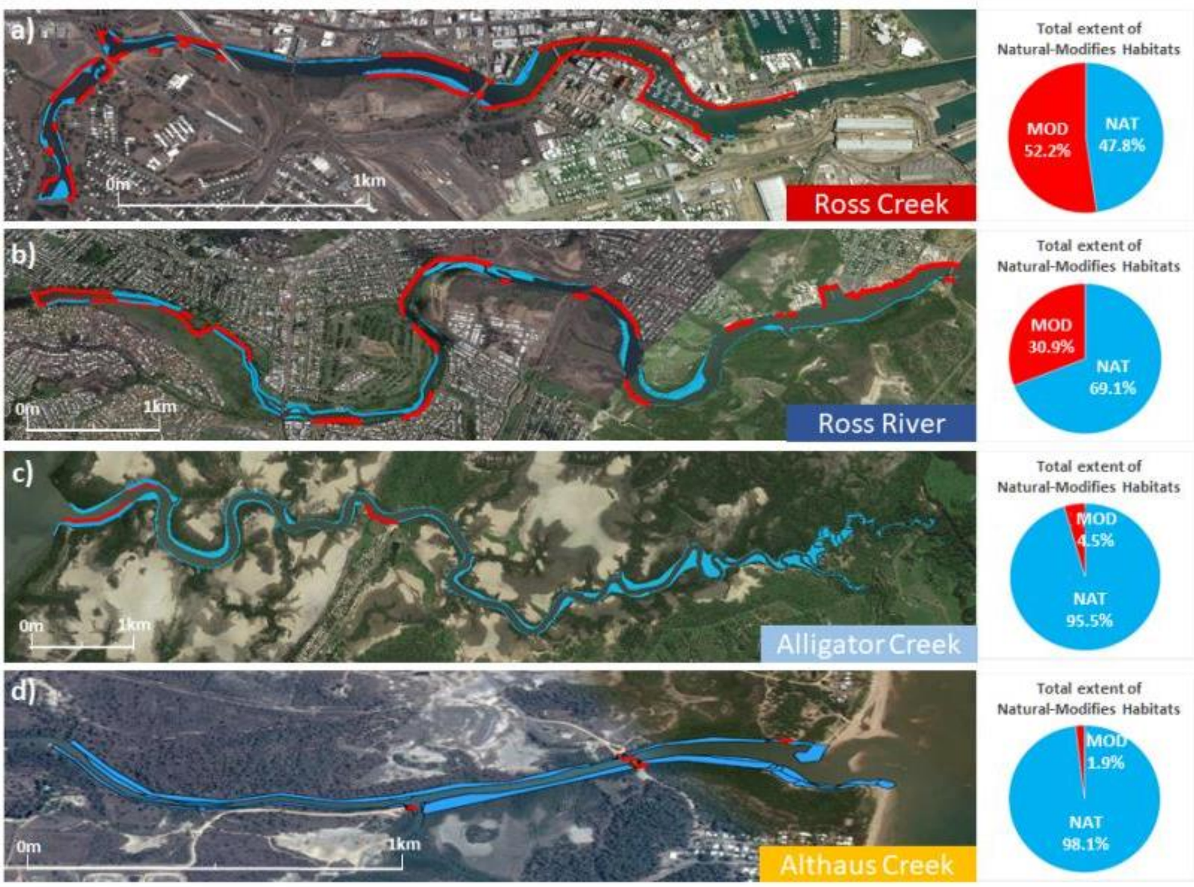


Figure 8a-d. Aerial map of the habitat mosaic distribution of natural (NAT = blue) and modified (MOD = red) structural habitats in the intertidal zone of Ross Creek (a), Ross River (b), Alligator Creek (c), and Althaus Creek (d).

In Ross Creek and Ross River MOD habitats were found on both riverbanks and distributed throughout the whole estuary, even though some areas showed a greater concentration/extent of modifications: closer to the mouth of the creek and the city centre for Ross Creek, and closer to the weir upstream for Ross River (Figure 8a-b). In Alligator Creek and Althaus Creek MOD habitats were found concentrated in few specific locations along the riverbanks that corresponded to boat ramps and other accesses to water, or as rubble in the downstream section close to the mouth of the river for Alligator Creek (Figure 8c-d).

3.3.2 Habitat composition

Only 13 of the 16 structural classes described in the classification scheme were observed in the four estuaries assessed for this study. The classes 'seagrass', 'macroalgae', 'non-native', and 'roads' were not found in this survey. Based on the combination of the observed classes, a total of 79 different structural habitats were identified in the four estuaries (Table 10). Sixty-four habitats (81% of the total) contained at least one artificial feature, be it in the form of an introduced artificial structure (Armouring (A), Drains (D), Raised structures (R), Level structures (L), or Pillars

(P)) or alterations of the sediment composition (indicated with the symbol '*'). These habitats were thus classified as 'MOD'. Less than 20% of the habitats identified (15 habitats) were devoid of any artificial feature. These habitats were thus classified as 'NAT'. Of the 64 modified habitats, 49 contained at least one artificial structure, such as bridges, piers, pontoons, boat ramps, and stormwater drains, while 45 were characterised by armouring of the banks in the form of boulder piles, cement slopes and rock/brick walls.

Table 10. Structural habitats identified in the survey listed by their acronym code in alphabetical order and colour-marked based on whether they are natural (blue) or modified (red). Each acronym represents an individual structural habitat type and lists in sequential order the different structural classes it is comprised of: sediment, vegetation, and artificial features.

HABITAT CODE	HABITAT CODE	HABITAT CODE
BLD*	MUD-GRV*-(A)-(D)	MUD-SAN-GRV*-MG-SM-(R)
BLD*-(A)	MUD-GRV*-(A)-(R)	MUD-SAN-GRV*-SM
BLD*-(A)-(D)	MUD-GRV*-BLD*-(A)	MUD-SAN-MG
BLD*-(A)-(R)	MUD-GRV*-BLD*-(A)-(D)	MUD-SAN-MG-SM
BLD*-MG-(A)	MUD-GRV*-BLD*-(A)-(R)	MUD-SAN-SM
BLD*-PAV*-(A)-(D)	MUD-GRV*-BLD*-MG-SM-(A)	MUD-SM
BLD*-PAV*-(A)-(R)-(P)	MUD-GRV*-BLD*-SM-(A)	PAV
BLD*-SM-(A)	MUD-GRV*-MG	PAV*-(A)
BLD*-SM-(A)-(P)	MUD-GRV*-MG-SM	PAV*-(A)-(D)
GRV*-(A)	MUD-GRV*-PAV*-(A)	PAV*-(A)-(L)
GRV*-BLD*-(A)	MUD-GRV*-SM	PAV*-(A)-(P)
GRV*-BLD*-(A)-(D)	MUD-MG	PAV*-(A)-(R)
GRV*-BLD*-MG-(A)	MUD-MG-SM	PAV*-(A)-(R)-(P)
GRV*-BLD*-MG-(A)-(D)	MUD-PAV	PAV*-MG-(A)
GRV*-BLD*-MG-SM-(A)	MUD-PAV*-(A)-(D)	PAV-MG
GRV*-BLD*-SM-(A)	MUD-PAV*-(A)-(L)	SAN
GRV*-MG-SM-(A)	MUD-PAV*-(A)-(R)	SAN-BLD
GRV*-PAV*-MG-(A)	MUD-PAV*-MG-(A)-(D)	SAN-GRV*
GRV*-SM-(A)-(D)	MUD-SAN	SAN-GRV*-BLD*
MUD	MUD-SAN-GRV*	SAN-GRV*-BLD*-MG-(A)
MUD-BLD*-(A)	MUD-SAN-GRV*-BLD*	SAN-GRV*-MG
MUD-BLD*-MG-(A)	MUD-SAN-GRV*-BLD*-(A)	SAN-GRV*-MG-SM
MUD-BLD*-MG-(A)-(R)	MUD-SAN-GRV*-BLD*-SM	SAN-MG
MUD-BLD*-MG-SM-(A)	MUD-SAN-GRV*-MG	SAN-MG-SM-(P)
MUD-BLD*-PAV*-(A)-(D)	MUD-SAN-GRV*-MG-(D)	SAN-SM
MUD-BLD*-SM-(A)	MUD-SAN-GRV*-MG-(R)	
MUD-GRV*	MUD-SAN-GRV*-MG-SM	

Vegetation was present in half of the habitat types classified. Of these 41 habitats, 18 featured mangroves only, 12 saltmarsh, and 11 a combination of both plant classes. Thirty-eight habitats, on the other hand, were completely devoid of vegetation.

The most frequently occurring substratum class observed was mud, found in 41 of the 79 habitats listed (51.8%). Following in decreasing order of frequency: gravel (37 habitats), boulders (32 habitats), sand (24 habitats), and pavement (19 habitats). Despite the presence of mud in more than half of the habitats classified and sand in approximately one third, only 12 habitats (15%) were characterised exclusively by soft sediment (mud and/or sand). Similarly, 28 habitats (35%) featured hard substratum types only, such as gravel, boulders, or pavement. Most habitats listed (39) were in fact characterised by a mix of soft and hard sediment types. Each of the four estuaries assessed had a unique composition of structural habitats (Table 11).

Table 11. List of the structural habitats found in each of the four estuaries assessed: Ross Creek, Ross River, Alligator Creek, and Althaus Creek.

Structural habitat types	ROSS CREEK	ROSS RIVER	ALLIGATOR CREEK	ALTHAUS CREEK
BLD*				X
BLD*-(A)	X	X		X
BLD*-(A)-(D)	X	X		
BLD*-(A)-(R)	X	X		
BLD*-MG-(A)	X	X	X	
BLD*-PAV*-(A)-(D)		X		
BLD*-PAV*-(A)-(R)-(P)		X		
BLD*-SM-(A)	X	X		
BLD*-SM-(A)-(P)		X		
GRV*-(A)				X
GRV*-BLD*-(A)				X
GRV*-BLD*-(A)-(D)	X	X		
GRV*-BLD*-MG-(A)		X		
GRV*-BLD*-MG-(A)-(D)		X		
GRV*-BLD*-MG-SM-(A)		X		
GRV*-BLD*-SM-(A)	X	X		
GRV*-MG-SM-(A)				
GRV*-PAV*-MG-(A)	X			
GRV*-SM-(A)-(D)		X		
MUD	X	X	X	X
MUD-BLD*-(A)	X	X		
MUD-BLD*-MG-(A)	X	X	X	
MUD-BLD*-MG-(A)-(R)	X	X	X	
MUD-BLD*-MG-SM-(A)		X		
MUD-BLD*-PAV*-(A)-(D)	X			
MUD-BLD*-SM-(A)	X			
MUD-GRV*	X	X	X	X
MUD-GRV*-(A)-(D)	X			
MUD-GRV*-(A)-(R)	X			
MUD-GRV*-BLD*-(A)		X	X	
MUD-GRV*-BLD*-(A)-(D)	X	X		
MUD-GRV*-BLD*-(A)-(R)		X		
MUD-GRV*-BLD*-MG-SM-(A)		X		
MUD-GRV*-BLD*-SM-(A)	X	X	X	
MUD-GRV*-MG	X	X		X
MUD-GRV*-MG-SM	X	X		X
MUD-GRV*-PAV*-(A)	X	X	X	
MUD-GRV*-SM		X		X
MUD-MG	X	X	X	X
MUD-MG-SM	X	X	X	X
MUD-PAV				X
MUD-PAV*-(A)-(D)	X	X		

MUD-PAV*-(A)-(L)				X
MUD-PAV*-(A)-(R)	X		X	
MUD-PAV*-MG-(A)-(D)	X			
MUD-SAN	X	X	X	X
MUD-SAN-GRV*	X	X	X	X
MUD-SAN-GRV*-BLD*	X			
MUD-SAN-GRV*-BLD*-(A)	X		X	
MUD-SAN-GRV*-BLD*-SM		X		
MUD-SAN-GRV*-MG	X	X		
MUD-SAN-GRV*-MG-(D)	X			
MUD-SAN-GRV*-MG-(R)	X			
MUD-SAN-GRV*-MG-SM	X	X		
MUD-SAN-GRV*-MG-SM-(R)	X			
MUD-SAN-GRV*-SM	X	X		
MUD-SAN-MG	X	X	X	X
MUD-SAN-MG-SM	X	X		
MUD-SAN-SM	X	X		
MUD-SM	X	X	X	
PAV		X		X
PAV*-(A)	X	X	X	X
PAV*-(A)-(D)	X	X		
PAV*-(A)-(L)		X		X
PAV*-(A)-(P)		X		
PAV*-(A)-(R)	X			
PAV*-(A)-(R)-(P)		X		
PAV*-MG-(A)	X			
PAV-MG			X	
SAN	X	X		X
SAN-BLD				X
SAN-GRV*				X
SAN-GRV*-BLD*	X			
SAN-GRV*-BLD*-MG-(A)	X	X		
SAN-GRV*-MG	X	X		
SAN-GRV*-MG-SM	X			
SAN-MG				X
SAN-MG-SM-(P)		X		
SAN-SM	X	X		

The estuaries located in the city centre had the highest diversity in habitat composition, with a total of 53 different habitats identified along the riverbanks of Ross River and 51 in Ross Creek. Althaus Creek had 23 habitats overall and Alligator Creek was the estuary with the least number of habitats, with only 18 recorded (Table 11).

Ross Creek and Ross River showed similarities not only in the number of habitats identified, but also in their types: 35 of the structural habitats observed were in fact found in both estuaries (Table 11). Most of these overlapping habitats contained modifications (MOD). It should be noted that Ross Creek and Ross River shared all but one of the natural (NAT) habitats identified in these two estuaries: MUD, MUD-MG, MUD-MG-SM, MUD-SAN, MUD-SAN-MG, MUD-SAN-MG-SM, MUD-SAN-SM, SAN, and SAN-SM. The natural habitat 'pavement' (PAV), representing in this case bedrock, was found in Ross River only and not in Ross Creek. Alligator Creek and Althaus Creek on the other hand showed little similarity in habitat composition. Only eight habitats were common to both estuaries, and those habitats were found in RR and RCk as well (Table 11). The eight habitats found in all estuaries assessed are: MUD, MUD-GRV*, MUD-MG, MUD-MG-SM, MUD-SAN, MUD-SAN-GRV*, MUD-SAN-MG, and PAV*-(A).

3.3.3 Habitat extent

Patch frequency and habitat extent were assessed for each habitat identified in the four estuaries. These measures were used to determine which habitats represented the 'dominant' structural habitats of the four estuaries. Similarities and/or patterns in habitat dominance between the four estuaries were also assessed. Each location on the riverbank could contain more than one type of habitat due to the presence of three intertidal levels: high, mid, and low (Figure 9-10).

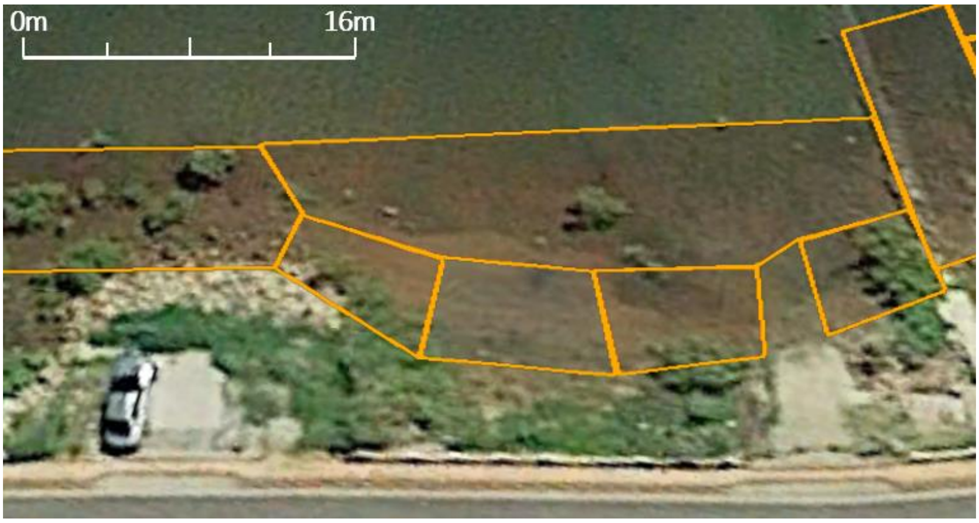


Figure 9. Example of an estuarine section with different habitats at different intertidal levels. Aerial view of a downstream section of Ross Creek, Townsville. Photograph taken from Google Earth 2019.

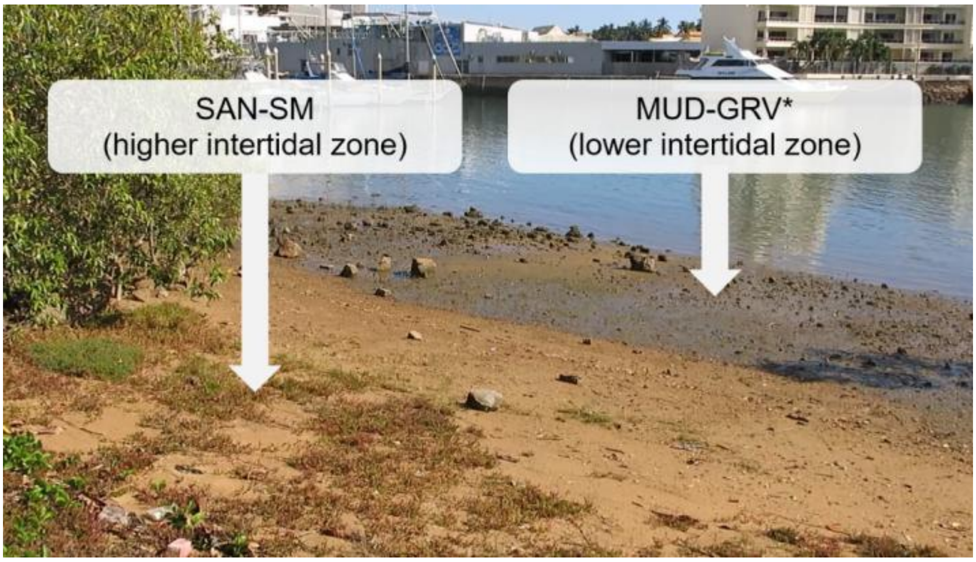


Figure 10. Photograph of the corresponding estuarine section with different habitats at different intertidal levels (see Figure 9). Photograph taken in the downstream section of Ross Creek, Townsville.

Thus, the measured sum of habitat extents for each estuary was greater than the linear measurement of the estuarine sectors assessed (see section 2.2 Habitat Composition) (Table 12).

Table 12. Comparison between the linear extent of sectors assessed and corresponding sum of habitat extent measured in each of the four estuaries.

Estuary	Sector assessed	Total measurement of habitat extents
Ross Creek	4 km	11.9 km
Ross River	10.9 km	32.8 km
Alligator Creek	14 km	32.5 km
Althaus Creek	2.5 km	6.5 km

Despite the high variety of habitats recorded in this study, only 1-3 habitats per estuary were identified as 'dominant' based on their habitat extent values and patch frequency (Figures 11-14; Tables 13-16). Most habitats classified were found either as single/scarce patches and had a linear extent smaller than 10% of the total length assessed of each estuary.

3.3.3.1 Ross Creek

Three dominant habitats were identified for Ross Creek: MUD-MG, MUD and PAV*-(A). The natural habitats MUD and MUD-MG represented the most extensive habitats, accounting for 42.8% of the overall length assessed (11.9 km) (Figure 11; Table 13; Appendices 3a and 4a). Over 3 km of the intertidal zone of RCk were comprised of unvegetated mud (MUD), accounting for 26% of the total extent of this estuary while 16.8% (1.9 km) was formed by mud and mangroves (MUD-MG). The combination of pavement and armouring (PAV*-(A)) was found in 1.3 km in total (10.9%). The substratum mix of mud and artificial gravel with (MUD-GRV*-MG), and without (MUD-GRV*) mangroves comprised for 5.6% and 6.8% of the overall extent, respectively. All other habitats identified in Ross Creek measured individually <5% of the total extent.

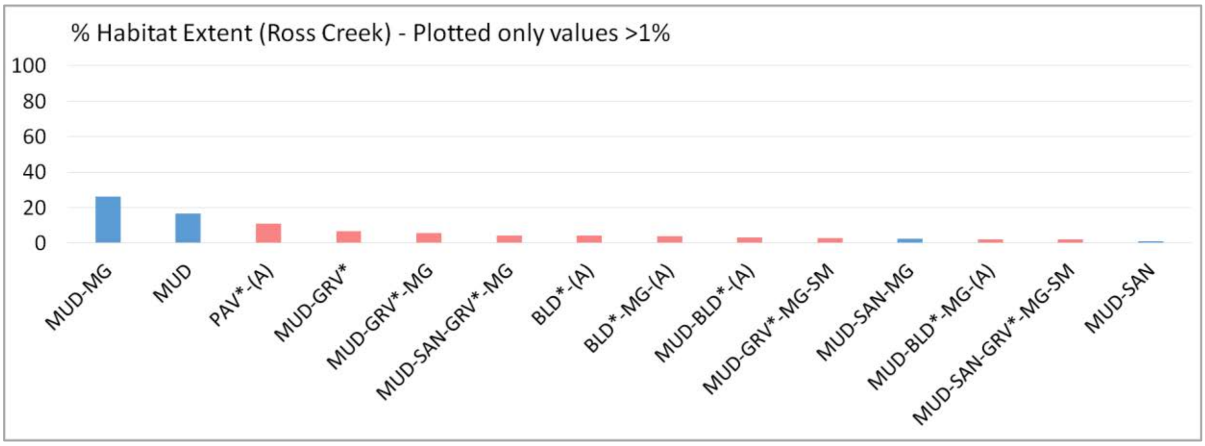


Figure 11. Percentage of overall extent of the structural habitats identified in Ross Creek (plotted only values >1%; Appendix 3a shows values for all 51 habitats).

Values of patch frequency for the different habitats found throughout the estuary varied between 1 and 27 (Table 13; Appendix 4a), the latter value belonging to the habitat MUD.

Table 13. Total extent, number of patches, mean patch size, and percentage of total extent of the ten most extensive habitat types of Ross Creek.

Structural habitat type	overall extent (m)	patches	mean patch size (m)	% total extent
MUD-MG	3094.0	27	114.6	26.05
MUD	1991.5	13	153.2	16.77
PAV*-(A)	1298.6	11	118.1	10.94
MUD-GRV*	813.4	16	50.8	6.85
MUD-GRV*-MG	661.3	16	41.3	5.57
MUD-SAN-GRV*-MG	497.6	6	82.9	4.19
BLD*-(A)	496.6	13	38.2	4.18
BLD*-MG-(A)	443.3	4	110.8	3.73
MUD-BLD*-(A)	366.4	5	73.3	3.09
MUD-GRV*-MG-SM	322.7	4	80.7	2.72

3.3.3.2 Ross River

The dominant habitat in Ross River, both in terms of extent and patch frequency, was the combination of mud and mangroves: MUD-MG. This habitat alone accounted for 36.8% of the overall extent, a value greater than that of all modified habitats combined (Figure 11). MUD-MG occupied over 12 km of the intertidal zone and was distributed over 69 different patches of various extent (Figure 12; Table 14; Appendices 3b and 4b). In descending order, other habitats were: MUD (8.3%), MUD-MG-SM (8%), SAN (7.7%) and MUD-GRV* (6.3%). Despite the higher number of modified habitats (MOD=42) compared to natural habitats (NAT=11), 69.1% of the extent of Ross River's intertidal zone was formed by natural habitats, predominantly with mud as substratum.

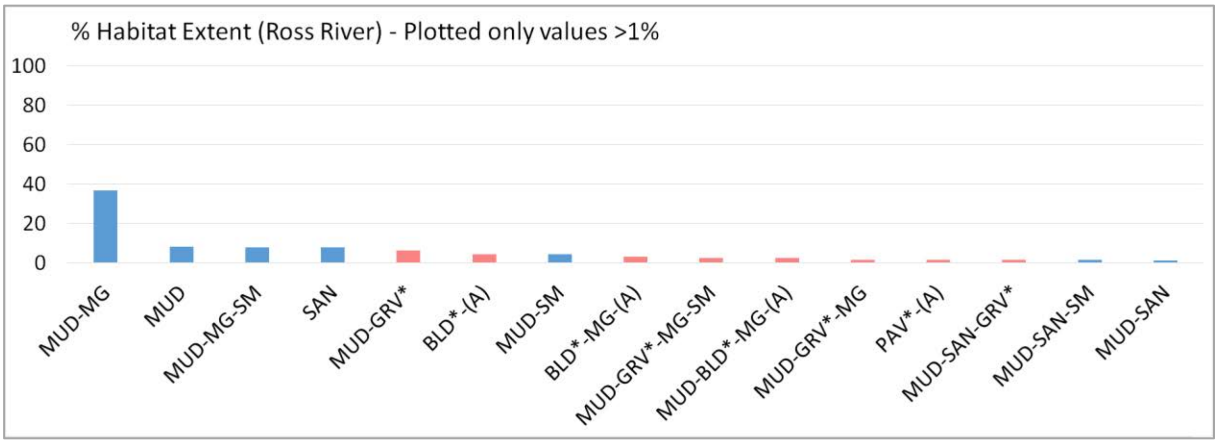


Figure 12. Percentage of overall extent of the structural habitats identified in Ross River (plotted only values >1%; Appendix 3b shows values for all 53 habitats).

Table 14. Total extent, number of patches, mean patch size, and percentage of total extent of the ten most extensive habitat types of Ross River.

Structural habitat type	overall extent (m)	patches	mean patch size (m)	% total extent
MUD-MG	12075.2	69	175.0	36.79
MUD	2721.9	15	181.5	8.29
MUD-MG-SM	2634.0	28	94.1	8.02
SAN	2534.9	13	195.0	7.72
MUD-GRV*	2075.0	15	138.3	6.32
BLD*-(A)	1490.3	45	33.1	4.54
MUD-SM	1438.6	28	51.4	4.38
BLD*-MG-(A)	1061.9	23	46.2	3.23
MUD-GRV*-MG-SM	853.7	13	65.7	2.60
MUD-BLD*-MG-(A)	838.9	13	64.5	2.56

3.3.3.3 Alligator Creek

Alligator creek had almost exclusively natural mud-based habitats: MUD-MG (69.8%), MUD-MG-SM (18.3%), and MUD-SM (5%) (Figure 13; Table 15; Appendices 3c and 4c). The only modified habitat appearing for more than 1% of the total extent was the substratum mix of mud and artificial gravel (MUD-GRV*), found predominantly in the downstream section of the river.

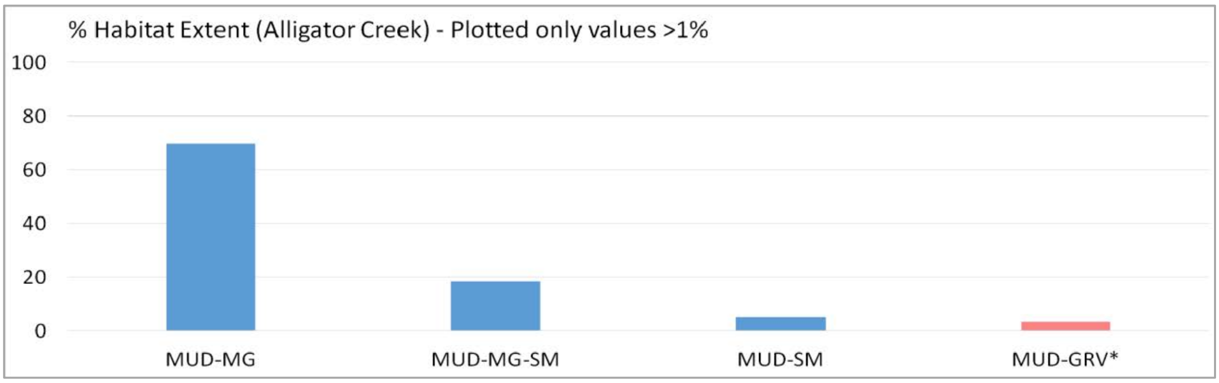


Figure 13. Percentage of overall extent of the structural habitats identified in Alligator Creek (plotted only values >1%; Appendix 3c shows values for all 18 habitats).

Table 15. Total extent, number of patches, mean patch size, and percentage of total extent of the ten most extensive habitat types found in Alligator Creek.

Structural habitat type	overall extent (m)	patches	mean patch size (m)	% total extent
MUD-MG	22657.7	79	286.81	69.76
MUD-MG-SM	5943.3	81	73.37	18.30
MUD-SM	1634.3	41	39.86	5.03
MUD-GRV*	1079	2	539.50	3.32
MUD	223.3	7	31.90	0.69
PAV-MG	222.3	2	111.15	0.68
MUD-SAN-MG	180	1	180.00	0.55
MUD-BLD*-MG-(A)	148.1	4	37.03	0.46
MUD-SAN	144.3	3	48.10	0.44
PAV*-(A)	58.9	2	29.45	0.18

3.3.3.4 Althaus Creek

Similar to Alligator Creek, Althaus' intertidal zone was comprised predominantly by natural habitats. In this estuary, however, the substratum 'sand' was much more prevalent than in the other estuaries. Of the total 6.5 km assessed, 3.9 km (59.7%) were characterised by the combination of natural mud and mangroves (MUD-MG), 0.7 km (11.3%) by unvegetated sand (SAN), 0.5 km (8%) by unvegetated mud (MUD), and 0.3 km (5.3%) by natural mud and bedrock (MUD-PAV) (Figure 14; Table 16; Appendices 3d and 4d). All modified habitats appeared no more than three times each, and all with an overall extent of <40 m (<1%). Compared to the other estuaries the habitats of Althaus Creek were present individually in fewer patch numbers (Table 16).

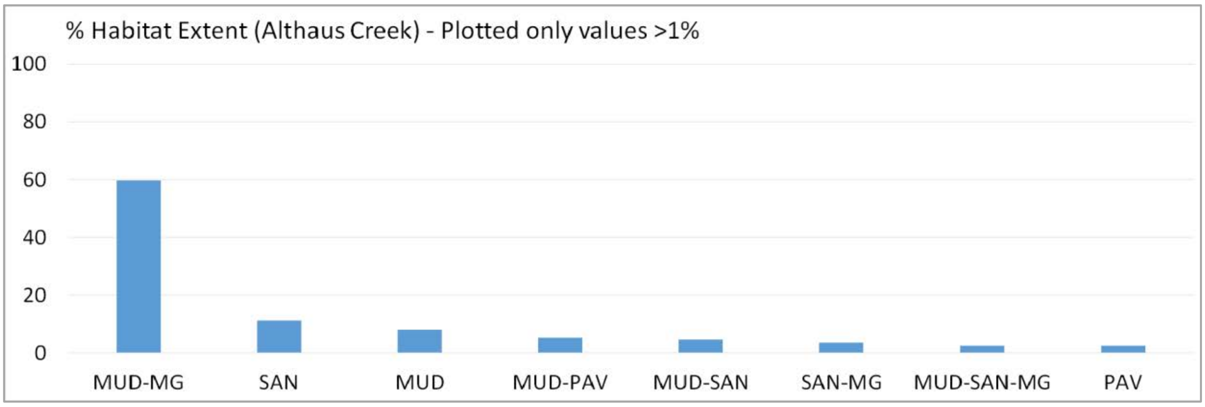


Figure 14. Percentage of overall extent of the structural habitats identified in Althaus Creek (plotted only values >1%; Appendix 3d shows values for all 23 habitats).

Table 16. Total extent, number of patches, mean patch size, and percentage of total extent of the ten most extensive habitat types found in Althaus Creek.

Structural habitat type	overall extent (m)	patches	mean patch size (m)	% total extent
MUD-MG	3875.3	8	484.41	59.66
SAN	734.5	7	104.9	11.31
MUD	518.8	5	103.76	7.99
MUD-PAV	345.6	3	115.20	5.32
MUD-SAN	297.7	4	74.43	4.58
SAN-MG	229.2	4	57.3	3.53
MUD-SAN-MG	157.1	7	22.44	2.42
PAV	156.8	3	52.27	2.41
SAN-BLD	51.5	1	51.5	0.79
SAN-GRV*	37.7	3	12.6	0.58

The most common habitat type (both in extent and frequency) among estuaries was natural mud and mangroves (MUD-MG), followed by unvegetated mud (MUD), different combinations of mud and vegetation (MUD-MG-SM and MUD-SM), or unvegetated sand (SAN) (Tables 13-16; Appendix 4a-d).

3.3.4 Habitat mosaic configuration and patterns of structural classes

Each of the four estuaries presented a unique mosaic configuration of the structural habitats identified in the survey (Appendix 2a-d). By examining the distribution of each habitat type and their structural characteristics throughout all four estuaries it was possible to understand the configuration of the different structural classes at ecosystem-scale and determine trends/similarities between the estuaries.

3.3.4.1 Vegetation

The proportion of vegetated intertidal zone was greater than that of unvegetated areas in all four estuaries. Alligator Creek was the estuary with the greatest extent of vegetation, comprised of mangroves and/or saltmarsh (VEG=95%). The other estuaries, while still being predominantly covered in vegetation, were less extensively vegetated. Ross River and Althaus Creek showed similar proportions, with VEG being 66.7% and 66.1% respectively. Ross Creek estuary had the smallest value with 52.6% of total vegetation cover.

Mangrove plants were found to cover most of the intertidal zone in all estuaries. For the most urbanised estuaries (RR and RCk) mangroves were predominantly present as narrow patches following the riverbanks' meandering, while in Alligator Creek and Althaus Creek they were found mostly as continuous forests that stretched up to a few hundred meters inland (Appendix 2a-d).

In Ross Creek mangroves occupied 51.5% of the overall extent and were found most extensively in the mid and upstream sections, where the presence of undeveloped land or parks still allows for thicker vegetated areas along the riverbanks. However, a few dense mangrove patches (either remnants or re-colonising a formerly cleared area) were also found in the more urbanised area closer to the city centre, despite the extensive modification of the intertidal zone of this section and overall lack of space due to the closeness of buildings and roads to the riverbanks (Figure 15; Appendix 2a).

Figure 15. Close-up of the downstream section of Ross Creek with the habitats featuring mangrove trees highlighted in green.

Ross River had an almost continuous mangrove cover, with the only exceptions being a section near Queens Road where one side of the riverbank has been completely cleared and armoured with cement and boulders, and the extensive boat ramp area located close to the mouth of the creek (Appendix 2b). Both Alligator Creek and Althaus Creek riverbanks were almost entirely fringed by mangrove forests (Appendix 2c-d).

Saltmarsh was found less frequently and extensively than mangroves. In Althaus Creek, saltmarsh was found in a small section (12.3 m) of the high-intertidal zone at one of the boat ramps (Appendix 2d). Ross Creek had only a few patches located almost exclusively in the upstream part of the creek (Appendix 2a), while Ross River had more sections of the riverbanks lined with saltmarsh, particularly in the Annandale wetlands area (Figure 16; Appendix 2b). The estuary with the highest presence of saltmarsh was Alligator Creek, with over 7 km distributed in patches of various size (ranging from 4.7 m to 529 m) along the entirety of the ecosystem (Appendix 2c). In AlCk, RR, and RCk saltmarsh was often found mixed with mangroves.

Figure 16. Annandale wetlands in Ross River with the habitats featuring saltmarsh plants highlighted in red.

3.3.4.2 Substratum

Mud was the predominant substratum type observed in all four estuaries, occupying between 77% –99% of the total intertidal extent (Appendix 2a-d). Sand on the other hand was present at a much smaller frequency and usually concentrated in emerging patches in the lower-intertidal zone, often on the accreting side of the riverbank (Appendix 2a-d). Althaus Creek was the estuary with the highest extent of sandy patches (23.2%), concentrated toward the mouth of the creek and in the more upstream area (Appendix 2d). With 14.7% and 12.2% respectively, Ross River and Ross Creek showed similar distribution and extent of sandy habitats (Appendix 2a-b). Alligator Creek was the estuary to present the least extent of intertidal sand: only 1% of the overall extent and concentrated in the furthest upstream section (Appendix 2c).

Gravel was the second most abundant substratum type, found most extensively in the urbanised estuaries – RCk 24.5% and RR 16.6% – but also present in the other estuaries, although in much smaller proportions (Appendix 2a-d). In Alligator Creek gravel was recorded predominantly at the mouth of the river on the eroding sides of the riverbanks (Figure 8c). Small patches of habitats with gravel were also found around the Cleveland Palms boat ramp, the only section of the estuary where the riverbank has been altered through construction and the introduction of artificial features (Appendix 2c). The gravel substratum class in Althaus Creek was found around the two boat ramps and in one location close to the mouth of the creek representing a popular access and fishing spot (Appendix 2d).

Boulders and pavement were found at low proportions throughout the four estuaries. Ross Creek and Ross River had the highest abundance in comparison to the other estuaries, mostly due to the introduction of boulders and pavement as armouring structures (Appendix 2a-d). 15.9% of the overall habitat extent measured in Ross Creek was comprised of boulders, and 13.2% by pavement in the form of brick walls, cement slopes and barriers. RCk was the only estuary with boulders and pavement present uniquely as artificial structures and not in any natural form. Alongside the artificial forms of these substratum classes, Ross River, Alligator Creek and Althaus Creek all featured at least one habitat patch formed by natural bedrock or boulders (Appendix 2a-d).

3.3.4.3 Artificial features

All estuaries examined here had some level of anthropogenic modification, ranging from alteration of the bank substratum to the introduction of artificial structures. Even though Ross Creek was the most heavily modified estuary (52.2%), Ross River had the highest diversity and distribution of artificial features (Appendix 2a-b). All five classes belonging to the attribute 'artificial features' were recorded in multiple locations along this estuary, while only some were found in the other estuaries.

Bank armouring was observed in all four estuaries, although it was highest in Ross River and Ross Creek: 29.3% (RCk), 16.1% (RR), 1% (AlCk), and 0.8% (AtCk). In Alligator Creek and Althaus Creek armouring structures were concentrated uniquely around boat ramps and other access to water. By contrast, Ross Creek and Ross River armoured sections of the banks could be found throughout the whole estuary (Appendix 2a-d).

Similarly, stormwater drains were recorded along both riverbanks of Ross Creek and Ross River, while no drain was observed in the two estuaries located outside the city area (Appendix 2a-d). Ross Creek had the highest frequency of occurrence of drains, even considering the substantial difference in the length of this estuary compared to Ross River.

Artificial structures residing on top of the water surface or extending in the water (*i.e.* boat ramps and pontoons) were observed in all estuaries, except Ross Creek (Appendix 2a-d). In Ross River such structures were concentrated predominantly in the downstream section, closer to the mouth of the river, while in Althaus Creek and Alligator Creek the three structures recorded were located up to 1.0 km and 4.5 km upstream, respectively.

Raised structures on the other hand were found in Ross Creek and Ross River distributed throughout both estuaries, based on the layout of the roads (bridges) and marinas (piers/docking stations). Only one account of raised structure was recorded in Alligator Creek, located at the boat ramp at the end of the Cleveland Palms residential area (Appendix 2c).

The structural class ‘pillars’ was recorded in Ross River only and mostly in association with raised structures (Appendix 2b).

3.4 Discussion

3.4.1 Structural habitat composition and extent of modification

The analysis of the habitat composition, extent and configuration of four tropical estuaries permitted the quantification of the variety in structural composition across estuaries exposed to different types of urban development. The four estuaries assessed had a high diversity in habitat composition and extent of modification. However, similarities were observed among the most urbanised estuaries (Ross Creek and Ross River) and among those located in less urbanised areas (Alligator Creek and Althaus Creek).

Due to the development of the city of Townsville along the riverbanks of Ross Creek and Ross River, it was expected that these two estuaries would have the highest level of structural modification of their intertidal zones (52.2% and 30.9% respectively). Ross Creek in particular has been exposed to over 150 years of progressive changes driven by the shaping of the waterway to fit the requirements of increasing urban expansion. Development, land reclamation, creation of a network of roads supplying access to water have all led to the reduction of the natural habitats located along the riverbanks. The same process has taken place in Ross River, with a gradual introduction of artificial structures and armouring of the banks leading to habitat fragmentation, and an overall decrease in the presence and extent of intertidal vegetation. Over the years the shoreline comprising of natural habitats in these two estuaries has been altered and replaced with a variety of artificial features. The similarities in habitat complexity between these two estuaries becomes more evident when their current habitat composition is considered: despite the differences in extent (4 km assessed in Ross Creek vs. 10.9 km in Ross River) the two estuaries contain almost the same number of habitat types (51 and 53, respectively) and display a similar habitat composition (35 habitat types overlapping) (Table 11).

Urban expansion and development have extensively affected the structural composition of these estuaries and changed from a more natural original state. A substantial difference in both extent of modification and number of structural habitats can in fact be observed between the more urbanised Ross Creek and Ross River, and the less developed Alligator Creek and Althaus Creek. Except for the artificial rubble recorded at the mouth of Alligator Creek, the modifications recorded in AlCk and AtCk were located at boat ramps, where the riverbanks have been altered, reinforced, and fitted with structures to provide an easy access to water for boats and other vessels. The artificial rubble in Alligator Creek has likely been transported downstream and accumulated at the mouth from the Cleveland Boat ramp section, where gravel and boulders have been introduced over the years to armour the banks close to the ramp and near other structures. Outside these small sections of the riverbanks, the rest of the intertidal zone of both Alligator Creek and Althaus Creek has remained relatively unchanged, with natural habitats extending uninterrupted along the riverbanks. Due to the low population density around these two estuaries there has been no need for extensive development of housing bordering the creeks. This also means that armouring of the banks, introduction of structures such as bridges, piers, and stormwater drains, or other features characteristic of highly populated areas were not carried out in these areas. ‘Natural’ estuaries such as Alligator Creek and Althaus Creek have less habitat types but greater patch extent and continuous habitats, while more urbanised estuaries like Ross River and Ross Creek are characterised by a greater variety of habitats and generally smaller, fragmented patches.

The greater variety of habitats observed in the more urbanised estuaries is caused primarily by the introduction of artificial features, rather than the fragmentation of natural habitats in smaller patches. The number of habitats recorded belonging to the 'modified' category greatly surpassed those classified as 'natural' (overall 64 MOD vs. 15 NAT). Only five of the sixteen structural classes were identified as major baseline natural features of tropical estuaries: mud, sand, pavement (bedrock), saltmarsh and mangroves. The combinations of these classes are quite limited in comparison to the high variety of habitats that can form with the introduction of artificial features, particularly given the possibility for multiple artificial classes to be present in the same habitat. The link between a greater diversity in habitats and the presence of anthropogenic modifications is evident in the most urbanised estuaries but can be observed in Alligator Creek and Althaus Creek as well. Even though less than 5% of the overall extent was recorded as structurally altered in each estuary, the number of modified habitats identified in these estuaries was greater than that of the natural habitats: NAT-MOD habitat count was 7-11 in AlCk and 10-13 in AtCk, respectively. Modified habitats were found concentrated in small areas, while the natural habitats tended to extend for long/wide patches along the banks.

3.4.2 Patterns of distribution of structural habitats

Patterns of distribution shared by two or more of the estuaries emerged when habitats were grouped based on their structural classes or presence/absence of modifications. In both Ross Creek and Ross River modified habitats were found distributed throughout the whole estuary but concentrated particularly in areas closer to the urban centre or to the more developed residential areas. This pattern is consistent with the fact that areas with denser population usually correspond to a reduction of the space available and an increase of the services and structures required (*e.g.* roads, docking stations, drains). Additionally, whenever there is high density of housing closer to the water edge, such as in cities and urban centres built around waterways, reinforcement of the banks through armouring in the form of boulder/cement slopes is required to ensure housing stability. Less urbanised areas, on the other hand, have little need for such radical alterations of the banks (as explained in section 4.1). For example, the distribution of modified habitats in the less population-dense Alligator Creek and Althaus Creek was concentrated around the only areas used frequently by the local community (*i.e.* boat ramps and water accesses), leaving the remaining sections of the estuaries unmodified and therefore characterised by extensive natural habitats. It should also be noted that Ross Creek and Ross River have both undergone decades of gradual urban modifications, often completed without a long-term ecological perspective set during the design phase (Browne *et al.* 1994; The State of Queensland 2007b). This has led to a patchy structural modification process of their riverbanks. The distribution and extent of different habitats along RCk and RR display how unplanned urban development contributes to the formation of a complex and varied shoreline mosaic. Such a trend is not unique to this area, but rather shared in coastal cities that have also been progressively expanding. Examples can be seen in Dubai (Burt *et al.* 2011), Sydney (Johnston *et al.* 2015), San Francisco (Nichols *et al.* 1986), and the southern California coast (Callaway and Zedler 2004). Urban expansion is a phenomenon responsible in many cases for the increase fragmentation of natural areas (Dobbs *et al*. 2017; Forman 2014; Li *et al.* 2017; Romano *et al.* 2017) as well as overall changes in spatial distribution and reduction of abundance of vegetation (Dobbs *et al.* 2017; Forman 2014; Li *et al.* 2017). This is particularly evident in areas with higher population density (Dobbs *et al.* 2017; Romano *et al.* 2017) or where urban expansion has occurred in an unplanned manner, meaning without an overarching landscape-focused perspective but rather through a series of uncoordinated and separate changes over time (Fiorini *et al.* 2019; Pauleit *et al.* 2005; Romano *et al.* 2017). Should further development occur in scarcely modified estuaries such as Alligator Creek and Althaus Creek, attention will be needed to carefully plan for and define the areas to be modified (both in location and extent) to limit as much as possible structural alterations to the environment and other long-term (and costly) negative impacts. This could be done by complementing the information collected on the structural habitat composition and configuration of these estuaries with knowledge on the biodiversity and functioning associated with the different habitat types. This would allow to identify areas to focus conservation efforts on and areas where potential future anthropogenic intervention would be less impactful on the environment. This of course needs to be planned on a case-by-case basis depending on the characteristics and extent of the development works planned. Moreover, information collected on estuaries that have already been affected by similar modifications could provide further perspective to adequately plan for impact mitigation rather than have to resort to a posteriori remediation/restoration efforts. Strategic landscape planning and modification based on environmental assessments are fundamental to ensure the appropriate management of natural resources while allowing development to occur in a sustainable manner from economic, ecological and social perspectives (Forman 2014). When such practices are not carried out appropriately, unchecked urban planning can lead to extensive alterations of the natural ecosystems which can be often irreversible or lead to long-term consequences with associated management/restoration costs (El Banna and Frihy 2009; Rydin 2012; Simenstad *et al.* 2005).

3.4.3 Dominant habitats and structural classes

Despite the differences in habitat composition, configuration and extent of modification, all estuaries analysed shared the same dominant habitats. These habitats are characterised by the presence of mud and/or sand, both with or without vegetation. The combination of MUD-MG in particular was the most extensive habitat type in all estuaries, ranging from 26.5% to 69.7% in total. Additionally, Ross Creek and Ross River shared the same set of NAT habitats (except for pavement), suggesting a comparable – if not identical – original natural composition of these two estuaries. This concept is further supported by the fact that these two estuaries were originally connected, with Ross Creek being a tributary of Ross River before the extensive development of the city of Townsville separated the two estuaries in the early 60s (The State of Queensland 2007; The State of Queensland 2011). The similarities in dominant natural habitat types between the four estuaries seem to indicate a common natural structural composition for the tropical estuaries in this region, a critical factor when considering the need for baseline information to be used in restoration and rehabilitation efforts. Features such as mud, sand, and intertidal vegetation are equally relevant for the conservation of the natural estuaries of this region and their services. The preservation, restoration or re-introduction of these structural components in modified estuaries is fundamental, particularly considering the role of vegetation and sediment type in the presence and survival of local biota (intertidal and subtidal). Mangrove forests and saltmarsh plants play a key role in providing shelter, spawning and feeding grounds for many terrestrial and aquatic animal species (Alongi 1998; Beck *et al.* 2001; Gopal and Junk 2000). Similarly, the presence of soft sediment such as mud and sand is essential for the macroinvertebrate communities of wetland regions (Anderson 2008; Jayaraj 2008; Kristensen 2008), which support a broader range of biota as part of complex food webs (Lugendo *et al.* 2006; Wallace and Webster 1996). Substratum alteration is one of the primary modifications resulting from urban development in wetland areas, either in the form of sediment removal (dredging, scouring from high flow events during cyclones), introduction (rubble and boulders as armouring features) or substitution (cemented slopes or walls). In many cases, there is a tendency to shift from soft sediments to mixed or hard sediments, such as gravel, boulders or pavement, as estuarine margins are armoured to prevent erosion (Bulleri and Chapman 2010; Morley *et al.* 2012). Most of the hard sediment recorded in this study was of anthropogenic origin: either armouring of the banks (boulder and cement slopes) or as rubble and debris originated from the gradual degradation of artificial structures over the years. If not properly planned and regulated, the change in substratum from soft to hard, and the introduction of hard artificial structures, could lead to changes in the biodiversity and functioning of the wetland/estuary subjected to development. For example, species dependent on the presence of soft sediment (such as crabs, polychaetes and other benthic infauna) are likely to decrease if not completely disappear from the area, along with the ecological services and functions they provide (Aller 1988; Gibson *et al.* 2001; Hutchings 1998; Mermillod-Blondin *et al.* 2004; Montague 1982). On the other hand, the introduction of new hard sediment and structures can provide favourable conditions for a different set of species to colonise the area: barnacles, oysters and other sessile microbiota can quickly settle on hard surfaces (Anderson and Underwood 1994), and gastropods, fish as well as other nektonic species can find refuge in the increased structural complexity provided by boulders or artificial structures (Barwick *et al.* 2004; Cermak 2002; Emson and Faller-Fritsch 1976; Henderson *et al.* 2019; Mayer-Pinto *et al.* 2018). Changes in substratum type and distribution were observed in all estuaries assessed in this study but resulted particularly extensive in Ross Creek and Ross River. Between 30%-52% of the overall intertidal zone of these estuaries currently presents alterations in substratum composition, and 16%-29% of the riverbanks have been armoured against erosion by introducing rubble/boulder/cement slopes or walls.

The four estuaries assessed showed very similar natural structural composition. As such, it is possible to hypothesise that if Alligator Creek and Althaus Creek were to be subjected to uncontrolled development, the number of their habitats and degree of fragmentation would increase, similarly to Ross Creek and Ross River's current status.

Another shared feature among the four estuaries was the presence of mangrove vegetation in most of the intertidal zone of these estuaries, with a total extent ranging between 51.5% and 89.9%. While in Ross Creek mangroves were concentrated predominantly in the mid/upstream sections, where the riverbanks had been subjected to fewer modifications, thick patches of vegetation were also found in the area in the middle of the city centre. In the other estuaries - including Ross River - mangroves were present as almost continuous patches throughout the estuary. Despite extensive alterations, it seems that mangrove plants have been able to (re)colonise many of the sections that have undergone structural changes, such as sediment type modification and introduction of artificial structures. The resilience of estuarine vegetation to substantial structural alterations and ability to adapt to new conditions and recolonise/thrive despite changes in sediment type or the introduction of artificial structures, as observed in these estuaries, needs to be considered during development planning and when prioritising restoration efforts of modified areas (Townsville City Council 2018c). Sometimes it can even result as a potential source of maintenance and costs associated with periodical mangrove removal from undesired zones (Lundquist *et al.* 2017). Saltmarsh plants had a similar pattern of recolonisation/resilience to the presence of artificial features, albeit in a reduced way when compared to mangroves, probably due to their occupation predominantly of the high intertidal zone (Daly 2013; Johns 2010).

3.4.4 Indicators of ecosystem status

Mangrove and saltmarsh plants were also found present in half of the modified habitats identified in this study. Vegetation cover and plant diversity are factors frequently used in landscape planning and management, particularly in the sense of important indicators of ecosystem status and composition (often used also to extrapolate extent of natural vs. modified areas), as well as baseline components for habitat conservation/restoration in development planning (Lindenmayer *et al.* 2008). However, the data presented in this study highlight how information on vegetation cover/composition alone will likely provide an incomplete picture of the habitat composition and configuration of tropical estuaries. Additionally, the VEG-UNVEG approach does not consider the presence of structurally modified habitats (*i.e.* with artificial structures, foundations) where vegetation has established (*e.g.* MUD-BLD*-MG-(A)-(R), or MUD-SAN-GRV*-MG-(R)), or the presence of natural habitats typically devoid of vegetation, such as mudflats and exposed sand banks (*e.g.* MUD or SAN). This leads to potential differences in the evaluation of the habitat composition and extent within an ecosystem based on the criteria used. The presence/absence of vegetation alone is an incomplete indicator for the extent of natural/modified sections of an ecosystem. While the NAT-MOD and VEG-UNVEG ratios were almost identical in Alligator Creek (95.5%–4.5% for NAT-MOD and 95%–5% for VEG-UNVEG), and quite similar in Ross River (69.1%–30.9% vs. 66.7%–33.3%, respectively), the situation for Ross Creek and Althaus Creek is substantially different. In Althaus Creek the extent of vegetation cover, while still representing most of the estuary, was smaller than the overall extent of natural habitats (VEG=66.1% and NAT=98.1%). By contrast, the values of overall extent of NAT-MOD and VEG-UNVEG resulted almost exactly inverted in RCk: 47.8%–52.2% vs. 52.7%–47.3%, respectively. A complete different perception of the status and composition of this estuary would occur if vegetation was used as an indicator of 'naturalness' or lack of modification.

3.4.5 Testing the adequacy of the classification scheme for structural habitats and future applications

The classification scheme for structural habitats employed in this study has demonstrated to rapidly provide fine-detailed information on the composition, extent, frequency and distribution of structural habitats in an ecosystem. Moreover, this assessment tool has been able to detect the differences in habitat complexity between four estuaries and provide an accurate quantification of the presence and extent of the various structural classes, structural habitats, and major subdivisions (NAT-MOD and VEG-UNVEG). This represents an advantage over classification schemes that only operate with coarser resolution (*e.g.* Butler *et al.* 2017; Davies *et al.* 2004; Howes *et al.* 2002), as it ensures the ability to detect all structural components present in estuaries, both natural and anthropogenic in origin, including those occupying sections smaller than a few meters (*e.g.* stormwater drains, pillars). The ability to provide fine-detailed information on the structural components of an estuary prevents misrepresentations and facilitates the accurate assessment of the presence, extent, and distribution of modification. Additionally, the simple layout and straightforward applicability of this classification scheme resulted in the completion of each round of habitat characterisation and mapping in a relatively small amount of time (*i.e.* less than three days per estuary), with the only limiting factor relating to the change of tide, which prohibited accessibility of the intertidal zone. The information obtained through the application of the classification scheme for structural habitats in four model estuaries with different extent of modification has confirmed the relevance of this novel and rapid assessment tool for the detailed characterisation and mapping of the structural composition of different tropical coastal wetlands. The integration of the classification scheme in assessment protocols would lead to the creation of standardised high-resolution datasets on the structural composition and extent of development of different estuaries/wetlands. Such standardised information would increase the comparability of different cases and/or study areas, thus potentially allowing the prediction of patterns of change or effects on spatial heterogeneity associated with future development using knowledge acquired through the analysis of similar areas that have already been affected by urban expansion (as in the case of Ross Creek and Ross River). The information could also be used to identify and monitor patterns of change over time as well as investigate differences in rates of structural modification associated with different types of development works occurring in a single estuary or wetland. If complemented with other information, such as connectivity, hydrology, biodiversity, and concurring stressors, the knowledge acquired through the application of the classification scheme proposed could be used to determine thresholds and potentials for recovery of the ecosystem as well as assess potential ripple effects on connectivity or biodiversity at larger landscape-scale over time. Such information would be of great relevance for landscape management and for the selection of appropriate strategies for ecological conservation/restoration in face of development.

3.5 Concluding remarks

The more heavily modified estuaries of Ross Creek and Ross River presented a greater number and variety of structural habitats, as well as larger extent of modification, compared to the less urbanised Alligator Creek and Althaus Creek, despite the very similar underlying patterns in natural composition observed between the four estuaries. Future studies could focus on performing repetitive assessments over time to monitor patterns of structural change following further development and/or restoration works within the individual estuaries. This would allow to determine rate of change and potentially link it to environmental resilience and/or potential for recovery of the estuary by complementing the information on structural composition and configuration with data on species presence, distribution, and functioning. The high variability in the number, distribution and extent of structural habitats present in estuaries within/near populated areas can, in fact, have consequences for the presence and distribution of physical resources available to flora and fauna as well. These factors are likely to influence species composition and habitat utilisation (Bulleri and Chapman 2010; Cermak 2002), with potential ripple effects and alteration of ecosystem structure and functions more broadly in a connected seascape (Lee et al. 2006). The increased heterogeneity in estuarine and wetland ecosystems following human development poses interesting questions about how native faunal communities responds to structural changes caused by development, and the extent to which the complexity of the new habitats provides enhanced opportunities for species colonisation. Both during and after development works the composition and abundance of the biotic communities is likely to change, potentially including a decline in local species and an increase of exotic/colonising species (e.g. Dafforn et al. 2009). The effect of habitat composition and presence/absence of artificial features on the flora and fauna (and thus on the functioning and productivity of an ecosystem) needs to be taken into consideration when planning new/further development. The next part of this project will focus on investigating the effect of different structural features, both natural and anthropogenic, on the presence and richness of species found in the urbanised tropical estuaries investigated in this study.

Chapter 4

Influence of structural attributes on species assemblages in urbanised estuaries.

4.1 Introduction

Urban development alters the presence and distribution of structural elements of coastal ecosystems, either in the form of change/removal of sediment and vegetation or with the introduction of artificial features (see Chapters 2 and 3). The most frequent transformations occurring with urbanisation of tropical estuaries are the shift from soft sediment (*i.e.* mud and sand) to hard sediment (*i.e.* gravel, boulders, and pavement) (Figure 17), the alteration of the vegetation present along the banks (*i.e.* removal/clearing, reduction, or thinning) (Figure 18), and the introduction of artificial features (*e.g.* bridges, ramps, pontoons, stormwater drains) (Figure 19).

Figure 17. Example of shift from soft sediment (mud) to hard sediment (pavement) in Ross Creek, Townsville.

Figure 18. Example of vegetation clearing for the introduction of bank armouring and stormwater drainage in Ross River, Townsville.

Figure 19. Examples of artificial features introduced in the estuaries around the Townsville region. Boulders as armouring and erosion mitigation in Ross River (top left); a stormwater drain in Ross Creek (top right); a bridge overpassing Ross Creek (bottom left); and a boat ramp in Althaus Creek (bottom right).

The fauna inhabiting these areas, particularly non-transient species, are often affected by changes in the sediment type and vegetation available, which can lead to a shift in species occurrence or a reduction in population size (Aguilera 2014; Bulleri and Chapman 2010; Connell 2000; Connell and Glasby 1999). Some species are able to inhabit a wide range of habitats and are thus less likely to be affected by structural changes resulting from urbanisation and development, but other species have more specific requirements and so are limited to few habitat types or specific structural components (*e.g.* LaSalle and de la Cruz 1985; Nobbs 2003). In these circumstances changes in the composition of structural elements of estuaries could result in shifts in species composition, distribution or density, which may then have broader ecological consequences on the function and services provided by those species (Alberti 2005; Bulleri and Chapman 2010; Connell and Glasby 1999; Mayer-Pinto *et al.* 2018).

Tropical estuaries are home to many terrestrial and aquatic species that require the presence of vegetation and soft sediments for their survival. Most notably, many invertebrate species utilise available soft sediments during most of their life cycles (*e.g.* polychaetes, molluscs, crustaceans).

For example, fiddler crabs require muddy and sandy environments to burrow and forage (Christy 1982; Crane 2015), while some bivalve species live entirely burrowed to escape predators (Ansell and Trevallion 1969). Vegetation such as mangroves and saltmarsh provide shelter, food, and other essential services/resources for many taxa inhabiting estuaries (Kathiresan and Bingham 2001). The introduction of artificial features including piers, pontoons, and armoured walls along the banks of estuaries can alter the presence/distribution of faunal species by providing novel habitats (Barwick *et al.* 2004; Becker *et al.* 2013; Connell 2000; Dugan *et al*. 2011). With the fast rate of development in many tropical coastal areas, understanding the role of different structural elements (vegetation, sediment, artificial features) to determine the presence and distribution of the native fauna is essential for appropriate planning and decision-making. Identifying how structural elements, individually or in combination, influence the fauna could facilitate the prediction of changes in species composition and community assemblages exposed to development, be it in the form of vegetation/substratum alteration or introduction of artificial features.

Examining the faunal community occupying the vast number of habitats identified in these urban waterways will provide a measure of how the different habitat patches support fauna, and indeed, whether a habitat combination, including artificial structures, supports a greater taxonomic diversity compared to others. Moreover, linking faunal communities to the different habitats will assist with determining how the different structural elements influence species occurrence. Understanding how species are affected by the presence or absence of specific structural elements is also essential to direct ecological restoration effectively.

To determine the influence on the faunal communities of the different structural elements of intertidal habitats in the tropical estuaries assessed (see Chapter 3) I sampled the species composition of each identified habitat type in the intertidal zones of Ross Creek, Ross River, and Alligator Creek over the course of a year to:

a) Collate an inventory of the faunal communities of the three estuaries and identify differences in the composition of non-transient species (*i.e.* species with a range of movement <20m in their adult life).
b) Determine the influence of structural elements (sediment, vegetation, and artificial features) on the occurrence of non-transient species across the three estuaries.

4.2 Materials and methods

4.2.1 Study area

The survey was carried out in three tropical estuaries located in the Townsville region exposed to different levels of development: Ross Creek, Ross River and Alligator Creek (see Chapter 2) (Figure 20). The banks of Ross Creek and Ross River have been extensively modified over the past decades, with 52% (RCK) and 31% (RR) of their overall extent being altered through sediment and vegetation changes as well as introduction of artificial features (see Chapter 3). By contrast, the composition and distribution of structural elements present in Alligator Creek has remained relatively unchanged, with only 4.5% of the banks having been subjected to modifications and development (see Chapter 3).

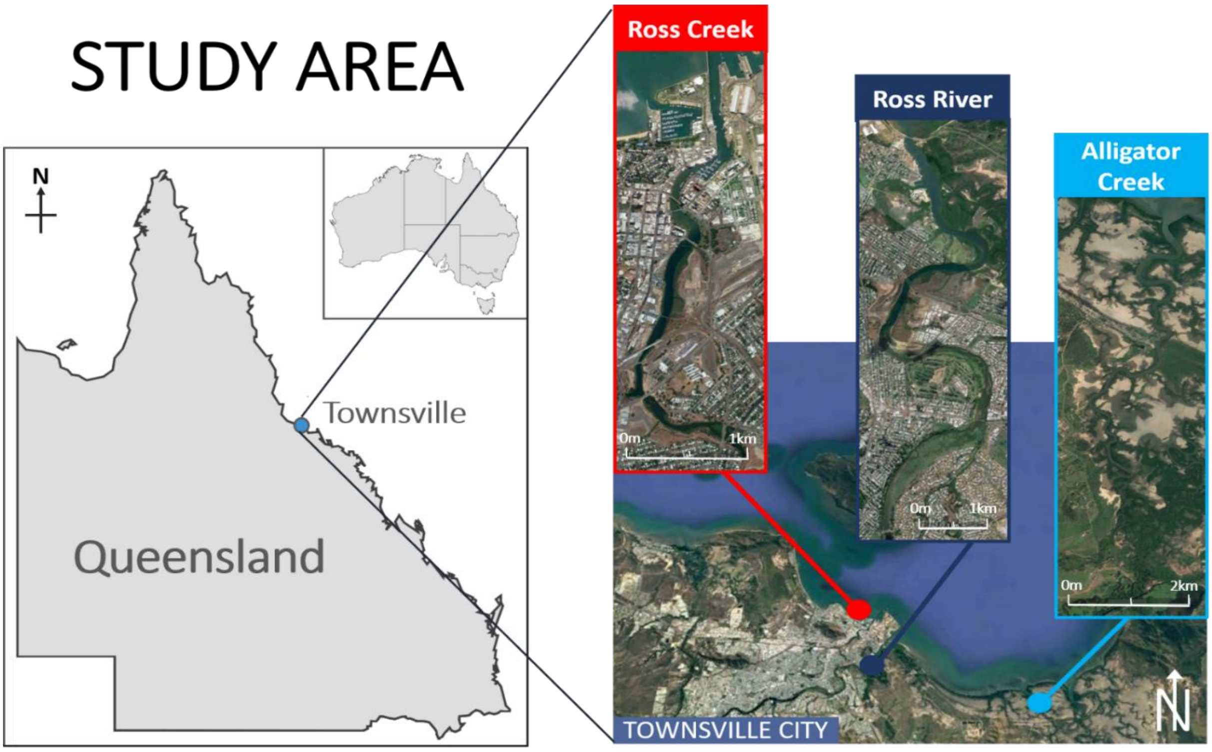


Figure 20. Map of the study area with the three estuaries assessed in this study highlighted: Ross Creek, Ross River, and Alligator Creek.

4.2.2 Macrofauna assessment

Macrofauna species composition was assessed through on-ground surveys carried out in each type of structural habitat in the three estuaries. In the context of this research the term 'macrofauna' represents fauna larger than 3 mm.

Firstly, a complete list of the structural habitats present in each estuary was prepared using the standardised classification scheme for structural habitats of tropical coastal wetland ecosystems described in Chapters 2 and 3 (Figure 21).

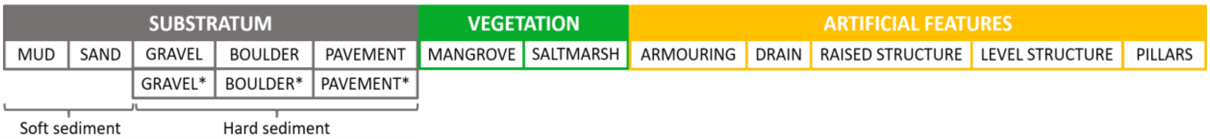


Figure 21. List of the different structural classes of the attributes 'Substratum', 'Vegetation', and 'Artificial features' found in the intertidal zone of three tropical estuaries: Ross Creek, Ross River, and Alligator Creek. The substratum classes can be further grouped in 'Soft sediment' and 'Hard sediment'.

A total of 53 structural habitats were identified in Ross Creek, 51 in Ross River and 18 in Alligator Creek. Within each estuary, three replicate 'sampling points' were selected for every structural habitat type. Sampling points were randomly selected among the different habitat patches (see Chapter 3). Only one or two sampling points could be selected for each structural habitat type with less than three patches within a single estuary.

A pilot study was carried out to select the most appropriate transect length for the macrofauna assessment in the different structural habitat types identified in the estuaries analysed. Despite the presence of some structural habitat patches that extended for over 30 meters across the intertidal zone (particularly in areas with sand/mud flats), most habitat patches measured between 3 and 6 meters. As such, 5 meters transects were found to be the most suitable as a standard measure to cover from low intertidal zone to high intertidal zone. Should this protocol be applied to other estuaries/wetlands/study areas, then transect length should be reconsidered and adjusted based on the characteristics of the intertidal zone of those areas.

At each sampling point two 5m transects were set perpendicular to the riverbank (*i.e.* moving from lower intertidal to higher intertidal) (Figure 22). Visual and photographic surveys (digital auto-focus camera) were carried out for each transect to assess the intertidal macrofauna by recording all species found on the sediment and vegetation located within 1m each side along the transect. Quadrats were not used in this assessment, but photographic evidence of single (or, where possible, multiple) resident macrofauna specimens to assist in their taxonomic identification. Where possible, rocks within the transect area were turned over to examine for the presence of macrofaunal species underneath. Where soft sediment (mud and/or sand) was present only epifaunal species or species emerging / visible in the sediment were recorded. To reduce the confounding effect of human interaction, two rounds of assessments were carried out where species were observed to flee/hide: a close-up round walking along the transect, in addition to a more distant (a few meters) observation survey over a period up to 15 minutes. Observation time was calculated during a pilot assessment as the maximum time required for fiddler crabs to re-emerge from borrows after a disturbance. All invertebrates observed were recorded. Birds were recorded only if sighted on the ground or perched on the vegetation at the time of the survey. Fish were recorded only if sighted within the transect area of the intertidal zone at low tide. Fauna were identified to the lowest possible taxa. Fauna that could not be identified on site were photographed for later identification.

Figure 22. Example of the disposition of the 5m transects laid at each sampling point. The image depicts the position of the transect for the first sampling point of the structural habitat SAN-GRV*-BLD*-MG-(A) located in Ross Creek. Each transect was sampled moving from the lower intertidal zone to higher intertidal zone.

Sampling was carried out on a three-monthly basis between October 2016 – September 2017:
Round 1: Oct 2016
Round 2: Feb 2017
Round 3: May-Jun 2017
Round 4: Aug-Sep 2017
All sampling rounds were completed at low spring tide to allow full access to the entire intertidal zone. The sampling period was characterised by lower than average rainfall values, particularly during the wet season (November-April), so almost all sampling occurred in periods without heavy/substantial rainfall (Appendices 5a-b and 6). Ross Creek macrofaunal sampling carried out in May 2017 was the only one that occurred close to a substantial rain event (Appendix 6). However, in this instance sampling was carried out a week after rainfall, during a period of time

that was deemed sufficient to negate the impact of rainfall. Rainfall was therefore excluded as factor potentially influencing differences in macrofaunal composition recorded between sampling rounds.

4.2.3 Statistical analyses

Species were divided in two groups based on their range of movement:

- Non-transient: organisms that are sessile or with a relatively small range of movement in their adult life (*i.e.* less than 20 m). Predominantly benthic invertebrates.
- Transient: organisms with a wide range of movement in their adult life (*i.e.* more than 20m). Predominantly vertebrates and flying invertebrates.

The data collected in the field were used to calculate:

- Species richness: the total number of species recoded in each habitat type or estuary.
- Species composition: list of the different species recorded in each habitat type or estuary.
- Total frequency of occurrence (%): proportion of occurrence of a species across the entire sampling pool (all habitat types collectively).
- Relative frequency of occurrence (%): proportion of occurrence of a species across habitats characterised by a specific structural parameter.

Faunal assemblages between the three estuaries sampled with focus on natural NAT-MOD structural habitats were investigated using multi-dimensional scaling (MDS) using the Sorensen index (taxa presence-absence) and with cluster groups superimposed for visual interpretation. These analyses were carried out using the software Primer v.6.

Analyses of the influence of structural components on the species richness and occurrence was only carried out for non-transient species, since their limited short-term dispersal makes them more reliable indicators of habitat usage and environmental impact. Due to the inherent differences in structural habitat composition between estuaries (RCK=51, RR=53, ALCK=18) and the subsequent differences in frequency of occurrence of each individual structural class (e.g. MUD, SAN, MG, SM, (A), (R)…) (see Chapter 3), differences in sampling sizes were observed between structural classes and between the three estuaries. While this posed an initial challenge in the choice of statistical analyses to perform, the differences in sampling size did not preclude the execution of significant tests to determine the influence of structural components on taxa richness and occurrence. Classification and Regression Trees (CART) were constructed for the entire "non-transient" dataset to determine whether the different structural components of these estuaries influence the species assemblages in the different habitats. The structural components investigated reflected the structural classes used for the standardised classification scheme for structural habitats of tropical coastal wetland ecosystems (see Chapter 2). Dependant variable: presence/absence of species. Predictor variables were: Site =RCK, RR, ALCK; Modification =NAT, MOD; Vegetation =MG, SM; Sediment class: MUD, SAN, GRV, BLD, PAV; and Sediment type = Soft, Hard. A ten-fold cross validation was applied to both total and marine non-transient macro-benthic taxa datasets to select the final tree models presented in this work (De'ath 2002). The selection was made following the principle presented by Breiman et al. in 1984: the final tree was chosen as the smallest tree having a cross validation error falling within 1 standard error of the minimum cross-validated error (1-SE trees). Analyses were run using the packages 'party' (Hothorn *et al.* 2010) and 'mvpart' (De'ath 2007) in the software R version 3.4.2.

4.3 Results

4.3.1 Species composition in the three estuaries

A total of 134 macrofaunal organisms were identified in the three estuaries assessed (Appendix 7). Most were identified to species level, while a few could only be identified to genus. Of the total macrofauna observed, 67 taxa were recorded as non-transient and further divided in 'terrestrial' (N=14) and 'marine' (N=53). The list of species observed in the four estuaries sampled was compared with the list of invasive species presented in Queensland Biosecurity Act (2014). None of the 33 invasive species listed in the Act were recorded in this study. However, it should be noted that it is not possible to state that all of the species recorded in this study are native species, due to the lack of official records existing for many of the species listed.

The more habitat-diverse and heavily modified estuaries of Ross Creek and Ross River presented the greatest values of richness and relative frequency of occurrence of non-transient macrofauna, with 47 and 57 taxa respectively (Figure 23; Appendix 8). Both these estuaries are characterised by a high number of structural habitats (51 and 53, respectively; see Chapter 3) and a greater number of anthropogenic modifications. Only 31 taxa were recorded in Alligator Creek (Appendix 8), the estuary with the least number of habitat types (18 in total) and extent of modification (<5% of its total linear length). A similar trend was observed for a number of taxa recorded in the individual habitats of each estuary, with Ross Creek and Ross River having overall greater values of taxonomic richness than Alligator Creek (Appendix 9).

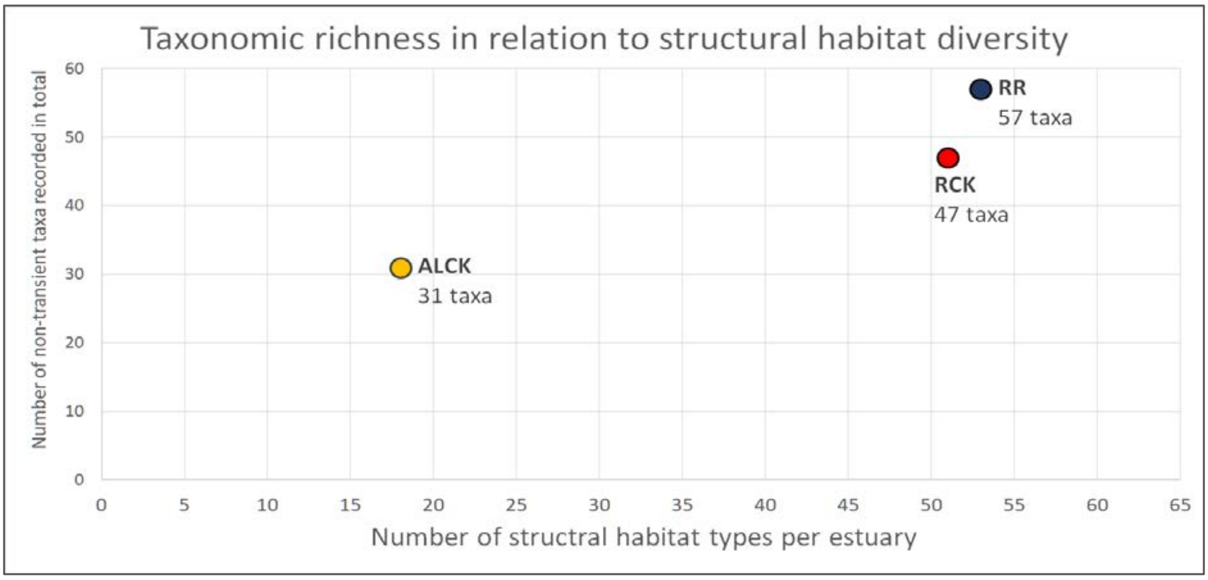


Figure 23. Correlation between values of non-transient taxa richness measured in Alligator Creek (yellow), Ross Creek (red), and Ross River (blue) and the number of structural habitats identified in each of the three estuaries.

The MDS and cluster analysis performed on taxa occurrence, particularly in relation to NAT-MOD structural habitat types, further confirmed the distinction between the more urbanised and less urbanised estuaries. Ross Creek and Ross River shared more similarities in occurrence of non-transient taxa compared to the less modified estuary of Alligator Creek (Figure 24). Additionally, the differences in taxa observed between NAT and MOD habitats were more evident in Alligator Creek than in the other more heavily urbanised estuaries (Figure 24).

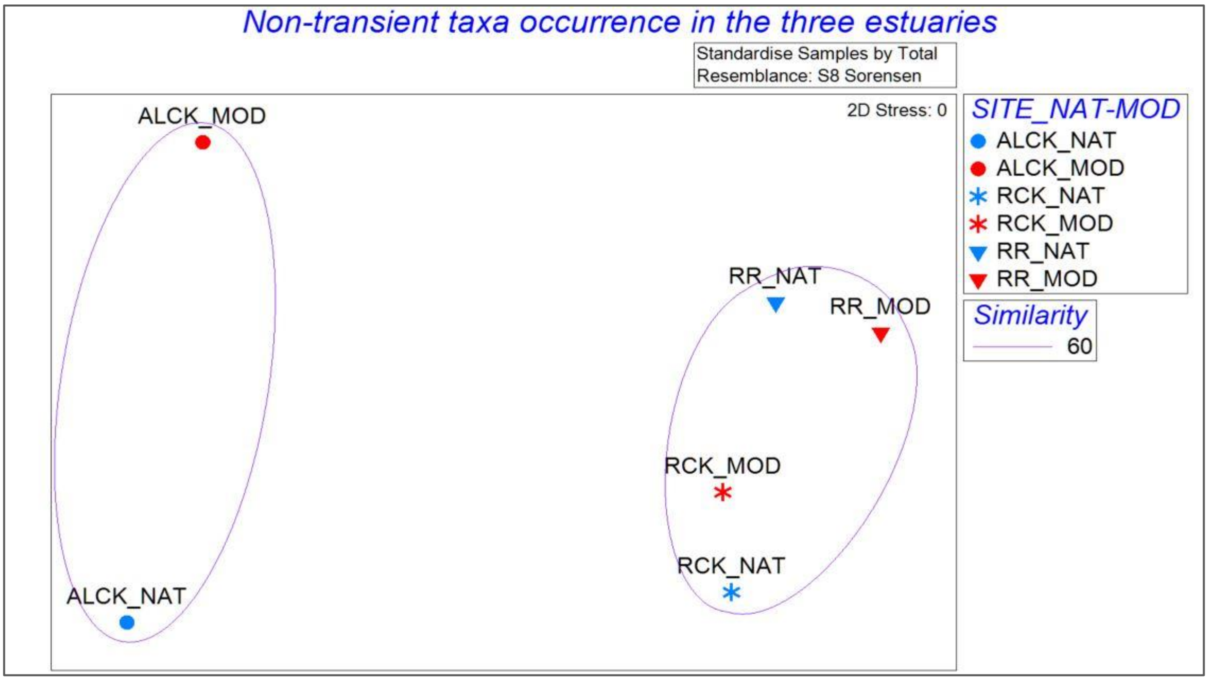


Figure 24. MDS ordination with Sorensen cluster analysis superimposed with 60% similarity of non-transient taxa occurrence in natural (NAT) and modified (MOD) structural habitats in the three estuaries of Ross Creek, Ross River, and Alligator Creek."

Of the 67 non-transient macrofauna identified, 24 occurred in all three estuaries (Table 17), the majority being crabs and gastropods.

Table 17. List of non-transient species found across all three estuaries: Ross Creek, Ross River and Alligator Creek.

Species list	
Balanus amphitrite	*Nerita planospira*
Camponotus sp.	*Periophthalmus sp.*
Crematogaster laeviceps	*Podomyrma gratiosa*
Gryllotalpa pluvialis	*Polyrhachis sp.*
Littoraria articulata	*Saccostrea cucullata*
Littoraria filosa	*Scylla serrata*
Littoraria pallescens	*Sesarma longicristatum*
Littoraria scabra	*Telescopium*
Macrophthalmus latreillei	*Thalassina sp.*
Macrophthalmus pacificus	*Uca coarctata*
Metopograpsus frontalis	*Uca seismella*
Metopograpsus latifrons	*Uca signata*

4.3.2 Influence of structural elements on species assemblages

The CART analyses showed how different structural parameters influenced the occurrence of the non-transient macro-benthic taxa among structural habitat types across the three estuaries. Presence of vegetation and anthropogenic features were the main drivers when considering all macro-benthic taxa (marine and terrestrial) (Figure 25). For marine taxa the parameters influencing species occurrence changed, with sediment type (hard/soft) becoming the main driver, followed by mangroves, then sampling sites, and finally gravel in the larger estuaries (Alligator Creek and Ross River) (Figure 26).

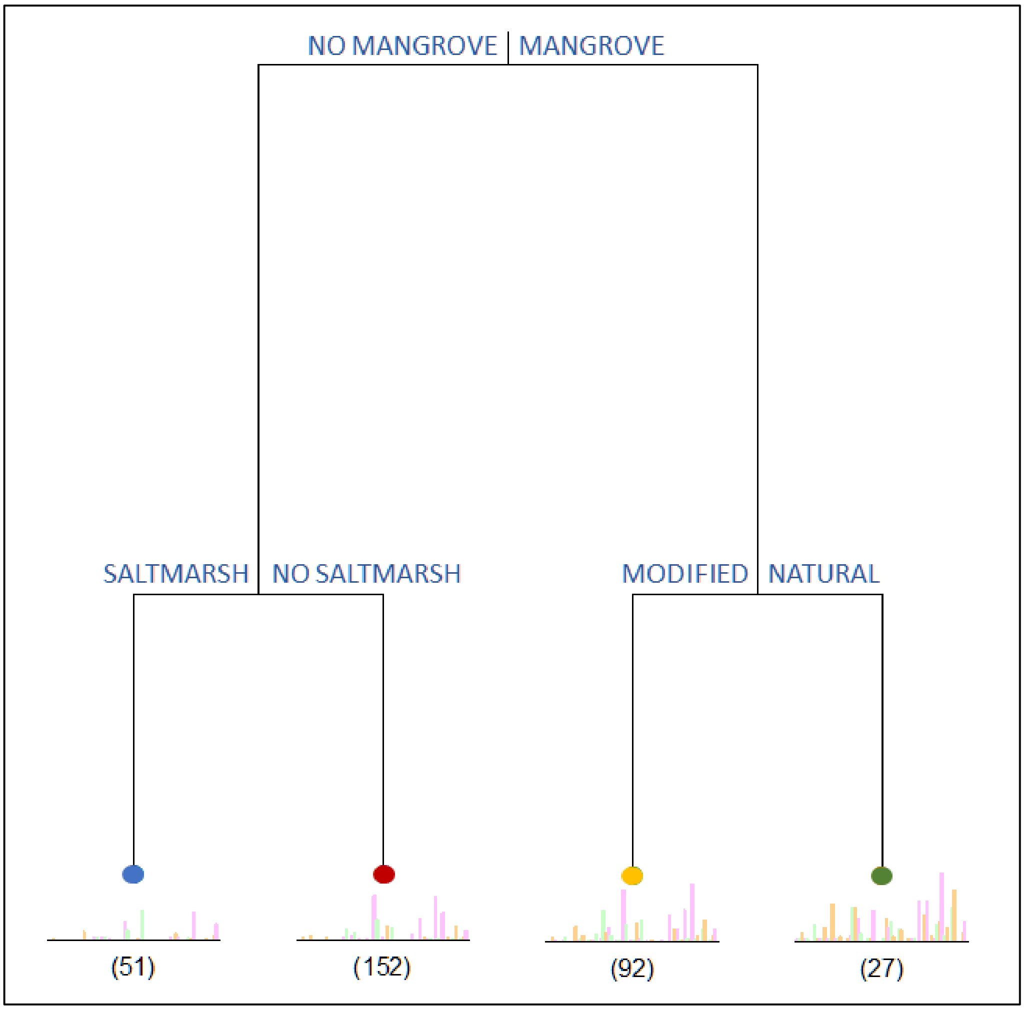


Figure 25. Classification and regression tree (CART) of occurrence of the 67 non-transient macro-benthic taxa identified in the three estuaries: Ross Creek, Ross River, and Alligator Creek. Labels indicate the parameter determining each split in the tree. Histograms indicate the relative frequency of occurrence of each taxon per split, with the number of samples indicated in brackets below.

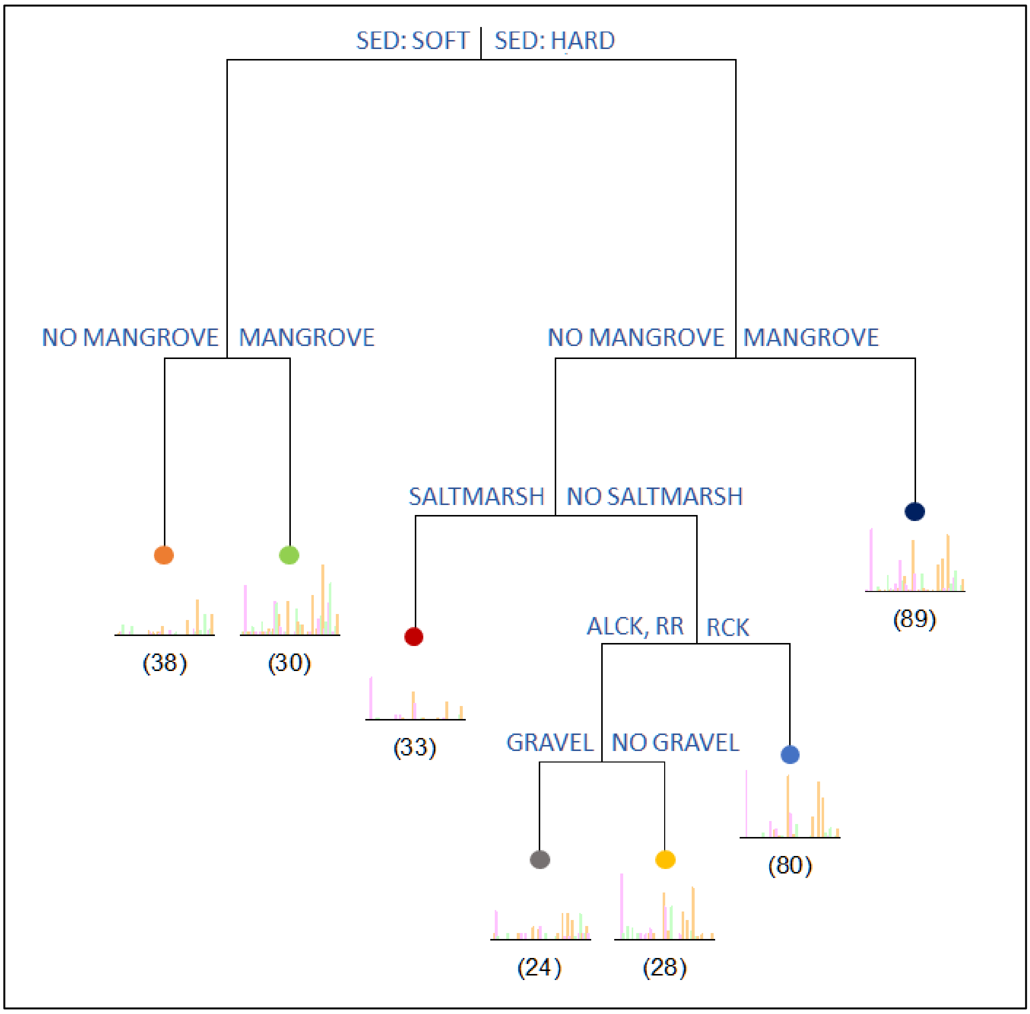


Figure 26. Classification and regression tree (CART) of the occurrence of the 53 non-transient marine macro-benthic taxa identified in the three estuaries: Ross Creek, Ross River, and Alligator Creek. Labels indicate the parameter determining each split in the tree. Histograms indicate the relative frequency of occurrence of each taxon per split, with the number of samples indicated in brackets below.

The presence or absence of mangrove plants was the most influential parameter for the frequency of occurrence of the entire non-transient macro-benthic species community (Figure 25). Even accounting for the difference in sampling size between habitats with mangroves (N=119) and habitats without (N=203), greater values of species richness and relative frequency of occurrence for most taxa were associated with presence of mangroves (Figure 27 and Figure 28):

51 taxa: higher relative frequency of occurrence in habitats with mangroves.

16 taxa: higher relative frequency of occurrence in habitats with no mangroves.

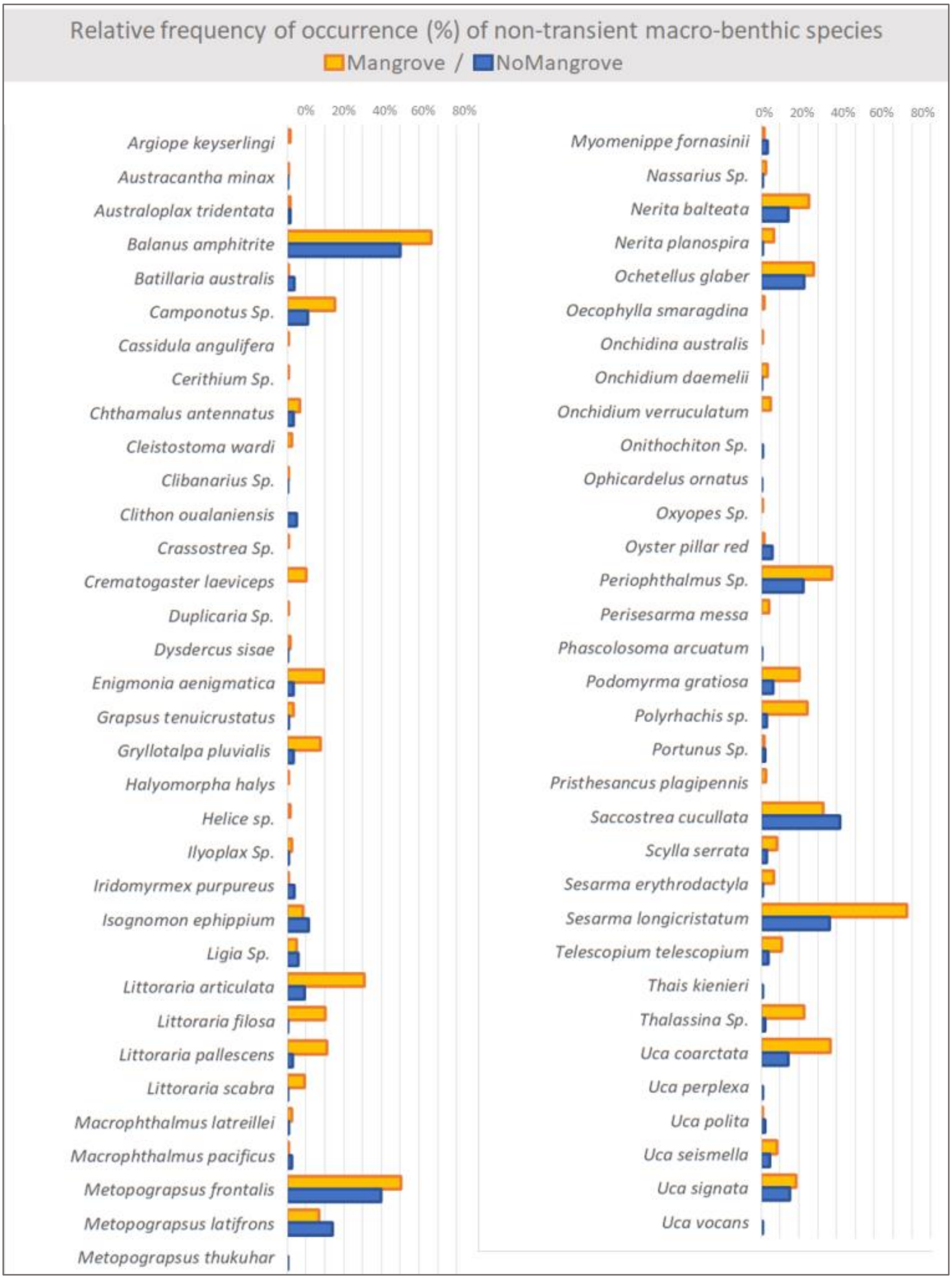


Figure 27. Relative frequency of occurrence (%) for each taxon across habitats with (yellow) and without (blue) mangroves.

It is notable that the only habitats without non-transient macro-benthic taxa were habitats characterised by the absence of mangroves (Figure 28).

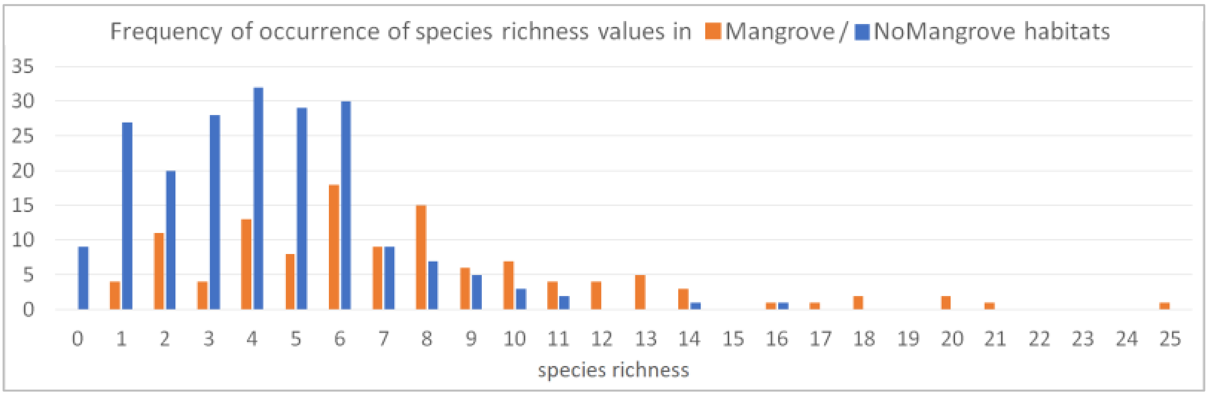


Figure 28. Frequency of occurrence of species richness values (ranging from 0 to 25 species per sample) for non-transient species in the sampled habitats for presence ('Mangrove') and absence ('NoMangrove') of mangroves.

Although most taxa exhibited a preference for habitats with mangroves, 66% were observed to utilise both Mangrove and NoMangrove habitats (Figure 27). Species like *Enigmonia aenigmatica* and several *Littorinidae* where recorded prevalently on mangrove plants (Figure 29), but in some occasions could be seen in habitats devoid of vegetation, attached to hard structures such as pillars and walls. Several other species however exhibited a clear preference for either of these two groups (Figure 27). Fifteen taxa, nearly half of which were terrestrial insects or arachnids, were located only on mangrove plants, while 8 taxa were found only in habitats devoid of mangroves (Table 18 and Figure 27).

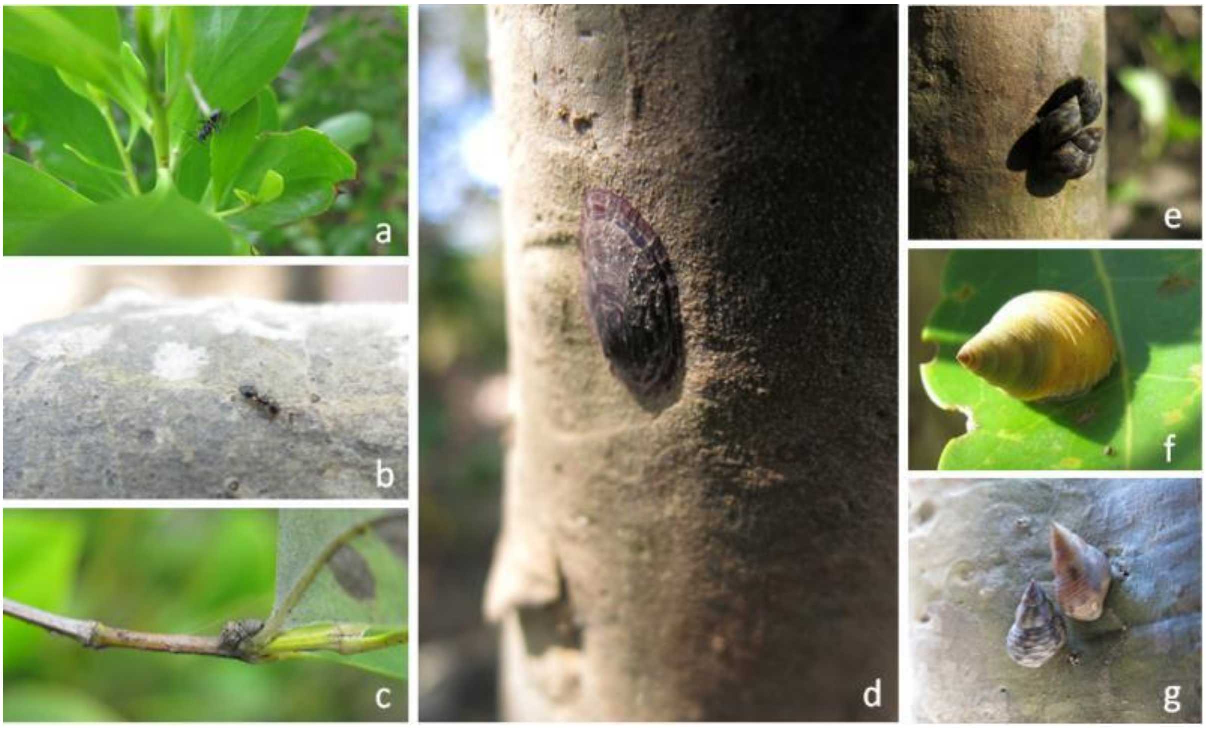


Figure 29. *Examples of* C. leviceps *(a, b),* Littorinidae *(e, f, g),* E. aenigmatica *(d) and other non-transient invertebrates (c) inhabiting habitats characterised by mangroves in the estuaries of Ross Creek, Ross River and Alligator Creek.*

Table 18. List of species found uniquely in habitats with ('Mangrove') or without ('NoMangrove') vegetation. Terrestrial species are highlighted in bold purple.

Species typical of Mangrove habitats	Class
Argiope keyserlingi	Arachnida
Cassidula angulifera	Gastropoda
Cerithium Sp.	Gastropoda
Cleistostoma wardi	Malacostraca
Crassostrea Sp.	Bivalvia
Crematogaster laeviceps	Insecta
Duplicaria Sp.	Gastropoda
Halyomorpha halys	Insecta
Helice sp.	Malacostraca
Oecophylla smaragdina	Insecta
Onchidina australis	Gastropoda
Onchidium verruculatum	Gastropoda
Oxyopes Sp.	Arachnida
Perisesarma messa	Malacostraca
Pristhesancus plagipennis	Insecta

Species typical of NoMangrove habitats	Class
Clithon oualaniensis	Gastropoda
Metopograpsus thukuhar	Malacostraca
Onithochiton Sp.	Polyplacophora
Ophicardelus ornatus	Gastropoda
Phascolosoma arcuatum	Phascolosomatidea
Thais kienieri	Gastropoda
Uca perplexa	Malacostraca
Uca vocans	Malacostraca

When considering only non-transient macro-benthic *marine* organisms (53 in total), the presence or absence of hard sediment (*i.e.* Gravel, Boulders, and Pavement) was the most influential parameter determining the occurrence of taxa (Figure 26). In this section all habitats without hard sediment are defined as 'Soft' and habitats that are characterised fully or partially by hard sediment are defined as 'Hard'. Presence and absence of mangrove plants was the second ranking structural parameter for both soft and hard sediment habitats (Figure 26). However, while no further splits occurred in the regression tree with soft sediments, the occurrence of taxa in habitats characterised entirely or partially by hard sediment were influenced by other factors: Saltmarsh, Sampling sites (estuaries), and Gravel (Figure 26).

Despite differences in sampling size between soft (N=68) and hard (N=254) habitats, the number of taxa observed for both groups were similar: 41 taxa in soft sediment and 48 in hard sediment (Figure 30). Frequency of occurrence of the different taxa on the other hand was higher in habitats with soft sediment, with seventeen taxa (predominantly gastropods) found uniquely or more frequently in habitats characterised by mud and/or sand, like the mangrove slug *O. damelii*, horn snail *Telescopium*, or fiddler crabs *Uca coarctata* and *Uca signata* (Figure 30 and Figure 32). Twelve taxa, half of which were crabs, were found only in hard sediments, and five taxa, almost all gastropods, were found only in habitats characterised by soft sediment (Table 19 and Figure 30).

Table 19. List of species found uniquely in habitats with hard sediment or soft sediment. Highlighted in colour: crabs (red) and gastropods (green).

Species typical of Hard sediment habitats	Class
Crassostrea Sp.	Bivalvia
Metopograpsus latifrons	Gastropoda
Metopograpsus thukuhar	Malacostraca
Myomenippe fornasinii	Malacostraca
Onchidina australis	Gastropoda
Onithochiton Sp.	Polyplacophora
Ophicardelus ornatus	Gastropoda
Phascolosoma arcuatum	Phascolosomatidea
Portunus Sp.	Malacostraca
Thais kienieri	Gastropoda
Uca perplexa	Malacostraca
Uca vocans	Malacostraca

Species typical of Soft sediment habitats	Class
Cassidula angulifera	Gastropoda
Cerithium Sp.	Gastropoda
Clibanarius Sp.	Malacostraca
Duplicaria Sp.	Gastropoda
Onchidium daemelii	Gastropoda

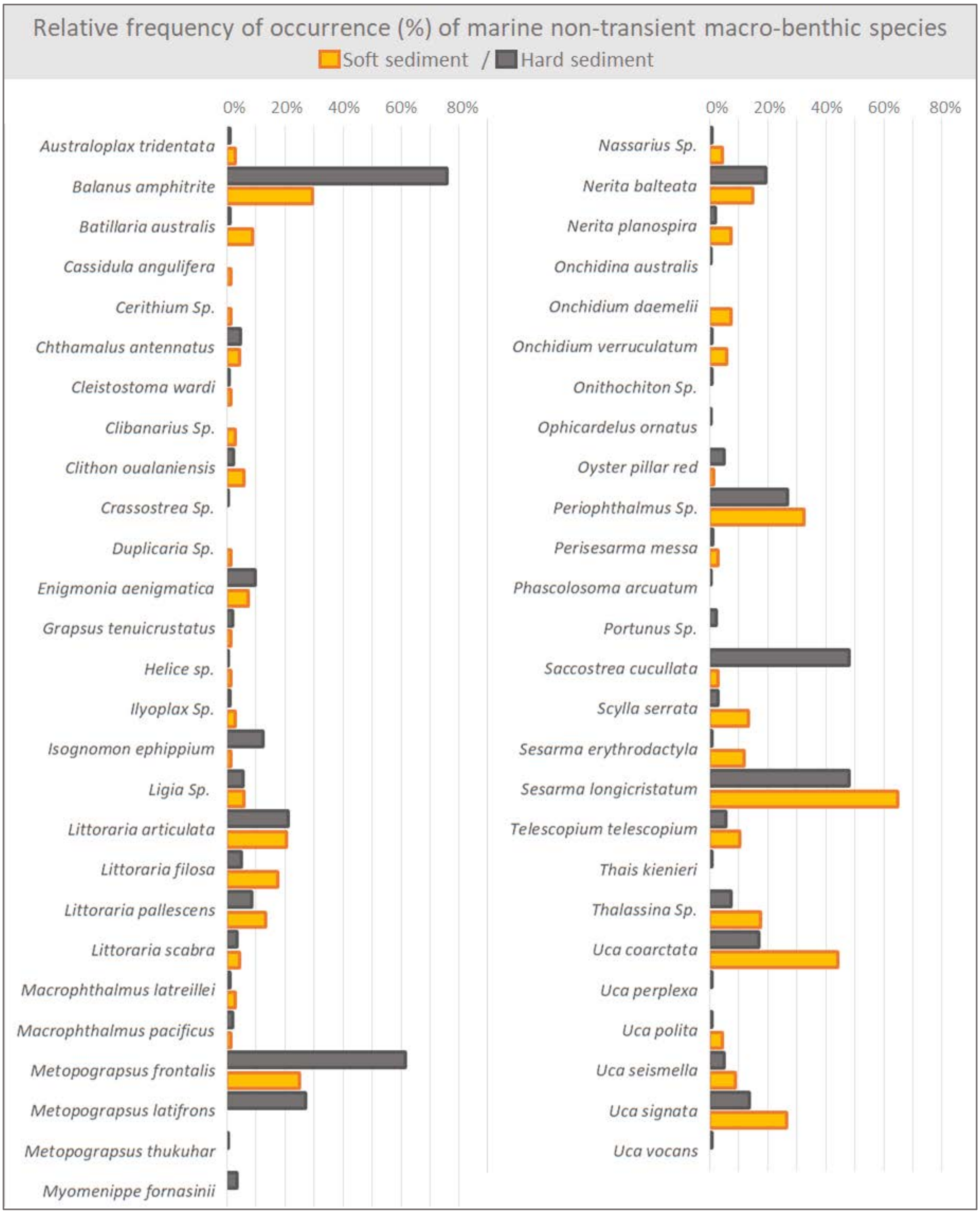


Figure 30. Relative frequency of occurrence (%) for each marine non-transient macro-benthic species in habitats with ('Hard', grey) and without ('Soft', yellow) hard sediment.

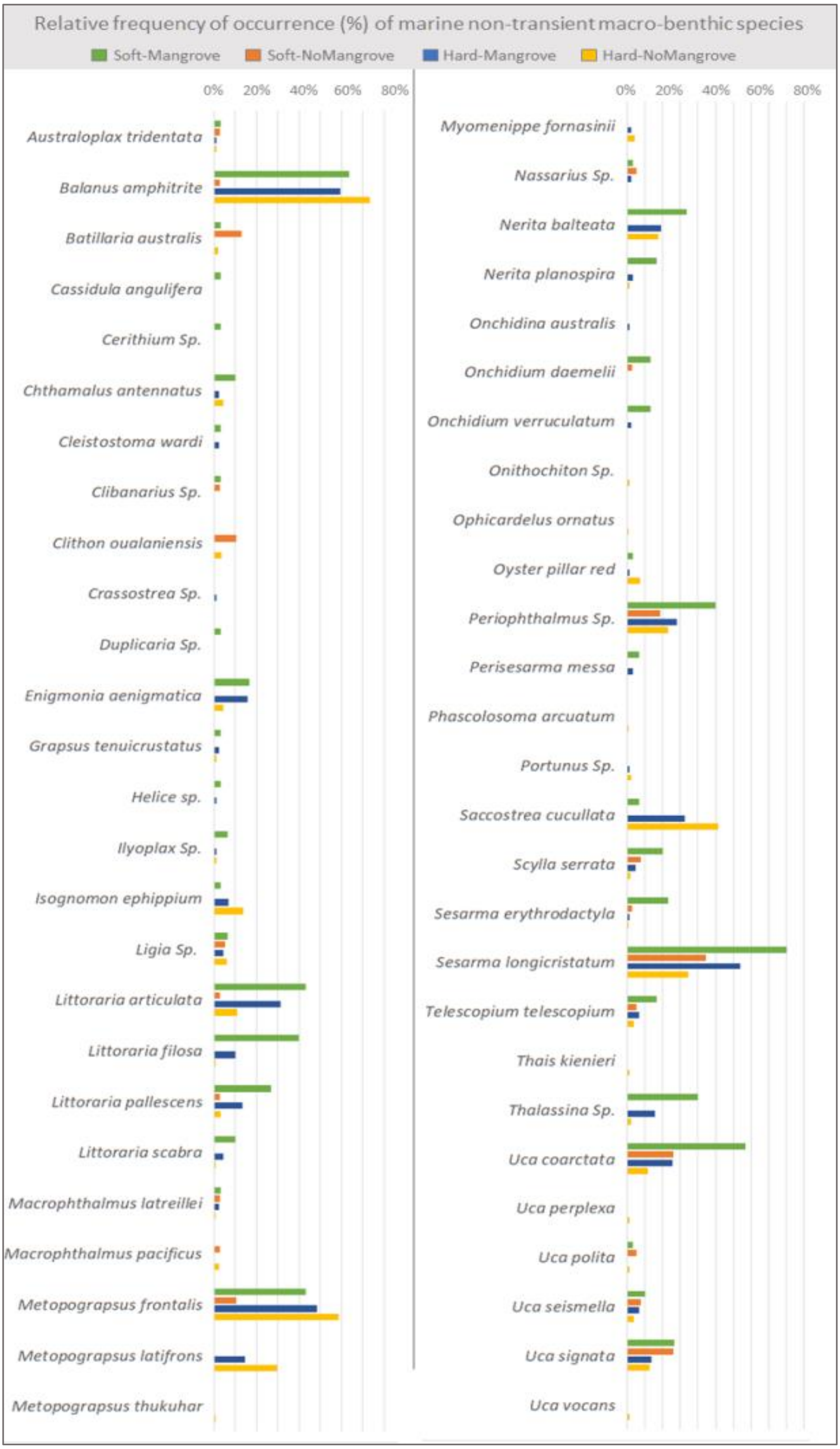


Figure 31. Relative frequency of occurrence (%) for each marine non-transient macro-benthic species across the four subgroups identified in the first two splits of the CART analysis: habitats with soft sediment and mangroves (green), habitats with soft sediment but no mangroves (orange), habitats with hard sediment and mangroves (blue), and habitats with hard sediment but no mangroves (yellow).

Figure 32. Examples of *T. telescopium* (a), *O. damelii* (b) and *U. coarctata* (c, d) inhabiting habitats characterised by soft sediment in the estuaries of Ross Creek, Ross River and Alligator Creek.

Looking at the next subdivisions identified by the CART analysis, the presence of mangrove vegetation, particularly in habitats characterised by soft sediment, corresponded to higher values of relative frequencies of occurrence for most taxa (34 of the total 53 marine macro-benthic taxa) (Figure 31). The combination of soft sediment and lack of mangroves showed the lowest number of taxa. Of the 53 taxa observed, only 14 were recorded across all four habitat subgroups: Soft-Mangrove, Soft-NoMangrove, Hard-Mangrove, and Hard-NoMangrove (Figure 31). Some taxa appeared to depend on the presence of vegetation, regardless of sediment type, including *C. wardi*, *Helice sp.*, *L. filosa*, *L. scabra*, *O. verruculatum*, and *P. messa* (Figure 31). When considering habitats characterised by hard sediment, frequency of occurrence of the different taxa in presence or absence of mangroves varied quite substantially (Figure 31), however, gastropods were observed to prefer habitats with mangrove vegetation (Table 20).

Table 20. List of species occurring more frequently in Mangrove (left) or NoMangrove (right) habitats, in presence of hard sediment. Highlighted in colour: crabs (red) and gastropods (green).

Mangrove habitats	Class	NoMangrove habitats	Class
Enigmonia aenigmatica	Bivalvia	*Anomiidae sp.*	Bivalvia
Grapsus tenuicrustatus	Malacostraca	*Balanus amphitrite*	Hexanauplia
Littoraria articulata	Gastropoda	*Chthamalus antennatus*	Hexanauplia
Littoraria filosa	Gastropoda	*Isognomon ephippium*	Bivalvia
Littoraria pallescens	Gastropoda	*Metopograpsus frontalis*	Malacostraca

Littoraria scabra	Gastropoda
Macrophthalmus latreillei	Gastropoda
Nerita planospira	Gastropoda
Periophthalmus Sp.	Actinopterygii
Scylla serrata	Malacostraca
Sesarma erythrodactyla	Malacostraca
Sesarma longicristatum	Malacostraca
Telescopium	Gastropoda
Thalassina Sp.	Malacostraca
Uca coarctata	Malacostraca
Uca seismella	Malacostraca
Metopograpsus latifrons	Malacostraca
Myomenippe fornasinii	Malacostraca
Portunus Sp.	Malacostraca
Saccostrea cucullata	Bivalvia

Habitats characterised by hard sediment and absence of mangroves corresponded almost entirely to modified habitats. Most of the 24 taxa across all three estuaries showed similarities in patterns of relative frequency of occurrence and were observed in both natural (NAT) and modified (MOD) habitats (Figure 34). Several taxa, however, occurred uniquely or more frequently in habitats characterised by anthropogenic features and hard sediment, such as the barnacle *Balanus amphitrite,* the crabs *Metopograpsus frontalis, Metopograpsus latifrons,* and the oyster *Saccostrea cucullata* (Figure 33 and Figure 34).

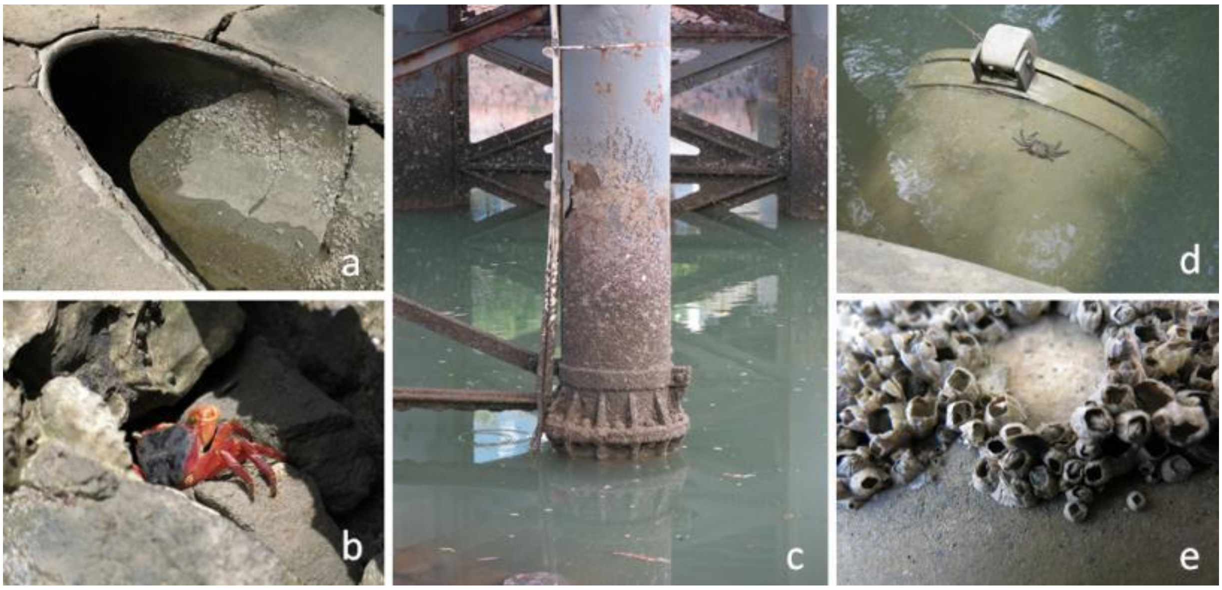


Figure 33. Examples of *S. cucullata* (a, c)*, B. amphitrite* (c, e)*, M. frontalis* (b), *M. latifrons* (d) and other non-transient invertebrates inhabiting modified habitats in the estuaries of Ross Creek, Ross River and Alligator Creek.

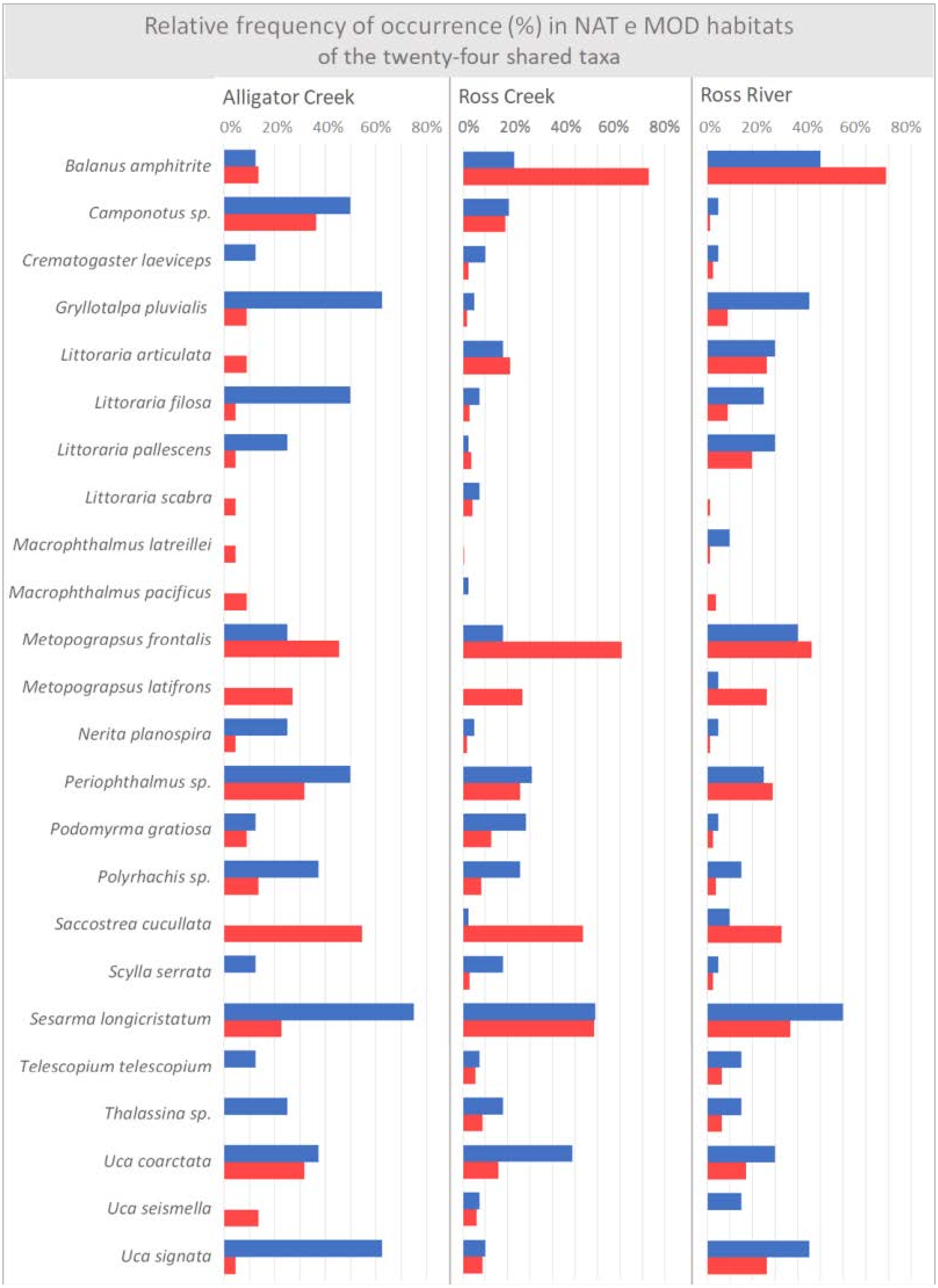


Figure 34. Relative frequency of occurrence (%) of the 24 'shared' taxa in Natural (NAT) and Modified (MOD) habitats across the three estuaries: Ross Creek, Ross River and Alligator Creek. Natural habitats are represented by the blue bars (upper) and Modified habitats by the red bars (lower).

4.4 Discussion

Estuaries characterised by a greater variety of structural habitats as a consequence of coastal development, particularly in the form of urban and industrial expansion, showed higher values of fauna richness compared to less modified and structurally diverse estuaries. Of the 67 non-transient taxa recorded, 86.5% were found in Ross River and 70% in Ross Creek. These estuaries have been extensively modified over the decades resulting in an increased number of structural habitats found in the intertidal zone (53 and 51, respectively) (see Chapter 3). By contrast, less than 50% of the non-transient taxa were recorded in the more 'natural' Alligator Creek, an estuary with only 18 structural habitats and substantially less altered by anthropogenic development (<5% of total linear length) (see Chapter 3). The introduction in an ecosystem of additional structural elements, such as artificial features and/or hard sediment provides novel resources and opportunities for a wider range of species to colonise and utilise the area (Anderson and Underwood 1994; Bulleri and Chapman 2010). For example, 'hard' surfaces such as cement slopes, boulders, pillars and walls create the optimal conditions for the settlement of many sessile species such as barnacles, oyster and mussels in areas predominantly formed by soft sediments. The results presented in this study provide compelling evidence that, in this case, estuaries that have been extensively modified by development, and are thus characterised by more combinations of structural elements, harbour more taxa (Figure 23). Thus, considering the positive correlation between variety of structural habitats and fauna richness, the assessment of the number of species in an ecosystem exposed to development does not generally provide a useful indicator of ecosystem health. The assumption that a greater number of species corresponds to a natural and healthy ecosystem is misleading as it does not consider the almost inevitable increases in richness linked to the introduction/colonisation of new species (potentially non-native, fouling or invasive) following changes caused by development (Bulleri and Airoldi 2005; Glasby *et al.* 2007; Tyrrell and Byers 2007).

The results obtained in this study showed how development, particularly involving changes in structural composition, can be associated with an increase in species richness. As such, species/taxonomic richness in itself is an inadequate indicator for the status and composition of an ecosystem altered by development. However, this measure is still often used as an ecological indicator in landscape management and restoration (Atauri and de Lucio 2001; Nally and Fleishman 2004; Noss 1990; Simmonds *et al.* 2019), particularly where the stated focus is on ensuring high numbers of species in the affected ecosystems. However, the focus shouldn't be on richness *per se*, but on ensuring that the species assemblages inhabiting an ecosystem modified by development still provide the natural ecosystem functioning and services, a priority for healthy and valuable wetlands (Barbier *et al.* 2011).

Despite the differences in the number and types of benthic macrofauna observed among the estuaries, twenty-four non-transient taxa overlapped consistently among the three estuaries (Table 17). Fifteen were observed in both modified and natural habitats, although their relative frequency of occurrence was overall higher in habitats devoid of any anthropogenic features, particularly in Alligator Creek. The ability to inhabit a wide range of habitats could be indicative of the capacity of these animals to adapt to or withstand the changes in structural elements occurring with development, and points to the existence of a range of taxa typical of the natural wetlands and estuaries that can exist and survive even in urban conditions. The conversion from an ecosystem primarily formed by natural habitats to a more heterogeneous and modified habitat mosaic would therefore not necessarily correspond to an overall decrease in occurrence of these taxa, as many could adapt to the new conditions and/or re-colonise the area. These observations are consistent with other cases where several marine species have been observed to inhabit both areas with natural structures and those with artificial structures (Cenci *et al.* 2011; Clynick *et al.* 2008; Wakefield *et al.* 2013). Although it should be noted that the natural areas described in these studies sharing similarities in species composition with artificial structures are characterised by rock formations and reefs, as opposed to the natural habitats described in this thesis which are predominantly characterised by soft sediment.

Focusing on the habitat utilisation of different taxa, preferences for certain structural features (either individually or grouped) were observed for many species. Overall, a strong effect of soft vs. hard sediment was observed for the occurrence of marine non-transient taxa, while the presence of terrestrial taxa was influenced predominantly by vegetation and then by anthropogenic modifications. Notably, several taxa where found uniquely/prevalently in structural habitats characterised by artificial features and hard sediment. The barnacle *B. amphitrite* and the hooded oyster *S. cucullata* utilise the hard surfaces characteristics of artificial structures and sediments to settle and form encrusting colonies (Holm 1991; Lam *et al*. 2009; Zvyagintsev and Korn 2003), while the crabs *M. latifrons* and *M. frontalis* seem to utilise the increased structural complexity presumably as suitable refuges from predators. *S. cucullata* is a species endemic of Australian estuaries and an ecological engineer able to form extensive oyster beds on natural intertidal rocky foreshore (Gillies *et al.* 2018). *B. amphitrite*, a fouling species able to spread through commercial shipping (Foster 1978; Jones 1992), can quickly form large encrusting colonies on artificial sediment and structures in the lower intertidal zone. The crabs *M.*

latifrons and *M. frontalis* are known to be associated with the presence of structures (Vermeiren and Sheaves 2015b) and as such it is not surprising that their occurrence is strongly associated with the presence of anthropogenic modifications (Figure 34). Taxa whose occurrence is linked to modified habitats can colonise new environments and increase in presence and distribution concurrently with modification in the form of a shift from soft to hard sediment and introduction of artificial structures. Such phenomenon can be observed in Ross Creek and Ross River, as well as in the boat ramp area of Alligator Creek. While this can result in an increase in the number of taxa of the ecosystem, the onset and distribution of species not previously observed can affect the overall species assemblages and related ecological functions, particularly considering the role of these species as ecosystem engineers (Kristensen 2008), and key components of the trophic network of these ecosystems (Vermeiren *et al.* 2015; Werry and Lee 2005).

Seventeen different taxa – mostly gastropods and a few crabs – were found uniquely or predominantly in soft sediment habitats (Figure 30). Most are deposit feeders and rely on the presence of mud for foraging and survival, such as the mud whelk *B. australis* (Hughes *et al.* 2014; Schneider *et al.* 2015), dog whelk *Nassarius sp*. (McKillup and McKillup 1995), mangrove slug *O. damelii* (Camilleri 1992), and horn snail *T. telescopium* (Rodelli *et al.* 1984). Presence of soft sediment also provides essential services for several crab species of the genus *Uca* and *Sesarma* as foraging ground and terrain to build their burrows (Slatyer *et al.* 2008; Vermeiren *et al.* 2015). All these species play key roles in the trophic web of estuaries by processing leaf litter and increasing the particulate organic matter in the sediment (Camillieri 1992; Hughes *et al.* 2014), as well as providing a source of food for many vertebrate species (Abrantes and Sheaves 2009; Beumer 1978). Changes in sediment characteristics associated with coastal development and, particularly reduction in the extent of soft sediment habitats, resulting in a shift from soft to hard sediments and structures would greatly disadvantage these taxa and likely result in a decrease in their occurrence, abundance and distribution, with repercussions on the services and functions they provide (Abrantes and Sheaves 2009). In addition, it should be pointed out that lack of changes in overall species richness or in presence of native species following the structural modification of an estuary for urban expansion do not necessarily mean that the anthropogenic modifications performed have had no negative impact on the local biotic community. Decline in the abundance of certain species, reduced functioning or alterations in species distribution linked to development could still have occurred without any noticeable impact on overall species richness/presence values."

Presence of vegetation has also been recorded as essential for numerous taxa, particularly terrestrial invertebrates (Hegerl and Davie 1977). Several ant and spider species like *C. laeviceps,* *H. halys*, and *O. smaragdina* were observed to inhabit predominantly, and in some cases uniquely, mangrove habitats (Figure 27). Many marine taxa showed apparent dependency on the presence of vegetation, often regardless whether the sediment is soft or hard: *C. wardi*, *Helice sp*., *L. filosa, L. scabra, O. verruculatum*, and *P. messa* (Figure 31). Mangrove trees provide shelter and foraging grounds to many invertebrates, intent and non-transient. They also contribute to sediment retention thus providing opportunities for burrowing species (Nielsen 1997), and their above-water structures offer refuge for arboreal ones during high tide (Clay and Andersen 1996). Several species, some of which recorded in this study like *O. glaber*, *Camponotus spp*. and *C. wardi*, are known to inhabit saltmarsh meadows (Taylor and Allanson 1993; Trave and Sheaves 2014) and have shown to prefer such vegetation and occur in higher frequency where in its presence. Similar to the species described for soft sediment, these taxa play key roles in the health and functioning of estuaries, be it by processing plant matter and cycling nutrients (Richoux and Froneman 2008; Uday Ranjan and Ramesh Babu 2014), as part of the food web (Sheaves and Molony 2000), or as ecosystem engineers (Mchenga *et al.* 2007). The decline or disappearance of mangrove-specialists from the ecosystem related to vegetation clearing or thinning would thus result in the loss of these services and functions within the immediate area, but also possibly more broadly in the seascape.

Presence of mangroves and soft sediments therefore represents key elements ensuring the occurrence and resilience of native species in estuaries subjected to urban and industrial development. The transition from soft sediments to hard structures and the reduction in native vegetation due to urban/industrial development are major drivers of changes in species assemblages and ecosystem dynamics (Heery *et al.* 2017; Lee *et al.* 2006; Lowe and Peterson 2014). Although the resulting increase in habitat types might correspond to an increase in the overall number of taxa (McKinney 2008), the species composition of the ecosystem would be altered and likely transition (partially or fully) from native soft-sediment communities and mangrove-specialists to a mixed community including sessile encrusting colonies of filter feeders and potentially invasive species. If the goal in coastal planning is merely to ensure the presence of a high number of species in the affected ecosystem, then the changes caused by development are likely to facilitate that outcome. By contrast, if the goal is to ensure the preservation/restoration of native communities and natural ecosystem functioning, a trend now common to many coastal development practices around the world (*e.g*. Bilkovic *et al.* 2016; Burt and Bartholomew 2019; Firth *et al.* 2014a; Sutton-Grier *et al.* 2018), then priority needs to be given to maintaining as much as possible the relevant conditions that favour native organisms and prevent irreversible changes in the species composition of the ecosystem. As such, the inclusion of structural parameters such as vegetation, sediment type, and artificial features in assessment criteria and protocols for monitoring of ecosystem status appears essential. Information collected on the structural habitat composition of an ecosystem and its effects on the biotic communities is in fact imperative for appropriate landscape planning and management of coastal areas, particularly in face of increasing urban and industrial expansion that is accelerating in tropical areas.

Chapter 5.

- General Discussion -
Analysing tropical coastal ecosystems in face of development: A new understanding of structural changes with implications for ecology and management

5.1 Introduction

This thesis presents a novel and easily applicable tool for managers and landscape developers to assess the structural composition of coastal ecosystems that are under pressure from sprawling coastal development (past, present or future). The data chapters outlined above expand on the current understanding of tropical coastal wetland ecosystems exposed to urban and industrial development and provide new insight for best practices and appropriate management strategies aimed at ecological conservation and restoration.

5.2 The classification scheme for structural habitats in coastal ecosystems

Urban and industrial expansion cause structural changes in the ecosystems where they take place, often with repercussions on faunal communities and on the ecological functions and services they provide (Alberti 2005; Bulleri and Chapman 2010; Connell and Glasby 1999; Mayer-Pinto *et al.* 2018). Such changes need to be appropriately assessed and managed to minimise degradation and adverse effects on the ecosystem (Crowder and Norse 2008; Douvere 2008; Long *et al.* 2015). This is both for areas that have already been developed and for those that are yet to be modified (Burt 2014; Diegues 1999; Yeung 2001). The standardised assessment of presence, extent, and distribution of structural components (both natural and artificial in origin) at the scale where coastal development takes place is a first essential step for a complete understanding of the composition and status of an ecosystem and, subsequently, for the selection of appropriate management protocols (Airoldi and Beck 2007; Morrissey *et al.* 2012; Wegscheidl *et al.* 2017; Zajac 1999).

Existing classification criteria, while adept at classifying natural coastal ecosystems, present a few key disadvantages in characterising ecosystems that have been structurally modified by urban/industrial expansion, or in providing information to be applied in the context of future coastal development or restoration (see Chapter 1). For example, while broadly applicable these classifications frequently focus on large scales or have quite coarse resolution (*e.g.* Butler *et al.* 2017; Davies *et al.* 2004; Howes *et al.* 2002). While this can simplify the assessment of large territories and potentially even reduce costs associated with remote-sensing and mapping (Verburg *et al.* 2011), it increases the risk of misrepresentation of the actual composition of an ecosystem, as any element smaller than the minimum mapping unit would, in fact, not be perceived or recorded (Verburg *et al.* 2011). This is particularly relevant in the context of development if we consider that existing classifications often operate at scales where the minimum mapping unit corresponds to a few hundred meters or a kilometre (*e.g.* Butler *et al.* 2017; Davies *et al.* 2004; Howes *et al.* 2002; Spalding *et al.* 2007), while many developments or structural alterations in coastal ecosystems occur at smaller scales (sometimes even down to a few meters). Unlike the classification tool developed here, other classifications are thus unsuitable to provide the level of detail on the composition of an ecosystem that is usually associated with small or local-scale works. Such misrepresentation could not only lead to a skewed perception of the actual status and composition of an ecosystem, but also potentially affect decision-making processes (Estes *et al.* 2018).

Another gap in current classification schemes is the lack of inclusion of anthropogenic modifications as independent physical components of the classification itself (Appendix 1b). Most classifications focus predominantly on hydrologic and geomorphic parameters (*e.g.* Commonwealth of Australia 2005; FGDC 2012; FGDC 2013; Spalding *et al.* 2007; Valentine *et al.* 2005) or on physical, chemical, and biological parameters (*e.g.* Butler *et al.* 2017; DEHP 2017; Madden *et al.* 2005). Anthropogenic features are rarely present, and often merely as further 'attributes', 'qualifiers', or 'modifiers' of other components (*e.g.* Auster *et al.* 2009; Butler *et al.* 2017; DEHP 2017; FGDC 2012; FGDC 2013; Lund and Wilbur 2007) rather than as independent layers/levels (for hierarchical classifications) or classes (Guarinello *et al.* 2010). For example, Seamap Australia (Butler *et al.* 2017) has put a little more focus on anthropogenic elements compared to other classifications available. However, the anthropogenic layer is still presented as a qualifier for substratum rather than as an individual component categorising different artificial structures integrated in an ecosystem. Guarinello *et al.* 2010 present a model where anthropogenic features are introduced as a separate component of the classification, alongside benthic and water column characteristics. However, the 'Human Component', as it is called in that model, focuses on human actions performed on the ecosystems and the 'use', rather than on physical constructions or structural elements of anthropogenic origin (Guarinello *et al.* 2010). While this can put more emphasis on the effect of human actions on the ecosystem, it makes this classification more descriptive than categorical, and does not provide a way to characterise and map the composition of an ecosystem in a clear and consistent way. This is further complicated by the lack of clearly defined classes/sub-components for the individual elements belonging to the Human Component (Guarinello *et al.* 2010) which could result in reduced consistency in classification when the assessment is performed by different users (Strong *et al.* 2018).

Including artificial features in ecosystem classification and mapping is essential to achieve a truly comprehensive understanding of the composition and status of an ecosystem (Guarinello *et al.*

2010; Zajac 1999), as well as the implications of structural modification on the biotic communities and functions (Alberti 2005; Bulleri and Chapman 2010; Connell and Glasby 1999; Martin *et al.* 2005). Coastal areas that have undergone agricultural, industrial, and urban expansion are characterised by the presence of different (and often widespread) artificial structures and anthropogenic modifications (Bulleri and Chapman 2010; Holland *et al.* 1995; Yeung 2001). As such, a distinct lack of inclusion of these elements in classification schemes would contribute to a misrepresentation of the ecosystem's composition, with potential repercussions on the understanding of the ecosystem's functioning and services (Cortina *et al.* 2006; Lamont 1995) and/or on policy or decision-making processes (Estes *et al.* 2018; Moberg and Rönnbäck 2003). Secondly, being able to accurately map and characterise the type, extent, and distribution of different artificial features present in an ecosystem would create a baseline dataset that could be used to track over time (with repeated assessments) patterns of change or progressive modifications linked to new development works, thus facilitating ecological monitoring for urban/industrial expansion. Moreover, the assessment of presence, extent, and distribution of modification could assist in determining where to target further sampling to collect the information required to decide if/where/how to intervene for repair/restoration or even to plan for further development (see Chapter 3 and 4). And finally, including artificial features in classification schemes for coastal ecosystems would also provide information useful for planning eco-engineering (Chapman *et al.* 2018), particularly when such practices are aimed at restoring or enhancing an ecosystem that has been impacted by the introduction of permanent artificial structures (*e.g.* Browne and Chapman 2014; Dyson and Yocom 2015; Evans *et al.* 2016; Firth *et al.* 2016b; Lundholm and Richardson 2010; Paalvast *et al.* 2012). Knowledge of the type, extent, and distribution of different artificial structures and substratum present in an ecosystem could, in fact, facilitate planning for the introduction of suitable eco-engineering structures (Chapman *et al.* 2018).

Despite the apparent need for detailed knowledge on the presence and distribution of artificial structures and anthropogenic modifications in coastal ecosystems, current classification schemes do not include such features as independent and clearly defined physical components, nor do they consider them as individual structural elements present in an ecosystem alongside substratum and vegetation. Moreover, the level of detail and resolution required for the characterisation of individual anthropogenic structures is rarely matched by broad classification schemes. This does not mean that the existing classification schemes are invalid or not exhaustive, but merely that they have been developed with scopes and purposes that might not adequately match the context of local-scale coastal management or ecosystem restoration in face of urban/industrial development (Lund and Wilbur 2007; Strong *et al.* 2018). The classification scheme presented in this thesis had been developed to address the issues listed above and provide an alternate methodology to be applied for coastal development and management at a small/local scale. It was created with the intention of complementing existing broader classification schemes by providing high resolution information at a small local scale that can be integrated into a much larger landscape perspective. It represents a rapid and standardised way to characterise and map the structural composition of an ecosystem, and assess type and extent of structural modification linked to coastal expansion (Chapter 2). Thanks to its simple structure, clearly defined classes, and straightforward applicability this classification scheme can be utilised by any manager, scientific technical officer or potentially community groups. No specific knowledge of coastal ecology or environmental sciences is required for someone to successfully apply this classification and to map the structural habitat composition of an ecosystem (see sections 2.2.5 and 2.2.6). The subdivision of the three structural attributes in clear-cut classes and the sequential approach in habitat identification (see sections 2.2.6 and 3.2.2) also assists in minimising classification errors caused by overlaps between classes or subjective assessments/nomenclature (Strong *et al.* 2018). The sequential nomenclature for structural habitats allows also for identification of potential hierarchical connections between structural habitat types formed by similar combinations of structural classes (e.g. Ch.2 - Figure 6). Such information, if complemented with the position and distribution of habitats in the study area and historical information (where available), could allow the identification of patterns of change linked to development works, such as the introduction and possible degradation over time of artificial features, or patterns of natural change in the structural composition of the study area (*e.g.* vegetation re-colonisation/recruitment, sediment accumulation). Knowledge of the changes occurring over time can be integrated in landscape management for restoration/repair of affected areas to prioritise areas for intervention based on the extent of modification and rate of change over time. The information on patterns of change can also be complemented with data on the effect of different structural features on biotic assemblages and used to hypothesise/predict subsequent effects on biodiversity and connectivity in areas where development has yet to occur. This knowledge can then be integrated in development planning to identify the best strategies to minimise adverse impacts of on the environment of structural changes associated with development, thus focusing on prevention rather than repair. It is an assessment tool that can be applied by different end-users, including researchers and managers, to collect information to be integrated in ecosystem-based management, planning, and monitoring. This classification scheme can provide information on the presence and distribution of different structural elements (of natural or anthropogenic origin) in an ecosystem and classify them as easily identifiable and clearly defined units, called structural habitats (Chapter 2). The inclusion of artificial features as elements of the classification scheme adds further value to this assessment tool in its ability to detect, characterise, and map structural modifications associated with urban and industrial development, a feature frequently absent in other existing classifications, as previously detailed.

The classification has been developed to provide fine-detailed information at a scale relevant for local-based management, which often occur in areas smaller than a few kilometres or even at a few meters. An example can be a city council addressing the introduction of stormwater drains, the construction of a new bridge, or the armouring of a section of the bank. Therefore, the applicability of this classification at a local scale (Level 3 ANAE or below) ensures the relevance of the information collected for ecosystem-specific or project-specific planning and intervention, while also considering the spatial range of movement of many sessile or non-transient species (Chapter 2 and 4).

The information collected can then be subsequently used to measure and map extent of structural modification (Chapter 3), characterise habitat complexity and compare ecosystems (Chapter 3). Moreover, it also links structural elements with local fauna (Chapter 4), and assists in identifying priorities for management and conservation.

5.3 Assessment of coastal estuaries exposed to different extent of development

I applied the classification scheme developed in Chapter 2 to a series of estuaries exposed to different extents of development to habitat complexity and relative flora/fauna communities (Chapter 3 and 4).

The resolution of the classification scheme for structural habitats allows for detailed measurement of the structural composition of an estuary. This provides in-depth information to be used for effective planning and decision making in face of development (past, present, or future). The results indicated a strong positive relationship between increasing urban development and habitat diversity and fragmentation, pointing to the dominance of modified structural habitats over natural ones as leading factors towards increase in diversity (Chapter 3). The high variety of structural habitats found in the estuaries was linked to changes resulting from progressive development works in the form of structural alterations, as shown by the many different combinations of artificial features and artificially introduced substrata identified in the more heavily developed estuaries (Chapter 3). Development works in an ecosystem are rarely one-off events, but rather a series of progressive and extensive works carried out over years/decades that increase the structural complexity, patchiness and habitat richness of an ecosystem (Chapter 3; Airoldi and Beck 2007; Alberti 2005). As such, it is not surprising that each of the estuaries assessed in this study showed unique composition and distribution of structural habitats, and that greater habitat richness was recorded for the more heavily modified estuaries of Ross Creek and Ross River (Chapter 3). A Greater number of habitats therefore should not necessarily be considered as an indicator of 'more naturally variable' ecosystems (Chapter 3).

The patterns of distribution and extent of structural habitats and/or individual structural classes can also assist in identifying the dominant features of an ecosystem. The comparison of the different structural habitats found in the four estuaries has provided a baseline assessment of the structural composition for estuaries, and assisted in identifying a common set of natural habitats shared by all of the estuaries comprising predominantly of a combination of mud, sand, mangrove, and saltmarsh (Chapter 3).

Once I had a thorough understanding of the structural composition of those estuaries, I assessed the influence of the different structural elements on faunal communities and highlighted the direct relationship between many species and the presence of specific structural elements such as sediment types, vegetation or artificial features (Chapter 4). Sediment type (hard vs. soft), presence of vegetation, and presence of artificial structures resulted parameters that strongly affect species occurrence (Chapter 4), which means that changes in the presence of these structural elements would affect the composition of faunal communities, with likely consequences on biodiversity and functioning as well (Alberti 2005; Bulleri and Chapman 2010; Connell and Glasby 1999; Mayer-Pinto *et al.* 2018). With the role played by artificial features in influencing the occurrence of different species, the inclusion of artificial structures and artificially introduced substratum in the classification scheme for structural habitats provides a new insight in ecological assessment of modified ecosystems and represents an advantage compared to other classifications that omit such features (Chapter 1).

Having confirmed the essential role that structural elements such as soft sediment (Anderson 2008; Kristensen 2008) and native vegetation (Gopal and Junk 2000; Nagelkerken *et al.* 2008) play in ensuring the presence and density of many macro-benthic species of key ecological value (Chapter 4), their preservation or restoration in areas exposed to development seems even more relevant.

5.4 Further considerations in the context of coastal development and management

The findings presented on the structural complexity of tropical coastal estuaries (Chapter 3) and on the influence of structural elements on faunal communities (Chapter 4) further highlight the need for the integration in development planning of ecosystem-based conservation/restoration strategies that focus on structural components to prevent ecological loss or irreversible changes in face of development, and to assist in the assessment and restoration of areas already impacted.

Mapping and measure of extent of modification can be used to evaluate the level of change occurred in an ecosystem over time and create a ranking scale for the comparison of ecosystems exposed to development (example provided in Table 21). This information should then be complemented with data on the species composition, distribution and functioning of the ecosystem to provide a comprehensive evaluation of the overall status and health of the ecosystem. Information on the type, extent, and distribution of modification collected with the classification scheme proposed could be also applied for the assessment of the resilience or the potential for recovery of an ecosystem and to calculate related thresholds and shifting points, if complemented with extensive knowledge of factors such as presence and type of concurrent stressors, other direct human interventions, connectivity of the ecosystem, hydrology, other abiotic/biotic parameters.

Table 21. Example of potential ranking scale to be used for the evaluation and definition of ecosystems exposed to different extent of structural modification.

Extent of structural modification (%)	Category/Definition	Class
0% – 10%	Minimally modified or Negligible	A
11% – 30%	Moderately modified	B
31% – 50%	Partially modified	C
51% – 70%	Substantially modified or Extensively modified	D
71% – 90%	Highly modified	E
91% – 100%	Completely modified	F

In addition, mapping the distribution of the different structural classes can assist in predicting patterns of change of accessibility and connectivity for different species throughout the entire ecosystem and adjacent areas. However, addressing the impact of a development work in coastal areas requires a level of understanding, analysis, and consideration that is not limited solely to the area directly affected, but focuses on a scale that includes other biologically or physically connected sections of the ecosystem and neighbouring ecosystems as well (Bishop *et al.* 2017; Crooks and Sanjayan 2006). Development works performed in an area can have radical effects on adjacent sections (*e.g.* upstream or downstream) or other ecosystems through changes in hydrology (Wolanski and Elliot 2015), morphology (Dallas and Barnard 2011; Surian and Rinaldi 2003) and connectivity (Bishop *et al.* 2017). This is particularly relevant considering many species utilise different habitats and ecosystems throughout their lives and need to move freely among them (Bradley *et al.* 2017; Sheaves 2009). Targeted planning based on accurate knowledge of the structural composition of an ecosystem can reduce the extent of habitat fragmentation and patchiness, ensuring the preservation or restoration of connectivity.

Information on the extent and distribution of individual structural habitats, or even the individual structural classes, can be used to select the most appropriate locations and strategies to carry out development works while minimising adverse/extensive changes in the structural composition of the ecosystem and subsequent effects on its overall health and functioning. The identification of a baseline set of natural habitats typical of tropical coastal ecosystems could provide insight in determining areas to focus further research and identify habitats to be prioritised in conservation and restoration. Information collected on the structural composition of an ecosystem and on the influence of structural components on local fauna occurrence can be used to select appropriate strategies for conservation of faunal communities and the many functions and services they provide (Airoldi and Beck 2007; Moberg and Rönnbäck 2003; Morrissey *et al.* 2012). Considering that shifts from soft to hard sediment are the most common and extensive structural alterations occurring with development, new strategies need to be devised to ensure the presence of mud, sand and vegetation in the ecosystem. Based on the results obtained in this work, I propose a few strategies that can be considered/integrated in the planning phase of a development to address and prevent the potential negative impacts of structural modification in estuarine ecosystems in the form of shift from soft to hard sediment and reduction of native vegetation. Selection and implementation of such strategies should be made on a case-by-case basis, depending on the characteristics of the development planned. This can be achieved by:

a) <u>Minimisation of sediment substitution</u>

   Reducing as much as possible the extent of areas where the natural sediment is fully replaced by artificial sediment/structures or limiting natural vegetation clearing (McAlpine *et al.* 2002). Radical changes in sediment type and presence of vegetation have shown to lead to an overall decrease in species richness (often such areas are bare and exposed;

Figure 35) or alteration in the composition of faunal assemblages, moving from soft-sediment dwellers and mangrove specialists to communities dominated by sessile species.

Figure 35. Examples of sections of Ross Creek where vegetated soft sediment has been completely replaced by artificial pavement for bank erosion mitigation.

To avoid such shifts in ecosystem composition, careful consideration needs to be given during the planning phase of development to reduce the extent of replacement of soft sediment with hard structures. Moreover, since complete sediment replacement in coastal development is predominantly linked to mitigation of progressive erosion, the use of alternative eco-engineering techniques (*e.g.* natural oyster beds, reefs, sediment-retaining vegetation) can further assist in fulfilling the requirement of coastal protection while also ensuring the preservation of natural ecological functioning (Borsje *et al.* 2011).

b) <u>Implementation of partial changes</u>

Instead of completely changing the sediment type of the intertidal zone, the introduction of hard sediment alongside/on top of the existing soft sediment (Figure 36) can prevent the loss of species associated with mud/sand while still providing the services required by the presence of hard substrate. Additionally, ensuring the presence of soft sediment facilitates the re-colonisation of the area by native wetland vegetation, such as mangroves and saltmarsh, and subsequently of wetland fauna.

Figure 36. Examples of sections of Ross Creek where natural soft sediment (mud) has been preserved alongside the introduction of hard sediment such as gravel and boulders.

c) Recreation of natural habitats and eco-engineering

Another option is to create the conditions for soft sediment to naturally accumulate in front of artificial structures and thus gradually re-create a natural habitat (Figure 37). This would best achieve the balance between having a structure which provide a service to humans, along with ensuring the presence of a natural section of the ecosystem, with its native biotic communities and ecological services.

Figure 37. Examples of sections of Ross Creek where soft sediment (mud) has naturally accumulated in front of artificial structures such as bridges and anti-erosion walls, thus creating new natural habitats to be utilised by the native fauna communities.

The rehabilitation of natural habitats in a modified ecosystem, be it by artificially re-creating them or by creating the conditions for soft sediment to naturally accumulate and be colonised by vegetation and then fauna, needs to be carefully planned to ensure the maximum result with minimum intervention (both in terms of effort, money and time). Many species inhabit and utilise predominantly the first few meters from the waterfront side of mangrove ecosystems due to several physicochemical and environmental factors (Huxham *et al.* 2004; Mattone and Sheaves 2017), so the re-creation of a 2.0 m – 5.0 m strip of mangrove habitats in front of pre-existing extensively modified sections may just be sufficient to increase the ecological value and use of that part of the bank, with hard engineering features behind the mangrove edge.

These principles for ecologically sustainable development and soft engineering have already been introduced in some guidelines and best practices for small-scale development (*e.g.* NSW Government 2012), but their application has so far been limited to few regions around the globe (De Jong *et al.* 2014; Department for Environment and Heritage 2005; Luo *et al.* 2015).

Knowledge of the original/natural composition of the ecosystem needs to be considered as well. The introduction of an artificial rocky reef or an oyster bed in an area that was once characterised by muddy wetlands does not constitute 'restoration', even if it has the potential to increase the species richness and productivity of the area. However, if the ultimate objective is not the restoration of ‘natural’ habitats but rather the conservation/restoration of ecosystem functioning and services (Moberg and Rönnbäck 2003), then (re)creating appropriate habitats that support biotic communities performing different ecological functions (Borsje *et al.* 2011) is a viable strategy to improve the overall ecosystem status. Interventions in the form of ecological rehabilitation, remediation, and mitigation (Abelson *et al.* 2015; Elliott et al. 2007) all focus on the improvement/restoration of functionality and biodiversity of an ecosystem without necessarily trying to return it to its past 'natural' state (i.e. prior to the changes and degradation caused by development; Dobson *et al.* 1997) (Abelson *et al.* 2015). These frameworks are the most suitable for urbanised areas (since in these instances reverting to a past 'natural' state is not really a feasible endeavour) and utilise information on ecosystem composition (including biotic and structural) and known ecological dynamics to select the most suitable strategy for the improvement of biodiversity and functioning (Elliott *et al.* 2007). The value of artificially-introduced sediment and structures as novel habitats for many species should not be dismissed (*e.g.* Connell 2001; Dugan *et al.* 2011). The increased structural complexity and coverage offered by modifications offer many opportunities for benthic and nektonic species to utilise (Barwick *et al*. 2004; Chapman and Bulleri 2003; Connell 2001). Artificial structures can also assist in creating novel habitats through the retention of sediment (*e.g.* Waltham and Sheaves 2018) or water (*e.g.* Claassens 2016; Evans 2016). Additionally, there are several eco-engineering techniques that have already proven to be successful in increasing species richness and abundance in developed areas (Chapman and Underwood 2011; Dyson and Yocom 2015; Firth *et al.* 2014b; Lundholm and Richardson 2010; Perkol-Finkel *et al.* 2008). In this case it is important however to determine whether this increase in species richness does not include invasive or fouling species and does not result in an irreversible ecosystem shift. Moreover, enhancement of species richness may not be a desirable goal since it does not necessarily consider whether the trophic dynamics, functioning and services of the ecosystem are preserved/restored (Hillebrand *et al.* 2018; Simmonds *et al.* 2019), so biodiversity and functional diversity should be priorities instead. Ensuring the presence of the ‘right’ species based on their functional roles and place in the overall network and dynamics of the ecosystem (Benayas *et al.* 2009; Dafforn *et al.* 2015) rather than having ‘many’ species should be a priority in coastal management and ecosystem-based planning.

5.5 Conclusions

The classification scheme for structural habitats presented in this thesis has not been developed with the intent to replace other existing classifications, but rather to complement them in providing a more suitable way to characterise the structural composition of coastal ecosystems in the context of development and management. Most importantly, the focus on small/local-scale (1:5000 to 1:10000) and the inclusion of anthropogenic features as individual structural components of the classification provide an advancement in addressing the conceptual gaps and issues identified for other classification schemes regarding their relevance and applicability for EBM and coastal development (see sections 1.3 and 5.2). This classification is in fact a tool that can be applied in research but also management, conservation and restoration. Its simple structure, clearly defined classes, and straightforward applicability ensures that this classification scheme can be easily adopted by stakeholders with different professional backgrounds without compromising the quality and standard of the data collected (see sections 2.2.5 and 2.2.6). It is a rapid and cost-effective tool that can provide information at a scale relevant to local-based management, which is advantageous in the context of the budgets and timelines involved in coastal development and management. It provides information on the composition and complexity of ecosystems, which can then be integrated in development planning and EBM to best decide the course of action to take, based on the set objectives. Understanding how development can impact the environment (composition and function) and devising new strategies to mitigate these impacts that is supported by scientific evidence are the core elements for a much needed science-based decision-making process (Crowder and Norse 2008; Douvere 2008; Elliott *et al.* 2007; Long *et al.* 2015). This would maximise the conservation of natural habitats and faunal communities, resulting in a healthy and functioning ecosystem (Crowder and Norse 2008; Long *et al.* 2015). The inclusion of artificial features as components of the classification assists in bridging a conceptual gap currently present in other existing classifications. Not accounting for the presence of artificial features as integrated components of an ecosystem could lead to inaccurate assessments of its actual status and composition, particularly considering the number and variety of artificial structures present in coastal areas to this day and the many that will be introduced in the future. The inclusion of artificial structures in classification schemes for the assessment of habitat composition is therefore essential also considering the effects that these structures have on the local biotic communities. Furthermore, the characterisation and quantification of artificial features in an ecosystem can be used to map development and extent of modification, a fundamental starting point to understand the status of an ecosystem and plan for adequate conservation/restoration strategies. The possibility to add further classes to suit other ecosystems that differ from those addressed in this work (*e.g.* coastal ecosystems from different climates, latitudes, or continents; ecosystems with different artificial features linked to development or eco-engineering) without affecting the structure, consistency, or stability of the classification highlights its broad applicability and versatility. Finally, the classification scheme for structural habitats can also facilitate the linking of structural elements with the presence and distribution of local biota, and act accordingly for the preservation of ecosystem functioning and services.

Overall, this simple and rapid assessment tool will allow managers to be in a stronger position to avoid wasted resources and/or time and increase the success of restoration works or to adequately plan for future development. The methodology, information and suggestions presented above are key steps forward and provide useful tools for managers and end-users to better approach the challenge of sustainable ecological development.

Glossary

Armouring: engineering coastline/river/estuary against erosion and collapse by introducing structural elements such as sandbags, boulders, walls or cement slopes to protect from water/wave action.

Artificial structure: structural element not naturally present in an environment and introduced to provide a specific service to humans.

Artificial feature/modification: a change performed on the structural composition of an ecosystem as consequence of development in the form of introduction of artificial features (*e.g.* piers, pontoons, bridges, and ramps) or artificially placed substratum (*e.g.* boulders, cement walls, pavement).

Attributes: descriptive characteristics or features of an ecosystem.

Banks/Riverbanks: the land (flat or inclined) bordering the edge of a river.

Biodiversity: an attribute of an area which specifically refers to the variety within and among living organisms, assemblages of living organisms, biotic communities, and biotic processes, whether naturally occurring or modified by humans. Biodiversity can be measured in terms of genetic diversity and the identity and number of different types of species, assemblages of species, biotic communities, and biotic processes, and the amount (*e.g.*, abundance, biomass, cover, rate) and structure of each. It can be observed and measured at any spatial scale ranging from microsites and habitat patches to the entire biosphere. (DeLong 1996).

Classes: see “Structural classes”

Classification scheme: assessment tool used to identify distinct ecological units (*e.g.* ‘structural habitat’) based on the presence of specific descriptive characteristics, often following a hierarchical or sequential order.

Coastline: the margin that forms the boundary between the land and the ocean. (Merriam-Webster dictionary).

Conservation: the act of preserving the natural environment including its ecological communities and the services and functions they provide.

Dominant habitat(s): the habitat(s) with the highest measure of habitat extent in the entire ecosystem or area assessed.

Ecological Engineering (Eco-engineering): the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. (Mitsch and Jørgensen 2003)

Ecological enhancement: the improvement of the ecological biodiversity, productivity and functioning of a specific area. This can be achieved through different means: 1) increase of species richness and/or abundance, 2) increase in the availability of habitats or other resources, 3) promotion of spatial connectivity.

Ecosystem: a geographic area with distinct geo-morphological characteristics where a community of organisms (flora and fauna) interact with the environment (*e.g.* rivers, lakes, coastlines, wetlands, reefs).

Ecosystem-Based Management (EBM): A management approach that considers the relationships between ecosystems, the consequences of impacts on ecosystems and informs decision-making around initiatives and actions to successfully manage ecosystems (Foley et al. 2010).

Ecosystem functioning: the sum of physical resources and processes involving fluxes of energy and matter between living organisms within the environment (Ghilarov 2000).

Ecosystem services: the components of nature, directly enjoyed, consumed, or used to yield human well-being (Boyd and Banzhaf 2007).

Estuary: the section of a river connected to the open sea and through which the sea water enters with the rhythm of the tides.

Fragmentation: the progressive reduction of a continuous area in smaller separate and distinct sections.

Frequency of occurrence (Relative): proportion of occurrence of a species across habitats characterised by a specific structural parameter.

Frequency of occurrence (Total): proportion of occurrence of a species across the entire sampling pool (all habitat types collectively).

Geomorphology: the geological and morphological characteristics of a specific area at a given time.

Habitat/Structural habitat: the specific combination of one or more of sixteen classes belonging to the three structural attributes (substratum, vegetation, and artificial features) found in the intertidal range (mean low water spring to mean high water spring) of an estuary.

Habitat complexity: the combination of habitat composition and habitat configuration of an ecosystem or area.

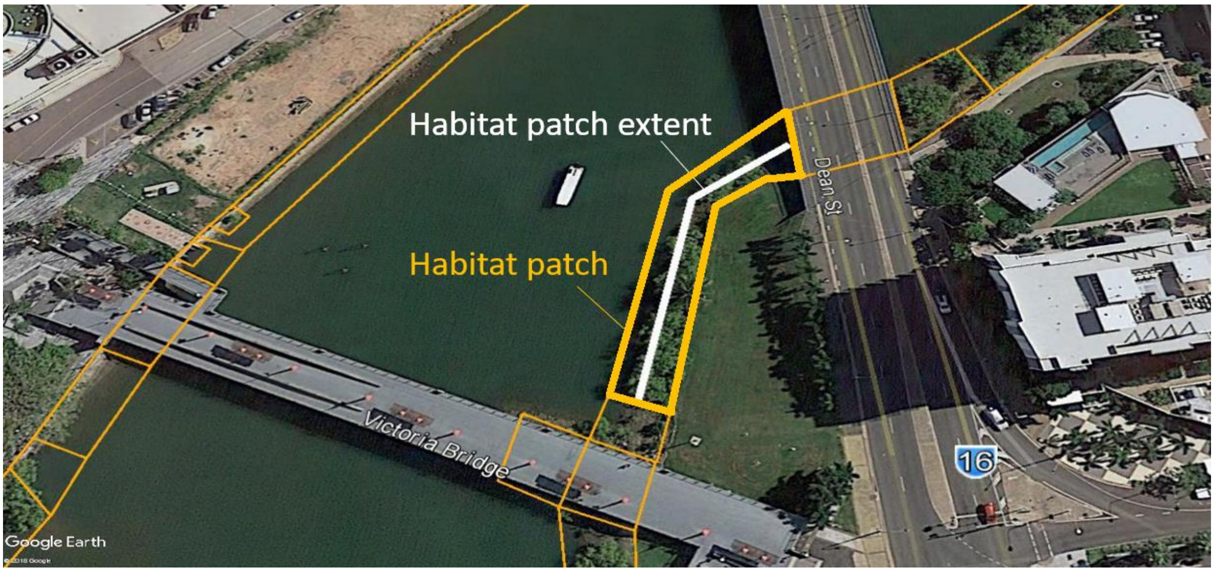
Habitat composition: the list of different types of (structural) habitats found in an ecosystem or area.

Habitat (mosaic) configuration: the spatial distribution or arrangement of habitats in an ecosystem or area.

Habitat extent: the combined extent of all patches belonging to a single habitat type in an ecosystem or area.

Habitat patch: A 'habitat patch' is defined as a continuous spatial unit with clearly defined boundaries that is occupied by a single structural habitat. On maps habitat patches are represented by polygons.

Habitat patch extent: the measurement in meters (m) of the distance between the two vertical boundaries that define the start and end of each habitat patch, in linear length following the riverbank meandering.



Intertidal zone: the area between land and sea which is regularly exposed to the air by the tidal movement of the sea. The shore zone between the highest and lowest tides. (Davies et al. 2004)

Minimum mapping unit (MMU): The smallest size areal entity to be mapped as a discrete entity (Lillesand and Kiefer 1995)

Modified: a natural area that has been physically and/or chemically altered by anthropogenic activities.

Natural: a geographical area that has not been physically/structurally disturbed by anthropogenic activities.

Non-transient organisms: species that are sessile or with a relatively small range of movement in their adult life (*i.e.* less than 20m). Predominantly benthic invertebrates.

Resilience: measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables (Holling 1973)

Restoration: the action of bringing an area or ecosystem back to a previous historical or natural state.

Scale: the parameter that describes the level of geographic resolution and extent, the context of space and time and helps define the positional accuracy (Quattrochi and Goodchild 1997)

Sector: a specific section of an ecosystem that delimits the spatial area where field assessment is carried out.

Sediment: naturally occurring material (mineral) that is broken down by processes of weathering and erosion, and is subsequently transported by the action of wind, water, or ice, and/or by the force of gravity acting on the particles. (Wang and Yang 2014).

Shoreface: the narrow littoral zone from the low watermark in which sediment is affected by waves and currents.

Species composition: the list of all different species recorded in a given location (*e.g.* single habitat type) or area (*e.g.* entire estuary). (Davies *et al.* 2017).

Species richness: the total number of species recoded in a given location (*e.g.* single habitat type) or area (*e.g.* entire estuary) at a specific time. (Davies *et al.* 2017).

Structural attributes/components: the constituting elements of an ecosystem forming physical and distinct structures and grouped based on whether they are biotic or abiotic as well as whether they are natural or artificial in origin. The main structural attributes identified in an ecosystem are: sediment (abiotic; natural or artificial), vegetation (biotic; natural), and artificial features (abiotic; artificial).

Structural classes/Classes: list of distinct and mutually exclusive elements belonging to a common structural component in a classification for structural elements.

Substratum: a base or a solid surface in which living things can adhere to while they grow.

Transient organisms: species with a wide range of movement in their adult life (*i.e.* more than 20m). Predominantly vertebrates and flying invertebrates.

Urban area/**Urbanised**: natural area converted partially or totally into an urban centre and characterised by the presence of artificial structural elements.

Waterway: a defined channel where water can flow.

Wetland: Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres (RAMSAR, Iran, 1971). Coastal wetlands include marine (coastal lagoons, rocky shores, seagrass beds and coral reefs) and estuarine (deltas, tidal marshes and mudflats, and mangrove swamps) wetlands.

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Appendices

Appendix 1a. Table listing the basic requirements and positive conceptual and practical attributes identified for the 31 different regional/national classification schemes for marine and/or coastal ecosystems around the word.

	British Columbia Marine Ecological Classification	Classification of wetlands of the central and southern California coast and coastal watersheds	Classification of benthic estuarine habitats in Mid-Atlantic USA	Classification of Marine Sublittoral Habitats	Classification of Wetlands and Deepwater Habitats of the United States (Cowardin *et al.* 1979)	Classification of Wetlands and Deepwater Habitats of the United States (FDGC 2013)	Coastal and Marine Ecological Classification Standard (CMECS) (V.2)	Coastal and Marine Ecological Classification Standard (CMECS) (V.6)	Coastal Marine Classification	CSIRO Marine Research hierarchical scheme for habitat mapping and classification	Estuarine Habitat Classification for a Complex Fjordal Island Archipelago (Alaska)	European Nature Information System (EUNIS)	GIS Mapping Classification Scheme (Victoria)	Habitat Classification Scheme	Hierarchical classification of marine environment	Hydrogeomorphic Classification for Wetlands	Integrated Marine and Coastal Regionalisation for Australia (IMCRA) (V4.0)	Interim Marine and Coastal Regionalisation for Australia (IMCRA) (V3.3)	Interim Marine Classification Scheme (MHC) Stage 3 (V.2)	Marine Ecoregions of the World (MEOW)	Marine Habitat Classification	Marine Habitat Classification for Britain and Ireland (MHC) (V04.05)	National Estuarine Research Reserve System (NERRS)	National Intertidal/Subtidal Benthic habitat classification scheme (NISB) (V.01)	National Marine Bioregionalisation of Australia (NMB)	Primary Shallow Habitat Classification Scheme (Victoria)	Queensland Intertidal and Subtidal Ecosystem Classification Scheme (V1.0)	Seamap Australia benthic habitat classification scheme (SEAMAP)	System for Classification of Habitats in Estuarine and Marine Environments (SCHEME)	Systematic Classification Scheme of Marine Habitats	The New Zealand Marine Environment Classification	U.S. Marine and Estuary Classification System	Wetland Mapping and Classification Methodology (Queensland EPA 2005) (V1.2)
POSITIVE ATTRIBUTES																																	
Hierarchical	x	x	x	-	x	x	x	-	x	x		x	x	x	x		x	-	x	x	x	x	-	x	x	x	x	x	x	x	-	x	x

POSITIVE ATTRIBUTES																																	
Mutually exclusive	x	x	x			x	x	x	x	x		x	x	x	x		x	x	x	x		x		x	x	x	x	x	x	x		x	x
Exhaustive (considers all habitats)	x	x		x	x	x	x	x	x	x		-	x	x	x		x			-	x	x	x	x	-	x	x	x	x			x	
Clearly described	x	x	x	-	-	x		x	x	x	x	x	-	x	x	x	-	-	x		-	x	x	-	x	x	x	x		x		x	x
Common language / Broadly understood	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Clear terms and definitions	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x
Scientifically sound	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Flexible and accommodates changes		x		x		x	x	x				x	x	x	x	x	x	x			x	x	x	x		x	x	x	x		x	x	
Compatible with existing classifications		x		x				x		x				x		x				x		x				x	x	x	x				
Simple and user-friendly		x	x			x			x		x	x			x	x	x	x	x			x				x	x	x				x	
Easily mappable	x	x	x		x	x	x	x		x		x	x	x	x		x	x	x	x			x	x	x	x	x	x	x	x		x	x
Not affected by differences in sampling techniques	x				x	x				x		x	x		x							x				x	x	x		x		x	
Relevant for many aquatic ecosystems		x			x	x		x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x		x	x		x		x	
Applicable at national or international level	x	x		x	x	x	x	x	x		x	x			x	x	x	x		x	x	x	x	x			x	x			x	x	
Possible to integrate existing knowledge	x	x		x	x		x	x			x				x	x	x	x				x		x			x	x	x	x	x	x	x
Formed by repeatable environmental units	x	x		x	-	x	x	x	x	x	x	x	x	x	-		x	x	x	x		x		-	x	x	x	x	x	x		x	
Individual components can be used autonomously or combined		x					x	x																				x					
Considers temporal variation		x						x			x										x				x								
Anthropogenic elements included as classes																					x		x					x				x	
Anthropogenic elements included as modifiers					x	x	x	x			x			x													x		x				

Appendix 1b. Table listing the different conceptual and practical issues or gaps identified for the 31 different regional/national classification schemes for marine and/or coastal ecosystems around the word.

	British Columbia Marine Ecological Classification	Classification of wetlands of the central and southern California coast and coastal watersheds	Classification of benthic estuarine habitats in Mid-Atlantic USA	Classification of Marine Sublittoral Habitats	Classification of Wetlands and Deepwater Habitats of the United States (Cowardin et al. 1979)	Classification of Wetlands and Deepwater Habitats of the United States (FDGC 2013)	Coastal and Marine Ecological Classification Standard (CMECS) (V.2)	Coastal and Marine Ecological Classification Standard (CMECS) (V.6)	Coastal Marine Classification	CSIRO Marine Research hierarchical scheme for habitat mapping and classification	Estuarine Habitat Classification for a Complex Fjordal Island Archipelago (Alaska)	European Nature Information System (EUNIS)	GIS Mapping Classification Scheme (Victoria)	Habitat Classification Scheme	Hierarchical classification of marine environment	Hydrogeomorphic Classification for Wetlands	Integrated Marine and Coastal Regionalisation for Australia (IMCRA) (V4.0)	Interim Marine and Coastal Regionalisation for Australia (IMCRA) (V3.3)	Interim Marine Classification Scheme (MHC) Stage 3 (V.2)	Marine Ecoregions of the World (MEOW)	Marine Habitat Classification	Marine Habitat Classification for Britain and Ireland (MHC) (V04.05)	National Estuarine Research Reserve System (NERRS)	National Intertidal/Subtidal Benthic habitat classification scheme (NISB) (V.01)	National Marine Bioregionalisation of Australia (NMB)	Primary Shallow Habitat Classification Scheme (Victoria)	Queensland Intertidal and Subtidal Ecosystem Classification Scheme (V1.0)	Seamap Australia benthic habitat classification scheme (SEAMAP)	System for Classification of Habitats in Estuarine and Marine Environments (SCHEME)	Systematic Classification Scheme of Marine Habitats	The New Zealand Marine Environment Classification	U.S. Marine and Estuary Classification System	Wetland Mapping and Classification Methodology (Queensland EPA 2005) (V1.2)
ISSUES OR GAPS																																	
Outdated					x											x																	

ISSUES OR GAPS																																	
Not hierarchical or nested				-				-			x					x		-					-								-		
Prescriptive (user has to match data to pre-existing habitats)				x						x		x					x	x		x					x						x		
Not exhaustive			x								x	-				x		x	x	-					-					x			
Hierarchical scheme not (fully) described				x			x						x				-				x			x							x		x
Attributes and their hierarchy not clearly defined							x						x				x	x		x	x			x	x				x		x		x
Inconsistencies within the document					x					x																							
Ambiguous terminology			x	x																	x										x		
No real definition of environmental units			x		x	x	x			x					x	x			x		x		x	x		x		x			x		x
Sampling technologies and protocols not clarified (risk of inconsistency)		x		x					x					x		x			x		x					x			x		x	x	
Variable measures and scales not clarified (risk of inconsistency)									x				x								x												
Requires multiple assessment methods	x	x		x	x	x	x	x		x	x	x		x	x						x	x	x	x	x		x	x	x	x	x	x	x
Costly (money and/or time)	x	x		x	x	x	x	x		x	x	x		x	x						x	x	x	x	x		x	x	x	x	x	x	
Requires the presence of pre-existing datasets							x	x		x		x	x		x		x	x		x			x		x		x			x	x		x
Some basic information is unavailable												x	x																				
Not widely applicable (regional/subregional scale)			x											x					x										x	x			x
Scale not clearly defined		x	x		x	x							x			x				x	x			x		x		x				x	
Depth thresholds/sectors not described																					x					x							x
Arbitrary selection of hierarchical levels					x		x																									x	
Some classes overlap												x																	x				
Some classes not always present in all levels				x	x			x				x											x			x			x			x	

ISSUES OR GAPS																																	
Parallel levels are not equivalent				x								x									x								x				
Details are not defined but left to the decision of the user (risk for inconsistency)					x																											x	
Biogeographical elements insufficiently varied to represent diversity			x									x																					
Focus on sediment and/or hydrology only															x	x																	x
Does not include many variables			x						x		x		x		x				x						x	x		x					x
Combinations of different substrata are not addressed		x			x	x			x			x												x					x	x		x	x
Sediment and biota mixed and not as nested layers		x				x																x							x	x			
Vegetation and sediment classes mutually exclusive		x			x																								x				
Does not consider biota	x		x						x						x	x																	x
Focus on species or taxa individually, not on the mixed community as a whole							x				x	x		x					x			x		x					x			x	
Modifiers not included	x		x						x				x		x			x		x					x	x				x			
Modifiers not equal or poorly described				x		x										x						x	x	x					x			x	
Does not consider anthropogenic elements	x	x	x	x					x	x		x	x		x	x	x	x	x	x		x		x	x	x				x	x		x
Anthropogenic elements classified in a generic manner						x		x			x			x							x						x	x	x			x	

Appendix 2a. Metadata of the structural composition and habitat mosaic configuration of Ross Creek. Layer group "Full List" contains the map of all structural habitats identified in the estuary. Layer group "NAT-MOD" presents the habitats divided in 'natural' and 'modified' based on whether they do/don't at least one artificial feature or sediment. Layer group "Sediment" maps the presence of the different substratum classes (Mud, Sand, Gravel, Boulders, and Pavement) in the estuary. Layer group "Vegetation" maps the presence of the two Vegetation classes (Mangrove and Saltmarsh) in the estuary. Layer group "Artificial Features" maps the presence of the different artificial features (Armouring, Drain, Raised structure, Level structure, and Pillars) in the estuary.
Link to the metadata:
RossCreek_StructuralHabitat.zip
https://cloudstor.aarnet.edu.au/plus/s/xpYaiNipNACws5C

Metadata record:
Citation: Trave, C. (2019): Structural habitat composition of Ross Creek (Townsville, QLD). James Cook University. (dataset). http://doi.org/10.25903/5d044035ce1b0
Digital Object Identifier (DOI):10.25903/5d044035ce1b0

Appendix 2b. Metadata of the structural composition and habitat mosaic configuration of Ross River. Layer group "Full List" contains the map of all structural habitats identified in the estuary. Layer group "NAT-MOD" presents the habitats divided in 'natural' and 'modified' based on whether they do/don't at least one artificial feature or sediment. Layer group "Sediment" maps the presence of the different substratum classes (Mud, Sand, Gravel, Boulders, and Pavement) in the estuary. Layer group "Vegetation" maps the presence of the two Vegetation classes (Mangrove and Saltmarsh) in the estuary. Layer group "Artificial Features" maps the presence of the different artificial features (Armouring, Drain, Raised structure, Level structure, and Pillars) in the estuary.
Link to the metadata:
RossRiver_StructuralHabitat.zip
https://cloudstor.aarnet.edu.au/plus/s/LmYDlAtRclTwxbb

Metadata record:
Citation: Trave, C. (2019): Structural habitat composition of Ross River (Townsville, QLD). James Cook University. (dataset). http://doi.org/10.25903/5d043c46647cd
Digital Object Identifier (DOI):10.25903/5d043c46647cd

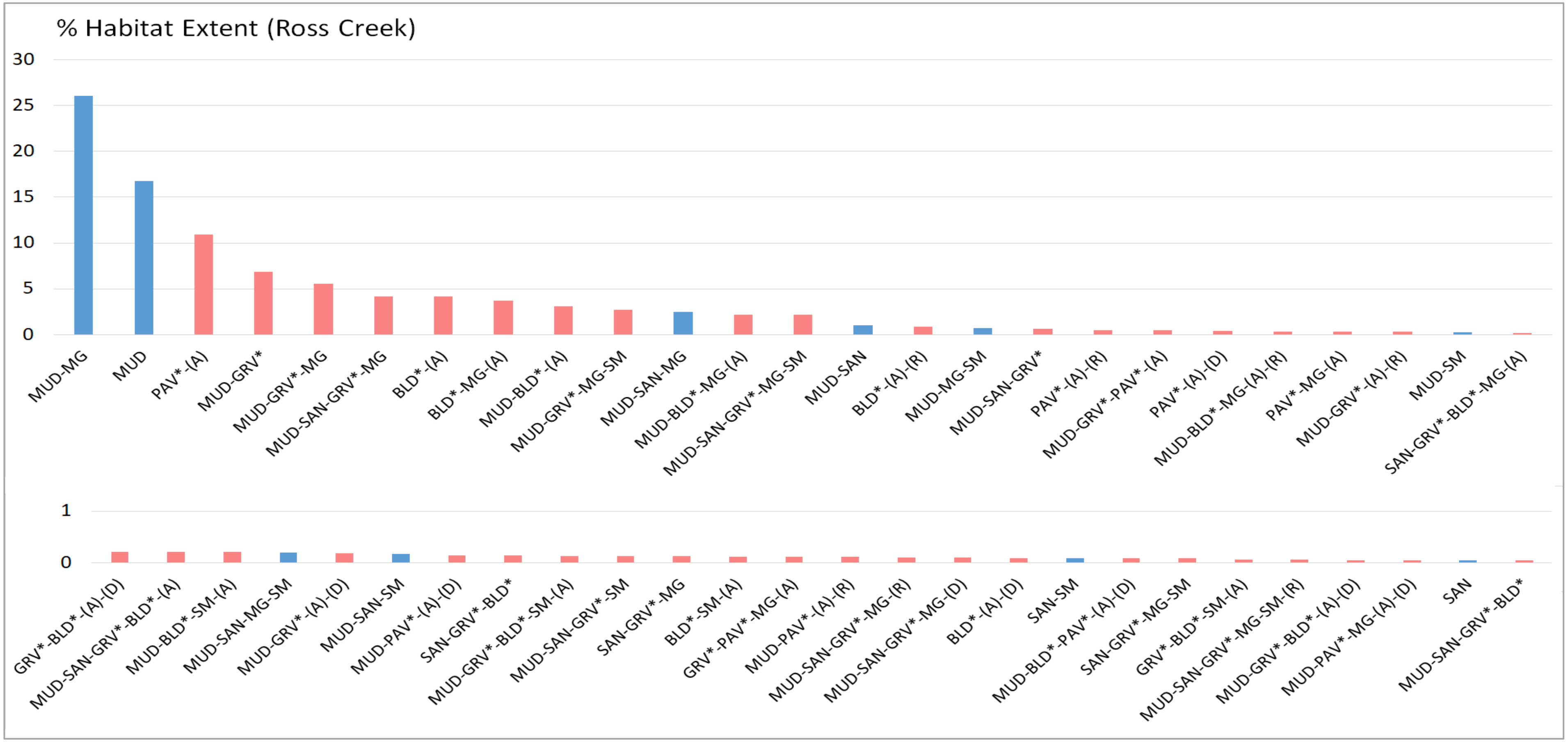
Appendix 2c. Metadata of the structural composition and habitat mosaic configuration of Alligator Creek. Layer group "Full List" contains the map of all structural habitats identified in the estuary. Layer group "NAT-MOD" presents the habitats divided in 'natural' and 'modified' based on whether they do/don't at least one artificial feature or sediment. Layer group "Sediment" maps the presence of the different substratum classes (Mud, Sand, Gravel, Boulders, and Pavement) in the estuary. Layer group "Vegetation" maps the presence of the two Vegetation classes (Mangrove and Saltmarsh) in the estuary. Layer group "Artificial Features" maps the presence of the different artificial features (Armouring, Drain, Raised structure, Level structure, and Pillars) in the estuary.
Link to the metadata:
AlligatorCreek_StructuralHabitat.zip
https://cloudstor.aarnet.edu.au/plus/s/7c4ySYCwoAovWW4

Metadata record:
Citation: Trave, C. (2019): Structural habitat composition of Alligator Creek (Townsville, QLD). James Cook University. (dataset). http://doi.org/10.25903/5d04389042aca
Digital Object Identifier (DOI):10.25903/5d04389042aca

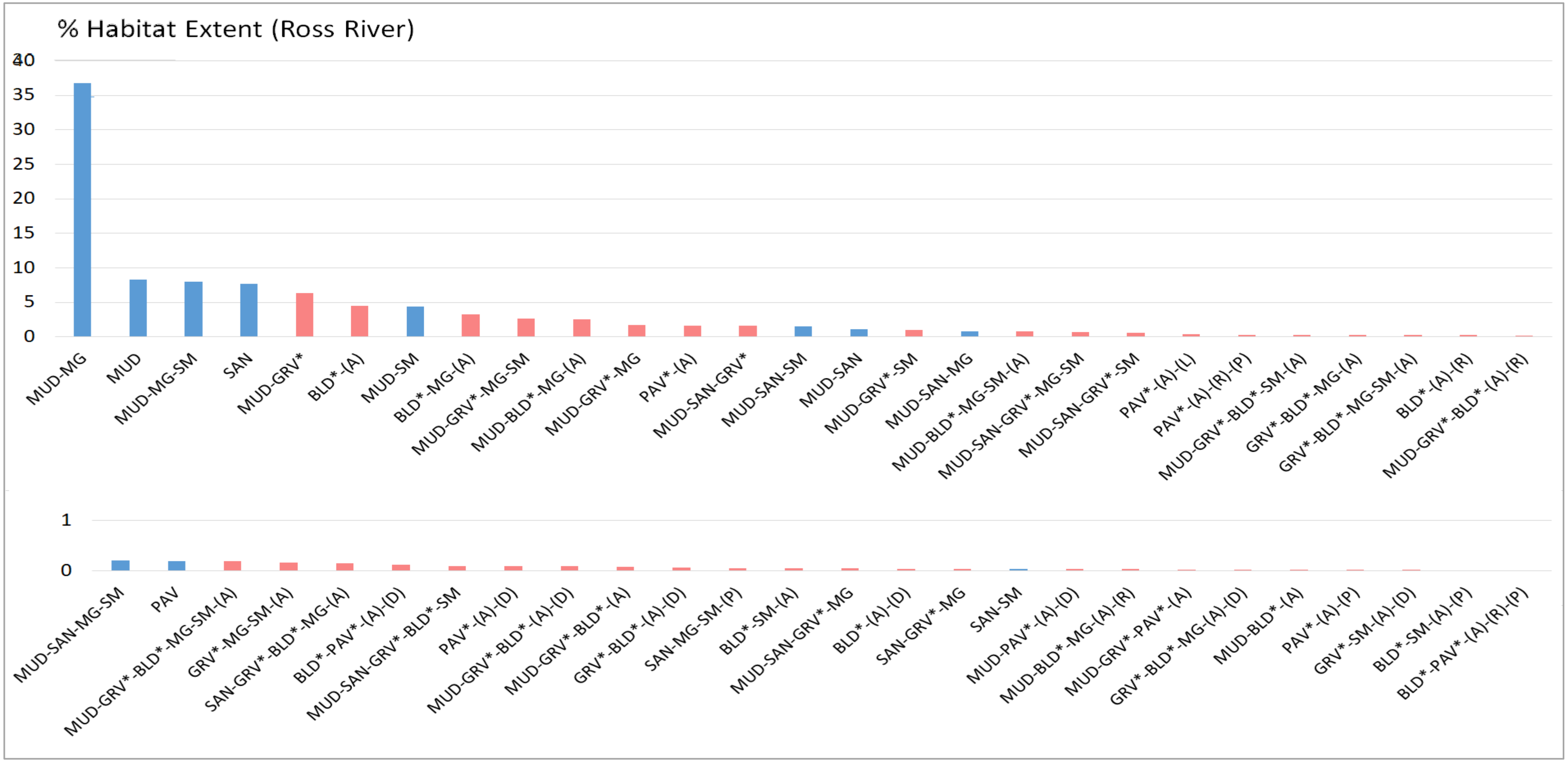
Appendix 2d. Metadata of the structural composition and habitat mosaic configuration of Althaus Creek. Layer group "Full List" contains the map of all structural habitats identified in the estuary. Layer group "NAT-MOD" presents the habitats divided in 'natural' and 'modified' based on whether they do/don't at least one artificial feature or sediment. Layer group "Sediment" maps the presence of the different substratum classes (Mud, Sand, Gravel, Boulders, and Pavement) in the estuary. Layer group "Vegetation" maps the presence of the two Vegetation classes (Mangrove and Saltmarsh) in the estuary. Layer group "Artificial Features" maps the presence of the different artificial features (Armouring, Drain, Raised structure, Level structure, and Pillars) in the estuary.
Link to the metadata:
AlthausCreek_StructuralHabitat.zip
https://cloudstor.aarnet.edu.au/plus/s/x43Nr0FBk2OPAQ8

Metadata record:
Citation: Trave, C. (2019): Structural habitat composition of Althaus Creek (Townsville, QLD). James Cook University. (dataset). http://doi.org/10.25903/5d043206e7f4f
Digital Object Identifier (DOI):10.25903/5d043206e7f4f

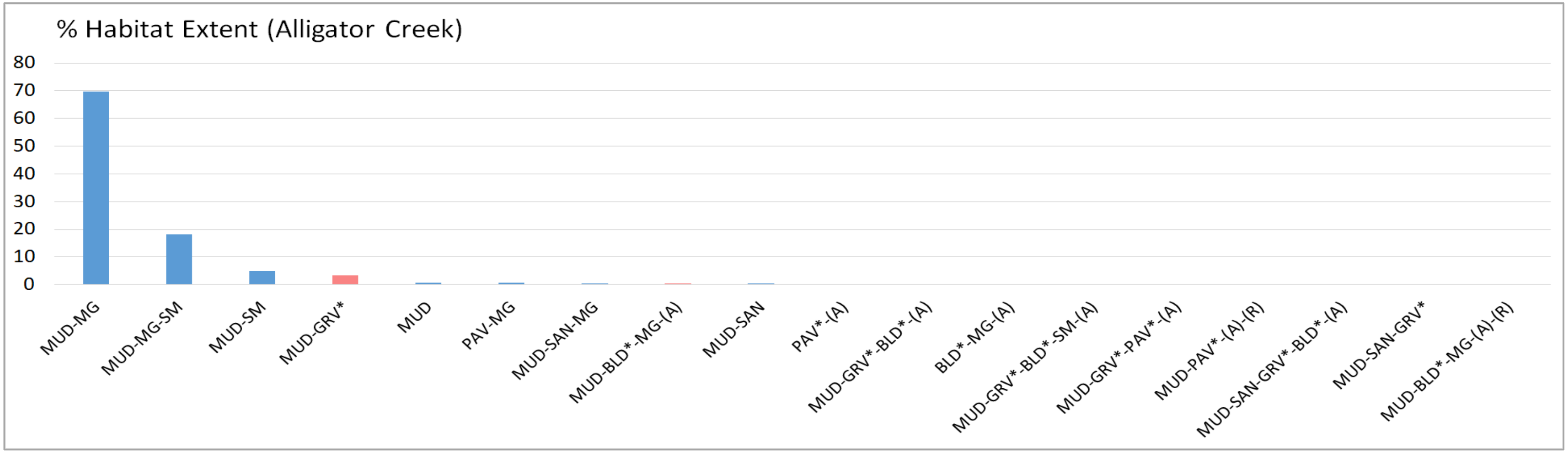
Appendix 3a. Percentage of overall extent of each of the 51 habitats identified in Ross Creek.



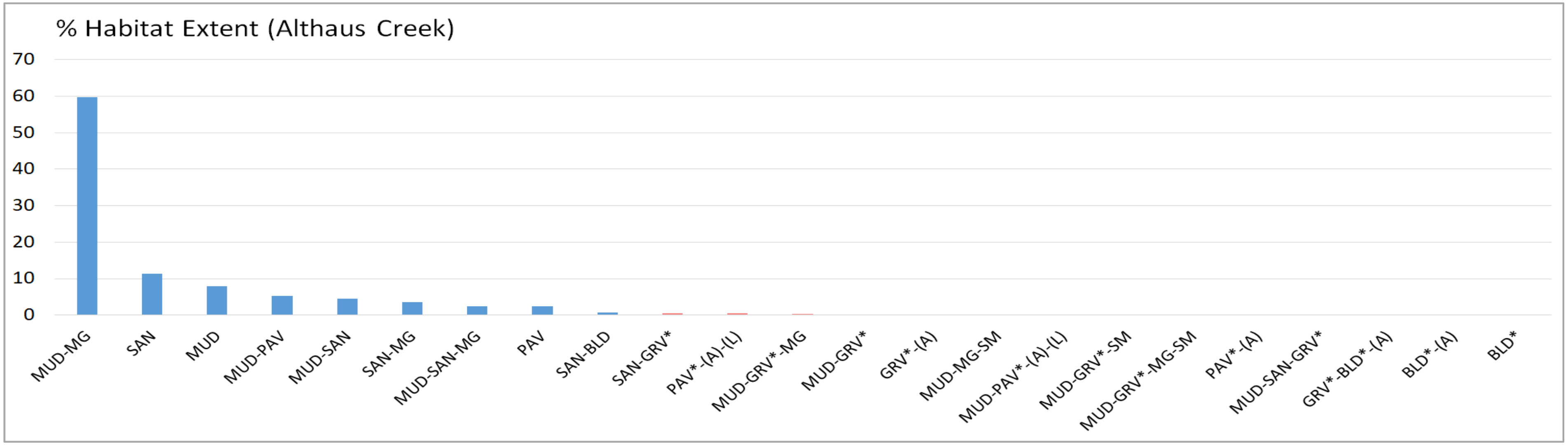
Appendix 3b. Percentage of overall extent of each of the 53 habitats identified in Ross River.



Appendix 3c. Percentage of overall extent of each of the 18 habitats identified in Ross River.



Appendix 3d. Percentage of overall extent of each of the 23 habitats identified in Althaus Creek.



Appendix 4a. Information on the total extent, number of patches, mean patch size, and percentage of total extent of each habitat type in Ross Creek.

	ROSS CREEK			
Structural Habitat types	Total extent (m)	Patches	Mean patch size (m)	% total Extent
BLD*				
BLD*-(A)	496.6	13	38.2	4.18
BLD*-(A)-(D)	10.2	2	5.1	0.09
BLD*-(A)-(R)	98.9	6	16.5	0.83
BLD*-MG-(A)	443.3	4	110.8	3.73
BLD*-PAV*-(A)-(D)				
BLD*-PAV*-(A)-(R)-(P)				
BLD*-SM-(A)	13.7	1	13.7	0.12
BLD*-SM-(A)-(P)				
GRV*-(A)				
GRV*-BLD*-(A)				
GRV*-BLD*-(A)-(D)	25.1	3	8.4	0.21
GRV*-BLD*-MG-(A)				
GRV*-BLD*-MG-(A)-(D)				
GRV*-BLD*-MG-SM-(A)				
GRV*-BLD*-SM-(A)	7.4	1	7.4	0.06
GRV*-MG-SM-(A)				
GRV*-PAV*-MG-(A)	13.3	1	13.3	0.11
GRV*-SM-(A)-(D)				
MUD	1991.5	13	153.2	16.77
MUD-BLD*-(A)	366.4	5	73.3	3.09
MUD-BLD*-MG-(A)	258.4	10	25.8	2.18
MUD-BLD*-MG-(A)-(R)	43.4	5	8.7	0.37
MUD-BLD*-MG-SM-(A)				
MUD-BLD*-PAV*-(A)-(D)	9.9	2	5.0	0.08
MUD-BLD*-SM-(A)	24.4	2	12.2	0.21
MUD-GRV*	813.4	16	50.8	6.85
MUD-GRV*-(A)-(D)	21.7	4	5.4	0.18
MUD-GRV*-(A)-(R)	37.4	3	12.5	0.31
MUD-GRV*-BLD*-(A)				
MUD-GRV*-BLD*-(A)-(D)	6.0	1	6.0	0.05
MUD-GRV*-BLD*-(A)-(R)				
MUD-GRV*-BLD*-MG-SM-(A)				
MUD-GRV*-BLD*-SM-(A)	15.3	2	7.7	0.13
MUD-GRV*-MG	661.3	16	41.3	5.57
MUD-GRV*-MG-SM	322.7	4	80.7	2.72
MUD-GRV*-PAV*-(A)	58.6	3	19.5	0.49
MUD-GRV*-SM				
MUD-MG	3094.0	27	114.6	26.05
MUD-MG-SM	82.1	1	82.1	0.69
MUD-PAV				
MUD-PAV*-(A)-(D)	16.7	2	8.4	0.14
MUD-PAV*-(A)-(L)				
MUD-PAV*-(A)-(R)	12.7	1	12.7	0.11
MUD-PAV*-MG-(A)-(D)	5.8	1	5.8	0.05
MUD-SAN	123.5	2	61.8	1.04
MUD-SAN-GRV*	76.9	2	38.5	0.65
MUD-SAN-GRV*-BLD*	4.9	1	4.9	0.04
MUD-SAN-GRV*-BLD*-(A)	24.8	4	6.2	0.21
MUD-SAN-GRV*-BLD*-SM				
MUD-SAN-GRV*-MG	497.6	6	82.9	4.19
MUD-SAN-GRV*-MG-(D)	12.0	1	12.0	0.10
MUD-SAN-GRV*-MG-(R)	12.2	1	12.2	0.10
MUD-SAN-GRV*-MG-SM	254.1	7	36.3	2.14
MUD-SAN-GRV*-MG-SM-(R)	6.2	1	6.2	0.05
MUD-SAN-GRV*-SM	14.9	2	7.5	0.13
MUD-SAN-MG	294.1	3	98.0	2.48
MUD-SAN-MG-SM	23.7	2	11.9	0.20
MUD-SAN-SM	19.6	1	19.6	0.17
MUD-SM	31.8	1	31.8	0.27
PAV				
PAV*-(A)	1298.6	11	118.1	10.94
PAV*-(A)-(D)	46.4	10	4.6	0.39
PAV*-(A)-(L)				
PAV*-(A)-(P)				
PAV*-(A)-(R)	60.9	5	12.2	0.51
PAV*-(A)-(R)-(P)				
PAV*-MG-(A)	41.3	7	5.9	0.35
PAV-MG				
SAN	5.1	1	5.1	0.04
SAN-BLD				
SAN-GRV*				
SAN-GRV*-BLD*	16.7	2	8.4	0.14
SAN-GRV*-BLD*-MG-(A)	25.6	1	25.6	0.22
SAN-GRV*-MG	14.7	2	7.4	0.12
SAN-GRV*-MG-SM	9.8	1	9.8	0.08
SAN-MG				
SAN-MG-SM-(P)				
SAN-SM	10.0	1	10.0	0.08

Appendix 4b. Information on the total extent, number of patches, mean patch size, and percentage of total extent of each habitat type in Ross River.

	ROSS RIVER			
Structural Habitat types	Total extent (m)	Patches	Mean patch size (m)	% total Extent
BLD*				
BLD*-(A)	1490.3	45	33.1	4.54
BLD*-(A)-(D)	14.83	3	4.94	0.05
BLD*-(A)-(R)	76.87	8	9.61	0.23
BLD*-MG-(A)	1061.9	23	46.17	3.23
BLD*-PAV*-(A)-(D)	41.1	4	10.28	0.13
BLD*-PAV*-(A)-(R)-(P)	4.1	1	4.10	0.01
BLD*-SM-(A)	18.6	1	18.60	0.06
BLD*-SM-(A)-(P)	4.3	1	4.30	0.01
GRV*-(A)				
GRV*-BLD*-(A)				
GRV*-BLD*-(A)-(D)	21.9	3	7.30	0.07
GRV*-BLD*-MG-(A)	100.9	4	25.23	0.31
GRV*-BLD*-MG-(A)-(D)	10.8	1	10.80	0.03
GRV*-BLD*-MG-SM-(A)	90	3	30.00	0.27
GRV*-BLD*-SM-(A)				
GRV*-MG-SM-(A)	55.7	3.0	18.57	0.17
GRV*-PAV*-MG-(A)				
GRV*-SM-(A)-(D)	7.4	1	7.40	0.02
MUD	2721.9	15	181.46	8.29
MUD-BLD*-(A)	7.8	1	7.80	0.02
MUD-BLD*-MG-(A)	838.9	13	64.53	2.56
MUD-BLD*-MG-(A)-(R)	11.5	1	11.50	0.04
MUD-BLD*-MG-SM-(A)	250.7	4	62.68	0.76
MUD-BLD*-PAV*-(A)-(D)				
MUD-BLD*-SM-(A)				
MUD-GRV*	2074.97	15	138.33	6.32
MUD-GRV*-(A)-(D)				
MUD-GRV*-(A)-(R)				
MUD-GRV*-BLD*-(A)	27.9	2	13.95	0.08
MUD-GRV*-BLD*-(A)-(D)	29.9	4	7.48	0.09
MUD-GRV*-BLD*-(A)-(R)	72.7	4	18.18	0.22
MUD-GRV*-BLD*-MG-SM-(A)	63.1	3	21.03	0.19
MUD-GRV*-BLD*-SM-(A)	103.4	3	34.47	0.32
MUD-GRV*-MG	549	9	61.00	1.67
MUD-GRV*-MG-SM	853.7	13	65.67	2.60
MUD-GRV*-PAV*-(A)	11	2	5.50	0.03
MUD-GRV*-SM	326.9	6	54.48	1.00
MUD-MG	12075.2	69	175.00	36.79
MUD-MG-SM	2634	28	94.07	8.02
MUD-PAV				
MUD-PAV*-(A)-(D)	12	1	12.00	0.04
MUD-PAV*-(A)-(L)				
MUD-PAV*-(A)-(R)				
MUD-PAV*-MG-(A)-(D)				
MUD-SAN	375.7	6	62.62	1.14
MUD-SAN-GRV*	539.9	5	107.98	1.64
MUD-SAN-GRV*-BLD*				
MUD-SAN-GRV*-BLD*-(A)				
MUD-SAN-GRV*-BLD*-SM	34.1	1	34.10	0.10
MUD-SAN-GRV*-MG	17.3	1	17.30	0.05
MUD-SAN-GRV*-MG-(D)				
MUD-SAN-GRV*-MG-(R)				
MUD-SAN-GRV*-MG-SM	212	1	212.00	0.65
MUD-SAN-GRV*-MG-SM-(R)				
MUD-SAN-GRV*-SM	188.6	3	62.87	0.57
MUD-SAN-MG	268.7	9	29.86	0.82
MUD-SAN-MG-SM	68.2	4	17.05	0.21
MUD-SAN-SM	503.2	10	50.32	1.53
MUD-SM	1438.6	28	51.38	4.38
PAV	63.3	1	63.30	0.19
PAV*-(A)	541.3	18	30.07	1.65
PAV*-(A)-(D)	32.1	4	8.03	0.10
PAV*-(A)-(L)	133.9	10	13.39	0.41
PAV*-(A)-(P)	7.8	1	7.80	0.02
PAV*-(A)-(R)				
PAV*-(A)-(R)-(P)	106.9	7	15.27	0.33
PAV*-MG-(A)				
PAV-MG				
SAN	2534.9	13	194.99	7.72
SAN-BLD				
SAN-GRV*				
SAN-GRV*-BLD*				
SAN-GRV*-BLD*-MG-(A)	48.6	2	24.30	0.15
SAN-GRV*-MG	14.4	1	14.40	0.04
SAN-GRV*-MG-SM				
SAN-MG				
SAN-MG-SM-(P)	20.3	1	20.30	0.06
SAN-SM	12.3	1	12.30	0.04

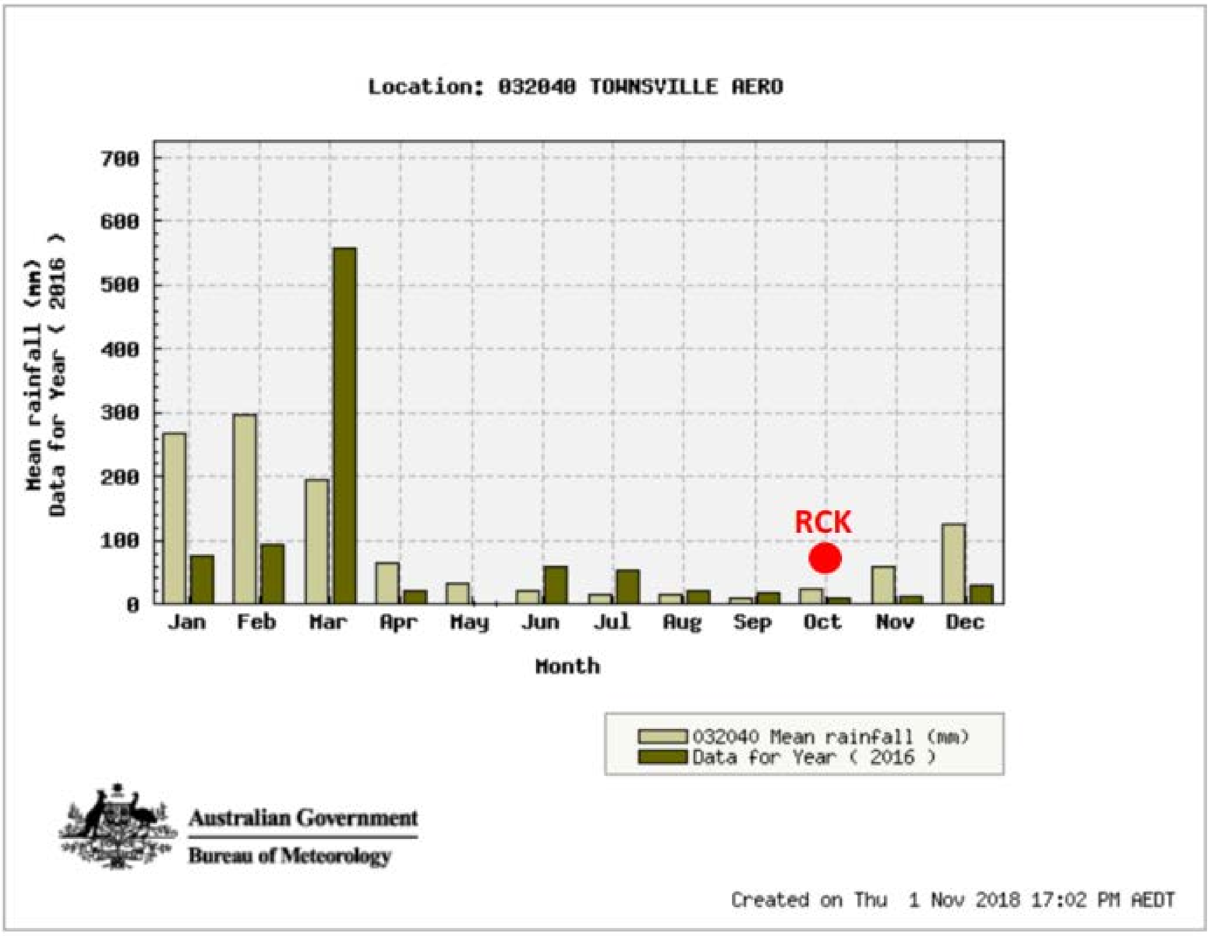
Appendix 4c. Information on the total extent, number of patches, mean patch size, and percentage of total extent of each habitat type in Alligator Creek.

	ALLIGATOR CREEK			
Structural Habitat types	Total extent (m)	Patches	Mean patch size (m)	% total Extent
BLD*				
BLD*-(A)				
BLD*-(A)-(D)				
BLD*-(A)-(R)				
BLD*-MG-(A)	28	3	9.33	0.09
BLD*-PAV*-(A)-(D)				
BLD*-PAV*-(A)-(R)-(P)				
BLD*-SM-(A)				
BLD*-SM-(A)-(P)				
GRV*-(A)				
GRV*-BLD*-(A)				
GRV*-BLD*-(A)-(D)				
GRV*-BLD*-MG-(A)				
GRV*-BLD*-MG-(A)-(D)				
GRV*-BLD*-MG-SM-(A)				
GRV*-BLD*-SM-(A)				
GRV*-MG-SM-(A)				
GRV*-PAV*-MG-(A)				
GRV*-SM-(A)-(D)				
MUD	223.3	7	31.90	0.69
MUD-BLD*-(A)				
MUD-BLD*-MG-(A)	148.1	4	37.03	0.46
MUD-BLD*-MG-(A)-(R)	8.6	1	8.60	0.03
MUD-BLD*-MG-SM-(A)				
MUD-BLD*-PAV*-(A)-(D)				
MUD-BLD*-SM-(A)				
MUD-GRV*	1079	2	539.50	3.32
MUD-GRV*-(A)-(D)				
MUD-GRV*-(A)-(R)				
MUD-GRV*-BLD*-(A)	51.5	2	25.75	0.16
MUD-GRV*-BLD*-(A)-(D)				
MUD-GRV*-BLD*-(A)-(R)				
MUD-GRV*-BLD*-MG-SM-(A)				
MUD-GRV*-BLD*-SM-(A)	25.5	1	25.50	0.08
MUD-GRV*-MG				
MUD-GRV*-MG-SM				
MUD-GRV*-PAV*-(A)	21.5	2	10.75	0.07
MUD-GRV*-SM				
MUD-MG	22657.7	79	286.81	69.76
MUD-MG-SM	5943.3	81	73.37	18.30
MUD-PAV				
MUD-PAV*-(A)-(D)				
MUD-PAV*-(A)-(L)				
MUD-PAV*-(A)-(R)	19.4	2	9.70	0.06
MUD-PAV*-MG-(A)-(D)				
MUD-SAN	144.3	3	48.10	0.44
MUD-SAN-GRV*	13.9	1	13.90	0.04
MUD-SAN-GRV*-BLD*				
MUD-SAN-GRV*-BLD*-(A)	18.8	2	9.40	0.06
MUD-SAN-GRV*-BLD*-SM				
MUD-SAN-GRV*-MG				
MUD-SAN-GRV*-MG-(D)				
MUD-SAN-GRV*-MG-(R)				
MUD-SAN-GRV*-MG-SM				
MUD-SAN-GRV*-MG-SM-(R)				
MUD-SAN-GRV*-SM				
MUD-SAN-MG	180	1	180.00	0.55
MUD-SAN-MG-SM				
MUD-SAN-SM				
MUD-SM	1634.3	41	39.86	5.03
PAV				
PAV*-(A)	58.9	2	29.45	0.18
PAV*-(A)-(D)				
PAV*-(A)-(L)				
PAV*-(A)-(P)				
PAV*-(A)-(R)				
PAV*-(A)-(R)-(P)				
PAV*-MG-(A)				
PAV-MG	222.3	2	111.15	0.68
SAN				
SAN-BLD				
SAN-GRV*				
SAN-GRV*-BLD*				
SAN-GRV*-BLD*-MG-(A)				
SAN-GRV*-MG				
SAN-GRV*-MG-SM				
SAN-MG				
SAN-MG-SM-(P)				
SAN-SM				

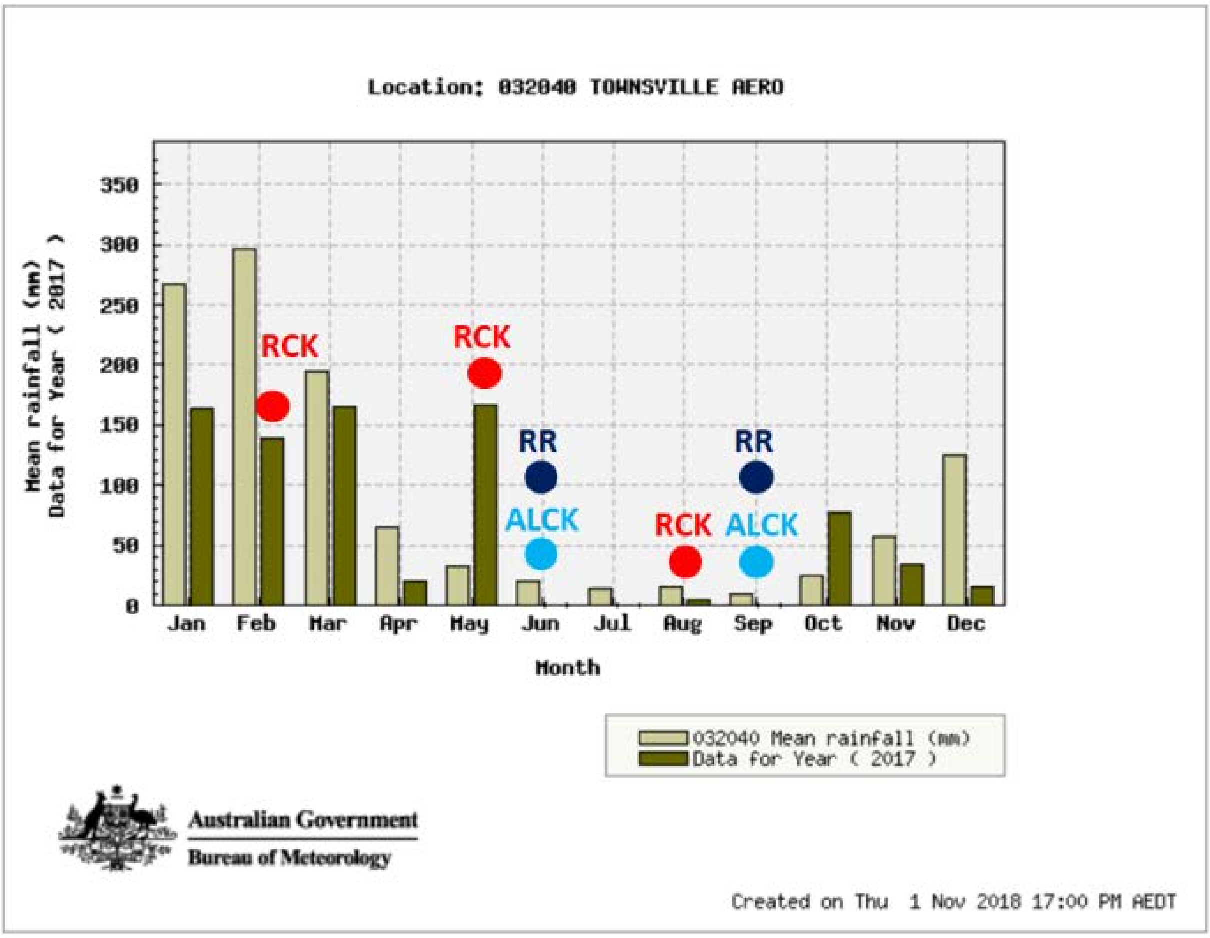
Appendix 4d. Information on the total extent, number of patches, mean patch size, and percentage of total extent of each habitat type in Althaus Creek.

	ALTHAUS CREEK			
Structural Habitat types	Total extent (m)	Patches	Mean patch size (m)	% total Extent
BLD*	1.5	1	1.50	0.02
BLD*-(A)	1.8	1	1.80	0.03
BLD*-(A)-(D)				
BLD*-(A)-(R)				
BLD*-MG-(A)				
BLD*-PAV*-(A)-(D)				
BLD*-PAV*-(A)-(R)-(P)				
BLD*-SM-(A)				
BLD*-SM-(A)-(P)				
GRV*-(A)	5.5	2	2.75	0.08
GRV*-BLD*-(A)	2.1	1	2.10	0.03
GRV*-BLD*-(A)-(D)				
GRV*-BLD*-MG-(A)				
GRV*-BLD*-MG-(A)-(D)				
GRV*-BLD*-MG-SM-(A)				
GRV*-BLD*-SM-(A)				
GRV*-MG-SM-(A)				
GRV*-PAV*-MG-(A)				
GRV*-SM-(A)-(D)				
MUD	518.8	5	103.76	7.99
MUD-BLD*-(A)				
MUD-BLD*-MG-(A)				
MUD-BLD*-MG-(A)-(R)				
MUD-BLD*-MG-SM-(A)				
MUD-BLD*-PAV*-(A)-(D)				
MUD-BLD*-SM-(A)				
MUD-GRV*	7.6	1	7.60	0.12
MUD-GRV*-(A)-(D)				
MUD-GRV*-(A)-(R)				
MUD-GRV*-BLD*-(A)				
MUD-GRV*-BLD*-(A)-(D)				
MUD-GRV*-BLD*-(A)-(R)				
MUD-GRV*-BLD*-MG-SM-(A)				
MUD-GRV*-BLD*-SM-(A)				
MUD-GRV*-MG	17	2	8.50	0.26
MUD-GRV*-MG-SM	3.1	1	3.10	0.05
MUD-GRV*-PAV*-(A)				
MUD-GRV*-SM	3.9	1	3.90	0.06
MUD-MG	3875.3	8	484.41	59.66
MUD-MG-SM	5.3	1	5.30	0.08
MUD-PAV	345.6	3	115.20	5.32
MUD-PAV*-(A)-(D)				
MUD-PAV*-(A)-(L)	5.3	1	5.30	0.08
MUD-PAV*-(A)-(R)				
MUD-PAV*-MG-(A)-(D)				
MUD-SAN	297.7	4	74.43	4.58
MUD-SAN-GRV*	2.4	1	2.40	0.04
MUD-SAN-GRV*-BLD*				
MUD-SAN-GRV*-BLD*-(A)				
MUD-SAN-GRV*-BLD*-SM				
MUD-SAN-GRV*-MG				
MUD-SAN-GRV*-MG-(D)				
MUD-SAN-GRV*-MG-(R)				
MUD-SAN-GRV*-MG-SM				
MUD-SAN-GRV*-MG-SM-(R)				
MUD-SAN-GRV*-SM				
MUD-SAN-MG	157.1	7	22.44	2.42
MUD-SAN-MG-SM				
MUD-SAN-SM				
MUD-SM				
PAV	156.8	3	52.27	2.41
PAV*-(A)	2.7	1	2.70	0.04
PAV*-(A)-(D)				
PAV*-(A)-(L)	33.1	3	11.03	0.51
PAV*-(A)-(P)				
PAV*-(A)-(R)				
PAV*-(A)-(R)-(P)				
PAV*-MG-(A)				
PAV-MG				
SAN	734.5	7	104.93	11.31
SAN-BLD	51.5	1	51.50	0.79
SAN-GRV*	37.7	3	12.57	0.58
SAN-GRV*-BLD*				
SAN-GRV*-BLD*-MG-(A)				
SAN-GRV*-MG				
SAN-GRV*-MG-SM				
SAN-MG	229.2	4	57.30	3.53
SAN-MG-SM-(P)				
SAN-SM				

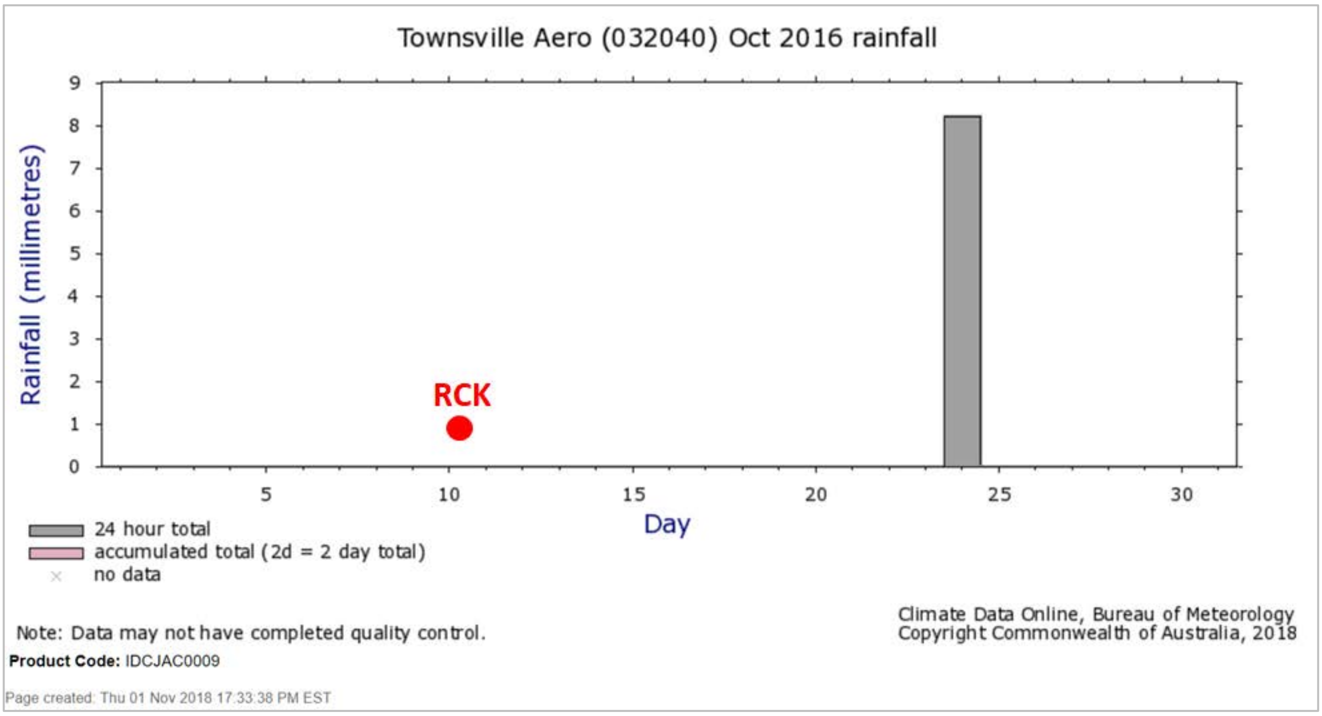
Appendix 5a. Mean monthly rainfall values of the Townsville region recorded in the period 2016 (dark brown) compared with the mean rainfall values for years 1940-2018 (light brown). Sampling rounds for the macrofaunal assessment carried out in Ross Creek (RCK, red).

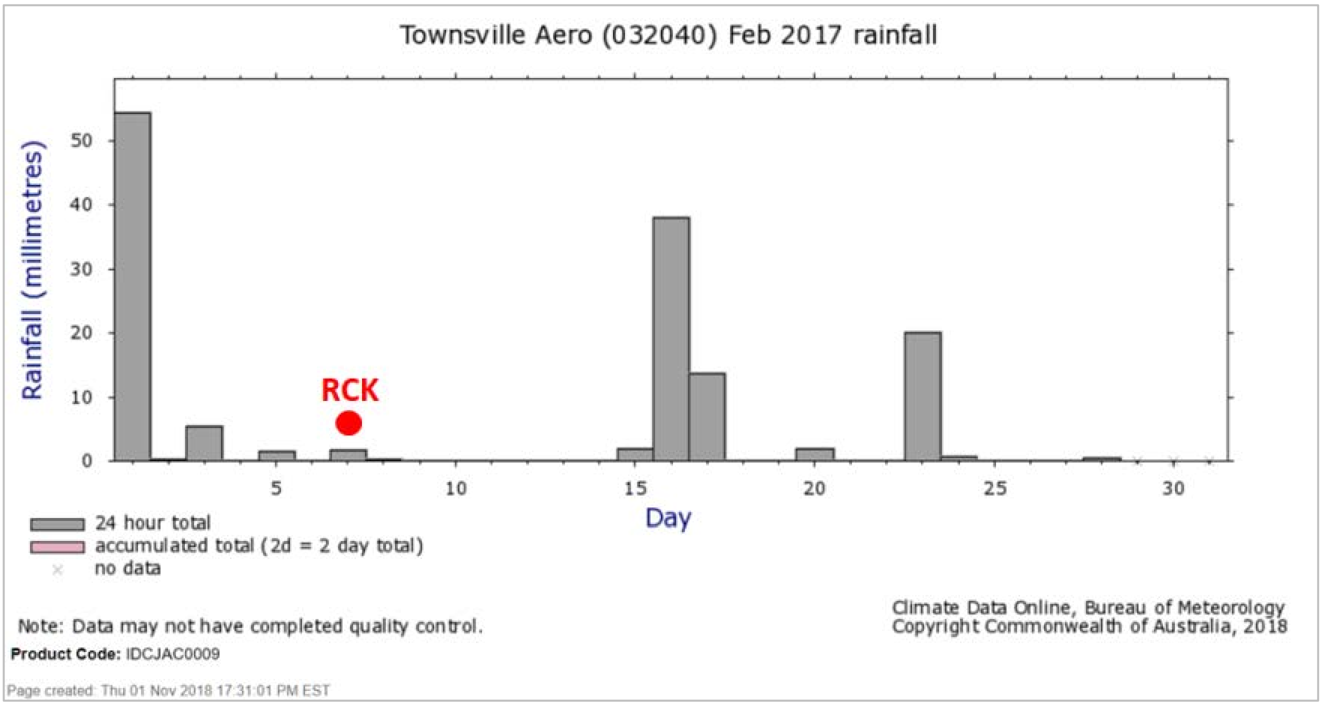


Appendix 5b. Mean monthly rainfall values of the Townsville region recorded in the period 2017 (dark brown) compared with the mean rainfall values for years 1940-2018 (light brown). Sampling rounds for the macrofaunal assessment carried out in the three estuaries are indicated by coloured dots: Ross Creek (RCK, red), Ross River (RR, dark blue) and Alligator Creek (ALCK, light blue).

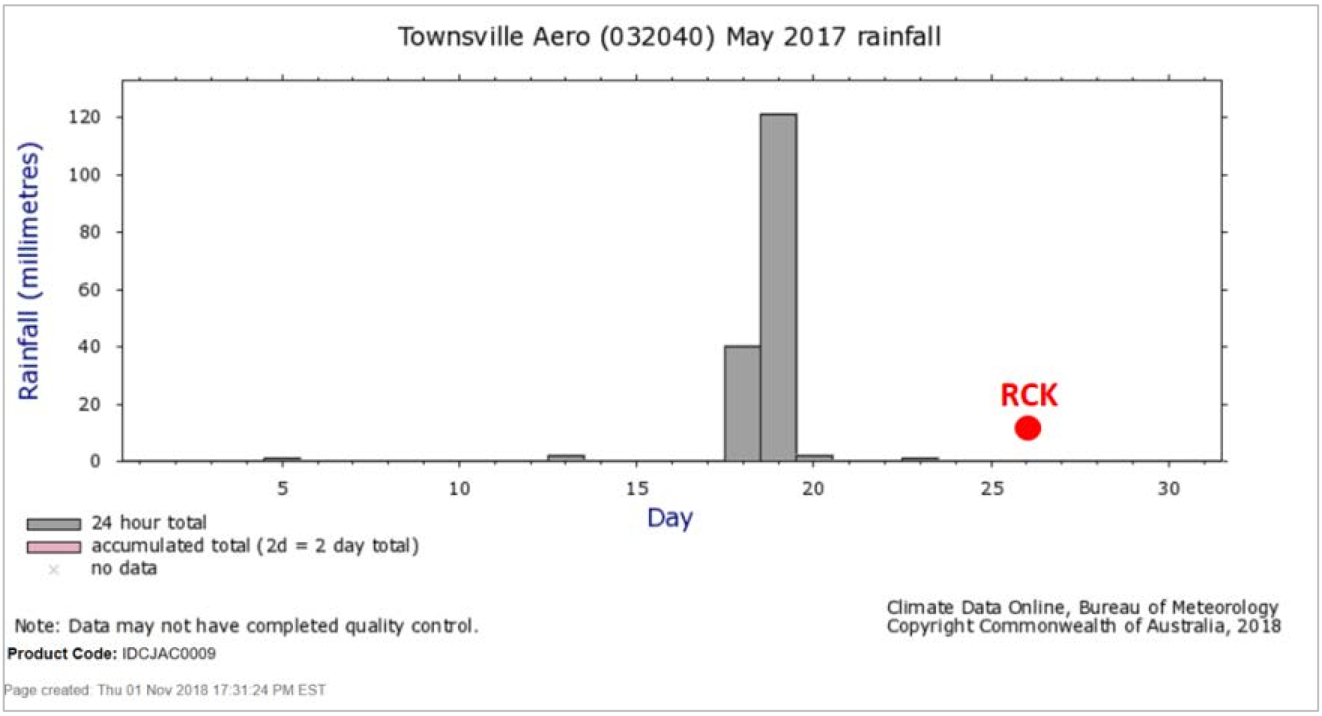


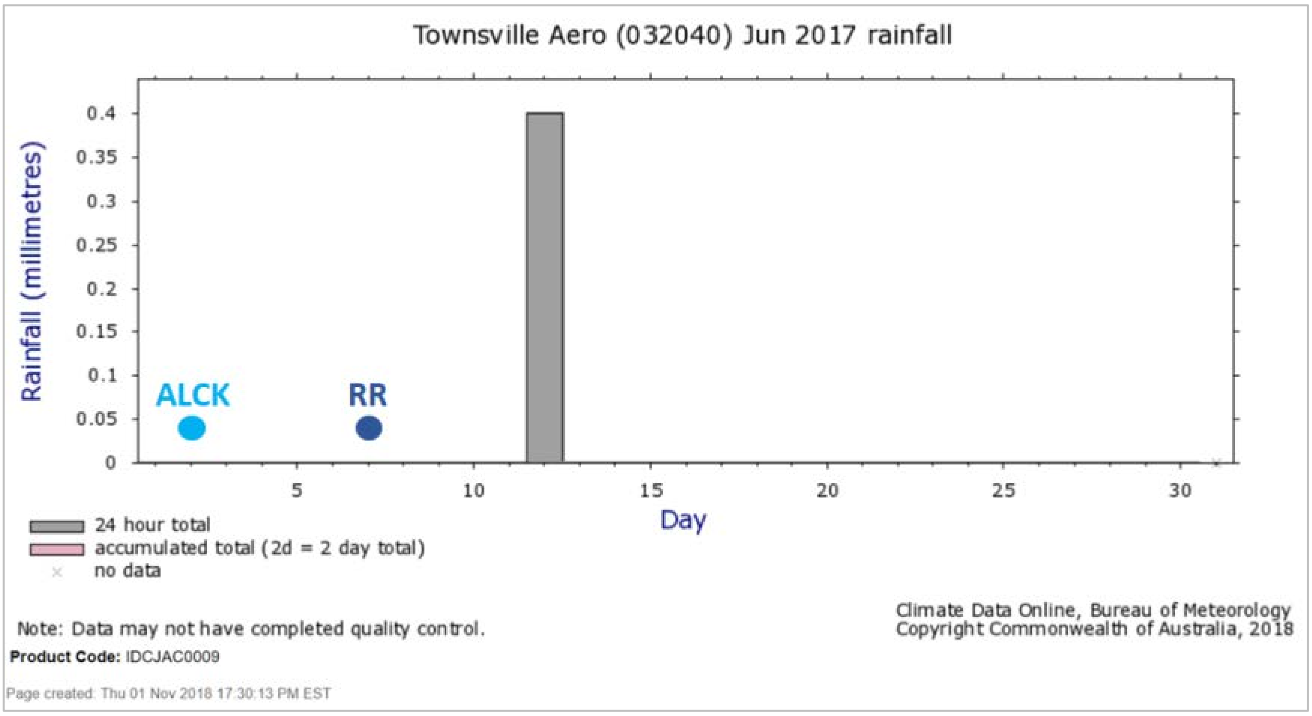
Appendix 6. Daily rainfall values of the Townsville region recorded around the sampling rounds carried in the period October 2016 – September 2017 for the three estuaries: Ross Creek (red), Ross River (dark blue) and Alligator Creek (light blue).



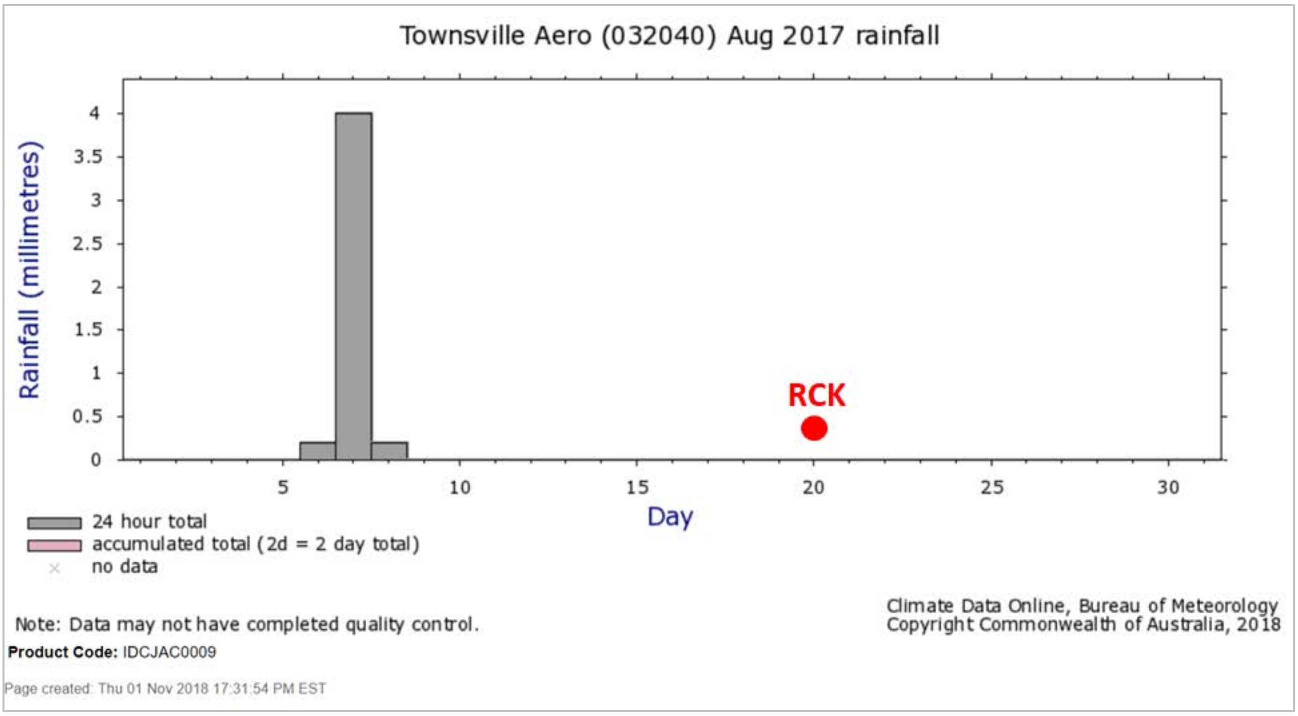


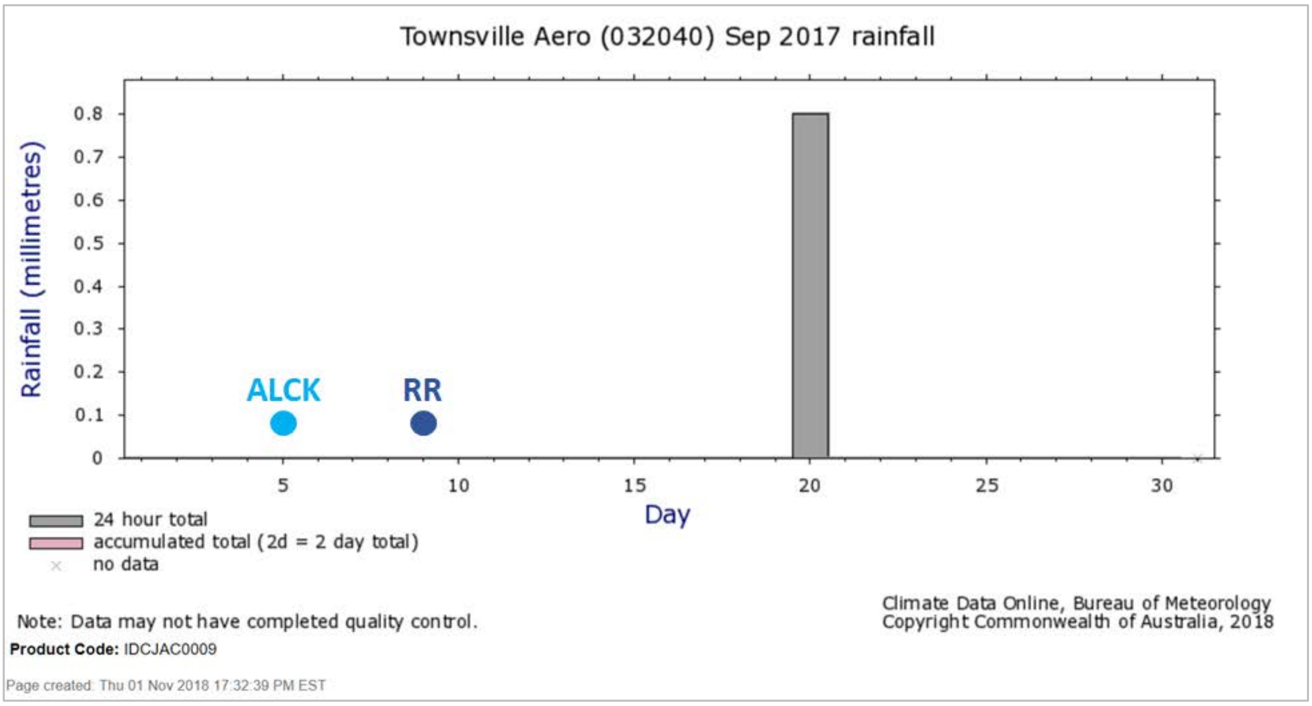
Appendix 6 (cont.). Daily rainfall values of the Townsville region recorded around the sampling rounds carried in the period October 2016 – September 2017 for the three estuaries: Ross Creek (red), Ross River (dark blue) and Alligator Creek (light blue).





Appendix 6 (cont.). Daily rainfall values of the Townsville region recorded around the sampling rounds carried in the period October 2016 – September 2017 for the three estuaries: Ross Creek (red), Ross River (dark blue) and Alligator Creek (light blue).





Appendix 7. List of all species identified in the macrofaunal survey across the three estuaries: Ross Creek, Ross River, and Alligator Creek.

Family	Species	Common name
Vespidae	*Abispa splendida*	Large mud-nesting wasp
Sergestidae	*Acetes australis*	Australian paste shrimp
Nymphalidae	*Acraea andromacha*	Glasswing butterfly
Nymphalidae	*Acraea terpsicore*	Tawny coster butterfly
Culcidae	*Aedes aegypti*	Yellow fever mosquito
Nymphalidae	*Agraulis vanillae*	Gulf fritillary butterfly
Apidae	*Amegilla Sp.*	Blue-banded bees
Anhingidae	*Anhinga novaehollandiae*	Australian darter
Apidae	*Apis mellifera*	European honey bee
Ardeidae	*Ardea Sp.*	White egret
Araneidae	*Argiope keyserlingi*	St Andrew's cross spider
Araneidae	*Austracantha minax*	Australian jewel spider
Macrophtalmidae	*Australoplax tridentata*	Furry-clawed crab
Tephritidae	*Bactrocera tryoni*	Queensland fruit fly
Balanidae	*Balanus amphitrite*	Striped barnacle
Batillariidae	*Batillaria australis*	Australian mud whelk
Ardeidae	*Butorides striata*	Striated heron
Cacatuidae	*Cacatua alba*	White cockatoo
Formicidae	*Camponotus Sp.*	Carpenter ants
Ellobiidae	*Cassidula angulifera*	Angulate shoulder ear shell
Pieridae	*Catopsilia pomona*	Emigrant butterflies
Acrididae	*Cedarinia Sp.*	Wingless grasshopper
Cerithiidae	*Cerithium Sp.*	Diplip welk
Chthamalidae	*Chthamalus antennatus*	Six-plated barnacle
Ocypodidae	*Cleistostoma wardi*	Ward's hairy-legged crab
Diogenidae	*Clibanarius Sp.*	Hermit crab
Neritidae	*Clithon oualaniensis*	Dubious Nerite
Coccinellidae	*Coelophora inaequalis*	Common Australian ladybug
Artamidae	*Cracticus Sp.*	Butcherbird
Ostreidae	*Crassostrea Sp.*	Pacific oyster
Formicidae	*Crematogaster laeviceps*	Black valentine ant
Scincidae	*Cryptoblepharus virgatus*	Snake-eyed skink
Ceratopogonidae	*Culiocoides Sp.*	Biting midges
Alcedinidae	*Dacelo novaeguineae*	Laughing kookaburra
Nymphalidae	*Danaus affinis*	Mangrove tiger butterfly
Deinopidae	*Deinopis subrufa*	Rufous net-caster spider
Heleomyzidae	*Diplogeomyza Sp.*	Heleomyzid fly
Terebridae	*Duplicaria Sp.*	Auger snail
Pyrrhocoridae	*Dysdercus sisae*	Pale cotton stainer
Ardeidae	*Egretta novaehollandiae*	White-faced heron
Ardeidae	*Egretta sacra*	Pacific reef heron
Anomiidae	*Enigmonia aenigmatica*	Mangrove jingle clam
Columbidae	*Geopelia placida*	Peaceful dove

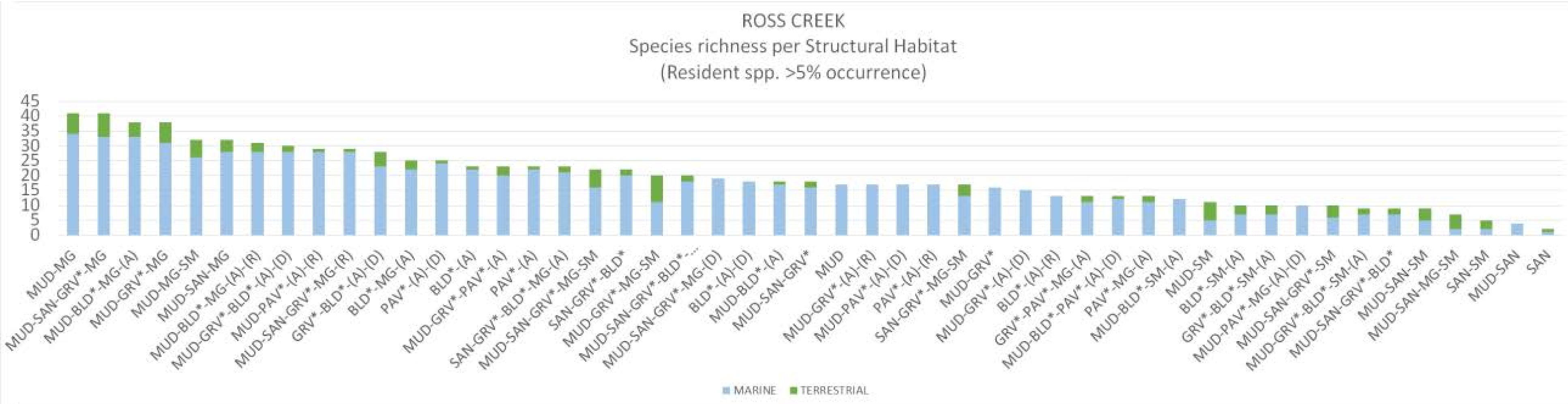
Family	Species	Common name
Monarchidae	*Grallina cyanoleuca*	Magpie-lark
Plagusiidae	*Grapsus tenuicrustatus*	Natal lightfoot crab
Gryllotaplidae	*Gryllotalpa pluvialis*	Mole cricket
Accipitridae	*Haliastur indus*	Brahminy kite
Pentatomidae	*Halyomorpha halys*	Brown marmorated stink bug
Grapsidae	*Helice sp.*	Tunnelling mud **crabs**
Recurvirostridae	*Himantopus*	Black-winged stilt
Hirundinidae	*Hirundo neoxena*	Welcome swallow
Lycaenidae	*Hypochrysops apelles*	Copper jewel butterfly
Lycaenidae	*Hypochrysops digglesii*	Silky jewel butterfly
Ocypodidae	*Ilyoplax Sp.*	Semaphore crabs
Formicidae	*Iridomyrmex purpureus*	Meat ants
Ostreidae	*Isognomon ephippium*	Rounded toothed pearl shell
Campephagidae	*Lalage sueurii*	White-shouldered triller
Laridae	*Larus novahoellandiae*	Silver gull
Meliphagidae	*Lichenostomus versicolor*	Varied honeyeater
Ligiidae	*Ligia Sp.*	Sea slaters
Littorinidae	*Littoraria articulata*	Articulated littorina
Littorinidae	*Littoraria filosa*	Thin periwinkle
Littorinidae	*Littoraria pallescens*	Polymorphic mangrove snail
Littorinidae	*Littoraria scabra*	Mangrove periwinkle
Calliphoridae	*Lucilia cuprina*	Australian sheep blowfly
Macrophtalmidae	*Macrophthalmus latreillei*	Giant sentinel crab
Ocypodidae	*Macrophthalmus pacificus*	Pacific blue-clawed sentinel
Macropodidae	*Macropus agilis*	Agile wallaby
Meliphagidae	*Manorina melanocephala*	Noisy miner
Meropidae	*Merops ornatus*	Rainbow bee-eater
Grapsidae	*Metopograpsus frontalis*	Mangrove climber crab
Grapsidae	*Metopograpsus latifrons*	Purple climber crab
Grapsidae	*Metopograpsus thukuhar*	Thukuhar shore-crab
Accipitridae	*Milvus migrans*	Black kite
Muscidae	*Musca vetustissima*	Australian bush fly
Menippidae	*Myomenippe fornasinii*	Stone crab
Braconidae	N/A	Braconid wasps
Gerridae	N/A	Water striders
Cerambycidae	N/A	Longhorned beetles
Armadillidae	N/A	Garden slater
Anomiidae	N/A	Red flat clam
Nassaridae	*Nassarius Sp.*	Nassa mud snail
Neritidae	*Nerita balteata*	Lined nerite
Neritidae	*Nerita planospira*	Flat spire nerite
Acrididae	*Nomadacris guttulosa*	Spur-throated locust
Scolopacidae	*Numenius madagascariensis*	Eastern curlew
Formicidae	*Ochetellus glaber*	Black house ant
Formicidae	*Oecophylla smaragdina*	Green tree ant

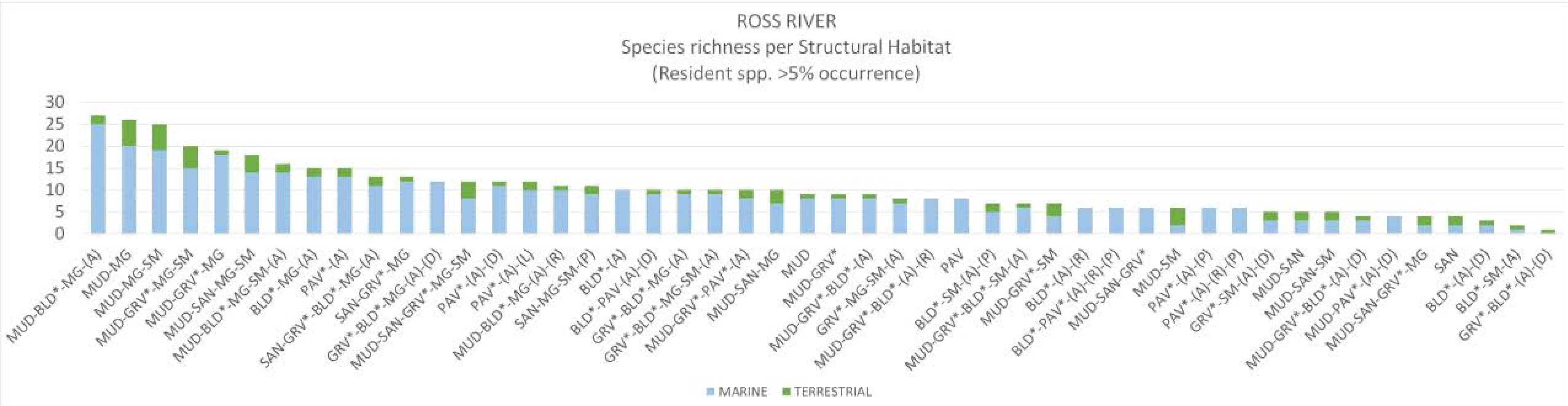
Family	Species	Common name
Asilidae	*Ommatius Sp.*	Robber flies
Onchidiidae	*Onchidina australis*	Onchidiid slug
Onchidiidae	*Onchidium daemelii*	Onchidiid slug
Onchidiidae	*Onchidium verruculatum*	Onchidiid slug
Chitonidae	*Onithochiton Sp.*	Chiton shell
Ellobiidae	*Ophicardelus ornatus*	Ornate mangrove snail
Lymantriidae	*Orvasca aliena*	Tussock Moth
Oxyopidae	*Oxyopes Sp.*	Lynx spiders
Passeridae	*Passer domesticus*	House sparrow
Pelecanidae	*Pelecanus conspicillatus*	Australian pelicans
Panaeidae	*Penaeus merguiensis*	Banana prawn
Gobidae	*Periophthalmus Sp.*	Mudskipper
Phalacrocoracidae	*Phalacrocorax Sp.*	Cormorant
Phascolosomatidae	*Phascolosoma arcuatum*	Peanut worm
Pieridae	*Pieris rapae*	Small cabbage white butterfly
Threskiornithidae	*Plegadis falcinellus*	Glossy ibis
Myrmicinae	*Podomyrma gratiosa*	Muscleman tree-ant
Formicidae	*Polyrhachis Sp.*	Golden tailed spiny ant
Portunidae	*Portunus Sp.*	Swimmer crab
Reduviidae	*Pristhesancus plagipennis*	Common assassin bug
Pteropodidae	*Pteropus alecto*	Black flying fox
Ptilonorhynchidae	*Ptilonorhynchus nuchalis*	Great bowerbird
Vespidae	*Ropalidia revolutionalis*	Small brown paper wasp
Ostreidae	*Saccostrea cucullata*	Hooded oyster
Ostreidae	*Saccostrea echinata*	Black lip oyster
Sphecidae	*Sceliphron laetum*	Mud-dauber wasp
Scoliidae	*Scolia soror*	Blue hairy flower wasp
Portunidae	*Scylla serrata*	Giant mud crab
Grapsidae	*Sesarma erythrodactyla*	Red-fingered marsh crab
Sesarmidae	*Sesarma longicristatum*	Saltmarsh burrowing crab
Grapsidae	*Sesarma messa*	Mangrove crab
Oriolidae	*Sphecotheres viridis*	Timor figbird
Chrysididae	*Stilbum cyanurum*	Large cuckoo wasp
Potamididae	*Telescopium*	Horn snail
Muricidae	*Thais Sp.*	Rock murex
Thalassinidae	*Thalassina Sp.*	Mud lobster
Lycaenidae	*Theclinesthes sulpitius*	Samphire blue butterfly
Threskiornithidae	*Threskiornis molucca*	Australian white ibis
Alcedinidae	*Todiramphus sanctus*	Sacred kingfisher
Ocypodidae	*Uca coarctata*	Orange-clawed fiddler crab
Ocypodidae	*Uca perplexa*	Perplexing fiddler crab
Ocypodidae	*Uca polita*	Polished fiddler crab
Ocypodidae	*Uca seismella*	Shaking fiddler crab
Ocypodidae	*Uca signata*	Signaling fiddler crab
Ocypodidae	*Uca vocans*	Two-toned fiddler crab
Charadriidae	*Vanellus miles*	Masked lapwing

Appendix 8. Occurrence of the 67 non-transient taxa across the three estuaries: Ross Creek (RCK), Ross River (RR), and Alligator Creek (ALCK).

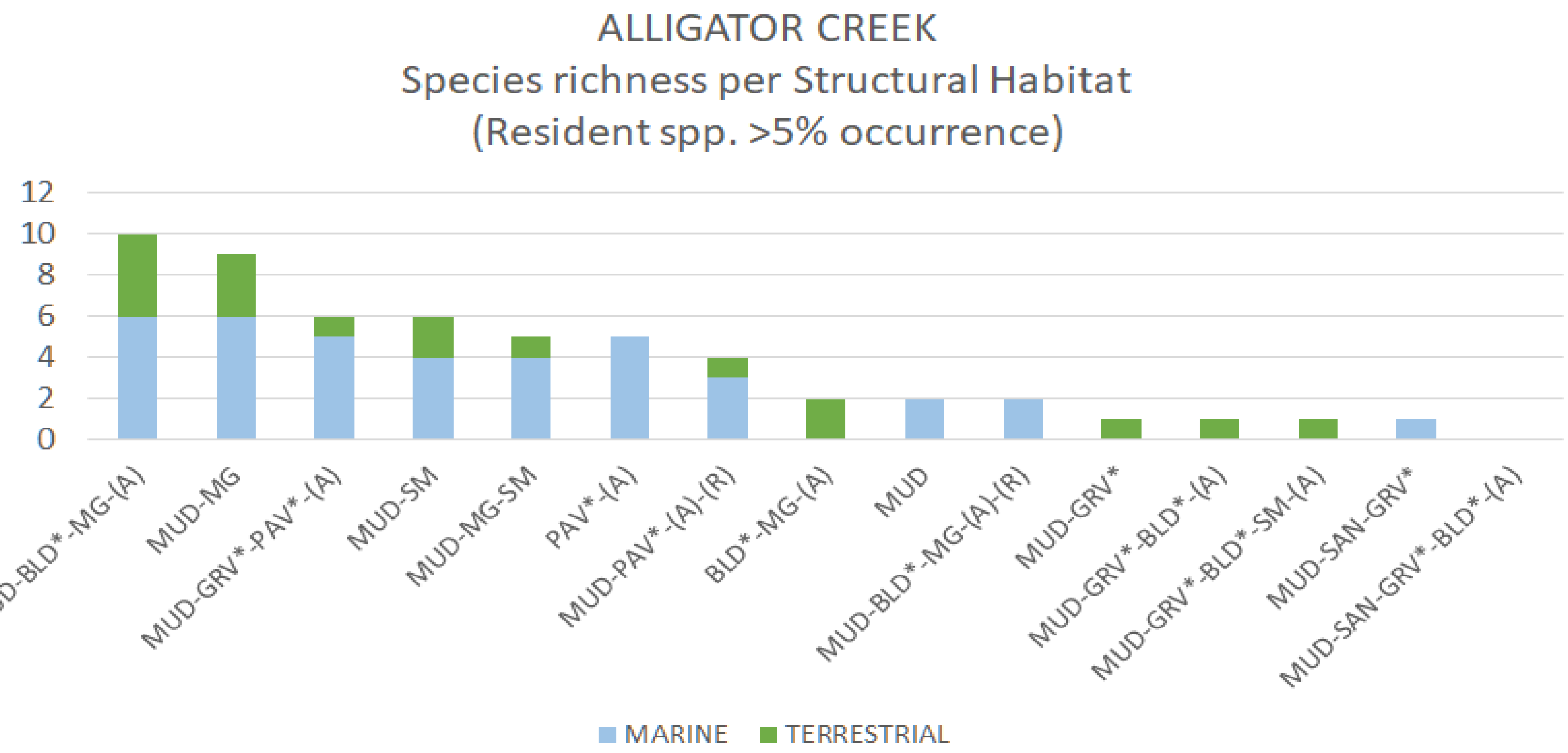
	RCK	RR	ALCK
Anomiidae sp.		■	
Argiope keyserlingi	■	■	
Austracantha minax		■	
Australoplax tridentata		■	■
Balanus amphitrite	■	■	■
Batillaria australis	■	■	
Camponotus sp.	■	■	■
Cassidula angulifera		■	
Cerithium sp.		■	
Chthamalus antennatus	■	■	
Cleistostoma wardi	■	■	
Clibanarius sp.	■		
Clithon oualaniensis		■	
Crassostrea sp.	■		
Crematogaster laeviceps	■	■	■
Duplicaria sp.	■		
Dysdercus sisae	■		
Enigmonia aenigmatica	■	■	
Grapsus tenuicrustatus	■	■	
Gryllotalpa pluvialis	■	■	■
Halyomorpha halys	■		
Helice sp.			■
Ilyoplax sp.		■	■
Iridomyrmex purpureus		■	■
Isognomon ephippium	■	■	
Ligia sp.	■	■	
Littoraria articulata	■	■	■
Littoraria filosa	■	■	■
Littoraria pallescens	■	■	■
Littoraria scabra	■	■	■
Macrophthalmus latreillei	■	■	■
Macrophthalmus pacificus	■	■	■
Metopograpsus frontalis	■	■	■
Metopograpsus latifrons	■	■	■
Metopograpsus thukuhar	■		
Myomenippe fornasinii	■	■	
Nassarius sp.	■	■	
Nerita balteata	■	■	
Nerita planospira	■	■	■
Ochetellus glaber	■	■	
Oecophylla smaragdina			■
Onchidina australis	■		
Onchidium daemelii	■	■	
Onchidium verruculatum	■		■
Onithochiton sp.		■	
Ophicardelus ornatus		■	
Oxyopes sp.		■	
Periophthalmus sp.	■	■	■
Periesarma messa	■	■	
Phascolosoma arcuatum		■	
Podomyrma gratiosa	■	■	■
Polyrhachis sp.	■	■	■
Portunus sp.	■	■	
Pristhesancus plagipennis		■	
Saccostrea cucullata	■	■	■
Scylla serrata	■	■	■
Sesarma erythrodactyla		■	■
Sesarma longicristatum	■	■	■
Telescopium telescopium	■	■	■
Thais kienieri		■	
Thalassina sp.	■	■	■
Uca coarctata	■	■	■
Uca perplexa		■	
Uca polita		■	
Uca seismella	■	■	■
Uca signata	■	■	■
Uca vocans		■	

Appendix 9. Species richness per structural habitat assessed in the estuaries of Ross Creek, Ross River, and Alligator Creek. Data includes only species occurring more than 5% of the total dataset. Marine species are represented by the colour light blue, while terrestrial species are represented by the colour green.





Appendix 9 (cont.). Species richness per structural habitat assessed in the estuaries of Ross Creek, Ross River, and Alligator Creek. Data includes only species occurring more than 5% of the total dataset. Marine species are represented by the colour light blue, while terrestrial species are represented by the colour green.



“E quindi uscimmo a riveder le stelle”

(Inferno XXXIV, 139)

Dante Alighieri – Divina Commedia