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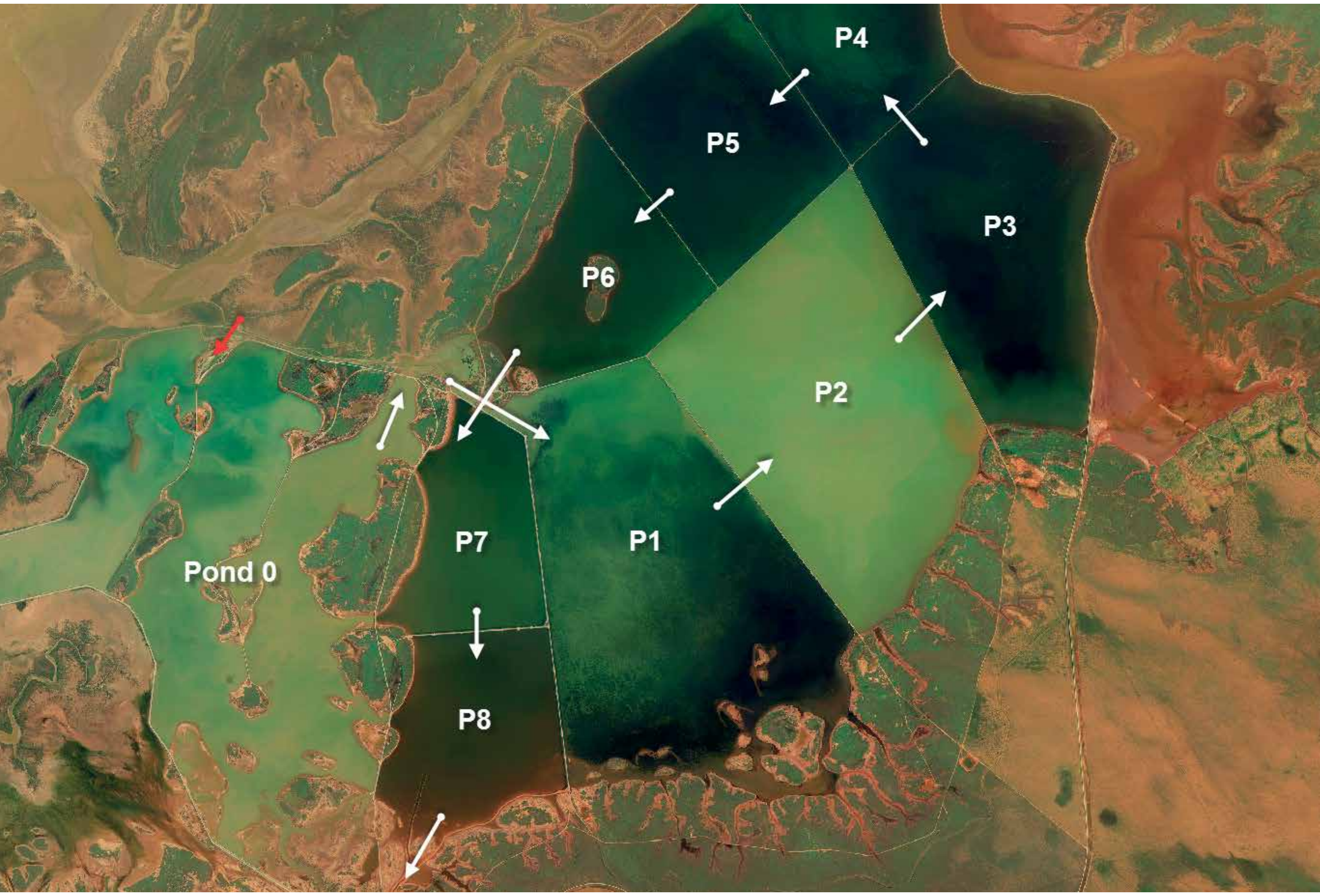
Shorebird foraging ecology in northwestern Australian saltworks



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EDITH COWAN UNIVERSITY

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Disclaimer

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Table of Contents

Acknowledgements 4

List of Figures 5

List of Tables 9

EXECUTIVE SUMMARY 11

INTRODUCTION 18

Background 18

Saltworks 19

OBJECTIVES 21

METHODS 23

Sampling sites 23

Approach to addressing objective 1. 28

Approach to address objective 2. 36

Approach to address objective 3. 39

Statistical analyses 40

RESULTS 42

Prey availability 42

Prey abundance 42

Macroinvertebrate daily vertical distribution 46

Shorebird diet 46

Diet from direct observations 46

Faecal analysis 54

Diet of birds feeding in the water column 54

Factors affecting shorebird habitat use 54

Wind 54

Tide 54

Water depth 57

Biotic factors affecting shorebirds' feeding and intake rates 57
Site and period 57
Prey density 69
Abiotic factors affecting shorebirds' feeding and intake rates 69
Water depth 69
Day-night feeding 74
Quality of the saltworks and salt lake as feeding grounds 74
Postmigration 74
Premigration 74
DISCUSSION 79
Prey abundance, biomass and availability 79
Diet 80
Shorebird habitat use 81
Feeding and intake rates 81
Day and Night feeding 83
Habitat quality as feeding grounds for shorebirds 84
Value of Dampier Salt Ltd. operations in the context of the East Asian-Australasian Flyway 86
CONCLUSIONS 88
Knowledge gaps 90
Species cards 91
References 96

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List of Figures

Figure 1: Dampier Salt Ltd. operations in Western Australia in red dots 23

Figure 2: Sampling sites at Lake MacLeod. Yellow stars indicate sites sampled both post and premigration (2013 and 2014).
Blue stars indicate sites sampled once. 24

Figure 3: Sampling sites at Port Hedland. Yellow stars indicate sites sampled both post and premigration (2013 and 2014). 25

Figure 4: Sampling sites at Dampier. Yellow stars indicate sites sampled both post and premigration (2013 and 2014).
Red stars indicate sites sampled once. 26

Figure 5: Video recording foraging behaviour at Whistler Pond, Lake MacLeod. (Photo: Rob Davis) 28

Figure 6: A) Benthic samples sieved (Godwit Beach, Lake MacLeod), B) nekton samples collected (Pond 6, Port Hedland) and C) samples preserved in 70% ethanol (Whistler Pond, Lake MacLeod). 31

Figure 7: Length measurement of brine shrimp *Artemia sp.* 33

Figure 8: Indicator of water depth used for statistical analyses. 34

Figure 9: Water chemistry data collection at Port Hedland.
Water quality meter Orion Star Series Meter TM. 36

Figure 10: Night observations Pond 0 Bay, Dampier, 2013. 36

Figure 11: Benthic macroinvertebrate density (mean ± SE) post and premigration at different sites at Lake MacLeod, Port Hedland and Dampier. 41

Figure 12: A) polychaete, B) amphipod and C) bivalve densities (mean ± SE) post and premigration at different sites at Lake MacLeod, Port Hedland and Dampier. *Sites only sampled once. 42

Figure 13: Chironomid densities (mean ± SE) post and premigration at different sites at Dampier. *Site only sampled postmigration. 43

Figure 14: Brine shrimp densities (mean ± SE) post and premigration at different sites at Port Hedland and Dampier. *Postmigration data from Actis Environmental Services Technical Report, October 2013. 43

Figure 15: Density (mean ± SE) of A) polychaetes and B) amphipods at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Godwit Beach, Lake MacLeod, postmigration. 46

Figure 16: Density (mean ± SE) of A) polychaetes, B) amphipods and C) bivalves at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Whistler Pond, Lake MacLeod, premigration. 48

Figure 17: Density (mean ± SE) of polychaetes at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Pond 0, Dampier, premigration. 48

Figure 18: Proportions of prey items in the diet of shorebirds using Lake MacLeod as a feeding habitat 50

Figure 19: Proportions of benthic prey in the diet of shorebirds using Port Hedland as a feeding habitat post and premigration. 51

Figure 20: Percentage of migratory shorebirds feeding or roosting at Port Hedland and Dampier (sites combined) postmigration, in relation to time to low tide. 54

Figure 21: Percentage of migratory shorebirds feeding or roosting at Port Hedland and Dampier (sites combined) premigration, in relation to time to low tide. 54

Figure 22: Proportion of small shorebirds feeding at different depths in relation to prey location in the sediment and water column, at all sites, post and premigration. 56

Figure 23: Proportion of small to medium-size shorebirds feeding at different depths in relation to prey location in the sediment and water column, at all sites, post and premigration. 56

Figure 24: Proportion of medium-size shorebirds feeding at different water depths in relation to prey location in the sediment and water column, at all sites, post and premigration. 56

Figure 25: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-necked Stints feeding at Lake MacLeod (LMC), Port Hedland (PH) and Dampier (DMP), post and premigration. 57

Figure 26: A) Feeding rates and B) energy intake rates (mean ± SE) of Broad-billed Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration. 60

Figure 27: A) Feeding rates and B) energy intake rates (mean ± SE) of Curlew Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration. 61

Figure 28: A) Feeding rates and B) energy intake rates (mean ± SE) of Sharp-tailed Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), postmigration. 63

Figure 29: A) Feeding rates and B) energy intake rates of Bar-tailed Godwits (mean ± SE) feeding at Port Hedland (PH) and Dampier (DMP), post and premigration. 64

Figure 30: A) Feeding rates and B) energy intake rates (mean ± SE) of Red Knots feeding at Lake MacLeod, premigration. 65

Figure 31: A) Feeding rates and B) energy intake rates (mean ± SE) of Banded Stilts feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration. 67

Figure 32: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-necked Avocets feeding at Lake MacLeod (LMC), Port Hedland (PH), and Dampier (DMP), postmigration. 68

Figure 33: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-capped Plovers feeding at Lake MacLeod, post and premigration. 69

Figure 34: Feeding rates of Red-necked Stints (RNS) and Sharp-tailed Sandpipers (STS) in Pond 5, Port Hedland, post and premigration, at 2 different water depths. 70

Figure 35: A) Probes per minute and B) steps per minute of Red-capped Plovers (RCP) and Red-necked Stints (RNS) feeding day and night in Whistler Pond, Lake MacLeod, premigration. 73

List of Tables

Table 1: Sampling sites at the three locations, Lake MacLeod, Port Hedland and Dampier. See Figures 1, 2 and 3. 28

Table 2: Morphometric data (tarsus length (mm), bill length (mm) and weight (g)) of the shorebird species studied. 29

Table 3: Allometric equations used to convert the length (mm) of specific benthic macroinvertebrates into biomass (g AFDM). 34

Table 4: Equations used to convert the length (mm) of hard remains to the size of prey items. 34

Table 5: Factorial ANOVA test results of the period of the day, sediment depth and period of the day x sediment depth effects on major benthic invertebrate taxa densities post and premigration at different sites at Lake MacLeod and Dampier. 45

Table 6: Number of birds recorded at Godwit Beach, Lake MacLeod, pre and postmigration, and wind conditions: speed (km/h) and direction. 53

Table 7: Number of birds feeding or roosting in different sections of the concentration ponds at Port Hedland, post and premigration, and wind conditions: speed (km/h) and direction. 53

Table 8: Factorial ANOVA, Kruskal-Wallis test, t-test and Mann-Whitney U test results to test the effect that site, period (post and premigration) and site x period have on the feeding rates and biomass and energy intake rates of shorebirds feeding at all sites, post and premigration 59

Table 9: Effect of prey density, period (post and premigration) and water depth on the feeding rates of shorebirds feeding in Dampier Salt Ltd. operations, WA in post and premigration. 70

Table 10: Feeding activity of birds observed at night at Dampier and Lake MacLeod, post and premigration. 72

Table 11: Factorial ANOVA results of the effect of species, day period (night/day) and the interaction factor species x day period on the probes per minute and steps per minute of Red-capped Plovers (RCP) and Red-necked Stints (RNS), feeding day and night in Whistler Pond, Lake Macleod, premigration. 72

Table 12: Theoretical Daily Energy Expenditure (DEE, Nagy 1987) of shorebirds post and premigration, based on their energy intake rates (kJ/min) and body mass (g) (from literature, see table 2), and the number of hours each species would need to fulfil their DEE. Bold font indicates species that could fulfil their DEE feeding exclusively at various study sites. 75

EXECUTIVE SUMMARY

Dampier Salt Ltd. has three operations in Western Australia, at Dampier, Port Hedland and Lake MacLeod. The three operations are listed as Important Bird and Biodiversity Areas (IBAs) by BirdLife Australia and are recognised as globally important habitats for shorebirds. Given this, it is essential that a sound knowledge base is developed regarding the ecology of shorebirds at these saltwork sites, the prey resources present, and shorebird interactions within feeding habitats. This information will allow the formulation of management strategies for these sites that reconcile production requirements with the needs of shorebird populations, and provide a scientific basis upon which saltworks can be managed postproduction. The specific objectives of this project were to:

1. Identify the major biotic factors that influence shorebird use of the saltworks, with special emphasis on trophic resources.
2. Identify the abiotic conditions that affect shorebird habitat use in the saltworks.
3. Evaluate the quality of the three sites as feeding habitats for shorebirds.

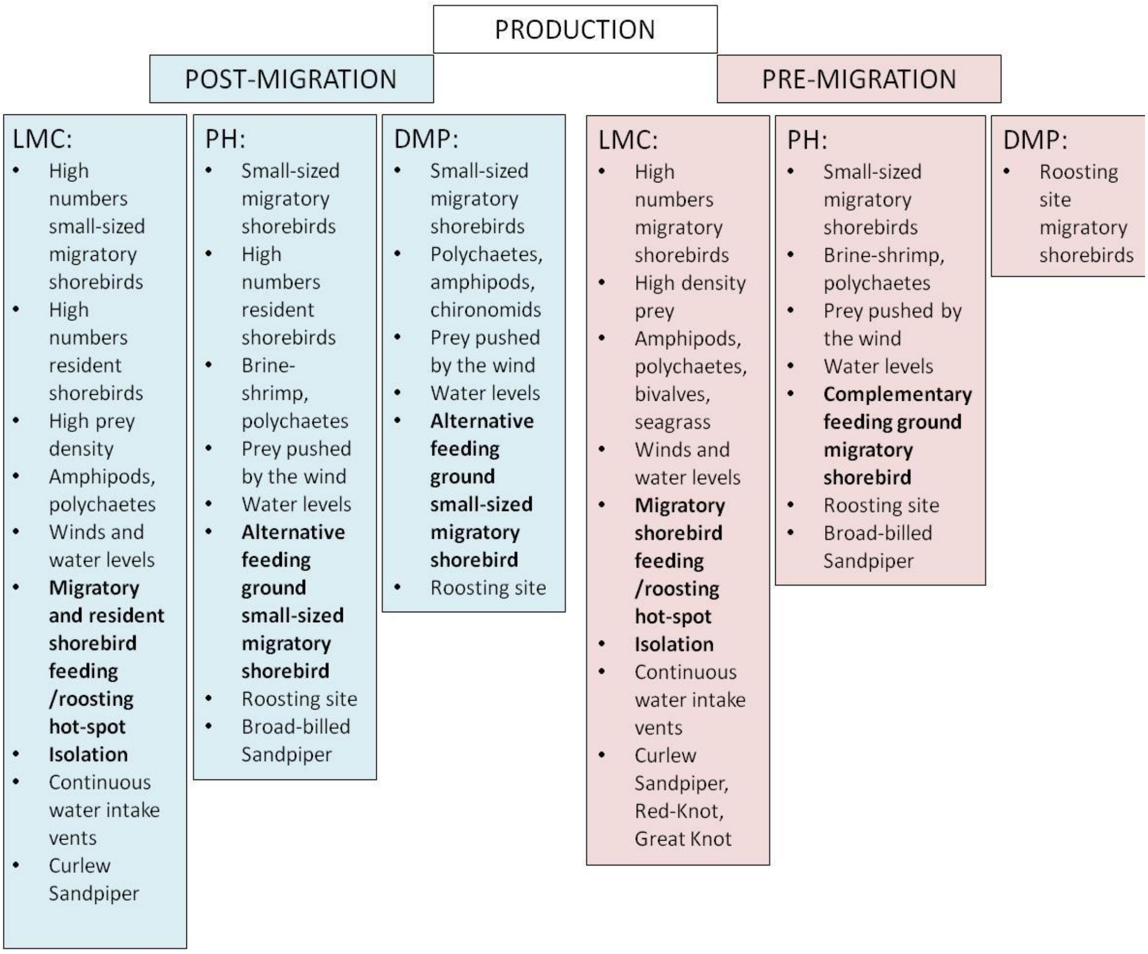
The Lake MacLeod study site can be distinguished from the other 2 sites (Dampier and Port Hedland) by the location of the shorebird foraging areas in relation to the working salt ponds. At Lake MacLeod the foraging areas are located in the ‘Northern Ponds’, a natural wetland some 60 km north of the saltworks themselves. The foraging areas at Dampier and Port Hedland on the other hand are located within parts of the operational salt ponds.

Of all the sites, Lake MacLeod had the highest abundance of macroinvertebrates. The maximum invertebrate prey densities at the lake were found in the first 5 cm of the sediment, indicating that food was always available for small to medium-size shorebirds. Amphipods were the primary benthic prey for shorebirds at Lake MacLeod while polychaetes were the primary benthic prey at both the Port Hedland and Dampier operations. When birds were observed feeding on prey suspended in the water column at the latter 2 sites, brine shrimp was the main prey item.

Wind played a major role in shorebird feeding behaviour at Lake MacLeod, resulting in either the availability or exclusion of large areas of mudflats as

foraging habitat. Wind also appeared to affect shorebird use of the concentration ponds at Port Hedland. Small to medium-size migratory shorebirds were limited in their habitat use by water depth, always feeding in shallow waters from 0 to 3 cm. Areas with a high abundance of macroinvertebrates that were not in shallow water, were not foraged in. The period of the day (day and night) appeared not to affect the use of the saltworks by shorebirds and several species (including both visual and tactile feeders) used the saltworks and the lake to feed at night, both post and premigration. We found that shorebirds modified their behaviour from day to night, with Red-necked Stints increasing feeding speed and Red-capped Plovers decreasing feeding speed at night.

Figure A: Summary diagram of main findings for Lake MacLeod (LMC); Port Hedland (PH); Dampier (DMP)



Migratory and resident shorebirds both achieved higher intake rates (energy/min) at Lake MacLeod than at Dampier and Port Hedland. These differences appeared to be related to differences in prey density, prey type and prey availability. Lake MacLeod was the highest-quality feeding habitat for small to medium-size migratory shorebirds, enabling them, theoretically, to fulfil their daily energy requirements (theoretical Daily Energy Expenditure - DEE) both post and premigration. This finding explains previous observations of high concentrations of migratory shorebirds at the lake. Small shorebirds could also achieve their DEE feeding exclusively at Port Hedland or Dampier postmigration. Therefore these operations could act as alternative feeding grounds for small migratory shorebirds postmigration. Premigration, none of the migratory species could reach their DEE feeding exclusively at Port Hedland or Dampier. Higher energy demands premigration mean that shorebirds also need to feed on the nearby intertidal areas in order to obtain their premigratory daily energy requirements. Nevertheless, during high-tide hours, small migratory shorebirds were able to obtain around 50% of their DEE feeding exclusively in the saltworks.

In conclusion, Dampier Salt Ltd. operations represent important and high-quality feeding grounds for small to medium-size migratory shorebirds both post and premigration, indicating that it would be appropriate for these sites to be granted some level of protection. Notably, the Northern Ponds of Lake Macleod (at least) meet several of the criteria required to be considered a Wetland of International Importance under the Ramsar Convention. Such a designation would provide additional protection for the wetland system.

Table A: Summary table of main findings. Resident species: Red-necked Avocet (RNAv); Banded Stilt (BS); and Red-capped Plover (RCP). Migratory species: Red-necked Stint (RNS); Curlew Sandpiper (CS); Sharp-tailed Sandpiper (STS); Broad-billed Sandpiper (BBS); Bar-tailed Godwit (BTG); Red Knot (RK); and Great Knot (GK). Locations: Port Hedland (PH); Lake MacLeod (LMC); Dampier (DMP)

Location	Site	Period	Main prey available	Main shorebird species using the site as feeding ground	Main prey consume	Factors afecting habitat use	Factors afecting prey capture	Able to fulfil energy demands
PH	concentration ponds	post-migration	brine-shrimp	RNS	brine-shrimp	tides, water level, wind	water level, prey density	**Yes**
				STS				No
				CS				No
				BS				No
		pre-migration		RNS				No
				CS				No
				BS				No
	Pond 0	post-migration	polychaetes, amphipods, bivalves	BBS	polychaetes	tides	prey density	**Yes**
				BTG				No
				RNAv				**Yes***
				CS				-
				RNS				-
				RCP				-
		pre-migration	polychaetes, amphipods	RNS	polychaetes			No
				BBS				No
				BTG				No
				CS				No
LMC	Godwit Beach	post-migration	Polychaetes, amphipods	RNS	amphipods	wind, water levels	prey density	**Yes**
				CS				**Yes**
				STS				**Yes**
				RCP				No
				RNAv				**Yes***
				BS				**Yes***
		pre-migration	Polychaetes, amphipods	RNS				No
				CS				No
				BS				No
				RCP				-
				BBS				-
				RK	polychaetes			**Yes**
	Whistler Pond	post-migration	polychaetes, amphipods,	RNS	amphipods	-	prey density	**Yes**
				RCP				**Yes**
				BS	bivalves			-
		pre-migration	polychaetes, amphipods, bivalves	RNS	Amphipods			**Yes**
				CS				**Yes**
				BBS				**Yes**
				RCP				**Yes**
				RK	polychaetes, seagrass			**Yes**
				GK	bivalves			**Yes**
DMP	concentration ponds	post-migration	brine-shrimp	RNS	brine-shrimp	tides, water level, wind	-	-
				CS				-
				BS				-
		pre-migration		BS				-
				RT				-
	Pond 0	post-migration	polychaetes, amphipods, bivalves, chironomids	RNS	polychaetes, amphipods	Tides	-	**Yes**
				CS				-
				STS	amphipods, bivalves			-
				RNAv	chironomids			**Yes***
				BTG	polychaetes			No
		pre-migration	polychaetes	BTG				No

Other operational recommendations are that:

1. Hydrological operations at Port Hedland and Dampier should be maintained, or enhanced -as described in subsequent recommendations – as these operations provide for the high densities of brine shrimp observed in this study.

2. Since shorebirds feed visually on brine shrimp, it is recommended that the Transfer at Port Hedland and all the transfer gates within the concentration ponds are active/open during the day and that any opening and activations scheduled for the night are rescheduled to the day where possible.

3. Since water depth and the existence of shoreline slopes (shallow areas) limit the access of small to medium-size migratory shorebirds to the concentration ponds or even to Pond 0 areas at the Dampier operations, the creation of beaches with smooth slopes (to yield water depths of 0 to 5cm) would benefit these birds by improving their access to feeding areas.

4. To obtain the maximum advantage that these beaches might offer, their locations need to be carefully considered. Wind appears to concentrate brine shrimp on the shores of the ponds, therefore any constructed shallow feeding areas need to be located such that prevailing winds will concentrate brine shrimp along them.

5. Because the transfer gates between concentration ponds attract shorebirds that feed on brine shrimp, the creation of shallow beaches next to these particular sites will also allow shorebird access.

6. At the Port Hedland and Dampier operations the intake of seawater at Pond 0 should be maintained and monitored to ensure the presence of high densities of macroinvertebrates, especially polychaetes and amphipods.

7. Important roosting sites have been observed in Pond 0 at Port Hedland. These were large sand banks only a few centimetres above water level and surrounded mostly by water (Figure B). Shorebirds are attracted to these types of roosting sites as they offer good visibility for detecting predators while limiting access for terrestrial predators. It is recommended that such sites are maintained and that new ones are created if possible, using the vegetated peninsulas and islands that already exist at the operation.

Figure B: Important roosting sites observed in pond 0, Port Hedland, circled. (Photo: Dampier Salt Ltd.)

8. The Northern Ponds at Lake Macleod have a very low disturbance level due to their remoteness. It is recommended that this important location for migratory shorebirds continues to have a low level of human disturbance. If human activities are proposed for the Northern Ponds, the proposals should be assessed according to the likelihood that these activities could disrupt feeding and other behaviours.

9. At the Northern Ponds of Lake MacLeod, water levels and hydrology should operate in such a way as to allow wind-blown shifts in water to continue and thereby to facilitate the sequential availability of different foraging sites within the lake. Production or postproduction management should ensure the maintenance of such wind-blown shifts.

10. Since all Dampier Salt Ltd. operations are important bird habitats, routine and regular shorebird/macroinvertebrate monitoring programs should be put in place to assess the internal management of the saltworks, and the effects of external drivers like climate change and shorebird habitat changes elsewhere. The present study provides an established methodology and baseline data for future monitoring programs.

Post-operational management recommendations are that:

11. At the Port Hedland and Dampier operations it is recommended that the hydrological system could be maintained much as it is, with several concentration

ponds able to host brine shrimp in shallow waters that are available for feeding shorebirds.

12. In the event that the concentration ponds are not kept, the most important hydrological artefact of the saltworks would be Pond 0 in both operations. Ideally these ponds would be maintained and the intake of seawater managed.

13. The post-operational Pond 0 should host feeding and roosting areas as described above (operational management recommendations point 7).

14. The post-operational Pond 0 should have extensive shallow sand flats of around 3 cm depth where small shorebirds could feed. Other deeper areas between 5 and 10 cm water depth would provide feeding grounds for larger shorebirds.

15. The feeding areas should be located relatively close to the intake points.

16. Water levels could be managed in accordance with shorebird annual energy requirements. After the majority of postbreeding migrants have arrived, water levels should be lowered to extend the availability of feeding grounds. During the non-breeding period, water levels should be maintained as indicated in point 14. During the premigration and migration periods, water levels could be lowered again.

17. A baseline study could be considered to evaluate the length of time that low water levels could be maintained without affecting the capacity of the benthic invertebrate communities to recover from desiccation and high predation. Such a study could also evaluate whether higher water levels can increase benthic invertebrate abundance (and if this can be demonstrated, water levels could be maintained at a greater depth when shorebirds numbers are low, that is during breeding and migration periods).

18. Management prescriptions will need to consider ways in which human disturbance in the post-operational period can be reduced.

19. Since all Dampier Salt Ltd. leases include important bird habitats, a shorebird/macroinvertebrate monitoring program should be considered to determine the effects of the postoperational management of the saltworks. The present study provides an established methodology and baseline data for future monitoring programs.

INTRODUCTION

Background

A major challenge in ecology and conservation research is to improve our understanding of the diversity and function of ecosystems in order to develop proper protection, monitoring and management programs that assure their existence for future generations. Because coastal ecosystems exist in the boundary between the ocean and the land, they include many diverse habitats (e.g. reefs, seagrass beds, salt-marshes, mangroves, supratidal habitats). As a result, coastal ecosystems are heterogeneous and are often characterised by high levels of production (Gattuso et al. 1998, Borges et al. 2006) and a high diversity of ecological processes (Constanza et al. 1993). However, coastal habitats are subjected to high levels of anthropogenic pressure and it has been suggested that coastal ecosystems represent some of the most endangered ecosystems in the world (Duarte 2007). More than one-third of the human population lives on the coast and between 30% and 50% of the world's principal coastal areas have been degraded in the last 3 decades (Duarte 2007). Pressures such as the overharvesting of marine organisms, land reclamation and more recently, nutrient loading and climate change are pervasively changing, degrading or destroying coastal-wetland ecosystems throughout the world (Agardy et al. 2005).

One group of organisms that are fundamental to coastal ecosystems and wetlands are migratory shorebirds. They represent a significant part of the biodiversity of coastal wetlands and play a pivotal role as apex predators (van Gils et al. 2006) in mass and energy flows within wetland food webs (Moreira 1997). Many of these species undertake long-distance migrations that impose extremely high energetic demands (Wikelski et al. 2003, Landys et al. 2005). During these migrations, shorebirds depend on a limited number of specific intertidal habitats as stop-over points, making them extremely vulnerable to the loss or degradation of these sites (Piersma and Baker 2000, Atkinson et al. 2003). The loss or degradation of these critical feeding habitats anywhere along their flyways is capable of precipitating a decline in populations (Galbraith et al. 2002, Thomas et al. 2006). Recent studies on population trends for a number of species of migratory shorebirds have demonstrated sharp declines (Stroud et al. 2006, Wetlands International 2006, Bart et al. 2007). On a worldwide scale, with respect to known population trends, 48% of shorebirds are in decline (IWSG 2003, Wetlands International 2006). Of the 8 main flyways recognised worldwide, Australia is situated in the East Asian-Australasian Flyway (EAAFW). The EAAFW hosts more waterbird and shorebird species listed as endangered or vulnerable by the IUCN, that any other flyway in the world (Kirby 2010). Studies in Australia have reported alarming reductions of migratory shorebird populations, with some species showing declines of 80% in the last 20 years (Wilson et al. 2011). Among them, populations of the Curlew Sandpiper *Calidris ferruginea* (listed as critically endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)) the Great Knot *Calidris tenuirostris* (listed as globally threatened by the International Union for Conservation of Nature (IUCN)), the Red Knot *Calidris canutus*, the Bar-tailed Godwit *Limosa lapponica* and the Eastern Curlew *Numenius madagascariensis* (listed as globally threatened by the IUCN) are decreasing at rates of more that 8% annually (Fuller et al. 2014). The situation for shorebird populations in the EAAFW was described at the 26th International Ornithological Congress (Tokyo 2014) and in the 9th Australasian Shorebird Conference (Darwin 2014) as being critical. Recent studies indicate that the loss and destruction of intertidal areas in the Yellow Sea (Murray et al. 2014) are responsible for these declines (Lok et al. 2014, Fuller et al. 2014). Therefore it is extremely important to find strategies and management actions to alleviate this impact.

Saltworks

Saltworks, also known as salt pans, *salinas* or solar salt operations, are important feeding grounds (Masero 2003, Sánchez, et al. 2006a, Estrella and Masero 2010), roosting sites (Dias 2009, Sripanomyom et al. 2011) and breeding areas (Powell 2001, Demers et al. 2008, Demers et al. 2010) for many species of shorebird. Several saltworks around the world have been recognised as important habitats by being listed, or being included in systems listed, under the Ramsar Convention on Wetlands of International Importance, especially as Waterfowl habitat (Ramsar Convention). Different species of shorebirds use saltworks as wintering and refuelling habitats (e.g. Masero 2003, Estrella and

Masero 2010, Sripanomyom et al. 2011), with some species selecting them as feeding grounds in preference to intertidal mudflats (Masero and Perez-Hurtado 2001, Masero 2003, Diaz 2009).

Shorebirds are able to exploit the low-diversity but high-biomass macroinvertebrate communities that bloom in these systems, using an enormous array of feeding and physiological mechanisms that allow them to take advantage of such extreme habitats and their rich prey (Estrella et al. 2007, Estrella and Masero 2007, Gutiérrez et al. 2011). With the continuing reduction in the extent and quality of coastal habitats, saltworks have the potential to play a significant role in mitigating habitat loss and arresting the decline of shorebirds.

Although numerous studies on the utilisation of saltworks by shorebirds have been made in other regions of the world, especially in the temperate zones (e.g. Spain, Portugal and San Francisco, USA), there is a lack of knowledge regarding the basic ecology of shorebirds at saltworks and salt lakes in tropical and subtropical areas, particularly in Australia and in the EAAFW.

OBJECTIVES

Dampier Salt Ltd. has 3 operations in Western Australia (WA), at Dampier, Port Hedland and Lake MacLeod, with the last of these operations located within a natural salt lake. Each of the 3 operations is listed among the Important Bird and Biodiversity Areas (IBAs) by BirdLife Australia and they are recognised as globally important habitats for the conservation of bird populations, especially shorebirds. To develop conservation and management plans for shorebird populations and their habitats, knowledge of the basic ecology of shorebirds and their interactions with feeding habitats is essential. Therefore the main objective of this study was to investigate shorebird foraging ecology in the saltworks at Dampier and Port Hedland and in Lake MacLeod. The ultimate goal was to provide Dampier Salt Ltd. with enough information to develop a management plan for the biodiversity of these systems, with special emphasis on shorebirds. To that end the following objectives were proposed:

1. Identify the primary biotic factors that influence shorebird use of habitats within the saltworks, with special emphasis on trophic resources. The extremely high energy demands of migratory shorebirds (Wikelski et al. 2003, Landys et al. 2005) must be met by exploiting highly available biomass of prey at feeding grounds. Several studies have found a positive correlation between habitat use and intake rates (energy obtained per unit of feeding time) with prey availability (e.g. Goss-Custard et al. 2006, VanDunsen et al. 2012, Schlacher et al. 2013). Prey availability often shows temporal variations, such as seasonal (Zwarts and Wanink 1993, Sánchez et al. 2006b) and daily trends (McNeil et al. 1995, Esser et al. 2008) which can in turn affect shorebird foraging behaviour.

Output objective 1: Investigate the temporal and spatial variation of prey availability, shorebird prey selection and diet at 3 different locations: 2 anthropogenic (saltworks) and 1 natural nontidal wetland (salt lake). Extend the knowledge of shorebird foraging behaviour in relation to prey availability and inter and intraspecific interactions in both anthropogenic and natural nontidal wetlands.

2. Identify the abiotic conditions that affect shorebird habitat use. There are several abiotic factors that may affect shorebird foraging behaviour and habitat use, including water depth and regime (Ntiamoa-Baidu et al. 1998, Masero 2003, Takekawa et al. 2009), wind (Verkuil et al. 1993, Kuwae 2007) and period of the day (day and night). Shorebirds sometimes modify their behaviour (Mouritsen 1994, Lourenço et al. 2008) and habitat use (Sitters et al. 2001, Gillings et al. 2005) between day and night hours. Night feeding activity of shorebirds has been hypothesised to be related to either a preference or a necessary supplement for their energy needs (McNeil et al. 1992). The first hypothesis states that shorebirds prefer to feed at night because it is more profitable. This hypothesis has been connected with the increased activity and availability of macroinvertebrates (e.g. Mouritsen 1994, Gilling and Sutherland 2007, Kuwae 2007), the avoidance of diurnal predators (Sitters et al. 2001) and/or the avoidance of heat stress. The second hypothesis proposes that when birds are not able to fulfil their energy needs during the day, they feed at night (Lourenço et al. 2008, Santiago-Quesada et al. 2014).

Output objective 2: Assess how factors such as water depth, tide time, period of the day, and wind affect shorebird foraging behaviour. Provide information about which of the above abiotic factors have major effects on shorebird feeding behaviour.

3. Evaluate the quality of the saltworks and salt lake as shorebird feeding habitat. The numbers of shorebirds using a site is not necessarily a reliable way of assessing site quality, since bird numbers depend not only on the conditions at the site, but also the conditions at other feeding sites during both the nonbreeding and breeding seasons (e.g. Goss-Custard et al. 1995, Stillman et al. 2005, Yang et al. 2011). One way to evaluate site quality for migratory shorebirds during the nonbreeding season is through energy budgets (Stillman et al. 2005). This approach involves assessment of the quantity of energy the birds are obtaining from the habitat, and whether that energy would be enough to fuel, for example, the prebreeding migration.

Output objective 3: Evaluate the quality of the 3 locations as nonmigratory and premigratory feeding grounds for long-distance migratory shorebirds. Compare the energy obtained by shorebirds feeding in 2 anthropogenic supratidal saline habitats (Port Hedland and Dampier saltworks) with a natural nontidal saline habitat (Lake MacLeod).

METHODS

Northwestern Australia is the most important region for migratory shorebirds on the continent and one of the few key areas for migratory shorebirds in the EAAFW. The Lake MacLeod, Port Hedland and Dampier operations are strategically situated in the southern section of this region (see Figure 1).

Sampling sites

Sampling sites were located at the Lake MacLeod (Figure 2), Port Hedland (Figure 3) and Dampier operations (Figure 4).

Lake MacLeod (LMC) is a large salt lake (220 000 ha) located between latitude 23°30'S and 24°40'S and longitude 113°30'E and 114°00'E, on the north-west coast of Australia. The northern sections of the lake are fed seawater via a karst system that connects the lake bed to the Indian Ocean and results in 2000 km^2 of the midsection of the lake being permanently inundated (Logan 1987, Davis et al. 2001, Russel 2004). In wet years, significant freshwater discharge can enter the lake via northern and southern rivers, causing the lake to expand considerably and triggering significant environmental changes such as mass mangrove mortality (Ellison 2001, Ellison and Simmonds 2003, George 2009). This geography results in a unique, permanent, inland, saline wetland that encompasses several habitats suitable for shorebirds, ranging from mangroves to large, shallow muddy expanses, to freshwater and brackish wetlands after significant rainfall. Though the water body is largely nontidal, persistent strong winds can move significant volumes of waters across the landscape causing flooding and drying of areas depending on wind direction and velocity. There are commercial (artificial) salt-pan operations at the southern end of the basin of the lake (see Figure 1). However, these are not used by shorebirds (Davis et al. 2001) and were excluded from this study.

The **Port Hedland** Saltworks (PH) are located close to the town of Port Hedland (coordinates 20°25'S 118°94'E) in an area with a tropical climate dominated by dry and wet (monsoon) seasons. Previously this area comprised natural tidal mudflats or dry salt marsh which periodically flooded and was used by shorebirds only during the highest tides and/or following significant rainfall (Bamford and Bamford 1997). Constructed in the mid-1960s the saltworks resulted in the area

Figure 1. Dampier Salt Ltd. operations in Western Australia (red dots).

becoming the 8th most important for shorebirds in Australia, hosting up to 66,800 birds (Bamford and Bamford 1997).

The layout of the concentration ponds consists of nine ponds (P0 to P8, Figure 3A) totalling an area of 7 600 ha, with water being pumped into the system via 2 intake pumps at pond 0 (Figure 3A) where salinity levels approximate that of sea water (Bamford and Bamford 1997, Hassell 2006). Other ponds are maintained at higher salinity levels and together they create a variety of habitats which vary in water depth and salinity (Bamford and Bamford 1997, Hassell 2006).

The **Dampier** Saltworks (DMP) are located near the settlement of Dampier (coordinates -20^{o}70’S and 116^{o}73’E). These saltworks experience the same climatic conditions as the Port Hedland Saltworks and were constructed around the same time.

The salt extraction method is similar to that used at the Port Hedland saltworks with seawater being pumped into Pond 0 (5 200 ha) before being pumped into Pond 1A (989 ha) (Figure 4) which is maintained at a higher salinity level (Hassell 2006). Most shorebirds are recorded in these 2 ponds with the rest of the

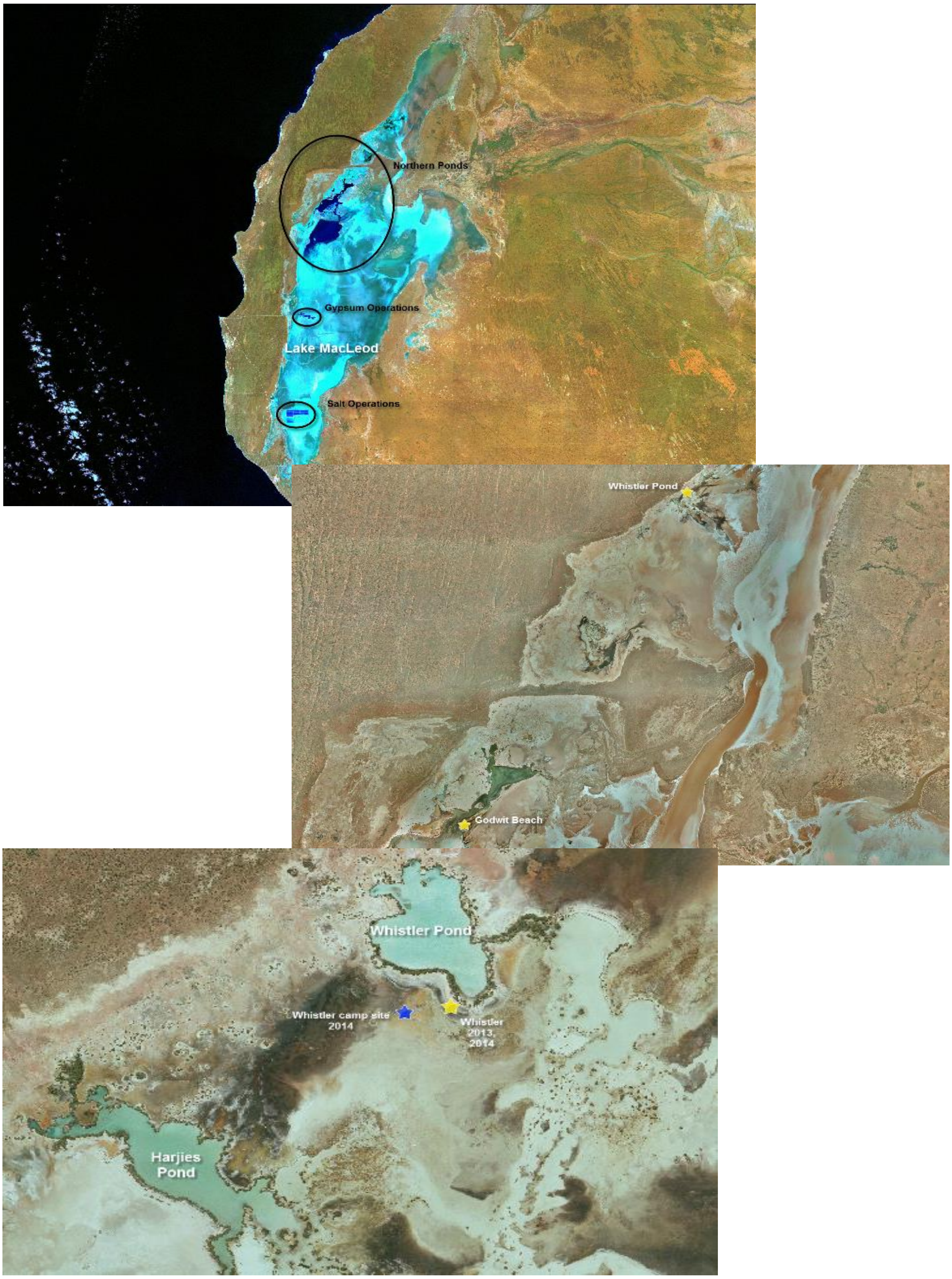


Figure 2. Sampling sites at Lake MacLeod. Yellow stars indicate sites sampled both post and premigration (2013 and 2014), blue stars indicate sites sampled once. (Photos: Dampier Salt Ltd.)

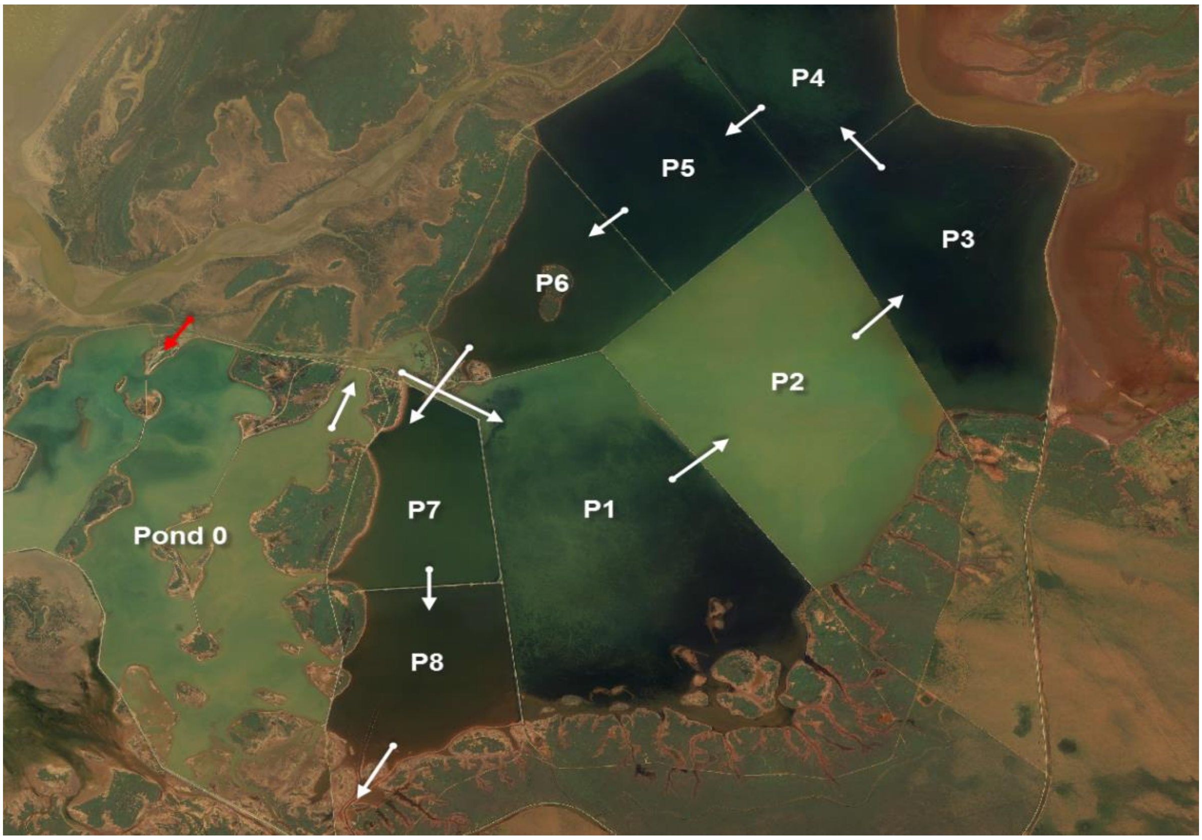


Figure 3. Sampling sites at Port Hedland. Arrows indicate the movement of water. Yellow stars indicate sites sampled both post and premigration (2013 and 2014).(Photos: Dampier Salt Ltd.)

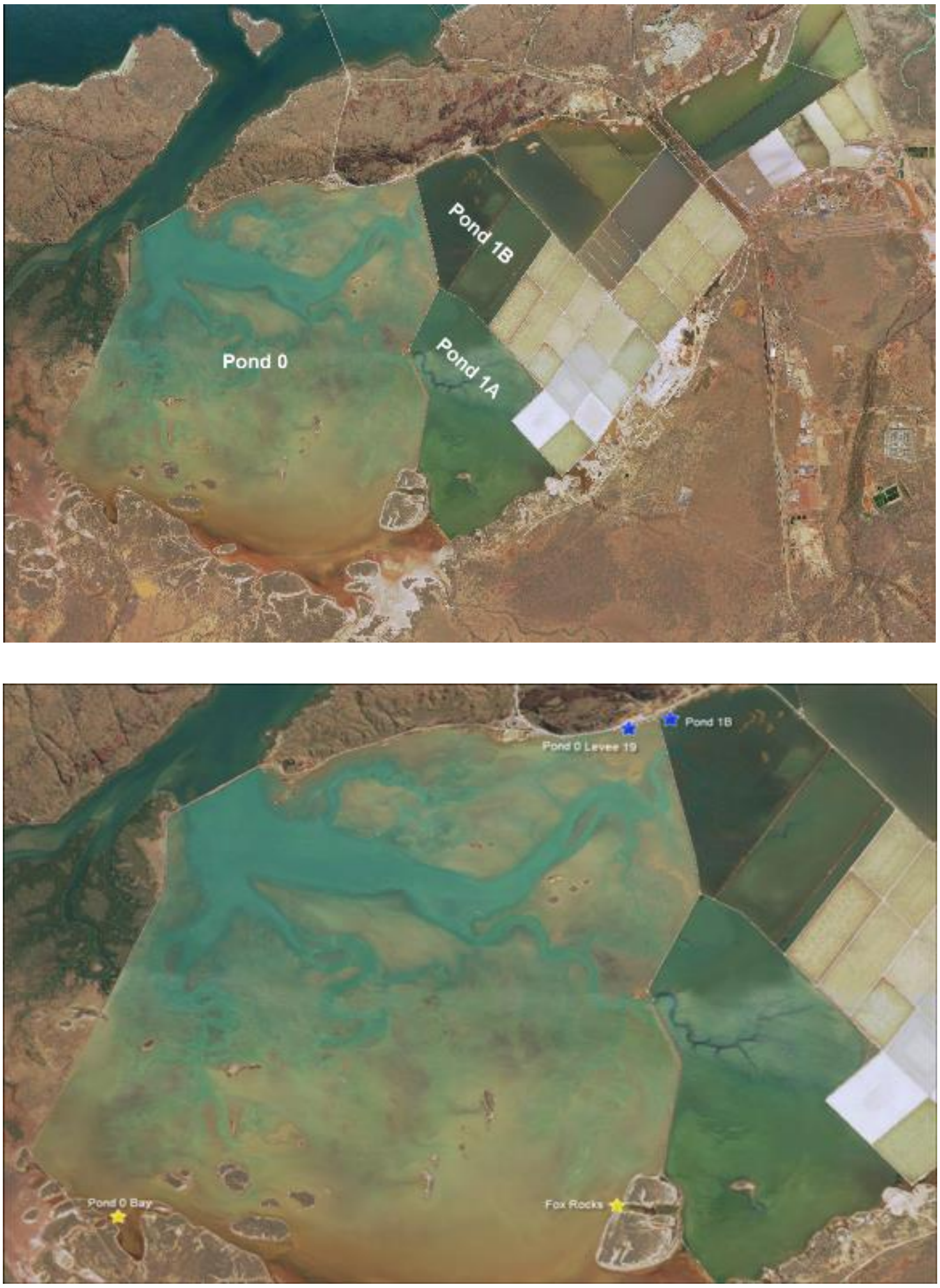


Figure 4: Sampling sites at Dampier. Yellow stars indicate sites sampled both post and premigration (2013 and 2014). Blue stars indicate sites sampled once. (Photos: Dampier Salt Ltd.)

1 400 ha lease possessing little habitat suitable for shorebirds (Hassell 2006).

Recent surveys at the Dampier and Port Hedland saltworks (Hassell 2006) have revealed high numbers of Sharp-tailed Sandpipers (4 204), Red-necked Stints (10 594), Curlew Sandpipers (1611), and Red-capped Plovers (3845).

Data for this study was obtained from at least 2 sites per location (see Figures 2, 3 and 4), with each site sampled during 2 periods, postmigration (October to the end of November) and premigration (February to the end of March). The terms postmigration and premigration are somewhat northern hemisphere centric: postmigration refers to the period after the birds have migrated *from* the northern hemisphere, while premigration refers to the period before the birds migrate *to* the northern hemisphere. Due to logistical constraints, the original objective of sampling 1 site representing a feeding area and 1 site that shorebirds do not use (control), was modified on some occasions (Table 1).

At Lake MacLeod, 1 sampling site was located on the sand flats formed by the spillage of Whistler and Harjies Ponds. For the sake of simplicity this site is called Whistler Pond throughout the report. The second sampling site at Lake MacLeod was located on the sand flats between Lynda's Creek and Godwit Beach; this site is called Godwit Beach or Godwit Beach Flats throughout the report.

Approach to addressing objective 1.

Identify the primary biotic factors that influence shorebird use of habitats within the saltworks, with special emphasis on trophic resources.

Direct observations: Provide information on shorebird foraging behaviour, inter and intraspecific interactions, diet, and prey selection.

A Sony RX 100 camera attached to a Swarovski telescope ATX (25-60 x 85) with a DSB II adaptor was used for video recording (Figure 5). Every individual of each species was observed for at least for 1 minute or video recorded for 30 seconds, a period that has been shown to be sufficient to represent 1 sampling event for small shorebirds feeding on small prey (Estrella et al. 2007). The migratory species were represented by the small species: namely Red-necked Stint *Calidris ruficollis*; Curlew

Sandpiper *Calidris ferruginea*; Sharp-tailed Sandpiper *Calidris acuminate*; Broad-billed Sandpiper *Limicola falcinellus*; and the medium-size species: Bar-tailed Godwit *Limosa lapponica*; Red Knot *Calidris canutus*; and Great Knot *Calidris tenuirsotris*. The Australian resident shorebird species were represented by the small species Red-capped Plover *Charadrius ruficapillus*, the medium-size species Banded Stilt *Cladorhynchus leucocephalus*, and Red-necked Avocet *Recurvirostra novaehollandiae*. There were not always enough individuals of each species to achieve statistically significant sample sizes and not all species were observed at all the operations during both study periods.

Table 1: Sampling sites at the three locations, Lake MacLeod, Port Hedland and Dampier. See Figures 1, 2 and 3.

	Feeding sites	**Control site**
Lake MacLeod	Godwit Beach and Whistler Pond flats	N/A
Port Hedland	Magic Point - Intake 2, Heritage sea side, Heritage operation side, Transfer, Ponds 5 and 6	Magic Point, Heritage sea side
Dampier	Pond 0 Bay, 1A, Fox Rocks	Levee 19 Petrol Station, Fox Rocks

Figure 5: Video recording foraging behaviour at Whistler Pond, Lake MacLeod. (Photo: Rob Davis)

Sp.	Tarsus (mm)	Reference	Average bill length (mm)	Reference	Average weight (g) post migration	Reference	Average weight (g) pre migration	Reference
RNS	20.1	Choi et al. 2009	18.25	Nebel et al. 2013	26.5	Choi et al. 2009	30.2	AWSG unpbl. data
BBS	21.9	Verkuil et al. 2006	31.29	AWSG unpbl. data	36.6	AWSG unpbl. data	49.9	AWSG unpbl. data
STS	29.7	Spencer 2010	25.3	Nebel et al. 2013	65.0	Handel and Gill 2011	80.0	Handel and Gill 2010
CS	31.0	Meisner and Gorecki 2006	38.55	Nebel et al. 2013	51.6	Masero 2003	61.5	Masero 2003
RK	32.6	Choi et al. 2009	32.9	Nebel et al. 2013	-		178.7	Hua et al. 2013
GK	37.7	Choi et al. 2009	44.1	Nebel et al. 2013	-		193.2	Battley et al. 2001
BTG	55.4	Spencer 2010	97.4	Wilson et al. 2007	255.7	AWSG unpbl. data	293.1	AWSG unpbl. data
RCP	26.5	Marchant et al. 2010	15.05	Nebel et al. 2013	40.5	Wiersma and Boesman 2013	40.5	Wiersma and Boesman 2013
RNAv	87.3	Pierce and Boesman 2013	91.25	Nebel et al. 2013	325.9	Dunning 2007	-	
BS	83.5	Pierce and Kirwan 2014	68.6	Nebel et al. 2013	240.0	Pierce and Kirwan 2014	240.0	Pierce and Kirwan 2014

Table 2: Morphometric data (tarsus length (mm), bill length (mm) and weight (g)) of the shorebird species studied. Migratory shorebird species: Red-necked Stint (RNS); Broad-billed Sandpiper (BBS); Sharp-tailed Sandpiper (STS); Curlew Sandpiper (CS); Red Knot (RK); Great Knot (GK); and Bar-tailed Godwit (BTG). Resident shorebird species: Red-capped Plover (RCP); Red-necked Avocet (RNAv) and Banded Stilt (BS).

An average of 36 (range 16 - 65) observations was recorded postmigration and 38 (range 23 - 82) premigration. These observations were collected from different individuals of each species and at each site. Direct observations and video recordings were made prior to the collection of other samples (droppings, core sampling, salinity etc). The following information was obtained from the video recordings and direct observations:

Feeding mode: The feeding mode was defined as either *visual*, when the birds located their prey visually or though visual cues, or *tactile* when birds located the prey by inserting their bills in the substratum and were not using visual cues.

Prey-capture strategy: Shorebirds employed 2 distinct capture strategies. *Pecking*, involved prey being captured from the water column or sediment surface as opposed to *probing,* where prey were captured by inserting the bill into the sediment, beyond the bill tip.

Number of prey capture attempts: The total number of attempts (successful and unsuccessful) that the focal individual made to capture prey. This data was transformed to attempts per minute.

Feeding rates: The number of individual prey captured. This data was transformed to the number of prey captured per minute.

Type of prey and prey size in relation to the bird's bill length: Average species bill sizes were obtained from a literature review (see Table 2). Prey types were identified visually as polychaetes, amphipods or bivalves.

Prey availability: This includes macroinvertebrates which are accessible, detectable, ingestible and digestible (Zwarts and Wanink, 1993). Temporal and spatial variation of prey availability was recorded during both periods, post and premigration, at each of the 3 locations, and at 2 or more sites per location. For benthic invertebrates, 6 or 12 cores, 10 cm in diameter were collected at each site. Samples were sieved on site with a 0.5 mm sieve size (Figure 7A).

A

B

C

Figure 6: A) Benthic samples sieved (Godwit Beach, Lake MacLeod); B) samples preserved in 70% ethanol (Whistler Pond, Lake MacLeod); C) nekton samples collected (Pond 6, Port Hedland). (Photo A: Rob Davis; Photos B & C: Sora M. Estrella)

For prey suspended in the water column, 2 to 3 replicates of 5 litre samples were collected and filtered through a 250 µm-meshed plankton net (Figure 7C). The samples were then labelled and preserved in 70% ethanol and returned to the laboratory for processing (Figure 7B). Rose Bengal was added to the samples to improve sorting efficiency. All samples were processed using a stereomicroscope (Leica 10 x 22). Every individual organism was removed, identified at least to family level, and the abundance of each family was recorded. The size of the most common and intact macroinvertebrates was also measured.

Prey availability: This was recorded from the core sediment samples and calculated as the number of individuals found per square metre.

Daily temporal variation of macroinvertebrate vertical distribution: This experiment was designed to test if there was a change in prey availability during a 24 hour period. Six cores of 6 cm diameter were collected every 6 hours (a total of 24 cores) to a maximum depth of 15 cm, except at Godwit Beach in 2013 when six cores of 10 cm diameter were collected. Samples were collected at Godwit Beach in 2013 and Whistler Pond in 2014, both sites at Lake MacLeod, and in Pond 0 Bay in 2014 at Dampier. The samples from Dampier in 2013 were not considered for analysis because a substantial change in habitat conditions occurred during the sampling. For the purpose of analysis the first 5 cm of sediment depth was considered as shallow sediment and below that as deep sediment.

Prey biomass (Ash Free Dry Mass – AFDM): AFDM is a measure of the organic content of an organism.

Fresh individuals of shorebirds' main prey (polychaetes, bivalves and chironomids) were collected from feeding locations and stored in labelled bags and frozen for subsequent analysis. In the laboratory each individual was measured using a graticule in the stereo microscope (Figure 8), dried for 24 hours at 60°C and weighed to the nearest 0.0001 g on a digital analytical balance to determine dry mass (DM). The dried sample was then combusted at 500 °C for 2 hours in a muffle furnace. AFDM was determined as the difference between the DM and the weight of the remaining ash. Allometric equations that correlate macroinvertebrate size and biomass were applied (see Table 3). In the case of the amphipods, we were not able to carry out the analysis and equations from the literature were used.

For chironomids it was not possible to develop an allometric equation because there were only a few class sizes, therefore average biomass was calculated per chironomid (0.000087 mg AFDM).

Dropping analysis (this offered information about diet and prey size selection): Eighty-eight fresh droppings were collected during the study. They were collected at each of the 3 operations and belong to 3 species of shorebirds: Red-necked Avocet; Red-necked Stint; and Broad-billed Sandpiper. Droppings were frozen and analysed in the laboratory. Droppings were disaggregated in filtered water and analysed using a dissecting microscope fitted with a graticule. Hard parts of prey (chironomid heads and polychaete jaws) were identified and measured. Correlations between prey size and prey hard-part size were calculated (see Table 4).

Figure 7: Length measurement of brine shrimp *Artemia sp.*

Table 3: Allometric equations used to convert the length (mm) of specific benthic macroinvertebrates into biomass (g AFDM).

	Equation	Source
Brine shrimp (*Artemia sp.*) pre-migartion	AFDM (g) = 0.00005 · length (mm) - 0.00009 (R^2 = 0.94, p = 0.000, n = 339)	This study
Brine shrimp (*Artemia sp.*) post-migartion	AFDM (g) = 0.00003 · $e^{0.2325 \cdot \text{length (mm)}}$ (R^2 = 0.77, p = 0.000, n = 212)	This study
Polychaete (Nereididae)	AFDM (g) = 0.00002 · length (mm) - 0.0001 (R^2 = 0.62, p = 0.000, n = 35)	This study
Bivalve (Lanternulidae)	AFDM (g) = 0.0000004 · length (mm)$^{3.593}$ (R^2 = 0.86, p = 0.000, n = 35)	This study
Amphipod (Corophiidae)	Ln AFDM (g) = -5.244 + 2.800 · Ln (length (mm))	Zwarts and Wanick 1993
Amphipod (Paracalliopidae)	AFDM (g) = 0.0000053 · length (mm)$^{2.5190}$*	Drake and Arias 1995

*The Drake and Arias (1995) allometric equation for the amphipod *Microdeutopus gryllotalpa* was used to calculate the biomass of the Paracallioopidae amphipods found at Godwit Beach, Lake MacLeod, postmigration as they are similar in size and shape.

Table 4: Equations used to convert the length (mm) of hard remains to the size of prey items.

	Equation	Source
Polychaete (Nereididae)	TL (mm) = 72.487 · teeth length (mm) -2.3352 (R^2 = 0.74, n = 40)	This study
Chrironomid	TL (mm) = 27.523 · max head width (mm)$^{1.904}$ (R^2 = 0.78, n = 23)	This study

Figure 8: Indicator of water depth used for statistical analyses. (Photo: Rob Davis)

Approach to address objective 2.

Identify the abiotic conditions that affect shorebird habitat use.

Tide: Time from/to low tide is a factor that may affect some shorebird use of the saltworks, as some birds will move to the intertidal mudflats to forage (e.g. Masero 2003, Diaz 2009). Time from/to low tide was obtained from the Australian Bureau of Meteorology (BOM) web page from the Carnarvon, Karratha and Port Hedland tide charts (http://www.bom.gov.au/australia/tides/).

Water depth: Water depth may limit access to the ponds or to prey (Ntiamoa-Baidu et al. 1998, Davis and Smith 2001, Takekawa et al. 2009). Water depth was inferred from the exposed tarsus of birds' legs (see Ntiamoa-Baidu et al. 1998) and recorded from the video footage (Figure 8).

Salinity: Salinity is an important factor in determining macroinvertebrate community structure in saltworks (Sánchez et al. 2006b). Water physico-chemistry data (pH, temperature and conductivity) were measured with a water-quality meter (Orion Star Series Meter TM, Figure 9).

Wind: Wind can have a significant effect on invertebrate distribution (Sánchez et al. 2006b) and therefore on prey availability for shorebirds (Verkuil et al. 2003). Wind direction and velocity was recorded (km/m) using a hand held anemometer (AM-14826- Handheld Anemometer TM). When field measurements were not made, wind data was obtained from the Australian Bureau of Meteorology (BOM) from the stations 004032 (Port Hedland airport), 004083 (Karratha airport) and 006011 (Carnarvon airport) (http://www.bom.gov.au/australia/).

Period of the day (day and night): The main objective of the night observations was to assess whether shorebirds feed at night at the 2 locations (Lake MacLeod and Dampier) and whether they modified their feeding behaviour between night and day. All locations are supratidal or nontidal habitats; therefore the birds can feed 24 hours and are not dependent on the tides. Night sampling sites were at Pond 0 Bay at Dampier, sampled both post and premigration, and at Lake MacLeod, where Godwit Beach was sampled postmigration and Whistler Pond premigration. Night sampling sites were accessed during daylight. Bird observations were undertaken with a night-vision monocular device

Figure 9: Water chemistry data collection at Port Hedland. Water quality meter Orion Star Series Meter TM. (Photo: Luca Chiaroni)

Figure 10: Night observations Pond 0 Bay, Dampier, 2013 (Photo: Amy R Griffiths).

(Voyager Night Vision Monocular 4.5 x, Gen 2+, ATN corp.) (Figure 10) and data were collected every 2 hours. All the night-work observations were carried out by the same researcher (SME).

Although observations of shorebirds foraging at night were obtained as described above, close-range videos of shorebirds feeding (Red-capped Plovers and Red-necked Stints) were only made at Whistler Pond premigration. From these videos and the daylight records, we analysed the following variables:

Steps per minute: This is a measurement of foraging speed and the area surveyed and therefore it can be empirically related with feeding effort (Beauchamp 2013).

Number of prey capture attempts: Number of attempts (successful and unsuccessful) that the focal individual made to capture prey. This data was transformed to attempts per minute.

Approach to address objective 3.

Evaluate the quality of the saltworks and salt lake as shorebird feeding habitat: The quality of different feeding habitats for shorebirds can be measured be comparing the energy consumption in each habitat with the total daily energy requirement via prey selection studies (point 1 of this proposal) and intake rates (e.g. Stillman et al. 2005).

Intake rates (biomass or energy ingested per unit of feeding time): Individuals from the study species that were feeding actively were selected and recorded for between 30 seconds and 1 minute during daylight. We recorded the number of successful prey captures (feeding rates) and type and size of prey caught during this time. Biomass intake rates were calculated by multiplying the number of each prey-size class taken per unit time by the biomass (AFDM) of that species size class observed, and their proportion in the diet. The biomass intake rates were converted to energy intake rates using energy values for common invertebrate species from Brey et al. (1988) and for seagrass from Dos Santos et al. (2012).

Balance between energy acquisition and expenditure: Comparing energy acquisition and expenditure will provide information to evaluate whether shorebirds are meeting their energy requirements at the saltworks and the lake, and will provide an indicator of the quality of the feeding grounds. Energy acquisition (EA) per species/per hour/per site/per period was compared with the daily theoretical energy expenditure (DEE) per period. Nagy's (1987) equation was used to calculate the DEE of each shorebird species as a function of their body mass in each period, post and premigration (see Table 2). Then it was calculated how much time a bird needed to forage in the saltworks or in the lake to accomplish their DEE in each period. Whenever the calculated time was ≥ 24 hours it was considered that the birds were not able to meet their DEE exclusively at the saltworks and were therefore using them as complementary feeding grounds to the adjacent intertidal areas. When the time needed to accomplish the DEE was < 24 hours it was considered that the saltworks could be used as alternative feeding ground for the species.

To calculate how much energy a bird obtained per hour (EA) the following equation was applied:

$$EA\ (kJ\ bird^{-1}\ hour^{-1}) = \sum AE \cdot IR \cdot Q \cdot P \cdot 60$$

where AE was the assimilation efficiency of the food, IR is the mean intake rate (biomass min^{-1}), Q was the mean energy content (kJ) of each prey item taken and P was the proportion of each prey in the diet.

Assimilation efficiencies recorded in the literature for shorebirds are 87.4 % for brine shrimp (Caudell and Conover 2006), for polychaetes 80 % (Castro et al. 2008), for amphipods 80 % (Zwarts et al. 1990a), for chironomids 85% (Caudell and Conover 2006) and for seagrass 14.14 % (Dixon 2009).

Statistical analyses

Normality and homoscedasticity were tested (Shapiro-Wilk and Levene's test respectively) for each variable prior to statistical analysis to confirm that the data met the assumptions of the relevant tests. If normality of the data was not achieved $\log_{10}(v+1)$ transformations were applied (Sokal and Rohlf 1995). Differences between sampling periods (postmigration and premigration) and between sites on shorebird feeding and intake rates were analysed using a factorial ANOVA test. Changes in benthic invertebrate abundance between day and night and sediment depth were also analysed using a factorial ANOVA test. The effect that shorebird species and day period (day and night) have in Red-capped Plover and Red-necked Stint feeding attempts and steps/min were also analysed using a factorial ANOVA test. When analyses show significant differences, post-hoc tests (parametric Tukey's test) were used to determine amongst which sampling periods or sites differences existed. General Linear Models were used to test the effect that bird interactions, period, prey density and water depth had in the feeding rate of shorebirds. If the variables did not meet the assumptions of parametric analysis after transformation, non-parametric tests were used.

Statistical significance was set at $P \leq 0.05$. All univariate statistical tests were conducted using Statistica 7.0 (StatSoft 2004).

RESULTS

Prey availability

Prey abundance

Prey abundance varied between study sites. There was a significant effect of site and of the interaction factor site x period on macroinvertebrate density (site: F = 15.60, df = 2, p = 0.0001; site x period: F = 12.81, df = 5, p = 0.0001), but the period (post or premigration) alone did not influence macroinvertebrate density (F = 1.77, df = 1, p = 0.19). Of the sites sampled in both periods, Whistler Pond at Lake MacLeod was the site that typically presented a significant major abundance of macroinvertebrates compared with any of the other sites, especially premigration (Figure 11).

Whistler Pond had the highest densities of the preferred shorebird prey items: polychaetes and amphipods (Figure 12). Godwit Beach, Lake MacLeod, and Levee 19, Dampier, were also characterised by high densities of polychaetes and amphipods postmigration. Bivalves were abundant at Levee 19 and Whistler Pond postmigration, although their numbers decreased in Whistler Pond premigration.

Chironomids were abundant only at Dampier, specifically at Fox Rocks, postmigration, with numbers decreasing premigration (Figure 13).

Brine shrimp (*Artemia spp*.) were present at Port Hedland and Dampier during both periods. Of the 3 sites sampled, the ponds that had the highest densities were Ponds 5 and 6 at Port Hedland. The density of brine shrimp was lower in the Transfer in both periods (Figure 14).

Of the sites sampled only once at each operation, macroinvertebrate density was similar across the 3 sites at Dampier: Pond 0 Bay; Fox Rocks and Levee 19 (F = 1.73, df = 2, p = 0.21, Figure 11), postmigration. However, at Lake MacLeod premigration, Godwit Beach was characterised by a significantly lower macroinvertebrate abundance than the 2 sites at Whistler Pond (F = 13.03, df = 2, p = 0.0002, Figure 11). At Port Hedland premigration, the ocean side of Heritage (Heritage original) held a statistically significant

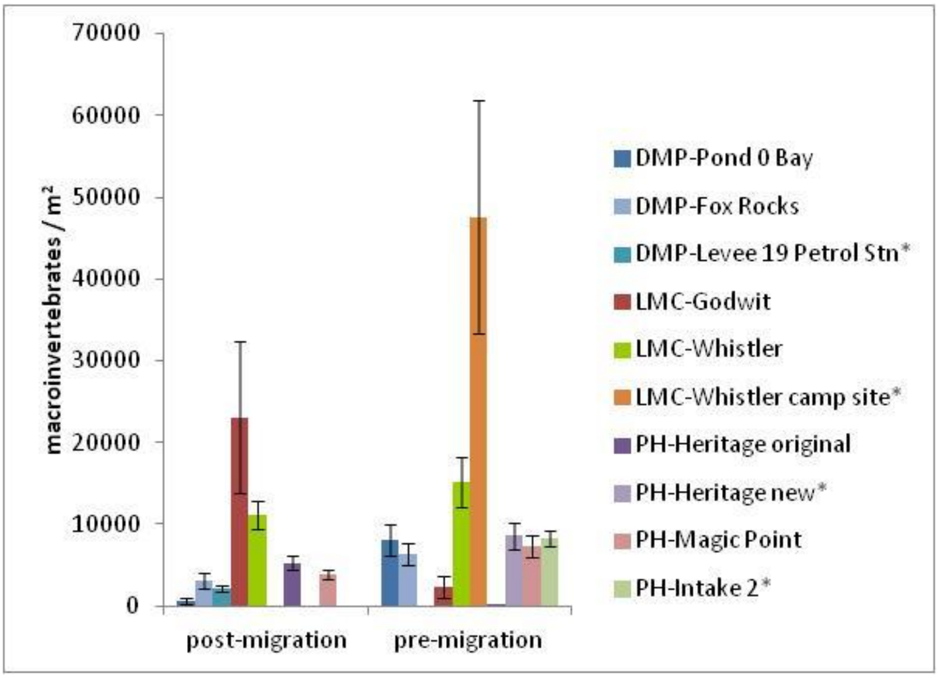
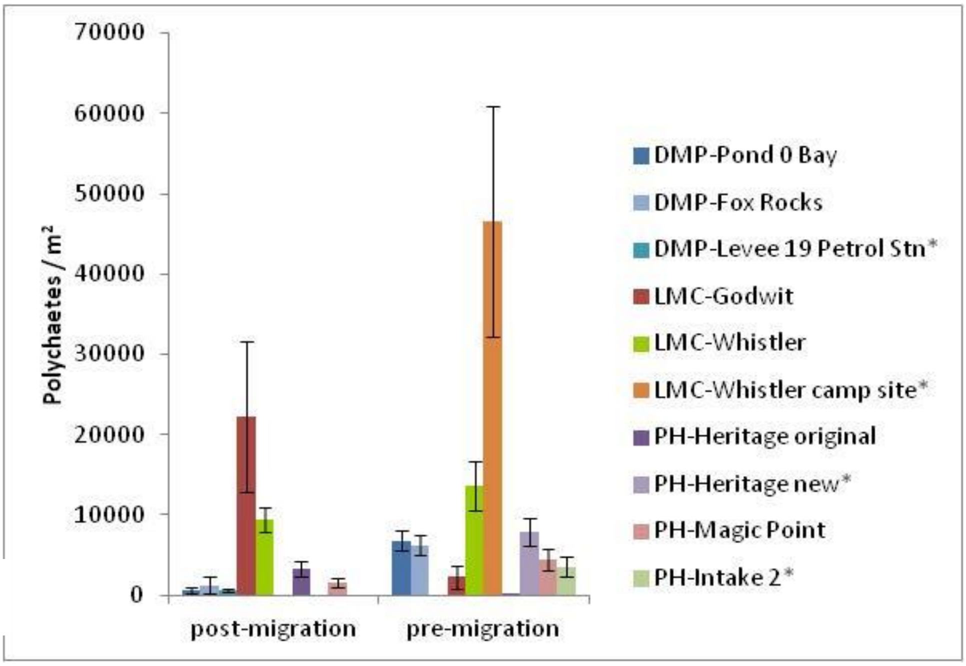


Figure 11: Benthic macroinvertebrate density (mean ± SE) post and premigration at different sites at Lake MacLeod (LMC); Port Hedland (PH); and Dampier (DMP).



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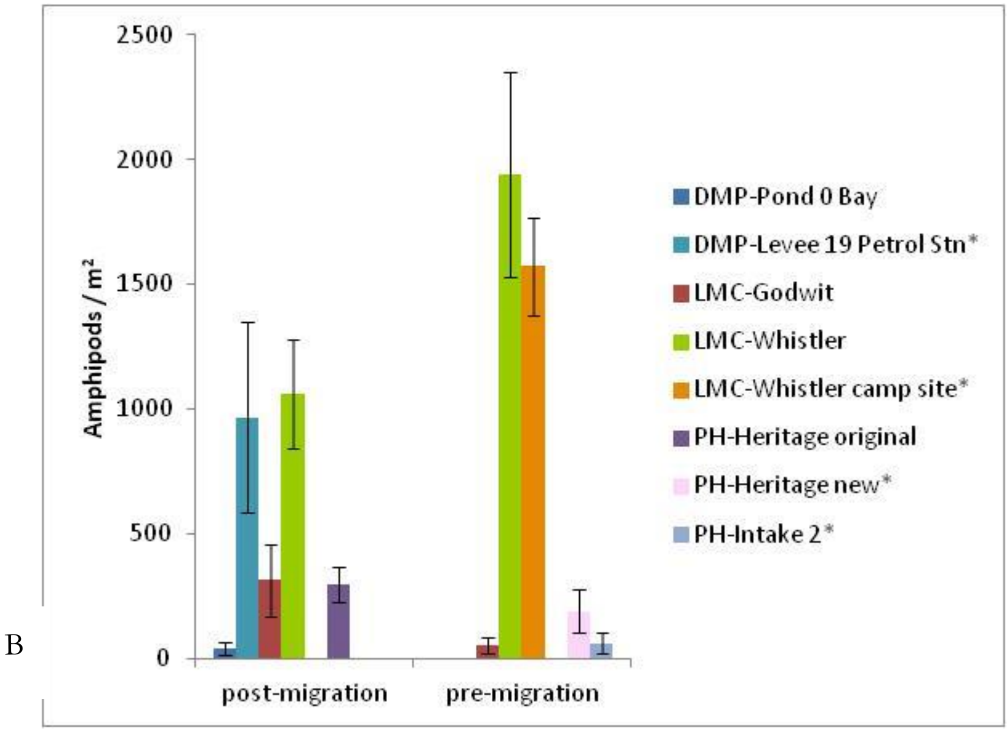


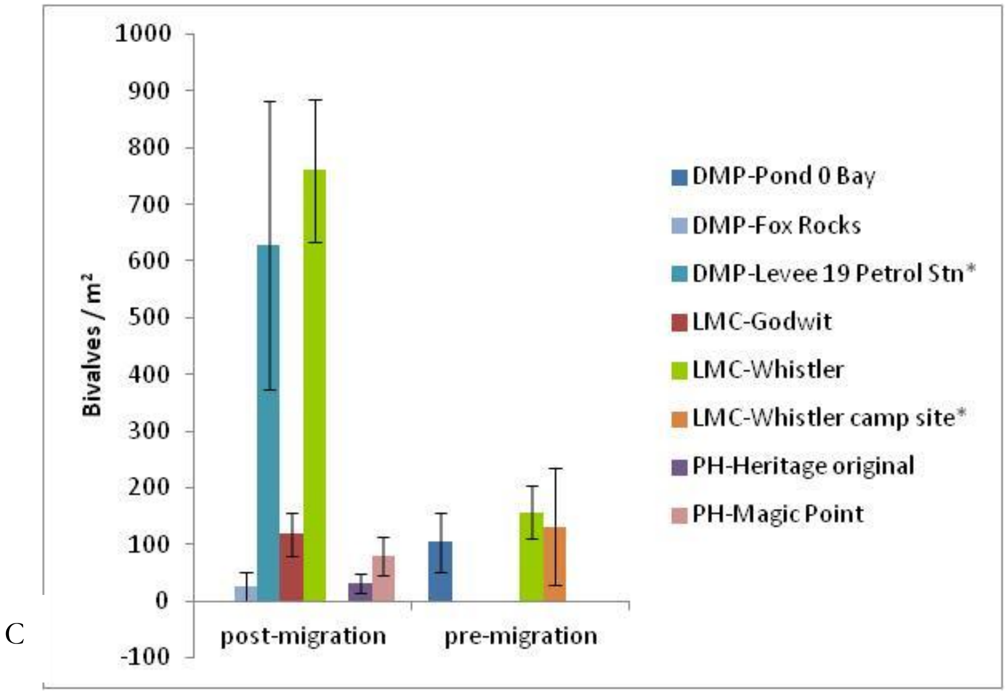


Figure 12: A) polychaete, B) amphipod and C) bivalve densities (mean ± SE) post and premigration at different sites at Lake MacLeod (LMC); Port Hedland (PH); and Dampier (DMP). *Sites only sampled once.

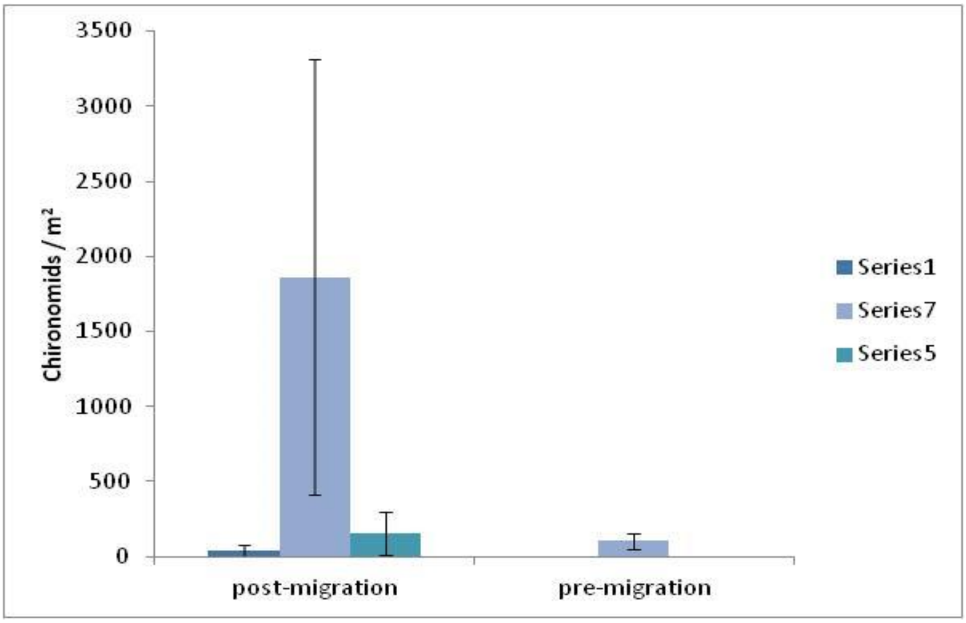


Figure 13: Chironomid densities (mean ± SE) post and premigration at different sites at Dampier. *Site only sampled postmigration.

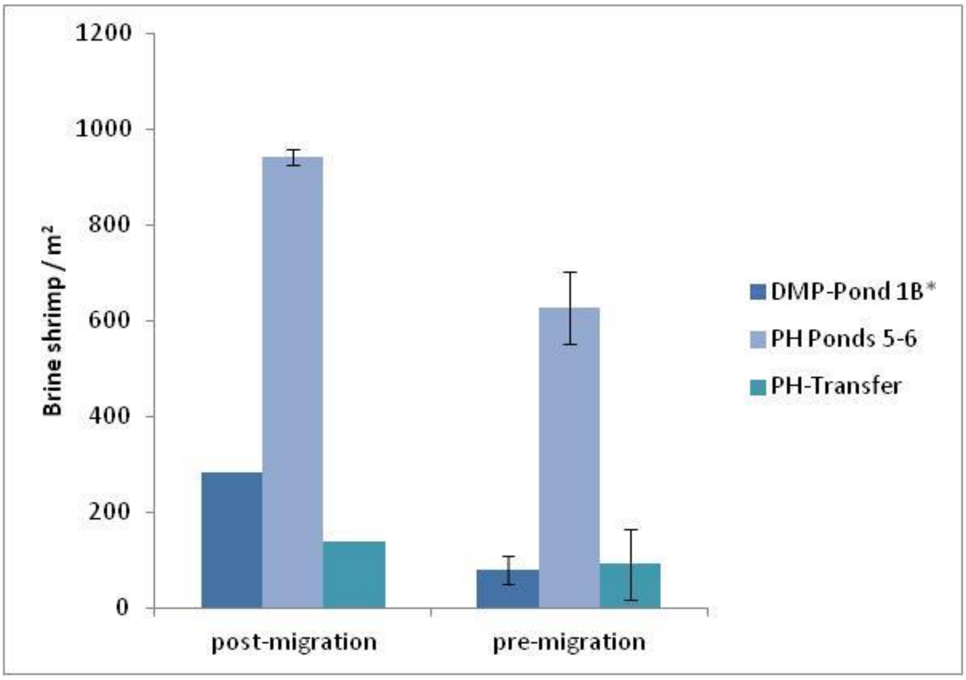


Figure 14: Brine shrimp densities (mean ± SE) post and premigration at different sites at Port Hedland and Dampier. *Postmigration data from Actis Environmental Services Technical Report, October 2013.

lower macroinvertebrate abundance than any of the other sites: Heritage new; Magic Point and Intake 2 (*F* = 6.2, df = 3, *p* = 0.001, Figure 11).

Macroinvertebrate daily vertical distribution

At Lake MacLeod both post and premigration, the density of polychaetes was always significantly higher in the first 5 cm of the sediment (shallow), while the period of the day did not affect their densities at either depth (shallow or deep) (Table 5, Figures 15A and 16A).

Amphipod densities at Godwit Beach postmigration were affected by the period of the day rather than sediment depth (Table 5), with the highest densities found at late afternoon (Figure 15B). Amphipods and bivalves followed a similar pattern to each other at Whistler Pond premigration, with significantly higher densities recorded in the first 5 cm of the sediment (Table 5; Figure 16).

In Pond 0 at Dampier, polychaete densities were significantly affected by the period of the day while the interaction factor period of the day x sediment depth was nearly significant (Table 5). The lowest polychaete densities were found in the early morning in the first 5 cm of the sediment while the highest densities were found at midday, also in the first 5 cm of the sediment (Figure 17).

Shorebird diet

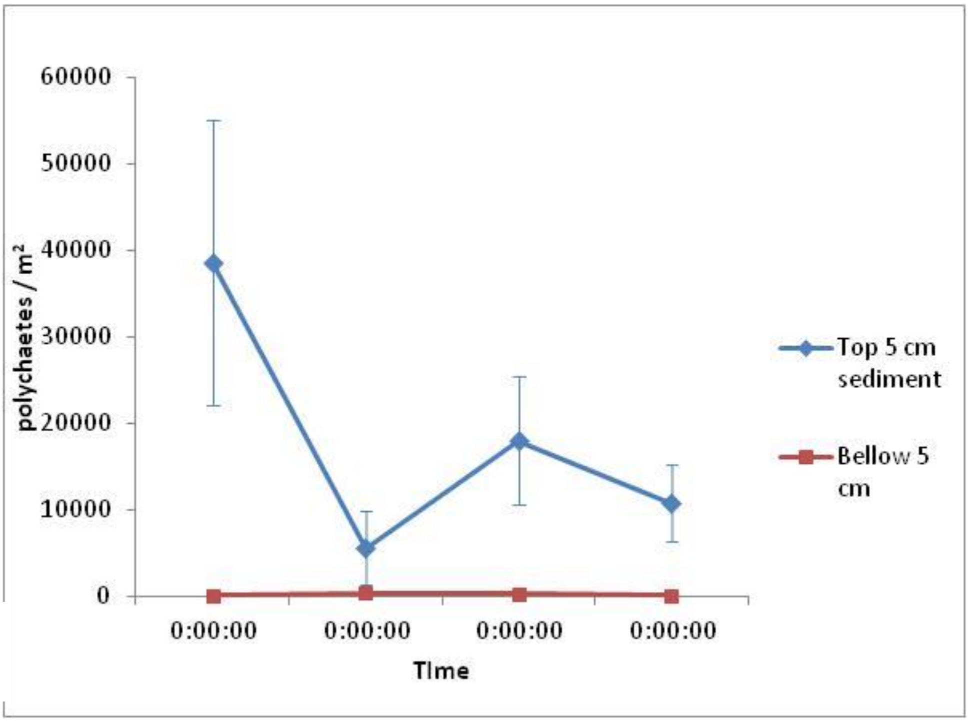
Diet from direct observations

Nearly 400 benthic prey items were identified postmigration, and 1008 premigration from both the videos and direct observations. Amphipods were the main benthic prey for shorebirds at Lake MacLeod both post and premigration (Figure 18), and polychaetes were the main benthic prey for shorebirds feeding in Pond 0 at Port Hedland (Intake 2 and Heritage) and Dampier in both periods (Figure 19). Only 2 shorebird species varied their diet at Lake MacLeod from this premigration pattern. Although amphipods were the most common prey for Red Knots at Whistler Pond, more than 35% of the prey consumed was seagrass, while the main prey for Great Knots at the same site were bivalves (Figure 18). At Godwit Beach the main prey items for Red Knots were polychaetes rather than amphipods (Figure 18).

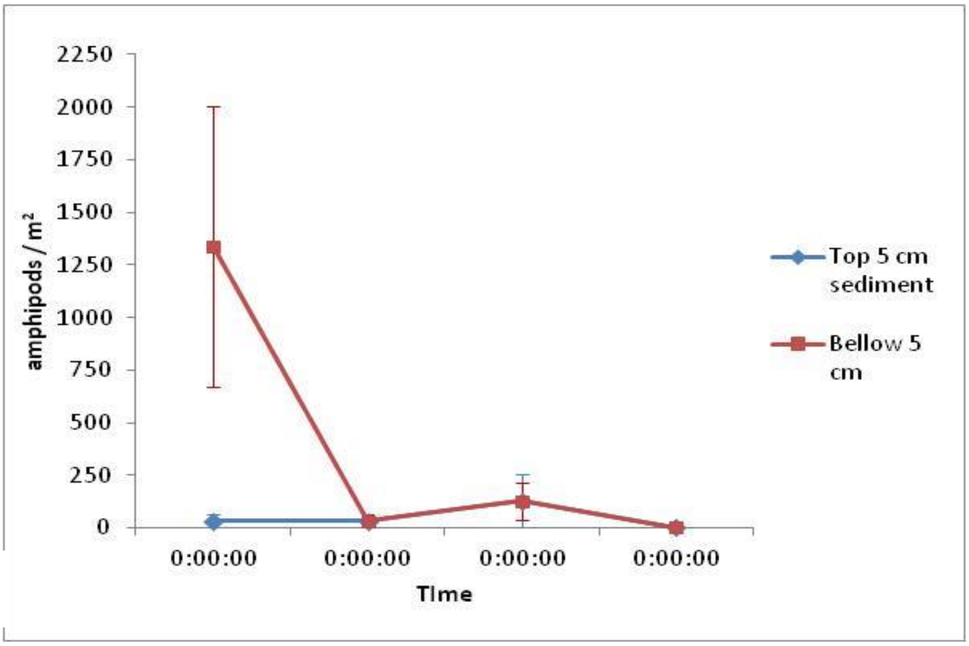
			F	df	*p*
Godwit Beach post-migration	Polychaetes	Day period	0.86	3	0.48
		Sediment depth	44.95	1	***
		Day period x depth	0.83	3	0.49
	Amphipods	Day period	4.13	3	**<0.05**
		Sediment depth	1.65	1	0.21
		Day period x depth	2.31	3	0.10
Whistler Pond pre-migration	Polychaetes	Day period	0.36	3	0.78
		Sediment depth	31.36	1	***
		Day period x depth	0.31	3	0.82
	Amphipods	Day period	0.99	3	0.41
		Sediment depth	10.74	1	*
		Day period x depth	0.41	3	0.75
	Bivalves	Day period	1.09	3	0.37
		Sediment depth	4.58	1	**<0.05**
		Day period x depth	0.69	3	0.57
Pond 0 Dampier pre-migration	Polychaetes	Day period	2.89	3	**<0.05**
		Sediment depth	2.12	1	0.15
		Day period x depth	2.37	3	0.08

Table 5: Factorial ANOVA test results of the period of the day, sediment depth and period of the day x sediment depth effects on major benthic invertebrate taxa densities post and premigration at different sites at Lake MacLeod and Dampier.

* p<0.01 ** p<0.001 *** p<0.0001

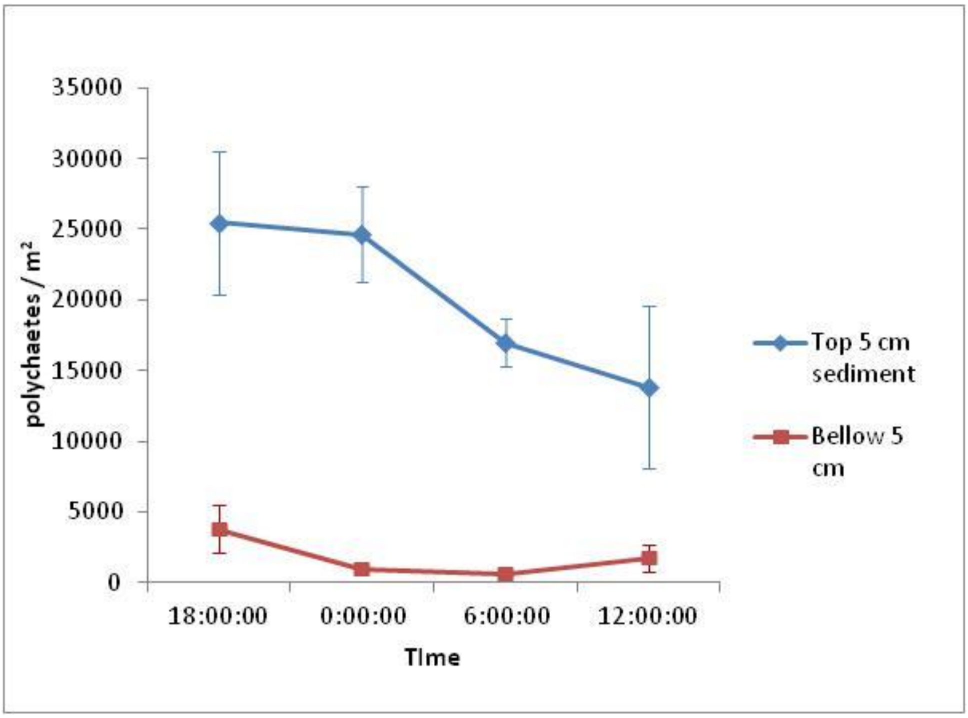


A

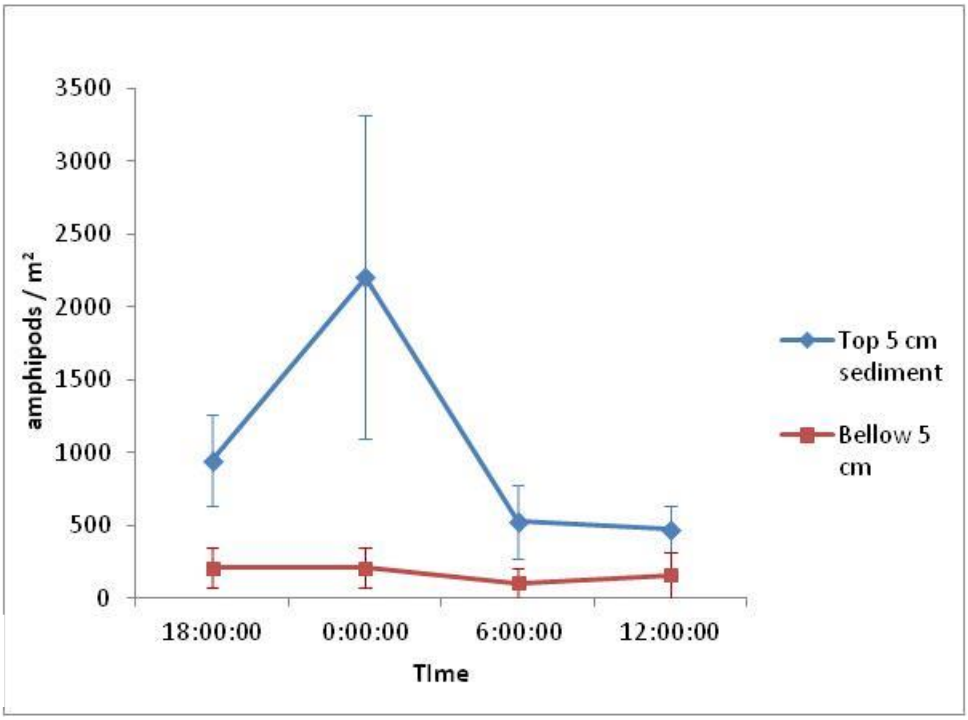


B

Figure 15: Density (mean ± SE) of A) polychaetes and B) amphipods at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Godwit Beach, Lake MacLeod, postmigration.


35000
30000
25000
20000
15000
10000
5000
0
polychaetes / m²
18:00:00
0:00:00
6:00:00
12:00:00
Time
Top 5 cm sediment
Bellow 5 cm

A


3500
3000
2500
2000
1500
1000
500
0
amphipods / m²
18:00:00
0:00:00
6:00:00
12:00:00
Time
Top 5 cm sediment
Bellow 5 cm

B

C

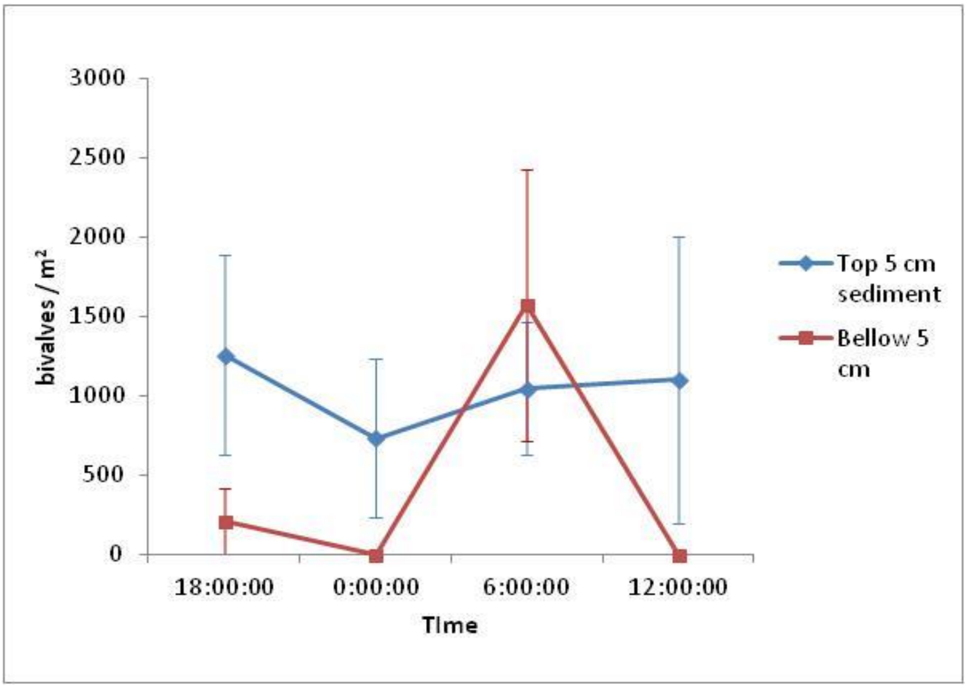


Figure 16: Density (mean ± SE) of A) polychaetes, B) amphipods and C) bivalves at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Whistler Pond, Lake MacLeod, premigration.

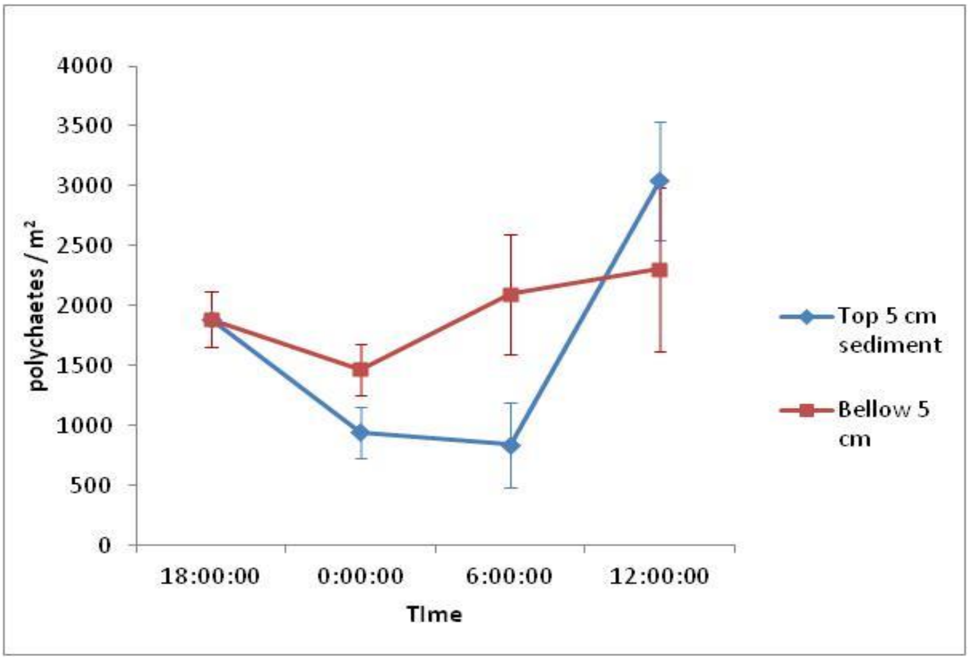
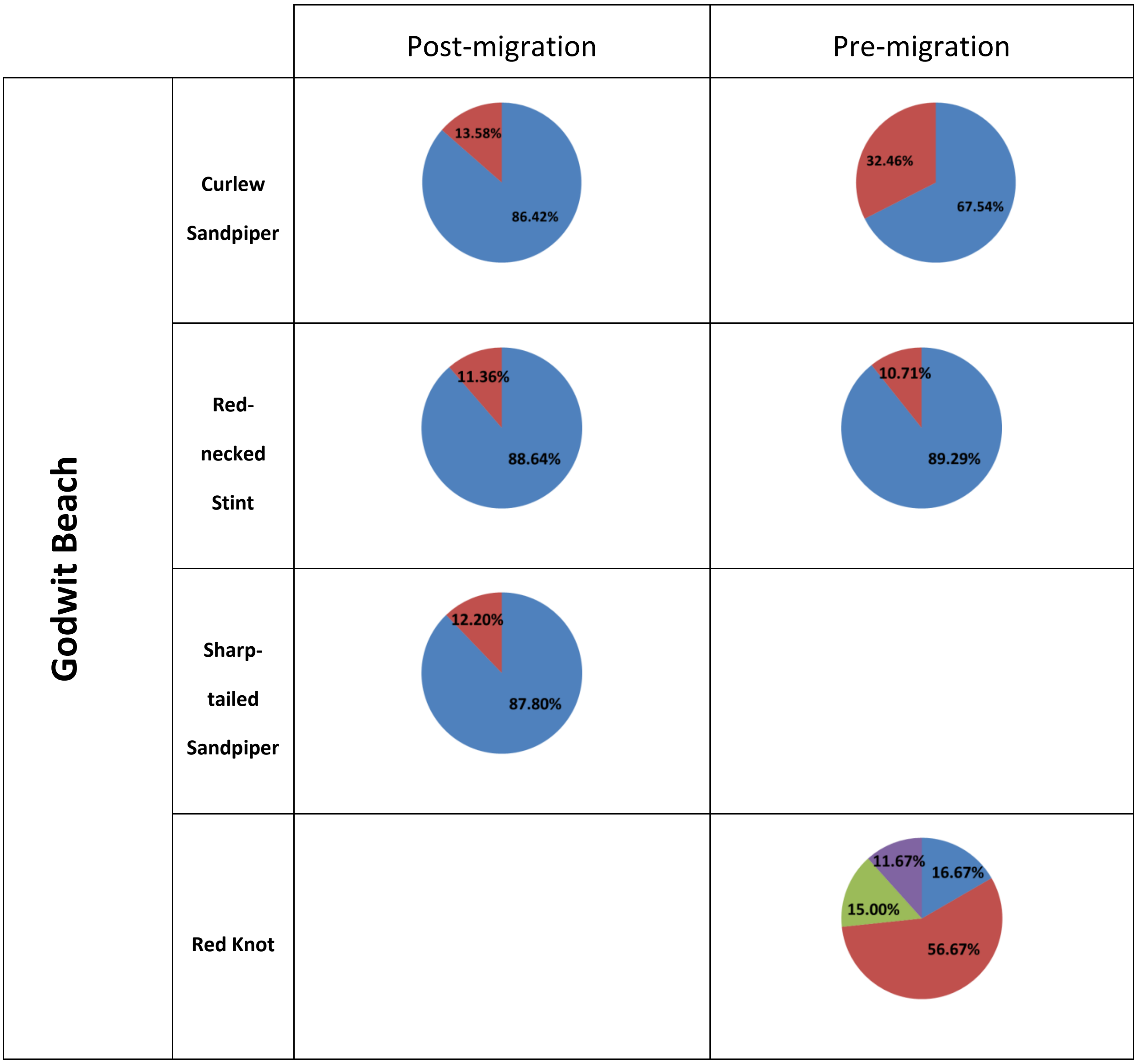
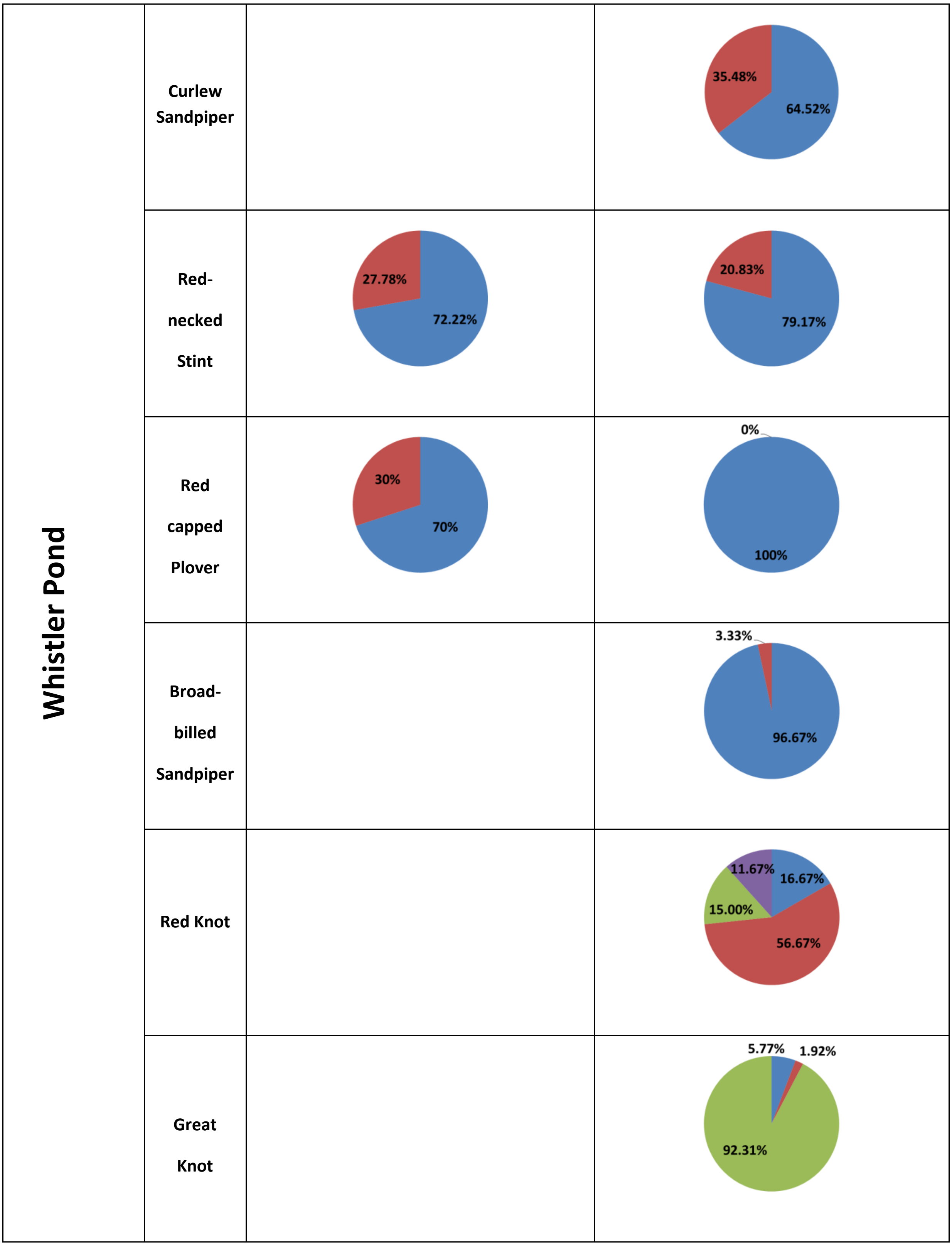


Figure 17: Density (mean ± SE) of polychaetes at 2 different sediment depths, ≤ 5 cm and > 5 cm, collected every six hours at Pond 0, Dampier, premigration.



A

Figure 18A: see over for details.



B

Figure 18: Proportions of prey items in the diet of shorebirds using A) Godwit Beach and B) Whistler Pond, Lake MacLeod as a feeding habitat.

Amphipods Polychaetes Bivalves Seagrass

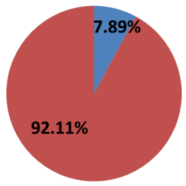
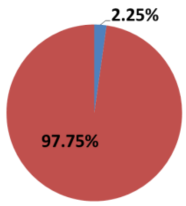
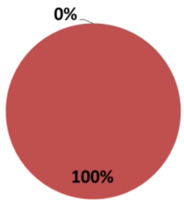
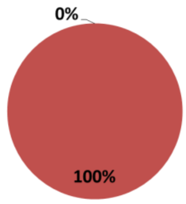
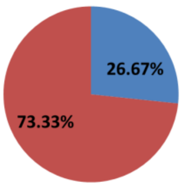
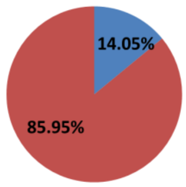
		Post-migration	Pre-migration
Intake 2	Red-necked Stint		
	Broad-billed Sandpiper		
	Bar-tailed Godwit		
Heritage	Broad-billed Sandpiper		

Figure 19: Proportions of benthic prey in the diet of shorebirds using Port Hedland as a feeding habitat post and premigration. **Amphipods** **Polychaetes**

Faecal analysis

Analysis of the faeces of Red-necked Avocets at Dampier postmigration indicated that the main prey of this tactile feeder were chironomids (99.62%), with a much lower proportion of nereid polychaetes (0.38%).

Diet of birds feeding in the water column

At Dampier and particularly at Port Hedland, birds were often observed feeding in the water column of concentration ponds. Samples from the water column (see Prey availability section) indicated that the most abundant invertebrate present were brine shrimp (*Artemia sp.*). Therefore, although it was not possible to identify the prey captured by the birds during field observations, birds feeding in the water column were almost certainly feeding on brine shrimp.

Factors affecting shorebird habitat use

Wind

Wind direction and wind speed appeared to have an important effect on shorebirds' habitat use. The lowest numbers of birds at Godwit Beach both post and premigration, were recorded when wind speed exceeded 30km/h from the S-SW. Higher numbers were recorded at lower wind speeds (< 30 km/h) or with wind directions NW-NE (Table 6).

At Port Hedland, foraging small shorebirds were normally situated on the shores of concentration ponds, opposite the direction from which the wind was blowing (Table 7).

Tide

Postmigration, at high tide (more than 3 hours before and after low tide), around 50 % of the migratory shorebirds at Port Hedland and Dampier were feeding while the other half were roosting (Figure 20).

Of the migratory shorebirds birds observed at Port Hedland and Dampier premigration, the majority of birds were using the saltworks for feeding independently of tide time (Figure 21).

Date	Wind direction	Wind speed (km/h)	No. birds
01-12-13	SSE-SSW	32.5	220
02-12-13	S	41.5	235
05-12-13	NNE-NW	38	**7707**
11-02-14	S	37	3
13-02-14	NW-WNN	19	**1720**
16-02-14	WSW	24	**2089**

Table 6: Number of birds recorded at Godwit Beach, Lake MacLeod, pre and postmigration, and wind conditions: speed (km/h) and direction.

Date	Wind direction	Wind speed (km/h)	Location of birds	No. birds feeding	No. birds roosting
13-12-13	E-NE	30	N corner pond 6 W corner pond 5	177	3
14-12-13	NE	13	N corner pond 6 W corner pond 5	17	288
10-03-14	SSW	11	E corner pond 6	112	0
13-03-14	NNW	9	N corner pond 6	163	3
13-03-14	N	20	S corner pond 4	187	0

Table 7: Number of birds feeding or roosting in different sections of the concentration ponds at Port Hedland, post and premigration, and wind conditions: speed (km/h) and direction

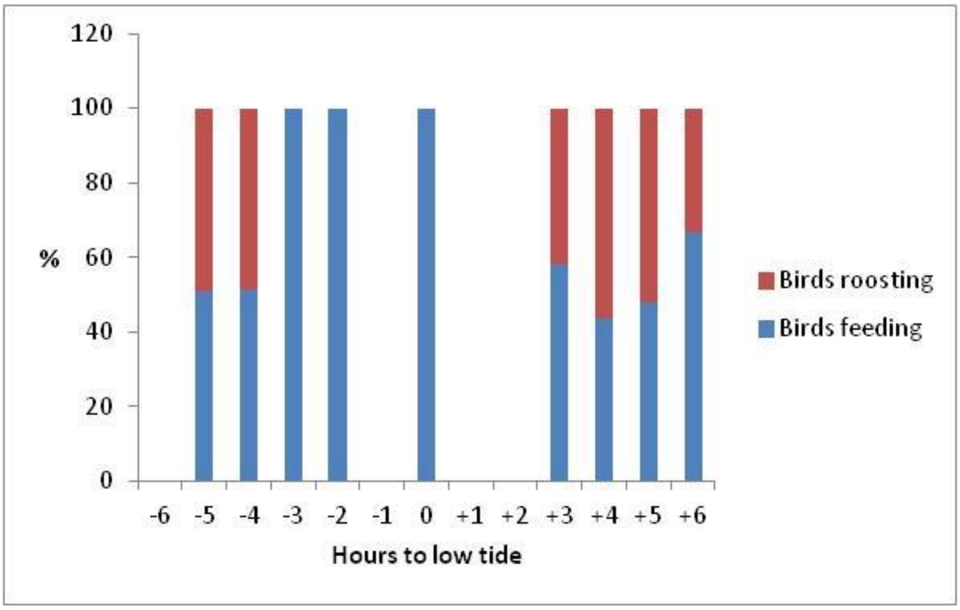


Figure 20: Percentage of migratory shorebirds feeding or roosting at Port Hedland and Dampier (sites combined) postmigration, in relation to time to low tide.

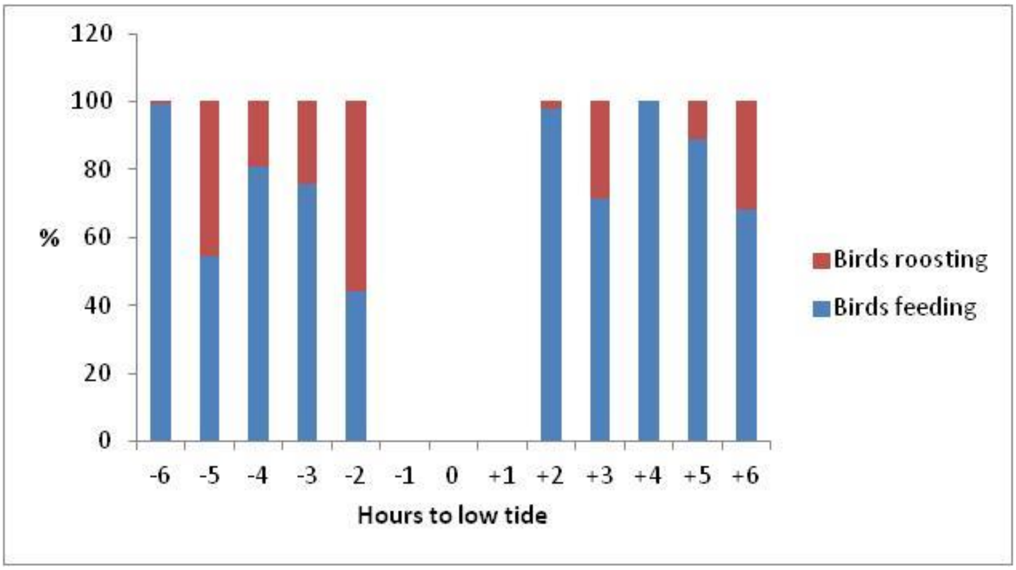


Figure 21: Percentage of migratory shorebirds feeding or roosting at Port Hedland and Dampier (sites combined) premigration, in relation to time to low tide.

Water depth

The small shorebirds (Red-capped Plover, Red-necked Stint and Broad-billed Sandpiper) tended to feed in shallow waters (≤ 2.3 cm) on prey localised in the sediment or in the water column (brine shrimp) (Figure 22).

Red Knots and Curlew Sandpipers fed at varying depths when feeding on prey burrowed in the sediment (both ≤ 3.3 cm and > 3.3 cm), while Sharp-tailed Sandpipers fed mostly deeper than 3.3 cm when feeding on prey burrowed in the sediment or suspended in the water column (Figure 23).

In total, 86.88 % of the Bar-tailed Godwits observed feeding in Pond 0 at both Port Hedland and Dampier, were feeding at a water depth > 5.5 cm. While Banded Stilts fed at different water depths (≤ 8.4 and > 8.4 cm) when feeding on benthic prey or prey suspended in the water column, Red-necked Avocets tended to feed at deeper water levels when feeding on benthic prey (Figure 24). When thousands of Banded Stilts were present at Port Hedland in October-November 2013 they were observed feeding on brine shrimp in concentration ponds 5 and 6. All the species observed feeding in the Transfer in Port Hedland (Red-necked Stints, Curlew Sandpipers, Sharp-tailed Sandpipers and Banded Stilts) were feeding at deep water levels.

Biotic factors affecting shorebirds' feeding and intake rates

Site and period

The feeding rates, biomass and energy intake rates of most of the shorebird species studied were affected by the feeding site and period (Table 8). In the case of the Red-necked Stints, Curlew Sandpipers and Banded Stilts, the interaction factor, site x period, also significantly affected the feeding and intake rates (Table 8).

Red-necked Stint

The feeding and intake rates of Red-necked Stints were significantly affected by site, period and the interaction factor site x period (Table 8). The feeding rates of the Stints at both sites at Lake MacLeod - Godwit Beach and Whistler Pond - decreased from postmigration to premigration (Figure 25A), while feeding rates in Pond 5 at Port Hedland were similar in both periods (Figure 25A). However, intake rates at

Figure 22: Proportion of small shorebirds feeding at different depths in relation to prey location in the sediment and water column, at all sites, post and premigration. Red-necked Stint (RNS); Broad-billed Sandpiper (BBS); Red-capped Plover (RCP).

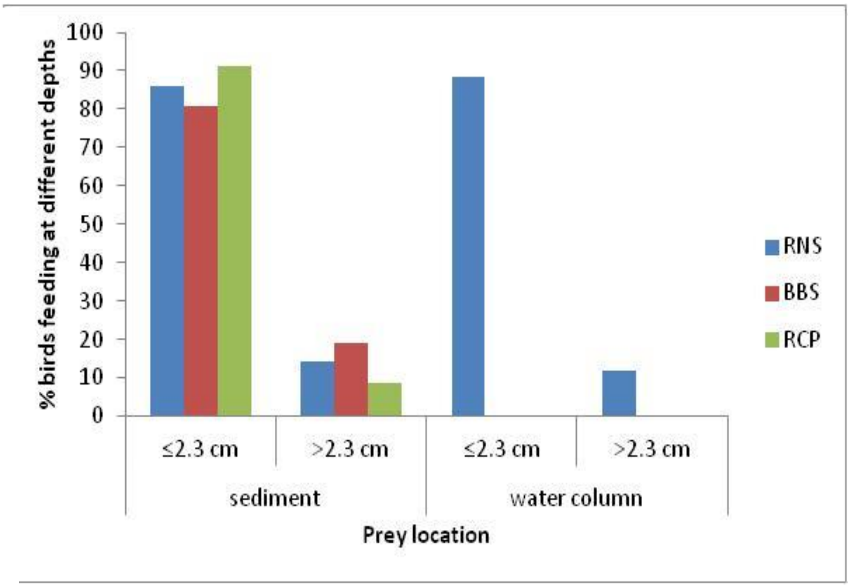


Figure 23: Proportion of small to medium-size shorebirds feeding at different depths in relation to prey location in the sediment and water column, at all sites, post and premigration. Sharp-tailed Sandpiper (STS); Curlew Sandpiper (CS); Red Knot (RK)

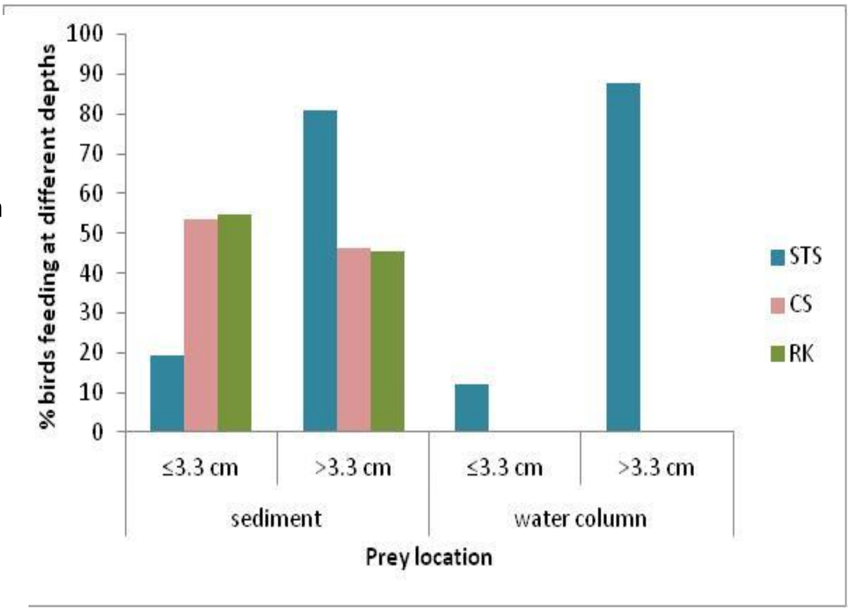
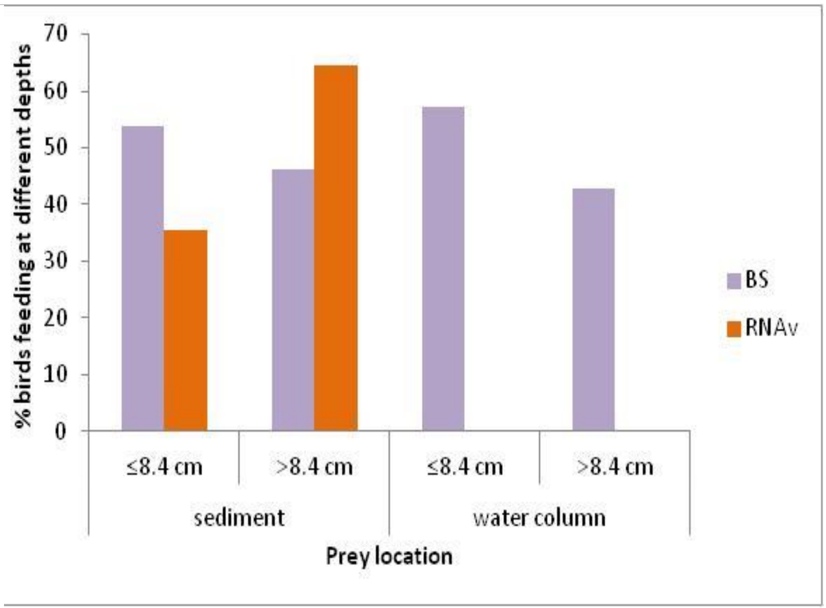
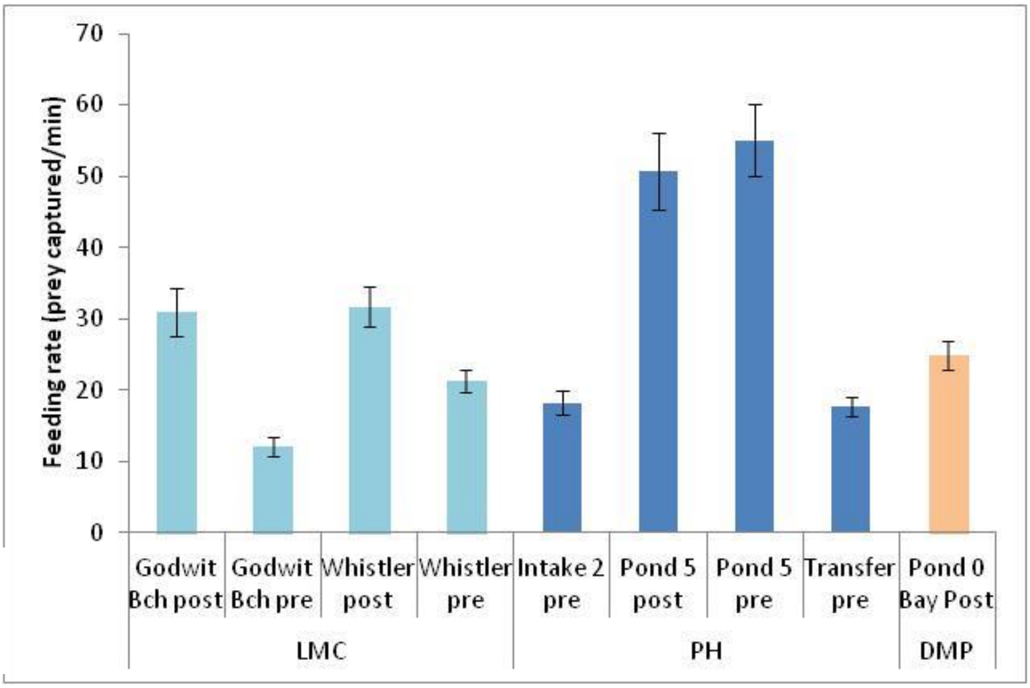


Figure 24: Proportion of medium-size shorebirds feeding at different water depths in relation to prey location in the sediment and water column, at all sites, post and premigration. Banded Stilt (BS); Red-necked Avocet (RNAv)





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B

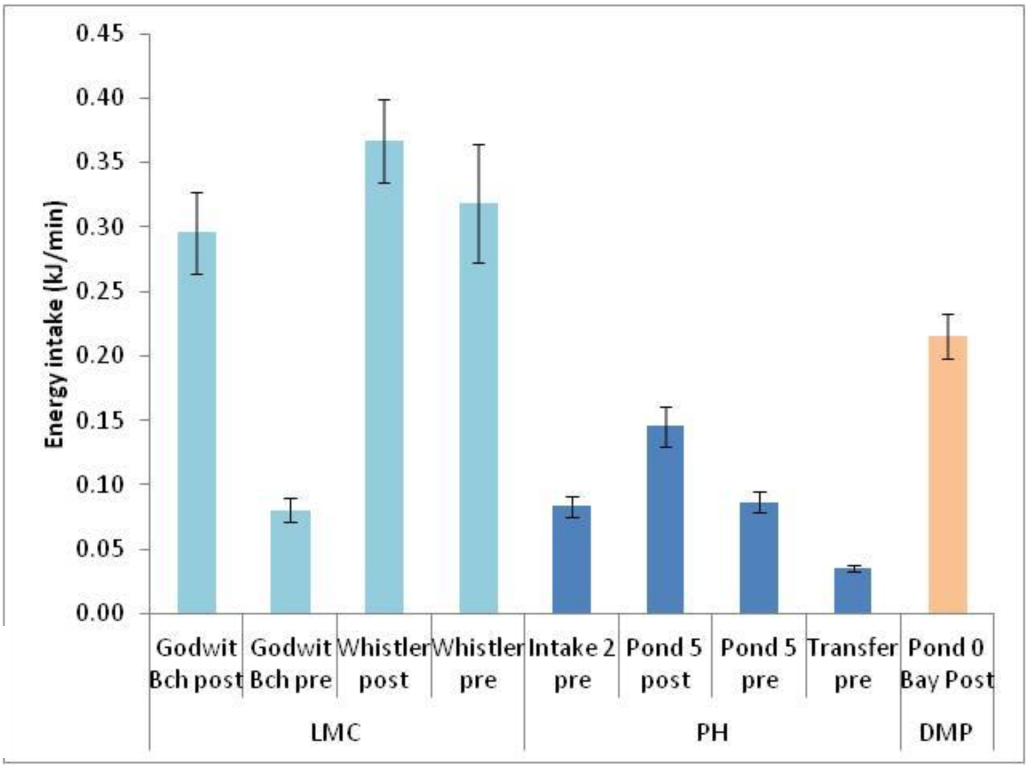


Figure 25: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-necked Stints feeding at Lake MacLeod (LMC), Port Hedland (PH) and Dampier (DMP), post and premigration.

Whistler Pond and Pond 5 were similar for both periods while at Godwit Beach there was a decrease in the intake rate from postmigration to premigration (Figure 25B).

Postmigration, there was a significant effect of the feeding site on the Stints' feeding rates and biomass and energy intakes. The feeding rates were highest at Pond 5, Port Hedland (Figure 25A), but the highest intake rates were recorded at the Lake MacLeod sites, Whistler Pond and Godwit Beach (Figure 25B).

Premigration, the feeding rates were highest at Pond 5, Port Hedland (Figure 25A), while the highest and the lowest intake rates were recorded at Whistler Pond, Lake MacLeod and the Transfer in Port Hedland respectively (Figure 25B). The intake rates at Godwit Beach at Lake MacLeod, and at the Intake 2 and Pond 5 at Port Hedland were similar (Figure 25B).

Broad-billed Sandpiper

The feeding and intake rates of Broad-billed Sandpipers were significantly affected by site and period (Table 8). There was a significant effect of the period in the feeding and intake rates of Broad-billed Sandpipers at Heritage site at Port Hedland: while the feeding rates were higher premigration, the intake rates were significant lower than those recorded postmigration (Table 8, Figure 26).

Premigration, there was also a significant effect of the feeding site on the feeding and intake rates of Broad-billed Sandpipers. The highest feeding rates were recorded at Whistler Pond, Lake MacLeod, while the lowest were recorded at the Intake 2 area at Port Hedland (Figure 26A). However, the intake rates at both sites at Port Hedland, Heritage and Intake 2, were similar, while the intake rates at Whistler Pond were significantly higher (Figure 26B).

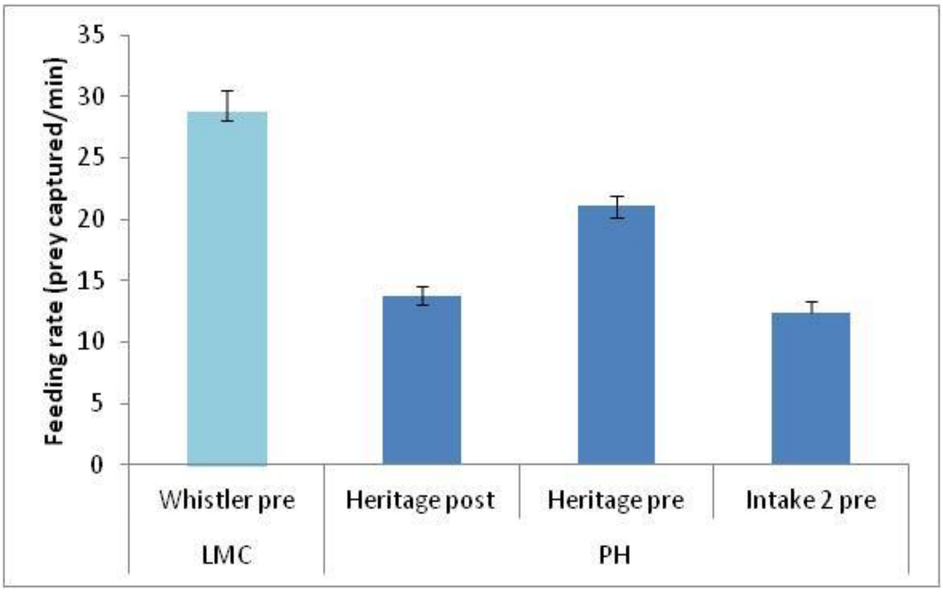
Curlew Sandpiper

The feeding and intake rates of Curlew Sandpipers were significantly affected by site, period and the interaction factor site x period (Table 8). There was an opposite trend between periods in the feeding rates of Curlew Sandpipers at Godwit Beach and at the Transfer at Port Hedland. At Godwit Beach the postmigratory feeding rates were higher than the premigratory rates, while at the Transfer the opposite was the case (Figure 27A). The feeding rates at Godwit Beach premigration were equivalent to the feeding rates at the Transfer postmigration (Figure 27A). However, the intake rates at

		Feeding rate			Biomass intake			Energy Intake			Feeding rate			Biomass intake			Energy Intake		
		F	df	*p*	*F*	df	*p*	*F*	df	*p*	*H*	df	*p*	*H*	df	*p*	*H*	df	*p*
	Site	51.80	2	***	27.71	2	***	33.75	2	***									
RNS	Period	29.46	1	***	4.25	1	***	26.43	1	***									
	Site x period	13.34	2	***	3.84	2	***	4.81	2	***									
RNS	Site-post	8.71	3	***	15.47	3	***	14.39	3	***									
RNS	Site-pre	62.54	2	***										91.21	2	***	84.56	2	***
BBS	Site-pre	43.32	2	***										73.71	2	***	73.91	2	***
	Site	24.14	1	***	529.52	1	***	594.33	1	***									
CS	Period	32.94	1	***	98.31	1	***	122.79	1	***									
	Site x period	122.17	1	***	80.07	1	***	96.93	1	***									
CS	Site-pre	10.46	2	***	116.91	2	***	148.99	2	***									
STS	Site-post	19.31	2	***										59.90	2	***	58.61	2	***
BTG	Site-pre	18.38	2	***	18.59	2	***	18.79	2	***									
	Site	18.91	1	***	77.95	1	***	57.52	1	***									
BS	Period	75.52	1	***	174.30	1	***	176.85	1	***									
	Site x period	91.99	1	***	282.11	1	***	316.73	1	***									
RNAv	site-post	8.23	2	***										25.13	2	***	24.66	2	***
BS	site-post	87.97	2	***										53.06	2	***	53.06	2	***
		t	df	*p*	*t*	df	*p*	*t*	df	*p*	*Z*	df	*p*	*Z*	df	*p*	*Z*	df	*p*
RK	Site	-1.71	73	0.09	-1.47	73	0.15	3.01	73	*									
BBS	Period	-6.68	138	***										5.41	138	***	5.01	138	***
BTG	Period	-2.39	96	0.01	-4.82	96	***	-4.82	96	***									
RCP	Period	1.56	73	0.12	2.79	73	*	2.66	73	*									
RCP	Site-Post										2.23	81	< 0.05	-6.61	81	***	-6.44	81	***

* $p < 0.01$ ** $p < 0.001$ *** $p < 0.0001$

Table 8: Factorial ANOVA, Kruskal-Wallis test, t-test and Mann-Whitney U test results to test the effect that site, period (post and premigration) and site x period have on the feeding rates and biomass and energy intake rates of shorebirds feeding at all sites, post and premigration. Red-necked Stint (RNS); Broad-billed Sandpiper (BBS); Curlew Sandpiper (CS); Sharp-tailed Sandpiper (STS); Bar-tailed Godwit (BTG); Banded Stilt (BS); Red-necked Avocet (RNAv); Red Knot (RK); and Red-capped Plover (RCP).



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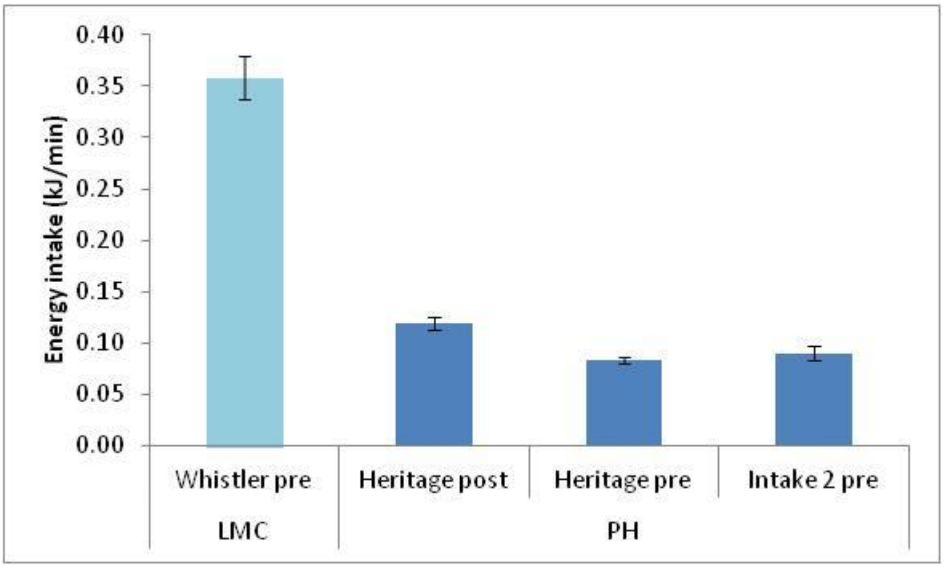
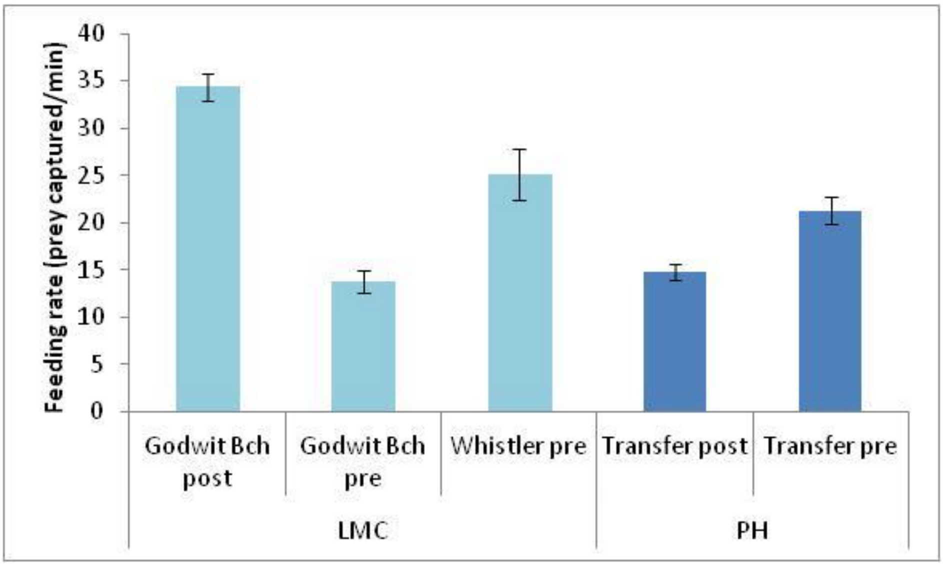


B

Figure 26: A) Feeding rates and B) energy intake rates (mean ± SE) of Broad-billed Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration.



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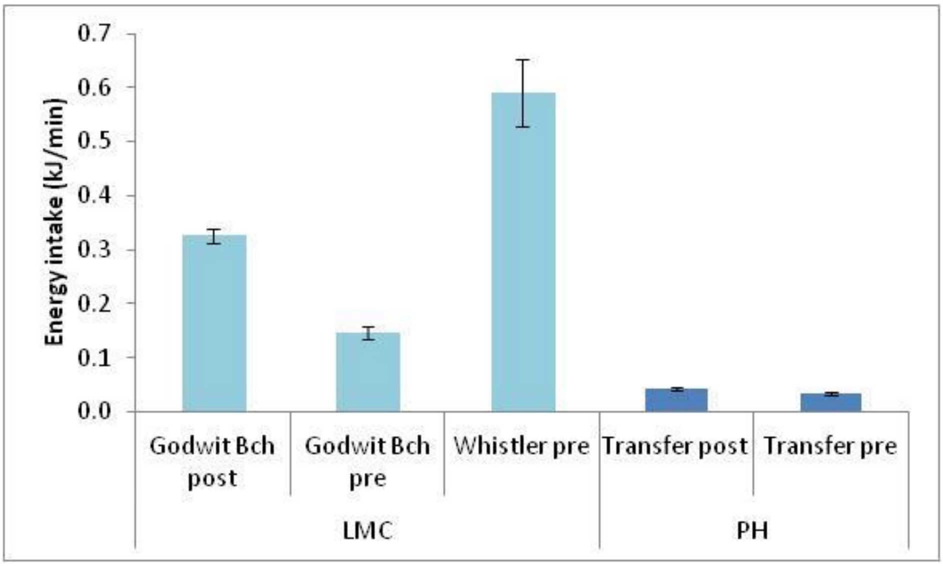


B

Figure 27: A) Feeding rates and B) energy intake rates (mean ± SE) of Curlew Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration.

Godwit Beach postmigration were significantly higher than the intake rates at Godwit Beach premigration and the intake rates at the Transfer in either period, with the intake rates at the Transfer being similar in both periods (Figure 27B). During premigration, although the feeding rates at Whistler Pond were similar to the feeding rates at Whistler Pond, the intakes rates were significantly higher than those recorded at Godwit Beach or at the Transfer (Figure 27B).

Sharp-tailed Sandpiper

Postmigration, the feeding and intake rates of Sharp-tailed Sandpipers were significantly affected by site (Table 8). The feeding rates were significantly lower at the Transfer, than at Godwit Beach, Lake MacLeod and Pond 5, Port Hedland, which were similar (Figure 28A). However, the biomass and energy intake rates at Godwit Beach were significantly higher than at Port Hedland (Figure 28B).

Bar-tailed Godwit

The feeding and intake rates of Bar-tailed Godwits were significantly affected by site and period (Table 8). Godwits had significantly higher feeding and intake rates premigration than postmigration at the Intake 2 area, Port-Hedland (Figure 29). Premigration, the Godwits at Intake 2 and Heritage, Port Hedland, displayed significantly higher feeding and intake rates than the Godwits at Pond 0, Dampier (Figure 29).

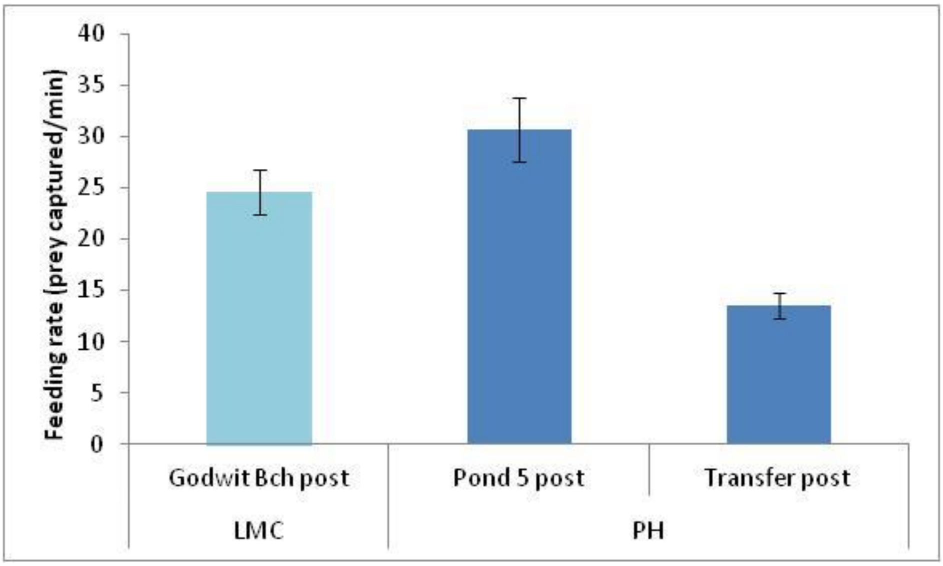
Red Knot

Premigration, the feeding and biomass intake rates of Red Knots were not affected by site (Table 8). The Red Knots at Whistler Pond had similar feeding rates to the birds feeding at Godwit Beach (Figure 30A). However, the energy intake rates of the birds feeding at Whistler Pond were significantly higher (Figure 30B).

Banded Stilt

The feeding and intake rates of Banded Stilts were significantly affected by site, period and the interaction factor site x period (Table 8). While the feeding rates of the Stilts increased from postmigration to premigration at Godwit Beach, their feeding rates at the Transfer, Port Hedland, were similar in both periods, as were their intake rates (Figure 31). The energy intakes rates at Godwit Beach premigration were significantly higher than the intake rates at Godwit Beach postmigration, or at the Transfer in either period.

A



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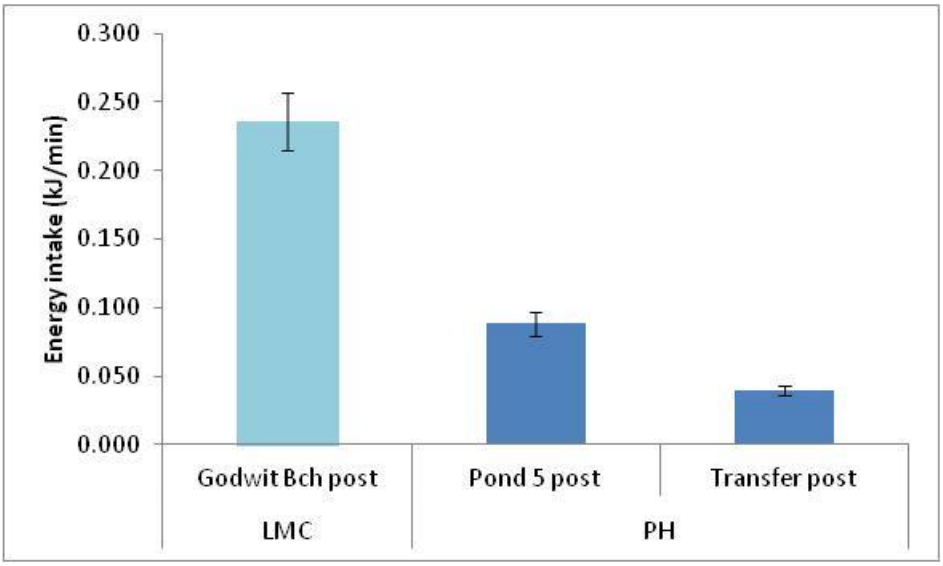
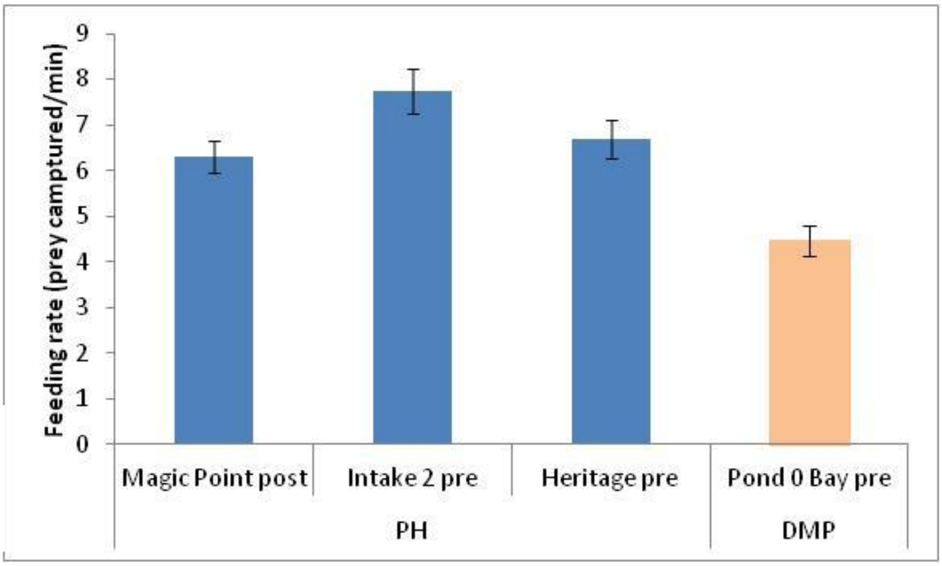


Figure 28: A) Feeding rates and B) energy intake rates (mean ± SE) of Sharp-tailed Sandpipers feeding at Lake MacLeod (LMC) and Port Hedland (PH), postmigration.

A



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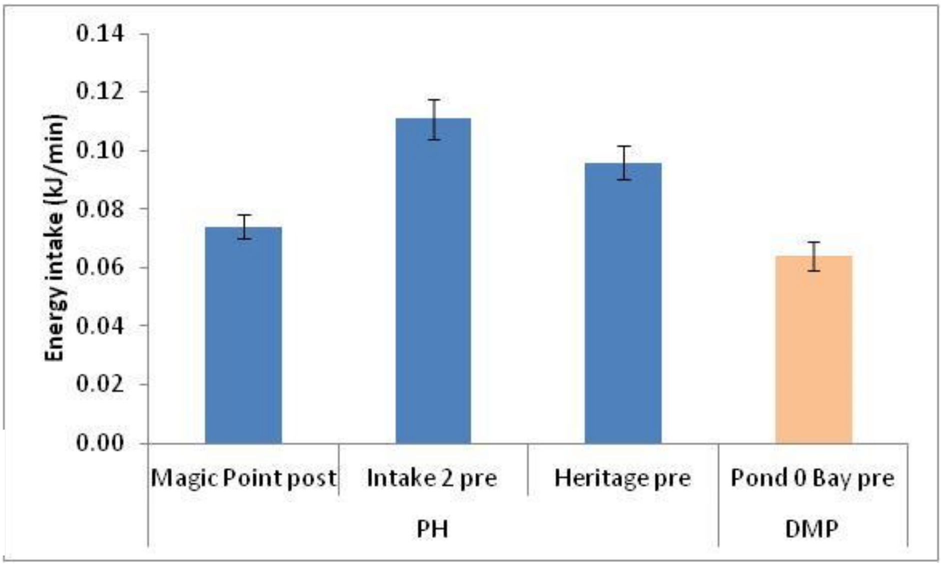
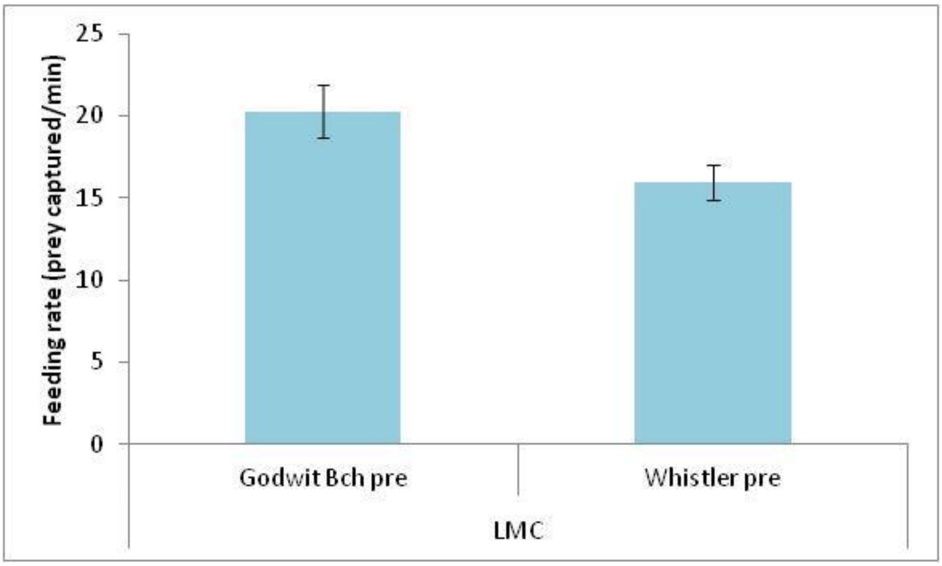


Figure 29: A) Feeding rates and B) energy intake rates of Bar-tailed Godwits (mean ± SE) feeding at Port Hedland (PH) and Dampier (DMP), post and premigration.

A



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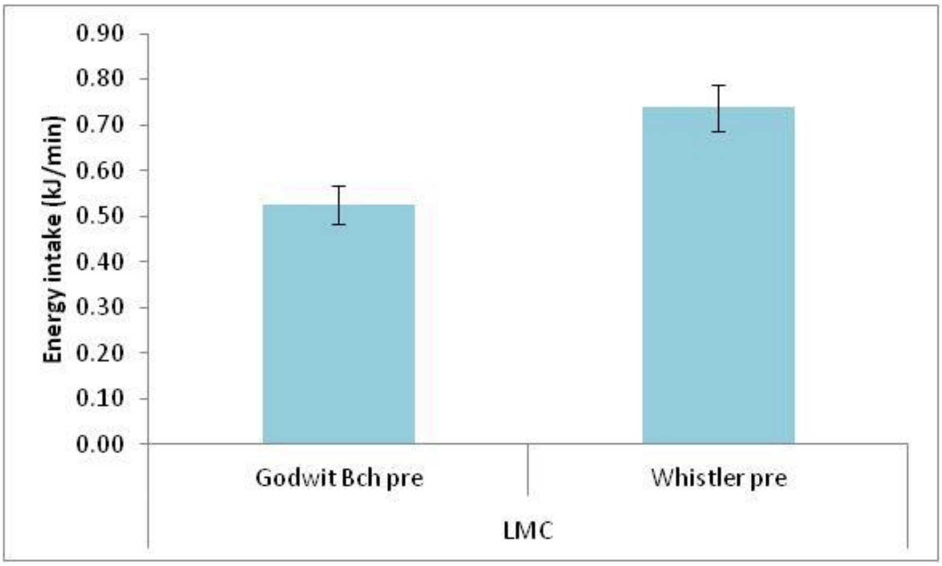


Figure 30: A) Feeding rates and B) energy intake rates (mean ± SE) of Red Knots feeding at Lake MacLeod, premigration.

Postmigration however, the birds feeding on brine shrimp at Pond 5 and at the Transfer, Port Hedland, displayed higher feeding and intake rates than the birds feeding at Godwit Beach, Lake MacLeod (Figure 31).

Red-necked Avocet

Postmigration, the feeding and intake rates of Avocets were significantly different between sites (Table 8). The feeding rates of Avocets at Magic Point, Port Hedland, were significantly lower than the feeding rates recorded at Godwit Beach, Lake MacLeod or Pond 0 Bay, Dampier (Figure 32A). However, the intake rates of Avocets at Magic Point were significantly higher than the intake rates recorded at Pond 0 Bay, and at Godwit Beach (Figure 32B).

Red-capped Plover

The feeding and intake rates of Red-capped Plovers were significantly affected by site and period (Table 8). The feeding and intake rates of Red-capped Plovers in Whistler Pond were significantly different post and premigration (Figure 33) Postmigration, the feeding and intake rates were significantly different at Whistler Pond and Godwit Beach, Lake MacLeod.

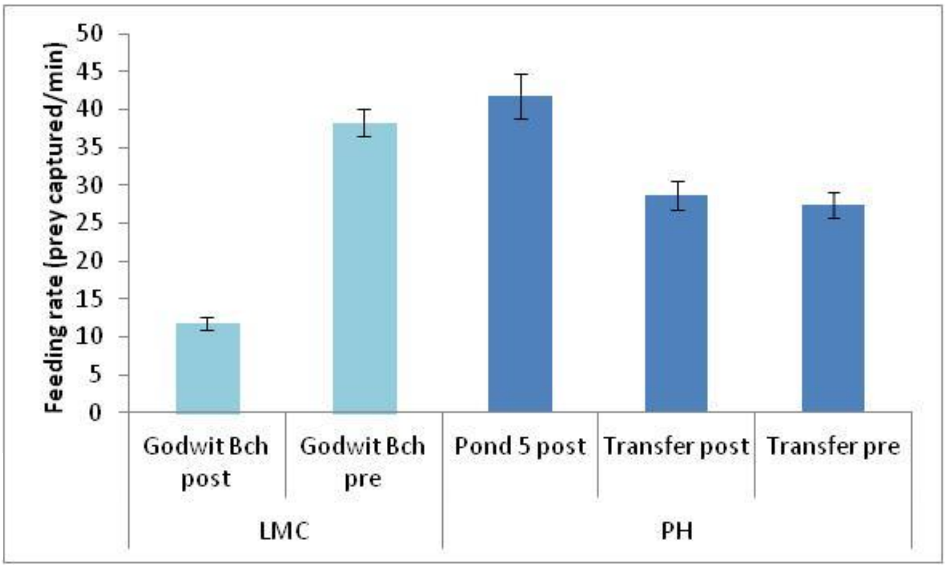
Prey density

The small shorebirds' (Red-necked Stint, Broad-billed Sandpiper, Curlew Sandpiper and Sharp-tailed Sandpiper) feeding rates were affected by prey density (Table 9). Bar-tailed Godwit and Red-necked Avocet feeding rates were not affected by prey density.

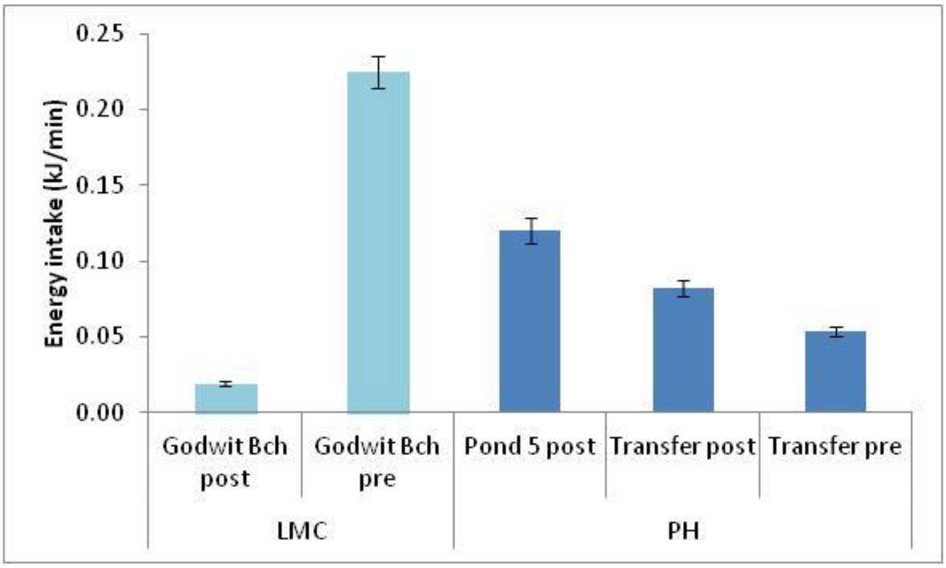
Abiotic factors affecting shorebirds' feeding and intake rates

Water depth

Where shorebirds were feeding on prey in the sediment, water depth did not affect their feeding rate (prey captured/min) (Table 9). However, in the case of migratory birds, water depth significantly affected their feeding rate postmigration when they were feeding on prey suspended in the water column (Table 9), with feeding rates higher in shallow waters (Fig 34).



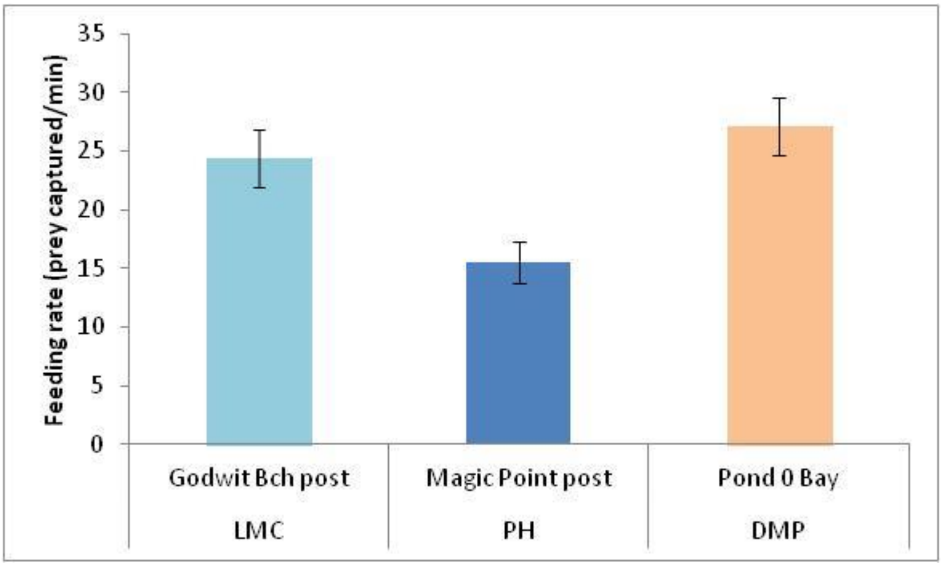
A



B

Figure 31: A) Feeding rates and B) energy intake rates (mean ± SE) of Banded Stilts feeding at Lake MacLeod (LMC) and Port Hedland (PH), post and premigration.

A



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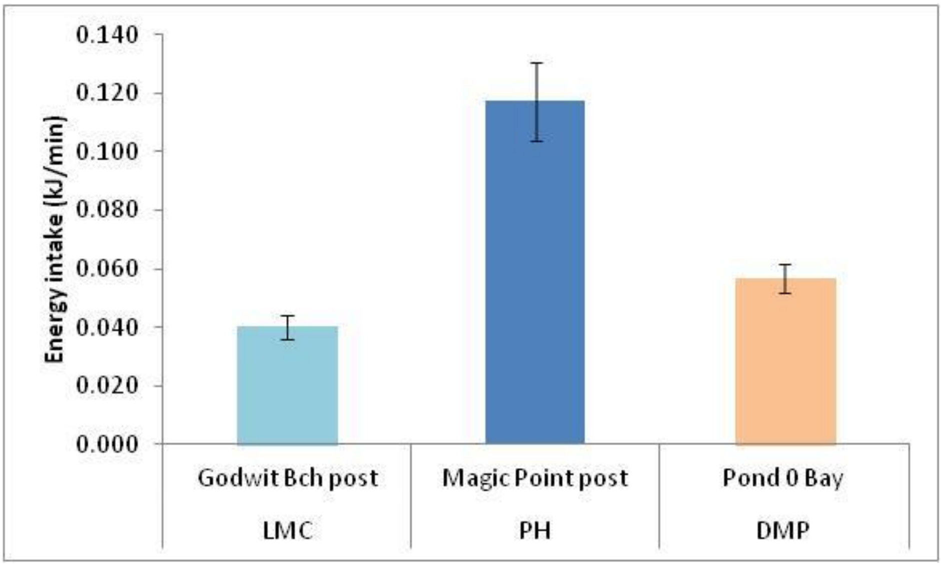
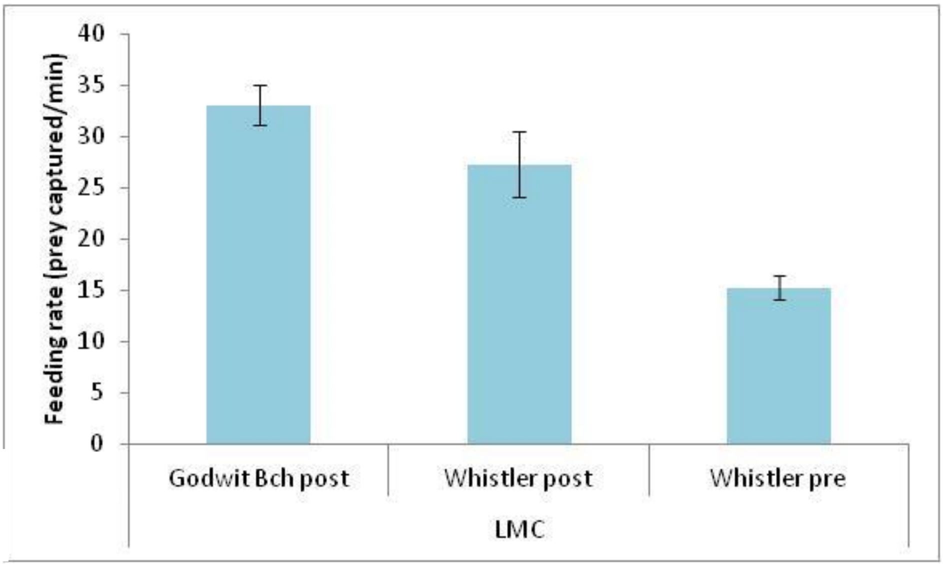


Figure 32: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-necked Avocets feeding at Lake MacLeod (LMC), Port Hedland (PH), and Dampier (DMP), postmigration.

A



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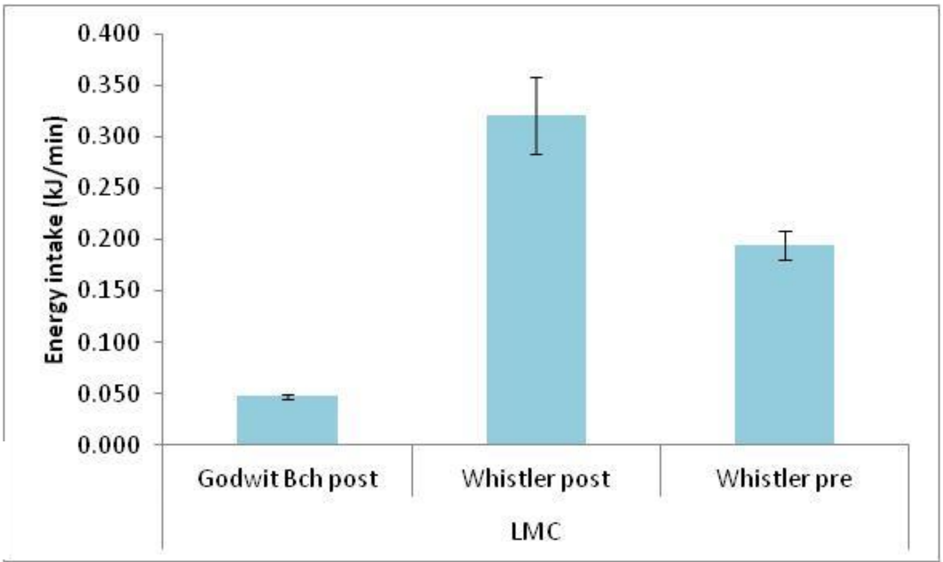


Figure 33: A) Feeding rates and B) energy intake rates (mean ± SE) of Red-capped Plovers feeding at Lake MacLeod, post and premigration.

		sediment prey			water column prey		
		F	df	*p*	*F*	df	*p*
RNS	Prey density	12.72	1	**	23.56	1	***
	Period	9.88	1	*	1.57	1	>0.05
	water depth	0.24	1	>0.05	7.27	1	*
	Period*water depth	2.00	1	>0.05	1.01	1	>0.05
BBS[a]	Prey density	26.04	1	***			
	water depth	5.26	1	*			
CS	Prey density	22.47	1	***			
	Period	9.29	1	*			
	water depth	0.01	1	>0.05			
	Period*water depth	2.15	1	>0.05			
STS[b]	Prey density				27.10	1	***
	water depth	0.06	1	>0.05	8.99	1	*
BTG[a]	Prey density	1.84	1	>0.05			
	water depth	2.28	1	>0.05			
RNAv[b]	Prey density	1.58	1	>0.05			
	water depth	0.36	1	>0.05			

*p<0.01 **p<0.001 ***p<0.0001

Table 9: Effect of prey density, period (post and premigration) and water depth on the feeding rates of shorebirds feeding in Dampier Salt Ltd. operations, WA in post and premigration. Migratory: Red-necked Stint (RNS); Broad-billed Sandpiper (BBS); Curlew Sandpiper (CS); Sharp-tailed Sandpiper (STS); and Bar-tailed Godwit (BTG). Resident: Red-

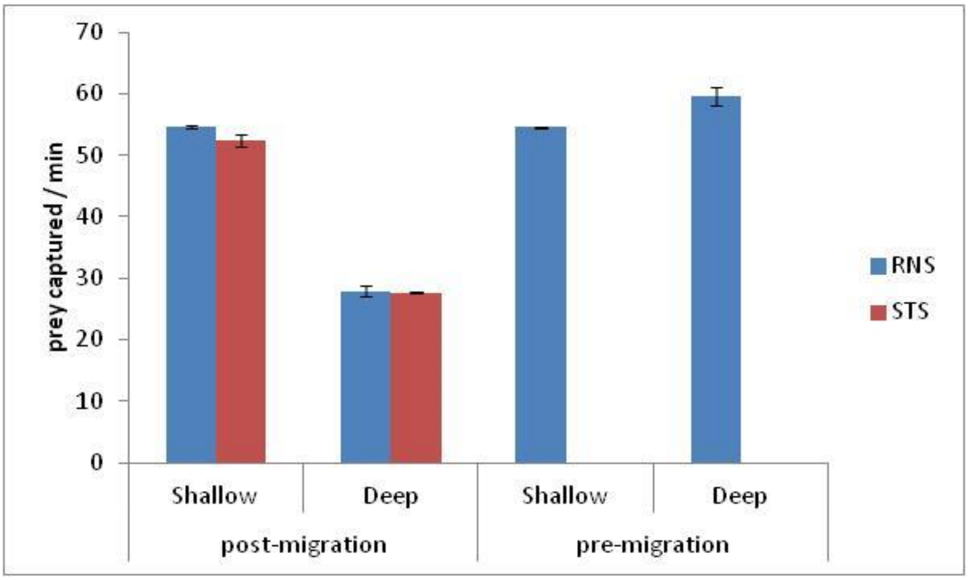


Figure 34: Feeding rates of Red-necked Stints (RNS) and Sharp-tailed Sandpipers (STS) in Pond 5, Port Hedland, post and premigration, at 2 different water depths.

Day-night feeding

Several species of shorebirds were observed feeding at night at Dampier and Lake MacLeod, both post and premigration (Table 10). For foraging behaviour, the number of probes and steps per minute were significantly related to the shorebird species (Red-necked Stint and Red-capped Plover) and the interaction factor species x day period, but not by the period of the day alone (Table 11).

While the rate of probes made by Red-capped Plovers increased from day to night, the rate of Red-necked Stints' probes varied little (Figure 35A). And whereas the rate of steps taken by the Plovers decreased from day to night, the rate of steps of the Stints increased (Figure 35B).

Quality of the saltworks and salt lake as feeding grounds

Postmigration

Postmigration, all the migratory species were able to obtain enough energy to fulfil their theoretical Daily Energy Expenditure (DEE) feeding exclusively at Lake MacLeod, while the resident species, Red-necked Avocet and Banded Stilt, could not (see discussion below) (Table 12). The resident Red-capped Plovers however were able to meet their energy requirements feeding exclusivley at Whistler Pond (Table 12). Red-necked Stints and Broad-billed Sandpipers were also able to meet their entire theoretical DEE feeding exclusively at Pond 5 and at the Heritage area Pond 0, Port Hedland, respectively (Table 12). Stints were also able to meet their theoretical DEE feeding exclusively at Pond 0, Dampier (Table 12). However the small to medium-size sandpipers (Curlew and Sharp-tailed Sandpipers), and the larger shorebirds (Bar-tailed Godwits, Red-necked Avocets and Banded Stilts) could not meet their theoretical DEE feeding exclusively at either Port Hedland or Dampier (Table 12).

Premigration

Premigration at Lake MacLeod, all migratory species were able to meet their theoretical DEE feeding exclusively at Whistler Pond, as were the resident Red-capped Plovers (Table 12). At Godwit Beach, the Banded Stilts, Curlew Sandpipers and Red-necked Stints could not fully meet their theoretical DEE, although the Red Knot could do so (Table 12).

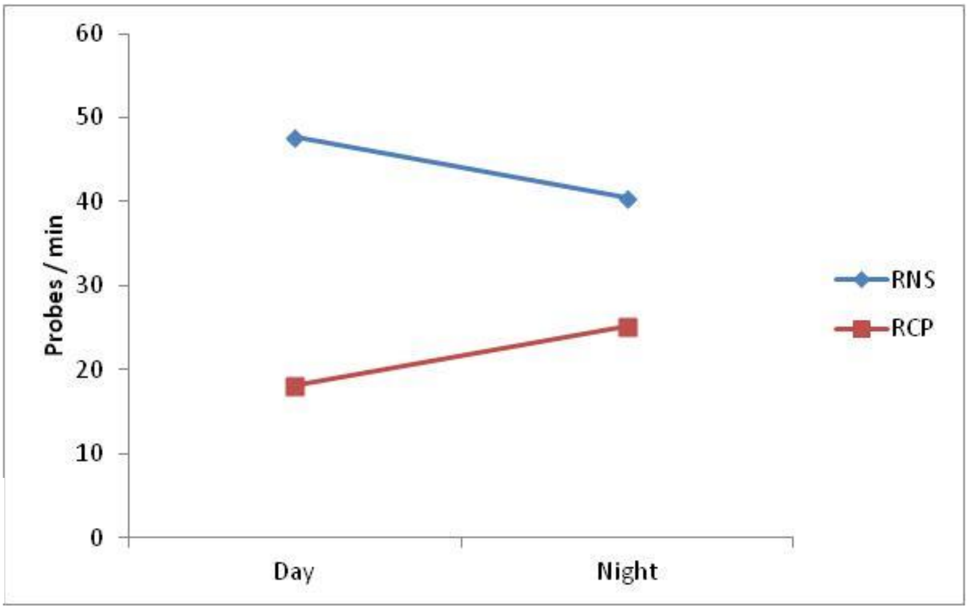
Period	Operation	Site	Species	Feeding at night
post-migration	Dampier	Pond 0 Bay	RNAv	yes
			RCP	yes
			BS	yes
			RNS	yes
			BTG	No
			WHM	No
			EC	No
	Lake MacLeod	Godwit Beach	RNAv	yes
			RCP	Yes
			BS	yes
pre-migration	Dampier	Pond 0 Bay	BTG	yes
	Lake MacLeod	Whistler Pond	RCP	yes
			RNS	yes

Table 10: Feeding activity of birds observed at night at Dampier and Lake MacLeod, post and premigration. Red-necked Avocet (RNAv); Red-capped Plover (RCP); Banded Stilt (BS); Red-necked Stint (RNS); Bar-tailed Godwit(BTG); Whimbrel (WHM); and Eastern Curlew (EC).

		F	df	*p*
Probes	Species	108.62	1	***
	Day period	0.73	1	0.39
	Species x Day period	15.72	1	***
Steps	Species	38.04	1	***
	Day period	0.35	1	0.56
	Species x Day period	25.70	1	***

Table 11: Factorial ANOVA results of the effect of species, day period (night/day) and the interaction factor species x day period on the probes per minute and steps per minute of Red-capped Plovers (RCP) and Red-necked Stints (RNS), feeding day and night in Whistler Pond, Lake Macleod, premigration.

A



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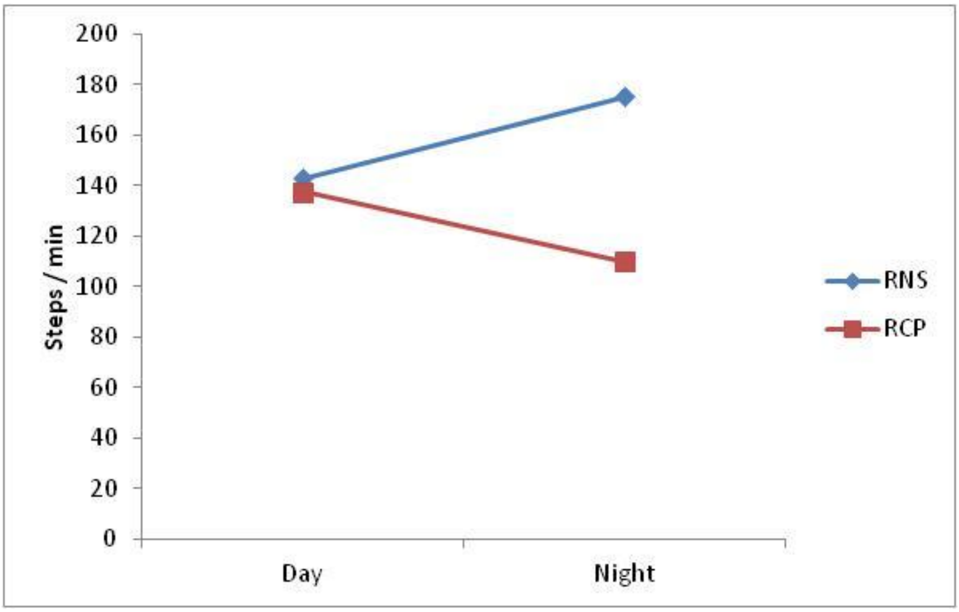

Figure 35: A) Probes per minute and B) steps per minute of Red-capped Plovers (RCP) and Red-necked Stints (RNS) feeding day and night in Whistler Pond, Lake MacLeod, premigration.

No shorebird species could meet the DEE feeding exclusively at Port Hedland or Dampier premigration, although the small shorebirds like Red-necked Stints and Broad-billed Sandpipers were close to obtaining their theoretical DEE (Table 12).

OPERATION	SITE	Period	SPECIES	$kJ \cdot min^{-1}$ (Mean ± SE)	Body Mass (g)	DEE ($kJ \cdot bird^{-1} \cdot day^{-1}$) (Nagy 1987)	Average hours need to meet DEE (Mean ± SE)
Dampier	Pond 0 Bay	post-migration	RNAv	0.057 ± 0.006	325.9	442.39	252.21 ± 0.67
Dampier	**Pond 0 Bay**	**post-migration**	**RNS**	0.216 ± 0.008	26.5	88.78	**9.09 ± 0.06**
Lake MacLeod	Godwit Beach	post-migration	BS	0.019 ± 0.003	240.0	363.72	378.07 ± 0.43
Lake MacLeod	**Godwit Beach**	**post-migration**	**CS**	0.326 ± 0.007	51.6	135.99	**7.41 ± 0.03**
Lake MacLeod	Godwit Beach	post-migration	RCP	0.048 ± 0.003	40.5	116.47	48.44 ± 0.13
Lake MacLeod	Godwit Beach	post-migration	RNAv	0.040 ± 0.006	325.9	442.39	242.89 ± 0.46
Lake MacLeod	**Godwit Beach**	**post-migration**	**RNS**	0.296 ± 0.013	26.5	88.78	**6.73 ± 0.06**
Lake MacLeod	**Godwit Beach**	**post-migration**	**STS**	0.236 ± 0.013	65.0	157.65	**14.93 ± 0.15**
Lake MacLeod	**Whistlers**	**post-migration**	**RCP**	0.320 ± 0.012	40.5	116.47	**12.53 ± 0.09**
Lake MacLeod	**Whistlers**	**post-migration**	**RNS**	0.366 ± 0.013	26.5	88.78	**5.14 ± 0.05**
Port Hedland	**Pond 0 Heritage**	**post-migration**	**BBS**	0.119 ± 0.004	36.6	109.25	**18.14 ± 0.06**
Port Hedland	Pond 0 Intake 2	post-migration	BTG	0.074 ± 0.003	255.7	378.79	109.37 ± 0.13
Port Hedland	Pond 0 Intake 2	post-migration	RNAv	0.117 ± 0.008	325.9	442.39	100.10 ± 0.23
Port Hedland	Pond 6	post-migration	BS	0.120 ± 0.010	240.0	363.72	56.03 ± 0.23
Port Hedland	**Pond 5**	**post-migration**	**RNS**	0.146 ± 0.010	26.5	88.78	**14.27 ± 0.11**
Port Hedland	Pond 5	post-migration	STS	0.088 ± 0.007	65.0	157.65	42.16 ± 0.15
Port Hedland	Transfer	post-migration	CS	0.052 ± 0.002	51.6	135.99	66.21 ± 0.08
Port Hedland	Transfer	post-migration	STS	0.039 ± 0.004	65.0	157.65	81.51 ± 0.16
Dampier	Pond 0 Bay	pre-migration	BTG	0.064 ± 0.004	293.1	413.39	135.06 ± 0.20
Lake MacLeod	Godwit Beach	pre-migration	BS	0.225 ± 0.007	240.0	363.72	29.13 ± 0.09
Lake MacLeod	Godwit Beach	pre-migration	CS	0.146 ± 0.007	61.5	152.16	23.90 ± 0.10
Lake MacLeod	**Godwit Beach**	**pre-migration**	**RK**	0.525 ± 0.014	178.7	301.15	**12.96 ± 0.08**
Lake MacLeod	Godwit Beach	pre-migration	RNS	0.091 ± 0.006	30.2	96.50	28.35 ± 0.12
Lake MacLeod	**Whistlers**	**pre-migration**	**BBS**	0.358 ± 0.011	49.9	133.19	**6.79 ± 0.05**
Lake MacLeod	**Whistlers**	**pre-migration**	**CS**	0.590 ± 0.023	61.5	152.16	**7.21 ± 0.14**
Lake MacLeod	**Whistlers**	**pre-migration**	**GK**	0.657 ± 0.025	193.2	316.57	**11.18 ± 0.12**
Lake MacLeod	**Whistlers**	**pre-migration**	**RCP**	0.194 ± 0.009	40.5	116.47	**11.72 ± 0.07**
Lake MacLeod	**Whistlers**	**pre-migration**	**RK**	0.737 ± 0.014	178.7	301.15	**8.22 ± 0.05**
Lake MacLeod	**Whistlers**	**pre-migration**	**RNS**	0.319 ± 0.012	30.2	96.50	**10.78 ± 0.07**
Port Hedland	Pond 0 Heritage	pre-migration	BBS	0.083 ± 0.002	49.9	133.19	30.04 ± 0.04
Port Hedland	Pond 0 Heritage	pre-migration	BTG	0.096 ± 0.006	293.1	413.39	79.95 ± 0.18
Port Hedland	Pond 0 Intake 2	pre-migration	BBS	0.090 ± 0.006	49.9	133.19	34.36 ± 0.14
Port Hedland	Pond 0 Intake 2	pre-migration	BTG	0.111 ± 0.006	293.1	413.39	74.59 ± 0.20
Port Hedland	Pond 0 Intake 2	pre-migration	RNS	0.084 ± 0.008	30.2	96.50	32.41 ± 0.24
Port Hedland	Pond 5	pre-migration	RNS	0.087 ± 0.006	30.2	96.50	28.09 ± 0.12
Port Hedland	Transfer	pre-migration	BS	0.054 ± 0.005	240.0	363.72	124.19 ± 0.23
Port Hedland	Transfer	pre-migration	CS	0.033 ± 0.003	61.5	152.16	99.80 ± 0.18
Port Hedland	Transfer	pre-migration	RNS	0.035 ± 0.003	30.2	96.50	57.94 ± 0.16

Table 12: Theoretical Daily Energy Expenditure (DEE, Nagy 1987) of shorebirds post and premigration, based on their energy intake rates (kJ/min) and body mass (g) (from literature, see table 2), and the number of hours each species would need to fulfil their DEE. **Bold font** indicates species that could fulfil their DEE feeding exclusively at various study sites. Resident species: Red-necked Avocet (RNAv); Banded Stilt (BS); and Red-capped Plover (RCP). Migratory species: Red-necked Stint (RNS); Curlew Sandpiper (CS); Sharp-tailed Sandpiper (STS); Broad-billed Sandpiper (BBS); Bar-tailed Godwit (BTG); Red Knot (RK); and Great Knot (GK).

DISCUSSION

Prey abundance, biomass and availability

Whistler Pond at Lake MacLeod was the site with the highest abundance and biomass of macroinvertebrates. Of the 3 operations, Lake MacLeod is the only one that has a continuous input of seawater, which may make the system more stable in terms of temperature and water chemistry. Of the 2 Lake MacLeod sites, Whistler Pond is an expansive, inundated spill sheet close to the vent, receiving a constant supply of water of, or close to the salinity of seawater, which would preclude the site from experiencing extreme conditions (high water salinity). There is also support for the idea that distance from the water input site (intake or vent) is an important influence on prey abundance and biomass at the saltwork sites, as sites closer to the water source experience less extreme salinity conditions and are more reliably inundated. Therefore, it is expected that these sites will have more prey (increased abundance, biomass or diversity). In Port Hedland premigration, the sites closer to Intake 2 had a higher biomass than the Heritage site. Future studies could examine this hypothesis.

At Lake MacLeod, the highest prey densities were found in the first 5 cm of the sediment during the day. The hypothesis that there would be daily changes in macroinvertebrate availability was therefore rejected, since macroinvertebrates were continuously available for shorebirds. The lack of a daily vertical movement of prey could be related to the small size of the macroinvertebrates at Lake MacLeod limiting their burying capacity. Other studies have found that large benthic invertebrates are able to move deeper in the sediment than small invertebrates (Esselink and Zwarts 1989). The shallowness of the reduced sediment layer (sediment depth with anoxic conditions) can also prevent invertebrates from moving deeper into the sediment (Nilsson and Rosenberg 2000). At Dampier premigration, the vertical distribution of polychaetes in the sediment was slightly different from the distribution found at Whistler Pond, Lake MacLeod, where there are similar abundances found in the shallow and deep layers of the sediment. The larger size of polychaetes at Dampier could allow them to bury deeper in the sediment to avoid predators, as has been described elsewhere (Esselink and Zwarts 1989).

Diet

Amphipods were the main prey for shorebirds at Lake MacLeod, except for both species of Knots, for whom bivalves, polychaetes and seagrass were the main food items. Amphipods were selectively eaten by the majority of shorebird species despite the presence of other highly available prey such as polychaetes. There are 2 complementary explanations for this finding. The available polychaetes at Lake MacLeod were relatively small and offered on average a smaller amount of biomass per unit of handling time than amphipods. Additionally, recent studies have shown that Semipalmated Sandpipers (*Calidris pusilla*) target the amphipod *Corophium vulator* which is rich in highly unsaturated fatty acids (HUFAs) (Maillet and Weber, 2006). HUFAs could improve shorebirds' exercise performance and thereby shorebird migrations (Maillet and Weber, 2006, 2007). Amphipods represented a small proportion of the shorebird diet at the Dampier and Port Hedland operations, probably due to their low density at Port Hedland and inaccessibility (though high density) at Dampier postmigration.

Bar-tailed Godwits and Great Knots were the only shorebirds to not favour amphipods in our study, probably because in the case of the godwits their large beaks made small amphipods difficult to handle (Zwarts and Wanink 1993) and Great Knots are known to be a highly specialized molluscivorous species (Tulp and de Goeij 1994). One possible explanation for the Red-necked Avocet selecting chironomids at Dampier is that chironomids can contain higher levels of HUFAs compared with other benthic invertebrates (Sushchik et al. 2003). Moreover, some species of chironomids of saline environments contain the highest proportion of eicosapentaenoic acid of all invertebrates, one of the most physiologically important HUFAs for animals (Zinchenko 2014).

At Dampier, small migratory shorebirds feed on brine shrimp but also on polychaetes and amphipods, while larger migratory shorebirds feed mostly on polychaetes. Other studies have found that the diet of small migratory shorebirds feeding in saltworks is composed mostly of brine shrimp (Masero 2003, Estrella et al. 2007). These differences with previous studies could be related to feeding habitat availability. In the studies of Masero (2003) and Estrella et al. (2007) the concentration ponds with brine shrimp were extensively available due to shallow waters, however at Port Hedland and Dampier, the availability of feeding habitats supporting brine shrimp appeared limited.

Shorebird habitat use

Small to medium-size shorebirds (Stints and Sandpipers) were particularly limited in their habitat use by water depth, always feeding in shallow waters from 0 to 3 cm. Areas that had a high abundance of macroinvertebrates but were not in shallow water (e.g. Dampier operation sampling site Levee 19) were not used. At Port Hedland, birds were able only to access the concentration ponds to feed where shallow beaches with reduced slopes existed.

At Godwit Beach Flats (behind Godwit Beach), Lake MacLeod, strong winds with directions NW-N-E pushed the water out of the mudflats and through Linda's Creek. Conversely, strong S-SW winds pushed the water into the flats from the creek. This wind-driven movement of water determined the availability of foraging habitat for shorebirds in that part of the Northern Ponds of Lake MacLeod. This sort of wind-driven system has been described previously for Black-fronted Plover (*Elseyornis melanops*) feeding in saline lagoons in Australia (Taylor 2004). Since Lake MacLeod is a complex system with extensive, patchily distributed mudflats, it is possible that strong winds blowing from a particular direction makes some areas unavailable for shorebirds while making other areas suitable by exposing alternative feeding habitats. This process is repeated in other parts of the lake with every change of wind direction. This progression of sequential availability of different foraging habitats has been previously identified as an important aspect of managing habitats in saltworks (Estrella and Masero 2010).

In Port Hedland, birds also made use of the wind to exploit prey pushed towards the shore in the concentration ponds, as has been observed in natural lakes (Verkuil et al. 1993). In our study, small shorebirds concentrated along the shores of the concentration ponds to feed on brine shrimp (*Artemia spp*.) aggregated by the wind.

Feeding and intake rates

Feeding location and period (post or premigration) had a significant effect on feeding and intake rates of shorebirds at all operations. In general, birds achieved higher feeding and intake rates at sites with high prey abundance, like Whistler Pond at Lake MacLeod. When prey availability decreased due to predation or seasonally related changes in abundance, the feeding rates and intake rates also decreased, as was recorded at Godwit Beach Flats, Lake MacLeod, from post to premigration. Long-distance migratory shorebird species have high energy requirements both post and premigration, in order to recover from the demanding migration or to build up the reserves that will allow them to migrate (Velasquez and Hockey 1992). To achieve this energy gain, birds tend to increase their intake rates (Zwarts et al. 1990b, Zharikov and Skilleter 2002) or the time they spend foraging (Zwarts et al. 1990b, Lourenço et al. 2008, Santiago-Quesada et al. 2014). Of the migratory species studied, most of them, except the Bar-tailed Godwit, had lower or similar intake rates premigration than postmigration, suggesting that the birds would need to feed for longer. In fact, the percentage of all migratory birds feeding at Port Hedland and Dampier at high tide was greater in premigration than in postmigration.

In most cases, migratory shorebirds had higher intake rates than resident shorebirds both post and premigration at Lake MacLeod. This difference could be related to the higher energy requirements for migration, something that is not a concern for resident species.

The intake rates of Red-necked Stints feeding on brine shrimp (*Artemia spp.*) postmigration at Port Hedland were similar to the intake rates of a similar size shorebird, the Little Stint (*Calidris minuta*) feeding on brine shrimp in winter at a European saltworks (Masero 2003). However, the intake rates of Curlew Sandpipers post and premigration and of Red-necked Stints premigration, (both feeding on brine shrimp in Port Hedland) were much lower than the intake rates of Curlew Sandpipers and Little Stints at other saltworks (Masero 2003). Although the size of the brine shrimp was similar at both saltworks, the densities differed, which can explain the lower feeding (number of prey captured per minute) and intake rates of the Port Hedland Curlew Sandpipers. However, Red-necked Stints were feeding at much higher brine shrimp densities than the European Little Stints, and even with that, their feeding, and especially their intake rates, were lower premigration. In this study we have calculated the biomass of brine shrimp for different class sizes for both periods and it appears that there is a decrease in brine shrimp biomass for the same class size, from postmigration to premigration. Masero (2003) however only used the winter biomass for brine shrimp, therefore if there was a change in biomass between periods, that change and the effect on the shorebirds' intake rates was unnoticed.

Day and Night feeding

Several species of shorebirds were observed feeding at night, including Red-necked Stints and Red-capped Plovers. Several theories have been hypothesised to explain nocturnal foraging in shorebirds. The supplementary hypothesis (McNeil et al. 1992) states that when birds are not able to achieve their energetic requirements during daylight, they feed at night (Lourenço et al. 2008, Santiago-Quesada et al. 2014). The Carnarvon area, where Lake MacLeod is situated, had nearly 13 hours of daylight every day in February 2014 when the data were collected, and the number of hours that plovers and stints needed to feed to achieve their DEE was 12 hrs and 11 hrs respectively. Consequently, birds should not need to feed at night. The preference hypothesis (McNeil et al. 1992), proposes that shorebirds prefer to feed at night because it is more profitable. The increase in profitability could be due to higher prey availability (Pienkowski 1983, Mouritsen 1994, Gilling and Sutherland 2007) or activity (Mouritsen 1994, Kuwae 2007) or a decrease in predators and/or disturbance (Sitters et al. 2001) at night.

Plovers' foraging speed (steps/min) decreased from day to night, while their prey capture attempts per minute increased. A decrease in night foraging speeds has been observed in several plover species (Turpie and Hockey 1993, Lourenço et al. 2008) and has been related to a lower capacity for visual prey detection at night (Tupie and Hockey 1993). However, higher availability and activity of the one Corophiidae amphipod species (*Corophium vulator)* recorded on the intertidal sediment surface, has been observed at night (Mouritsen 1994) and this could explain the increase in Red-capped Plover feeding attempts without an increase in the foraging area. It is well known that birds tend to move more slowly on highly profitable patches (Nolet and Mooij 2002, Lourenço et al. 2005). In addition, plovers are well-adapted to nocturnal visual searching for prey because of their large eyes and retinal visual receptors (Rojas de Azuaje et al. 1993; Rojas de Azuaje et al. 1999, Thomas et al. 2006).

Contrary to other studies on sandpiper nocturnal foraging behaviour, Red-neck Stints continued feeding visually at night, increasing their feeding speed while marginally lowering their capture attempts. A study of Dunlins (*Calidris alpina*) tactile feeding at night on highly available surface *Corophium* also recorded a higher foraging speed than that in daylight, but this was accompanied by a higher number of capture attempts (Mouritsen 1994). Assuming that Whistler Pond also had a higher availability and activity of amphipods on the sediment surface at night, it is reasonable to suggest that the stints kept trying to detect their prey visually. However, with a lower night-vision capacity than the plovers (Thomas 2006), they likely increased their foraging speed while maintaining their prey capture attempts at similar rates to those recorded in daylight.

Our results therefore appear to support the preference hypothesis, at least for Red-capped Plovers, which reduced their feeding area at night but increased their number of feeding attempts. However is not clear why Red-necked Stints fed at night.

Habitat quality as feeding grounds for shorebirds

Whistler Pond at Lake MacLeod was the best feeding ground for shorebirds of all the study sites, with all the species able to meet their theoretical DEE both post and premigration. The importance of this site as a feeding ground for shorebirds, especially small to medium-size shorebirds, appears to be related to the abundance of amphipods, especially the family Corophiidae, and bivalves. However, its small surface area precludes it being listed as an important site based on shorebird numbers.

Godwit Beach Flats was also an exceptional feeding ground for small shorebirds postmigration, although its quality as a feeding ground decreased towards the pre-nuptial migration due to a decrease in prey availability. Although monthly data on prey availability were not collected, it is possible that the decrease in prey abundance at Godwit Beach Flats was related to prey depletion by shorebirds during the non-breeding period. Previous surveys and the current study have found high numbers of shorebirds feeding on Godwit Beach Flats (Hassell 2005, Hassell 2006, Berteltezos et al. 2013), which can significantly impact prey abundance (Szekely and Bamberger 1992, Zharikov and Skilleter 2002, Sánchez et al. 2006b).

The results of the time needed to achieve the theoretical DEE suggest that the Port Hedland and Dampier operations may be acting as alternative feeding grounds for small migratory shorebirds postmigration, and as supplementary feeding habitats premigration. If so, it is expected that premigration, migratory shorebirds would feed at low tide in the intertidal areas and at high tide in the saltworks, while postmigration, a proportion of the small migratory shorebirds would be able to feed exclusively in the saltworks.

It appears that the Broad-billed Sandpipers were trying to compensate for the small size of available polychaetes premigration at the Heritage site, Port Hedland, by increasing their feeding rates. However, there was still a decrease in the intakes rates from postmigration to premigration. Premigration intakes rates did not allow Broad-billed Sandpipers to meet their DEE.

None of the resident species met their theoretical DEE except the Red-capped plover feeding at Whistler Pond post and premigration. For these calculations it was assumed that Red-necked Avocets and Banded Stilts were capturing a single prey when feeding with the sweeping technique, however it is possible that they captured more than a single prey within each stroke, especially in areas with high prey abundance. In fact, Ross et al. (2012) found that the Pied Avocet (*Recurvirostra avocetta*), when feeding with the sweeping technique on benthos that contained macroinvertebrate densities similar to the present study, was able to obtain an average of 18 prey items per minute. If we consider the same number of prey captured per minute by the Red-necked Avocet, the average time to achieve the theoretical DEE would be 14.01± 0.16 hours, 13.49 ± 0.11 hours and 5.56 ± 0.06 hours for Dampier, Lake MacLeod and Port Hedland respectively. Therefore, based on the observations (see Ross et al.2012) that Red-necked Avocets could capture more than a single prey with each stroke, they would be able to achieve their DEE at all locations. In the same manner, Banded Stilts feeding with the sweeping technique would probably capture more than 1 prey per stroke. In the case of Banded Stilts feeding on brine shrimp, it was assumed that the average brine shrimp captured was of the average size available in the ponds, although it is likely that Banded Stilts are able to select the biggest class sizes of brine shrimp available in the ponds, therefore increasing their intake rates.

Value of Dampier Salt Ltd. operations in the context of the East Asian-Australasian Flyway

The East Asian–Australasian flyway is the one that holds the highest number of shorebirds (Milton 2003), but is also the flyway that holds more globally threatened or near-threatened species than any other (Milton 2003, Kirby 2010). The region of the flyway also contains over 45% of the world's human population and consequently extensive areas of intertidal flats have been lost to urban, industrial, and agricultural land reclamations (Barter 2002, Yang et al. 2011, Murray et al. 2014). At the same time, serious population declines of migratory shorebird species that use sites in Southeast Asia as a stopover have been observed (Amano et al. 2010, Wilson et al. 2011, Szabo et al. 2012). In fact, of the 7 species of migratory shorebirds included in this report, 1 (Curlew Sandpiper) is listed as critically endangered under the EPBC Act, 3 (Bar-tailed Godwit, Red Knot and Great Knot) are listed as vulnerable under the *Wildlife Conservation Act 1950* of Western Australia, and under the Action Plan for Australian Birds 2010 (Garnett et al. 2011). The Great Knot is listed as vulnerable globally in the IUCN Red List of Threatened Species 2014.

This study reveals for the first time the remarkable value that Lake MacLeod has as a feeding ground for nonbreeding migratory shorebirds. Although the study has been focused on 2 particular sites, is not unexpected that other similar or better feeding grounds may occur at Lake MacLeod, due to its complex of aquatic ecosystems which include many different ponds, vents and extensive mudflats, especially on the southeastern side of Cygnet Pond. This valuable habitat supports high numbers of shorebirds (Davis 2001, Hassell 2006, Bertzeletos et al. 2012) and is also a nonbreeding foraging site for migratory and nonmigratory species, strategically situated between the southern part of the continent and the northwest and its future protection is of high importance for shorebirds.

In the last decade, several studies have pointed out the importance of anthropogenic feeding habitats for migratory shorebirds, especially during periods of high energetic demand such as premigration and migration (Masero 2003, Navedo et al. 2013, Dias et al. 2014). Such sites are also important for maintaining nonbreeding populations (Masero and Perez-Hurtado 2001, Sripanomyom et al. 2011) and can also act as offsets against the loss and degradation of natural habitats (Masero 2003, Navedo et al. 2013). The use of saltworks such as Port Hedland and Dampier by migratory shorebirds premigration and during migration would allow these birds to develop the reserves needed to migrate or even migrate early. Moreover, the quality of non-breeding foraging sites can have significant carry-over effects on the dynamics of migratory shorebird populations (Norris 2005). Thus the improvement or degradation of the quality of non-breeding foraging sites can have positive or negative effects on shorebird populations (Gill et al. 2001, Burton et al. 2006, Duriez et al 2012).

Therefore the existence of isolated shorebird habitats that are virtually free of human disturbance at Lake MacLeod, as well as the supratidal saltworks such us at Port Hedland and Dampier, which act as alternative or supplementary feeding habitats, can have positive effects on the survival of migratory shorebird populations.

CONCLUSIONS

■ The operation with the highest benthic macroinvertebrate abundance was Lake MacLeod and particularly the inundated flats adjacent to Whistler Pond. Polychaetes were the most abundant taxa at all sites.

■ At Lake MacLeod the highest benthic macroinvertebrate abundances were found in the top 5 cm of the sediment whereas at Dampier, they were normally found below the first 5 cm.

■ The highest abundance of brine shrimp (*Artemia sp.*) was found in concentration ponds 5 and 6 at Port Hedland.

■ Amphipods and polychaetes were the main benthic prey for shorebirds at Lake MacLeod and Port Hedland-Dampier respectively. The Red Knot and the Great Knot at Lake MacLeod were the only species which deviated from this feeding pattern, with polychaetes preferred by Red Knots and bivalves being the most common prey for Great Knots.

■ The main prey captured from the water column by shorebirds was brine shrimp.

■ Wind appeared to play a major role in shorebird habitat use at Lake MacLeod, making available or unavailable large areas of mudflats as foraging sites. Wind also appeared to affect shorebird use of concentration ponds at Port Hedland.

■ There was segregation in the range of water depths where the birds tend to feed in relation to bird size. For birds feeding on benthic prey, small shorebirds (Red-necked Stint, Broad-billed Sandpiper and Red-capped Plovers) tended to feed at water levels ≤ 2.3 cm, while small to medium-size shorebirds fed equally at water levels higher or lower than 3.3 cm (but < 5 cm), except Sharp-tailed Sandpipers, which tended to feed at water levels > 3.3 cm (but < 5 cm). Bar-tailed Godwits fed at water depths > 5.5 cm (but < 10 cm) and Red-necked Avocets at water depths > 8.4 cm. Banded-Stilts fed equally at water depths ≤ 8.4 or > 8.4 cm.

■ For birds feeding on prey suspended in the water column, small shorebirds fed in shallow waters ≤ 2.3 cm, small to medium-size shorebirds fed in medium to shallow waters > 3.3 cm (but < 5 cm), and Banded Stilts fed at a range of water depths, being able to swim.

■ Small to medium-size shorebirds feeding in shallow water depths (≤ 3. 3 cm) had higher feeding rates when feeding on prey suspended in the water column than when feeding at greater depths.

■ In general, migratory and resident shorebirds achieved higher feeding and intake rates at Lake MacLeod than at the other 2 operations. These differences appear to be related to differences in prey density, prey availability and prey type.

■ Migratory species showed higher intake rates than resident species on most occasions.

■ Several species were observed feeding at night, among them Red-necked Avocets, Bar-tailed Godwits, Red-capped Plovers and Red-necked Stints. Red-capped Plovers walked significantly less at night that during daylight and their feeding attempts increased at night, indicating higher prey availability at the sediment surface. Red-necked Stints walked more at night but their feeding attempts were similar both day and night.

■ Of the 3 operations studied, Lake MacLeod provided the best quality feeding areas for small to medium-size migratory shorebirds, which were able to achieve their theoretical Daily Energy Expenditure (DEE) both post and premigration. Small shorebirds could also achieve their DEE feeding exclusively at Port Hedland or Dampier postmigration. Therefore these operations could act as alternative feeding grounds for small migratory shorebirds postmigration. Premigration however, none of the migratory species would be able to obtain their DEE feeding exclusively at Port Hedland or Dampier. This suggests that the birds fed on the adjacent intertidal area at low tide and that the saltworks acted as complementary feeding grounds.

■ Dampier Salt Ltd. operations and Lake MacLeod in particular, are strategically located in northwestern Australia, within the western section of the East Asian-Australasian flyway. The high numbers and diversity of shorebirds that these sites host and the important feeding grounds they provide, suggest that it would be appropriate for them to be granted a higher level of protection. Notably, Lake MacLeod meets several of the criteria (e.g. criteria 1, 2, 5 and 6) required to be considered a Wetland of International Importance under the

Ramsar Convention, and as such, it should be considered for nomination and be better protected.

Knowledge gaps

1 Gather knowledge on shorebird intertidal and supratidal habitat use in different periods of their annual cycle at the Dampier and Port Hedland operations.

2 Obtain information about shorebird use of Lake MacLeod under different wind regimes and in different periods of their annual cycle.

3 Assess experimentally how different water levels or water depths affect shorebird habitat use of the Dampier and Port Hedland operations.

4 Study seasonal variability in the abundance and community composition of benthic invertebrates at all locations.

Species cards

Curlew Sandpiper
Calidris ferruginea

Status: Critically Endangered (EPBC). Least Concern (IUCN).

Small-sized migratory shorebird, weight 57 g[1].
Thousands occur in Lake Macleod in post- and pre-migration. Hundreds occur in Port Hedland operations in post and pre-migration. Dampier only in post-migration.
Prey at Lake MacLeod: amphipods and polychaetes.
Prey at Port Hedland operations: brine-shrimp and polychaetes.
Water levels: Tend to feed at 3 cm of water depth.
MANAGEMENT RECOMMENDATIONS: Lake MacLeod should acquire a higher level of protection. In Port Hedland and Dampier water levels should be managed to ensure bird access to concentration ponds and shallow areas of Pond 0 close to the intakes. Port Hedland and Dampier should be managed to ensure high densities of brine shrimp.

[1]Data from Department of the Environment (2015). *Calidris ferruginea* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Sharp-tailed Sandpiper
Calidris acuminate

Status: Least Concern (IUCN).

Small-medium migratory shorebird, weight of 65 g[1].
Common in Lake Macleod (thousands) and Port Hedland (hundreds) in post-migration, few in pre-migration. Observed in Dampier only in post-migration.
Prey at Lake MacLeod: amphipods and polychaetes.
Prey in Port Hedland and Dampier operations: brine-shrimp, polychaetes, amphipods and bivalves.
Water levels: Tend to feed at water depths 3 - 5cm.
MANAGEMENT RECOMMENDATIONS: Lake MacLeod should acquire a higher protection level. In Port Hedland and Dampier water levels should be managed to ensure access to concentration ponds and shallow areas of Pond 0 close to the intakes. Port Hedland and Dampier operations should be managed in a way to ensure high densities of brine shrimp.

[1]Data from Department of the Environment (2015). *Calidris acuminata* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Red-necked Stint
Calidris ruficollis

Status: Least Concern (IUCN).
The smallest migratory shorebird in Australia, 25 g weight[1].
High numbers occur in Lake Macleod (thousands) and Port Hedland (hundreds) in post and pre-migration. High numbers (thousands) in Dampier only in post-migration.
Prey at Lake MacLeod: amphipods and polychaetes.
Prey in Port Hedland and Dampier operations: brine-shrimp, polychaetes, brine-fly.
Water levels: feed at shallow water depths < 2 cm.
MANAGEMENT RECOMMENDATIONS: Lake MacLeod should acquire a higher protection level. In Port Hedland and Dampier water levels should be managed in a way to ensure accessibility to concentration ponds and shallow areas of Pond 0 close to the intakes. Port Hedland and Dampier should be managed in a way to ensure high densities of brine shrimp.

[1]Data from Department of the Environment (2015). *Calidris ruficollis* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Broad-billed Sandpiper
Limicola falcinellus

Status: Least Concern (IUCN).
Small-sized migratory shorebird, weight of 40 g[1].
High numbers (hundreds) occur in Port Hedland in post and pre-migration in specific areas of Pond 0. Relatively high numbers observed in Lake MacLeod in pre-migration (hundred).
Prey in Port Hedland operations: polychaetes, amphipods.
Prey at Lake MacLeod: amphipods and polychaetes.
Water levels: shallow water depths < 2 cm.
MANAGEMENT RECOMMENDATIONS: Port Hedland water levels should be managed in a way to ensure accessibility to shallow areas of Pond 0 close to the intakes.

[1]Data from Department of the Environment (2015). *Limicola falcinellus* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Red Knot
Calidris canutus

Status: Least Concern (IUCN). Vulnerable (Wildlife Conservation Act WA).
Small to medium-sized migratory shorebird, weight of 120 g[1].
Relatively high numbers observed in Lake MacLeod in pre-migration (thousand).
Prey at Lake MacLeod: polychaetes, seagrass and bivalves.
Water levels: depths around 3 cm but < 5cm.
MANAGEMENT RECOMMENDATION: Lake MacLeod should acquire a higher protection level.

[1]Data from Department of the Environment (2015). *Calidris canutus* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Great Knot
Calidris tenuirostris

Status: Vulnerable (IUCN and Wildlife Conservation Act WA).
Medium-sized migratory shorebird, weight between 115–248 g[2].
Observed in Lake MacLeod in pre-migration (hundreds).
Prey at Lake MacLeod: bivalves.
Water levels: depths < 5 cm.
MANAGEMENT RECOMMENDATION: Lake MacLeod should acquire a higher protection level.

[2]Van Gils, J., Wiersma, P. & Sharpe, C.J. (2015). Great Knot (*Calidris tenuirostris*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. & de Juana, E. (eds.) (2015). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Bar-tailed Godwit
Limosa lapponica

Status: Least Concern (IUCN). Vulnerable (Wildlife Conservation Act WA).
Large-sized migratory shorebird, weight between 250–450 g[1].
Observed feeding and roosting in Pond 0 in Dampier and Port Hedland operations in post and pre-migration. Observed in Lake MacLeod in low numbers in pre-migration.
Prey at Dampier and Port Hedland: polychaetes.
Water levels: depths > 5 cm but < 10 cm.
MANAGEMENT RECOMMENDATION: Port Hedland and Dampier operations water levels should be managed in a way to ensure access to shallow areas of Pond 0 close to the intakes.

[1]Data from Department of the Environment (2015). *Limosa lapponica* in Species Profile and Threats Database, Department of the Environment, Canberra. Available from: http://www.environment.gov.au/sprat.

Red-capped Plover
Charadrius ruficapillus

Status: Least Concern (IUCN).
Small, resident shorebird, weight between 27–54 g[1].
Observed feeding and roosting in Pond 0 in Dampier and Port Hedland and in Lake MacLeod in post and pre-migration.
Prey at Lake Macleod: amphipods.
Prey at Dampier and Port Hedland: polychaetes.
Water levels: depths < 3 cm.
MANAGEMENT RECOMMENDATION: Port Hedland and Dampier water levels should be managed in a way to ensure access to shallow areas of Pond 0 close to the intakes.

[1]Wiersma, P. & Boesman, P. (2013). Red-capped Plover (*Charadrius ruficapillus*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. & de Juana, E. (eds.) (2013). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Red-necked Avocet
Recurvirostra novaehollandiae

Status: Least Concern (IUCN).

Medium-sized, resident shorebird, weight between 270–390 g[4]. Observed feeding and roosting in Pond 0 in Dampier and Port Hedland and in Lake MacLeod in post-migration. Only a few birds observed at Lake MacLeod in pre-migration.

Prey at Lake MacLeod and Port Hedland operations: polychaetes.

Prey at Dampier: chironomids and polychaetes.

Water levels: water depths ≥ 8 cm but < 10 cm.

MANAGEMENT RECOMMENDATION: Port Hedland and Dampier water levels should be managed in a way to ensure access to shallow areas of Pond 0 close to the intakes.

[4]Pierce, R.J. & Boesman, P. (2013). Red-necked Avocet (*Recurvirostra novaehollandiae*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. & de Juana, E. (eds.) (2013). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Banded Stilt
Cladorhynchus leucocephalus

Status: Least Concern (IUCN).

Medium-sized, resident, nomadic shorebird, weight between 220–260 g[5]. Observed feeding and roosting in high numbers at concentration ponds in Port Hedland and in Lake MacLeod in post-migration. Few individuals observed in Dampier in pre-migration.

Prey at Dampier and Port Hedland: brine-shrimp.

Prey at Lake Macleod: Polychaetes, amphipods.

Water levels: depths > 8 cm but are able to swim.

MANAGEMENT RECOMMENDATION: Banded Stilts appeared not to be limited by water levels. Port Hedland and Dampier operations should be managed in a way to ensure high densities of brine shrimp.

[5]Pierce, R.J. & Kirwan, G.M. (2014). Banded Stilt (*Cladorhynchus leucocephalus*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. & de Juana, E. (eds.) (2014). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

References

Agardy, T., Alder, J., Dayton, P., Curran, S., Kitchingman, A., Wilson, M., ... and Vörösmarty, C. (2005). Coastal systems. Ecosystems and human well-being: current state and trends, 1, 513-549.

Amano, T., Székely, T., Koyama, K., Amano, H., and Sutherland, W. J. (2010). A framework for monitoring the status of populations: an example from wader populations in the East Asian–Australasian flyway. Biological Conservation, 143: 2238-2247.

Atkinson, P. W., Clark, N. A., Bell, M. C., Dare, P. J., Clark, J. A., and Ireland, P. L. (2003). Changes in commercially fished shellfish stocks and shorebird populations in the Wash, England. Biological Conservation, 114: 127-141.

Bamford, M. J. and A. R. Bamford. (1997). Cargill Salt Environmental Management Programme- Shorebird Monitoring; 1993-1997 Final Report.

Bart, J., Brown, S., Harrington, B., and Morrison, R. I. G. (2007). Survey trends of North American shorebirds: population declines or shifting distributions? Journal of Avian Biology, 38: 73-82.

Barter, M. (2002). Shorebirds of the Yellow Sea: importance, threats and conservation status. Wetlands International-Oceania.

Battley, P. F., Dietz, M. W., Piersma, T., Dekinga, A., Tang, S., and Hulsman, K. (2001). Is long-distance bird flight equivalent to a high-energy fast? body composition changes in freely migrating and captive fasting great knots. Physiological and Biochemical Zoology, 74(3), 435-449.

Beauchamp, G. (2012). Foraging speed in staging flocks of semipalmated sandpipers: evidence for scramble competition. Oecologia, 169: 975-980.

Bertzeletos, D., Davis, R. A., and Horwitz, P. (2012). Importance of Lake MacLeod, North Western Australia, to shorebirds: a review and update. Journal of the Royal Society of Western Australia, 95: 115–124.

Borges A.V., Schiettecatte L. S., Abril G., Delille B., and Gazeau, F. (2006). Carbon dioxide in European Coastal waters. Estuarine Coastal and Shelf Science 70: 375-387.

Brey, T., Rumohr, H., and Ankar, S. (1988). Energy content of macrobenthic invertebrates: general conversion factors from weight to energy. Journal of Experimental Marine Biology and Ecology, 117: 271-278.

Burton, N. H., Rehfisch, M. M., Clark, N. A., and Dodd, S. G. (2006). Impacts of sudden winter habitat loss on the body condition and survival of redshank *Tringa totanus*. Journal of Applied Ecology, 43: 464-473.

Castro, M., Masero, J. A., Megina, C., Amat, J. A., and Pérez-Hurtado, A. (2008). Energy and macronutrient assimilation efficiencies of Snowy Plover (*Charadrius alexandrinus*) feeding on the polychaete ragworm *Nereis diversicolor*. The Auk, 125: 368-373.

Caudell, J. N., and Conover, M. R. (2006). Energy content and digestibility of brine shrimp (Artemia franciscana) and other prey items of eared grebes (Podiceps nigricollis) on the Great Salt Lake, Utah. Biological Conservation, 130: 251-254.

Choi, C., Gan, X., Ma, Q., Zhang, K., Chen, J., and Ma, Z. (2009). Body condition and fuel deposition patterns of calidrid sandpipers during migratory stopover. Ardea, 97: 61-70.

Costanza R., Kemp W.M. and Boynton, W.R. (1993). Predictability, scale, and biodiversity in coastal and estuarine ecosystems: Implications for management. Ambio, 22: 88-96.

Davis, C. A., and Smith, L. M. (2001). Foraging strategies and niche dynamics of coexisting shorebirds at stopover sites in the southern Great Plains. The Auk, 118: 484-495.

Demers, S. A., Colwell, M. A., Takekawa, J. Y., and Ackerman, J. T. (2008). Breeding stage influences space use of female American Avocets in San Francisco Bay, California. Waterbirds, 31: 365-371.

Demers, S. A., Takekawa, J. Y., Ackerman, J. T., Warnock, N., and Athearn, N. D. (2010). Space use and habitat selection of migrant and resident American Avocets in San Francisco Bay. The Condor, 112: 511-520.

Dias, M. P. (2009). Use of salt ponds by wintering shorebirds throughout the tidal cycle. Waterbirds, 32: 531-537.

Dias, M. P., Lecoq, M., Moniz, F., and Rabaça, J. E. (2014). Can Human-made Saltpans Represent an Alternative Habitat for Shorebirds? Implications for a Predictable Loss of Estuarine Sediment Flats. Environmental management, 53: 163-171.

Dixon, H. D. J. (2009). Effect of Black Swan Foraging on Seagrass and Benthic Invertebrates in Western Golden Bay. (Master's thesis, Massey University). Retrieved from http://hdl.handle.net/10179/1214

Dos Santos, V. M., Matheson, F. E., Pilditch, C. A., and Elger, A. (2012). Is black swan grazing a threat to seagrass? Indications from an observational study in New Zealand. Aquatic botany, 100: 41-50.

Drake, P., and Arias, A. M. (1995). Distribution and production of Microdeutopus gryllotalpa (Amphipoda: Aoridae) in a shallow coastal lagoon in the Bay of Cádiz, Spain. Journal of Crustacean Biology, 15: 454-454.

Duarte C., Ed., Global Loss of Coastal Habitats (Fundación BBVA, Madrid, 10 October 2007). A video of the conference is available at www.fbbva.es/coastalhabitats;

Duriez, O., Ens, B. J., Choquet, R., Pradel, R., and Klaassen, M. (2012). Comparing the seasonal survival of resident and migratory oystercatchers: carry-over effects of habitat quality and weather conditions. Oikos, 121: 862-873.

Ellison, J. C. (2001). Massive mortality of mangrove strands at Ibis and Cygnet Pond, Lake MacLeod, Western Australia.

Ellison, J. and S. Simmonds. (2003). Structure and Productivity of inland mangrove stands at Lake MacLeod, Western Australia. Journal of the Royal Society of Western Australia 86:21-26.

Esselink, P. and Zwarts, L. (1989).Seasonal trend in burrow depth and tidal variation in feeding activity of *Nereis diversicolor*. Marine Ecology Progress Series 56: 243-254.

Esser, W., Vöge, S., and Exo, K. M. (2008). Day-night activity of intertidal invertebrates and methods to estimate prey accessibility for shorebirds. Senckenbergiana maritima, 38: 115-122.

Estrella, S. M., and Masero, J. A. (2007). The use of distal rhynchokinesis by birds feeding in water. The Journal of Experimental Biology, 210: 3757-3762.

Estrella, S. M., Masero, J. A., and Pérez-Hurtado, A. (2007). Small-prey profitability: field analysis of shorebirds' use of surface tension of water to transport prey. The Auk, 124: 1244–1253.

Estrella, S. M., and Masero, J. A. (2010). Prey and Prey Size Selection by the Near-Threatened Black-Tailed Godwit Foraging in Non-Tidal Areas During Migration. Waterbirds, 33: 293-299.

Fuller, R., Clemens, R., Dhanjal-Adams, K., Iwamura, T., Kendall, B., Murray, N., Possingham, H., Studds, C., and Wilson, H. (2014). Conserving migratory shorebirds in a rapidly changing world. 26th International Ornithological Congress, Tokyo, August 2014.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., and Page, G. (2002). Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Waterbirds, 25: 173-183.

Garnett, S., Szabo, J., and Dutson, G. (2011). Action Plan for Australian Birds 2010.

Gattuso J. P., Frankignoulle M. and Wollast R. (1998). Carbon and carbonate metabolism in coastal aquatic ecosystems. Annual Review of Ecology and Systematics 29: 405-34.

George, L. (2009). Shorebirds and their known habitat/status in the Gascoyne Region, Western Australia. Stilt 55:40-50.

Gill, J. A., Norris, K., Potts, P. M., Gunnarsson, T. G., Atkinson, P. W., and Sutherland, W. J. (2001). The buffer effect and large-scale population regulation in migratory birds. Nature, 412: 436-438.

Gillings, S., Fuller, R. J., and Sutherland, W. J. (2005). Diurnal studies do not predict nocturnal habitat choice and site selection of European Golden Plovers (*Pluvialis apricaria*) and Northern Lapwings (*Vanellus vanellus*). The Auk, 122: 1249-1260.

Gillings, S., and Sutherland, W. J. (2007). Comparative diurnal and nocturnal diet and foraging in Eurasian golden plovers *Pluvialis apricaria* and northern lapwings *Vanellus vanellus* wintering on arable farmland. Ardea, 95: 243-257.

Goss-Custard, J. D., Caldow, R. W. G, Clarke, R. T., Durell, S. E. A. le V dit, Urfi, J. and West, A. D. (1995) Consequences of habitat loss and change to populations of wintering migratory birds - predicting the local and global effects from studies of individuals. Ibis, 137: 56–66.

Goss-Custard, J. D., West, A. D., Yates, M. G., Caldow, R. W., Stillman, R. A., Bardsley, L., ... and Pettifor, R. A. (2006). Intake rates and the functional response in shorebirds (Charadriiformes) eating macroinvertebrates. Biological Reviews, 81: 501-529.

Gutiérrez, J. S., Masero, J. A., Abad-Gómez, J. M., Villegas, A., and Sánchez- Guzmán, J. M. (2011). Understanding the energetic costs of living in saline environments: effects of salinity on basal metabolic rate, body mass and daily energy consumption of a long-distance migratory shorebird. The Journal of Experimental Biology, 214: 829-835.

Hassell, C. (2005). Bird Survey Reports For Damper Salt Limited. Lake MacLeod- September 27-30 2005. Port Headland- November 2 2005. Dampier- November 3 & 4 2005. Report for Dampier Salt Limited, Perth (unpubl.).

Hassell, C. (2006). Bird Survey Reports for Rio Tinto Minerals. Lake MacLeod - October 3-5 2006. Port Headland- November 7 2006. Dampier- November 8 & 9 2006. Report for Dampier Salt Limited, Perth (unpubl.).

Handel, C. M., and Gill Jr, R. E. (2010). Wayward youth: trans-Beringian movement and differential southward migration by juvenile Sharp-tailed Sandpipers. Arctic, 273-288.

Hua N, Piersma T, Ma Z (2013) Three-Phase Fuel Deposition in a Long-Distance Migrant, the Red Knot (*Calidris canutus piersmai*), before the Flight to High Arctic Breeding Grounds. PLoS ONE 8(4)

International Wader Study Group - IWSG. (2003). Waders are declining worldwide. Wader Study Group Bulletin, 101/102: 8-12.

Kirby, J. (2010). Review 2: Review of Current Knowledge of Bird Flyways, Principal Knowledge Gaps and Conservation Priorities. CMS Scientific Council: Flyway Working Group Reviews.

Kuwae, T. (2007). Diurnal and nocturnal feeding rate in Kentish plovers *Charadrius alexandrinus* on an intertidal flat as recorded by telescopic video systems. Marine Biology, 151: 663-673.

Landys, M. M., Piersma, T., Guglielmo, C. G., Jukema, J., Ramenofsky, M., and Wingfield, J. C. (2005). Metabolic profile of long–distance migratory flight and stopover in a shorebird. Proceedings of the Royal Society B: Biological Sciences, 272: 295-302.

Logan, B. W. (1987). The MacLeod Evaporite Basin, Western Australia: Holocene environments, sediments and geological evolution. American Association of Petroleum Geologists (Tulsa, Okla, USA).

Lok, T., Hassell, C., and Piersma, T. (2014) Simultaneous decreases in shorebird summer survival suggest a flyway at risk. 26th International Ornithological Congress, Tokyo, August 2014.

Lourenço, P. M., Granadeiro, J. P., and Palmeirim, J. M. (2005). Importance of drainage channels for waders foraging on tidal flats: relevance for the management of estuarine wetlands. Journal of Applied Ecology, 42: 477-486.

Lourenço, P. M., Silva, A., Santos, C. D., Miranda, A. C., Granadeiro, J. P. and Palmerim, J. M. (2008). The energetic importance of night foraging for waders wintering in a temperate estuary. Acta Oecol. 34: 122-129.

Masero, J. A., and Pérez-Hurtado, A. (2001). Importance of the supratidal habitats for maintaining overwintering shorebird populations: how redshanks use tidal mudflats and adjacent saltworks in southern Europe. The Condor, 103: 21-30.

Masero, J. A. (2003). Assessing alternative anthropogenic habitats for conserving waterbirds: salinas as buffer areas against the impact of natural habitat loss for shorebirds. Biodiversity and Conservation, 12: 1157-1173.

Maillet, D., and Weber, J. M. (2006). Performance-enhancing role of dietary fatty acids in a long-distance migrant shorebird: the semipalmated sandpiper. Journal of Experimental Biology, 209: 2686-2695.

Maillet, D., and Weber, J. M. (2007). Relationship between n-3 PUFA content and energy metabolism in the flight muscles of a migrating shorebird: evidence for natural doping. Journal of Experimental Biology, 210: 413-420.

Marchant, J., Hayman, P., and Prater T. (2010). Shorebirds. A and C Black.

McNeil, R., Díaz, O. D., Liñero I. and Rodriguez J. R. (1995). Day-and night-time prey availability for waterbirds in a tropical lagoon. Canadian Journal of Zoology, 73: 869-878.

McNeil, R., Drapeau, P., and Goss-Custard, J. D. (1992). The occurrence and adaptive significance of nocturnal habits in waterfowl. Biological Reviews, 67: 381-419.

Meissner, W, and Górecki, D. (2006). Biometrics and body mass variation of Curlew Sandpiper *Calidris ferruginea* caught on the Puck Bay coast, Poland, during southward migration. International Wader Studies, 19: 125-129.

Milton, D. (2003). Threatened shorebird species of the East Asian-Australasian Flyway: significance for Australian wader study groups. Wader Study Group Bulletin 100: 105-110.

Moreira, F. (1997). The importance of shorebirds to energy fluxes in a food web of a south European estuary. Estuarine, Coastal and Shelf Science, 44: 67-78.

Mouritsen, K. N. (1994). Day and night feeding in dunlins *Calidris alpina*: choice of habitat, foraging technique and prey. Journal of Avian Biolology. 25: 55-62.

Murray, N. J., Clemens, R. S., Phinn, S. R., Possingham, H. P., and Fuller, R. A. (2014). Tracking the rapid loss of tidal wetlands in the Yellow Sea. Frontiers in Ecology and the Environment, 12: 267-272.

Nagy, K. A. (1987). Field metabolic rate and food requirement scaling in mammals and birds. Ecological Monographs. 57: 111-128.

Navedo, J. G., Arranz, D., Herrera, A. G., Salmón, P., Juanes, J. A., and Masero, J. A. (2013). Agroecosystems and conservation of migratory waterbirds: importance of coastal pastures and factors influencing their use by wintering shorebirds. Biodiversity and Conservation, 22: 1895-1907.

Nebel, S., Rogers, K. G., Minton, C. D., and Rogers, D. I. (2013). Is geographical variation in the size of Australian shorebirds consistent with hypotheses on differential migration? Emu, 113: 99-111.

Nilsson, H. C., and Rosenberg, R. (2000). Succession in marine benthic habitats and fauna in response to oxygen deficiency: analysed by sediment profile-imaging and by grab samples. Marine Ecology Progress Series, 197: 139-149.

Nolet, B. A., and Mooij, W. M. (2002). Search paths of swans foraging on spatially autocorrelated tubers. Journal of Animal Ecology, 71: 451-462.

Norris, D. R. (2005). Carry-over effects and habitat quality in migratory populations. Oikos, 109: 178-186.

Ntiamoa-Baidu, Y. A. A., Piersma, T., Wiersma, P., Poot, M., Battley, P., and Gordon, C. (1998). Water depth selection, daily feeding routines and diets of waterbirds in coastal lagoons in Ghana. Ibis, 140: 89-103.

Pienkowski, M. W. (1983). Changes in the foraging pattern of plovers in relation to environmental factors. Animal Behaviour, 31: 244-264.

Pierce, R.J. and Boesman, P. (2013). Red-necked Avocet (*Recurvirostra novaehollandiae*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. and de Juana, E. (eds.) (2013). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Pierce, R.J. and Kirwan, G.M. (2014). Banded Stilt (Cladorhynchus leucocephalus). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. and de Juana, E. (eds.) (2014). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Piersma, T., and Baker, A. J. (2000). Life history characteristics and the conservation of migratory shorebirds. Conservation Biology Series – Cambridge, 105-124.

Powell, A. N. (2001). Habitat characteristics and nest success of snowy plovers associated with California least tern colonies. The Condor, 103: 785-792.

Rojas de Azuaje, L. M., Tai, S., and McNeil, R. (1993). Comparison of rod/cone ratio in three species of shorebirds having different nocturnal foraging strategies. The Auk, 110: 141-145.

Rojas de Azuaje, L.M., McNeil, R., Cabana, T., and Lachapelle, P. (1999) Diurnal and nocturnal visual capabilities in shorebirds as a function of their feeding strategies. Brain, Behaviour and Evolution, 53: 29-43.

Ross, K., Stillman, R. A., and Herbert, R. J. H. (2010). Understanding fitness-maximising foraging behaviour of overwintering pied avocets (*Recurvirostra avosetta*). British Ecological Society Annual Meeting, Leeds, September 2010.

Russel, P. J. (2004). Geological and geomorphic features and evolution of the Lake MacLeod-Ningaloo-Cape Range-Exmouth Gulf area, Western Australia. Department of Conservation and Land Management, Western Australia

Sánchez, M. I., Green, A. J., and Castellanos, E. M. (2006a). Spatial and temporal fluctuations in presence and use of chironomid prey by shorebirds in the Odiel saltpans, south-west Spain. Hydrobiologia, 567: 329-340.

Sánchez, M. I., Green, A. J., and Castellanos, E. M. (2006b). Temporal and spatial variation of an aquatic invertebrate community subjected to avian predation at the Odiel salt pans (SW Spain). Archiv für Hydrobiologie, 166: 199-223.

Santiago-Quesada, F., Estrella, S. M., Sánchez-Guzmán, J. M., and Masero, J. A. (2014). Why water birds forage at night: a test using black-tailed godwits *Limosa limosa* during migratory periods. Journal of Avian Biology, 45: 406-409.

Santos, C. D., J. M. Palmeirim, and J. P. Granadeiro. 2010. Choosing the best foraging microhabitats: individual skills constrain the choices of dunlins *Calidris alpina*. Journal of Avian Biology 41:18-24.

Schlacher, T. A., Meager, J. J., and Nielsen, T. (2013). Habitat selection in birds feeding on ocean shores: landscape effects are important in the choice of foraging sites by oystercatchers. Marine Ecology.

Sibly, R. M., Witt, C. C., Wright, N. A., Venditti, C., Jetz, W., and Brown, J. H. (2012). Energetics, lifestyle, and reproduction in birds. Proceedings of the National Academy of Sciences, 109: 10937-10941.

Sitters, H. P., González, P. M., Piersma, T., Baker, A. J., and Price, D. J. (2001). Day and night feeding habitat of red knots in Patagonia: profitability versus safety?. Journal of Field Ornithology, 72: 86-95.

Sokal, R. R. and F. J. Rohlf. (2003). Biometry: the principles and practice of statistics in biological research. 3rd edition. W. H. Freeman and Co.: New York. 887 pp.

Spencer, J. A. (2010). Migratory shorebird ecology in the Hunter Estuary, South-Eastern Australia. Ph.D Thesis. Australian Catholic University.

Sripanomyom, S., Round, P. D., Savini, T., Trisurat, Y., and Gale, G. A. (2011). Traditional salt-pans hold major concentrations of overwintering shorebirds in Southeast Asia. Biological Conservation, 144: 526-537.

StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com.

Stillman, R. A., West, A. D., Goss-Custard, J. D., McGrorty, S., Frost, N. J., Morrisey, D. J., ... and Drewitt, A. L. (2005). Predicting site quality for shorebird communities: a case study on the Humber estuary, UK. Marine Ecology Progress Series, 305: 203-217.

Stroud, D. A., Baker, A., Blanco, D. E., Davidson, N. C., Delany, S., Ganter, B., Gill, R., González, P., Haanstra, L., Morrison, R. I. G., Piersma, T., Scott, D. A., Thorup, O., West, R., Wilson, J. and Zockler, C. (on behalf of the International Wader Study Group). (2006). The conservation and population status of the world's waders at the turn of the millennium. pp. 643–648 in G. C. Boere, C. A. Galbraith and D. A. Stroud, eds. Waterbirds around the world. Edinburgh, UK: The Stationery Office.

Sushchik, N. N., Gladyshev, M. I., Moskvichova, A. V., Makhutova, O. N., and Kalachova, G. S. (2003). Comparison of fatty acid composition in major lipid classes of the dominant benthic invertebrates of the Yenisei River. Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology, 134: 111-122.

Szabo, J. K., Butchart, S. H., Possingham, H. P., and Garnett, S. T. (2012). Adapting global biodiversity indicators to the national scale: A Red List Index for Australian birds. Biological Conservation, 148: 61-68.

Székely, T., and Bamberger, Z. (1992). Predation of waders (Charadrii) on prey populations: an exclosure experiment. Journal of Animal Ecology, 61: 447-456., Takekawa, J., A. Miles, D. Tsao-Melcer, D. Schoellhamer, S. Fregien, and N. Athearn. (2009). Dietary flexibility in three representative waterbirds across salinity and depth gradients in saltworks of San Francisco Bay. Hydrobiologia 626: 155-168.

Taylor, I. R. (2004). Foraging ecology of the Black-fronted Plover on saline lagoons in Australia: the importance of receding water levels. Waterbirds, 27: 270-276.

Thomas, G. H., Lanctot, R. B., and Szekely, T. (2006). Can intrinsic factors explain population declines in North American breeding shorebirds? A comparative analysis. Animal Conservation, 9: 252-258.

Thomas, R. J., Székely, T., Powell, R. F., and Cuthill, I. C. (2006). Eye size, foraging methods and the timing of foraging in shorebirds. Functional Ecology, 20: 157-165.

Tulp, I., and de Goeij, P. (1994). Evaluating wader habitats in Roebuck Bay (north-western Australia) as a springboard for northbound migration in waders, with a focus on Great Knots. Emu, 94: 78-95.

Turpie, J. K., and Hockey, P. A. (1993). Comparative diurnal and nocturnal foraging behaviour and energy intake of premigratory grey plovers *Pluvialis squatarola* and whimbrels *Numenius phaeopus* in South Africa. Ibis, 135(2), 156-165.

VanDusen, Beth M., Stephen R. Fegley, and Charles H. Peterson. (2012). Prey Distribution, Physical Habitat Features, and Guild Traits Interact to Produce Contrasting Shorebird Assemblages among Foraging Patches. PloS ONE 7: e52694.

van Gils, J. A., Piersma, T., Dekinga, A., Spaans, B., and Kraan, C. (2006). Shellfish dredging pushes a flexible avian top predator out of a marine protected area. PLoS Biology, 4: e376. doi:10.1371/journal.pbio.0040376

Velasquez, C. R., and Hockey, P. A. R. (1992). The importance of supratidal foraging habitats for waders at a south temperate estuary. Ardea, 80: 243-253.

Verkuil, Y., A. Koolhaas, and Van Der Winden, J. (1993). Wind effects on prey availability: how northward migrating waders use brackish and hypersaline lagoons in the Sivash, Ukraine. Netherlands Journal of Sea Research, 31: 359-374.

Verkuil, Y., van der Have, T. M., van der Winden, J., and Chernichko, I. I. (2003). Habitat use and diet selection of northward migrating waders in the Sivash (Ukraine): the use of brine shrimp *Artemia salina* in a variably saline lagoon complex. Ardea, 91: 71-83.

Verkuil, Y., Van Der Have, T. M., Van Der Winden, J., Keijl, G. O., Ruiters, P. S., Koolhaas, A., ... and Chernichko, I. I. (2006). Fast fuelling but light flight in Broad-billed Sandpipers *Limicola falcinellus*: stopover ecology at a final take-off site in spring (Sivash, Ukraine). Ibis, 148: 211-220.

Weber, J. M. (2009). The physiology of long-distance migration: extending the limits of endurance metabolism. Journal of Experimental Biology, 212: 593-597.

Wetlands International (2006). Waterbird Population Estimates – 4th Edition. Wageningen, The Netherlands.

Wiersma, P. and Boesman, P. (2013). Red-capped Plover (*Charadrius ruficapillus*). In: del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. and de Juana, E. (eds.) (2013). Handbook of the Birds of the World Alive. Lynx Edicions, Barcelona.

Wilson, J. R., Nebel, S., and Minton, C. D. T. (2007). Migration ecology and morphometrics of two bar-tailed godwit populations in Australia. Emu, 107: 262-274.

Wilson, H. B., Kendall, B. E., Fuller, R. A., Milton, D. A., and Possingham, H. P. (2011). Analyzing variability and the rate of decline of migratory shorebirds in Moreton Bay, Australia. Conservation Biology, 25: 758-766.

Wikelski, M., Tarlow, E. M., Raim, A., Diehl, R. H., Larkin, R. P. and Visser G. H. (2003) Costs of migration in free-flying songbirds. Nature, 423: 703-704.

Yang, H. Y., Chen, B., Barter, M., Piersma, T., Zhou, C. F., Li, F. S., and Zhang, Z. W. (2011). Impacts of tidal land reclamation in Bohai Bay, China: ongoing losses of critical Yellow Sea waterbird staging and wintering sites. Bird Conservation International, 21: 241-259.

Zharikov Y. and Skilleter G.A. (2002). Sex-specific intertidal habitat use in subtropically wintering Bar-tailed Godwits. Canadian Journal of Zoology 80: 1918-1929.

Zinchenko, T. D., Gladyshev, M. I., Makhutova, O. N., Sushchik, N. N., Kalachova, G. S., and Golovatyuk, L. V. (2014). Saline rivers provide arid landscapes with a considerable amount of biochemically valuable production of chironomid (Diptera) larvae. Hydrobiologia, 722: 115-128.

Zwarts, l., A. M. Blomert, B. Ens, R. Hupkes, and T. M. van Spanje. (1990a). Why do waders reach high feeding densities on the intertidal flats of the Banc d’Arguin, Mauritania?. Ardea 78: 39–52.

Zwarts, L., Blomert, A., and Hupkes, R. (1990b). Increase of feeding time in waders preparing for spring migration from the Banc d'Arguin, Mauritania. Ardea 78: 237-256.

Zwarts, L., and Wanink, H. J. (1993). How the food supply harvestable by waders in the Wadden Sea depends on the variation in energy density, body weight, biomass, burying depth and behaviour of tidal-flat invertebrates. Netherlands Journal of Sea Research, 31: 441–476.

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