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A baseline assessment of contaminants in western school prawns (*Metapenaeus dalli*) in the Swan Canning Estuary and associated human health consumption guidance

Peter Novak and Steeg Hoeksema

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GOVERNMENT OF WESTERN AUSTRALIA

Department of **Biodiversity, Conservation and Attractions**

Department of Biodiversity, Conservation and Attractions
Locked Bag 104
Bentley Delivery Centre WA 6983
Phone: (08) 9219 9000
Fax: (08) 9334 0498

www.dbca.wa.gov.au

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This report/document/publication was prepared by Peter Novak and Steeg Hoeksema

Questions regarding the use of this material should be directed to:
River and Estuaries Science Program
Biodiversity and Conservation Science
Department of Biodiversity, Conservation and Attractions
Locked Bag 104
Bentley Delivery Centre WA 6983
Email: riversandestuariesscience@dbca.wa.gov.au

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Western school prawns were collected from the Swan Canning Estuary by staff from the Department of Biodiversity, Conservation and Attractions, the Australian Centre for Applied Aquaculture Research, Challenger Institute of Technology and volunteers of the Department's Prawn Watch Program.

Analyses for metal and organic contaminants in whole prawns and prawn tails were conducted by ChemCentre, Western Australia.

Summary

The western school prawn (*Metapenaeus dalli*) is an iconic species in the Swan Canning Estuary and was once associated with a significant commercial and recreational fishery, which declined in the 1970's. In the Swan Canning Estuary this species is an estuarine resident, completing its lifecycle within the system and is therefore susceptible to any water and sediment borne contamination that exists within the estuary. Given improvements in *M. dalli* population due to restocking (2013-2015) and the known contaminant profile in the estuary, an assessment of the contaminants in this popular recreational species and the potential risk to human health from consumption of captured prawns was implemented.

Previous contaminant investigations in the Swan Canning Estuary have identified the presence of a range of contemporary and legacy contaminants within the Swan Canning Estuary (e.g. Nice, 2009). These findings had prompted community concern regarding the safe consumption of seafood from the Swan Canning Estuary. In 2015 contaminants in black bream were investigated and a human consumption guidance was subsequently reported (Hoeksema, 2015). A recommendation of that investigation was to expand the understanding of contamination in other estuarine species. The current study addressed that recommendation and sought to determine the composition and concentration of contaminants in *M. dalli* and determine which contaminants, if any, pose a human health risk through consumption of the prawns.

Composite samples of whole prawns and prawn tails were collected in 2014 and 2015 from the Swan Canning Estuary. Samples were analysed for an extensive suite of 79 contaminants, of which 20 were detected in the prawn tails and 22 were detected in the whole prawns. Concentrations were generally higher in the whole prawns than the prawn tails, indicative of the accumulation of contaminants in the cephalothorax of crustaceans. However, higher concentrations of DDT and metabolite DDD, and the polychlorinated biphenyl Aroclor 1254 were higher in the prawn tails then the whole prawns. A difference in contaminant concentration and composition between 2014 and 2015 was also determined, suggesting annual differences in contaminant exposure patterns.

This report, and that on black bream (Hoeksema 2015) found that while contaminants are present within the body tissues of prawns and fish within the estuary, the concentrations of these contaminants were not high enough to restrict consumption of either species. This consumption guidance only applies to adults excluding pregnant women and children, it does not consider exposure from other sources, the impact of cooking and the potential antagonistic or synergistic effects of other contaminants. This consumption guidance may be updated and replaced by a periodically reviewed human health risk assessment produced by the Department of Health.

1 Introduction

In 2009, comprehensive baseline contaminant investigations of water and sediment in the Swan Canning Estuary (Nice, 2009) and its catchment (Foulsham et al., 2009; Nice, 2009). These studies identified regions within the estuary where elevated concentrations of heavy metals, organochlorine pesticides, petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAH) were detected (Nice, 2009, 2013b). The sources of contamination in the estuary were primarily associated with historic and current agricultural, industrial and urban land uses The potential impact of these contaminants on ecological and animal health is dependent on concentrations and exposure duration (Nice, 2011; Nice & Fisher, 2011). Risk to humans may occur through consumption of affected biota but is dependent on the level of contamination of targeted fauna and consumption amounts.

Metapenaeus dalli is a resident species (completes its life cycle within the estuary) within the Swan Canning Estuary and has been highly sought-after by both recreational and commercial fishers since the 1900s. The commercial catch of *M. dalli* peaked in 1959 and has not been the focus of a commercial fishery since the 1970s (Broadley, Tweedley, & Loneragan, 2017). The recreational fishery was very popular throughout much of the later 1900s and became a dominant recreational and cultural past time (Smithwick, 2011). However, throughout the 1990s recreational catches of *M. dalli* declined and consecutive low annual catches resulted in substantial drop in the number of people targeting the species. The decline was largely thought to be the result of fishing pressure, poor recruitment and environmental changes (K. Smith, Lenanton, & Valesini, 2007; Tweedley et al., 2017). Between 2013-2015 a concerted restocking effort increased the population of *M. dalli* in the estuary and reignited recreational interest in the fishing (Tweedley et al., 2017).

As an estuarine resident species, completing its entire life history in the Swan Canning Estuary (Broadley et al., 2017; Tweedley et al., 2017), any potential contaminant load in *M. dalli* would reflect that in the estuary. In addition, prawns exhibit behavioural characteristics that may increase their susceptibility to estuarine contaminants. Members of the genus *Metapenaeus*, including *M. dalli* and *M. macleayi*, have been identified as spending a significant proportion of a diurnal period buried in sediments (Bennet, 2014; Ruello, 1973). Finer sediments are easier to burrow into and are favoured by prawns, especially juveniles (Bennet, 2014; Ruello, 1973). Many contaminants, including heavy metals and organic compounds such as pesticides and hydrocarbons, preferentially bind to the sediment rather than remain dissolved in the water column. In addition, the sediments with a finer particle size and higher organic matter content have a greater surface area on which the contaminants adsorb. Thus, fine sediments associated porewaters will generally have higher contaminant loads than coarser sediments. Burrowing behaviour potentially exposes the prawns to higher concentrations of contaminants within the sediment porewater than they would be exposed to if they remained on the surface (Lewtas, Birch, & Foster-Thorpe, 2014). Contaminant exposure pathways include the

absorption of contaminants in the water and sediment pore water through the gills and skin (e.g. Cresswell, Simpson, Mazumder, Callaghan, & Nguyen, 2015). Dietary pathways are also likely as prawns are benthic detritivores and ingest a substantial quantity of sediment when feeding, thereby increasing their exposure to sediment contaminants (e.g. Cresswell, Smith, Nugegoda, & Simpson, 2014). As a result of these factors, prawns and other decapods can often have higher concentrations of certain contaminants than higher trophic order species (Hu et al., 2010).

A survey of Perth residents in relation to the Swan Canning Estuary in 2007, identified the safety of the fish and crustaceans for human consumption as a key concern (Research Solutions, 2007). These concerns were raised again following the publication of baseline contaminant surveys in 2009 (Foulsham et al., 2009; Nice, 2009; Nice et al., 2009) and prompted an investigation of organic contaminants in some key recreationally targeted estuarine fish and invertebrate species (Smith, 2010). A more comprehensive investigation was undertaken by Hoeksema (2015) examining the occurrence of extensive suite of 79 contaminants in the fillets of a key recreational angling species, black bream (*Acanthopagrus butcheri*) in the Swan Canning Estuary. Of the 79 contaminants, only 16 were detected in black bream fillets. Additionally, Hoeksema (2015) developed a method to determine human health consumption guidance of key recreational fishing species. When applied to black bream in the Swan Canning Estuary, the consumption guidance revealed that singularly (without allowing for antagonistic or additive effects of multiple contaminants), no contaminant was of sufficient concentration in the muscle tissue to restrict consumption. A key recommendation of that report and consistent with guidance contained in the United States EPA report (United States Environmental Protection Agency, 2000a) was to investigate the contaminants in at least one other key aquatic species in order to provide an overall assessment of the risk to human health from consumption of aquatic species in the estuary. The current report has sought to address this recommendation.

1.1 Aims

The primary purpose of this study was to assess the background concentration of contaminants in *M. dalli* and determine the risk to human health by applying the consumption guidance methodology developed by Hoeksema (2015). To determine the human health risk the concentration of 79 contaminants in both prawn tails and whole prawns were evaluated. Although prawn tails are most often consumed by recreational anglers it was recognised that some culinary practice would utilize whole prawns. Additionally, the inclusion of whole prawns enables the partitioning of contaminants within prawns to be understood, information that is crucial in determining potential impact of contaminants on *M. dalli* in the Swan Canning Estuary.

2 Materials and methods

2.1 Sampling regime

Metapenaeus dalli were collected from the Swan Canning Estuary between February and March in both 2014 and 2015 using hand trawl nets (width = 4 m, mesh = 9 mm) and opportunistically with hand dip nets (width = 0.5 m, mesh = 10 mm). Sampling targeted *M. dalli* at Canning Bridge in the Canning Estuary in both years and in the Lower Swan Canning estuary at Heathcote in 2014 and Matilda Bay in 2015 (Figure 1). *Metapenaus dalli* are highly mobile, and distribution and abundance throughout the estuary can vary substantially throughout the year, thus samples were collected opportunistically (where they were sufficiently abundant to collect a composite sample) during a concurrent and extensive sampling regime throughout the Swan Canning Estuary and prawn brood-stock collection associated with a restocking program (Tweedley et al., 2017). As a result of the high mobility of the species and its variable distribution throughout the estuary, targeted sampling at sites specifically identified as high priority sites by Nice (2007) was not practicable and thus this study does not aim to determine location effects.

Hand trawls were conducted to a maximum depth of 1.5 m and over approximately 50 m. Trawls over new ground were completed at each site until a sufficient number of prawns were collected or trawls no longer yielded prawns. After each trawl, the net was dragged to the beach and placed onto a plastic tarp where the catch was sorted. Dip nets were used opportunistically by wading in shallow waters at a sampling site and targeting individual prawns. Immediately following capture, prawns were identified to species and *M. dalli* greater than 50 mm total length were retained. All non-target species and *M. dalli* below 50 mm TL were returned live to the water. Additionally, because the restocking program was in progress during sampling, ovigerous females were either retained for brood-stock purposes or released at the site of capture. Hence no females were retained for the contaminant study in 2014 and there was a bias towards males in 2015. Retained *M. dalli* were stored live in an aerated esky filled with site water for 12 hours prior to processing to ensure the gastrointestinal tract was empty (noting this period is less than known contaminant depuration rates e.g Robinson et al (2002)). Immediately prior to processing they were euthanised in an ice slurry.

Figure 1. Map showing prawn collection sites in the Swan Canning Estuary

2.2 Sample processing and analysis

Prior to processing of each sample, all surfaces and instruments (polyethylene or ceramic) were cleaned, washed with methanol, rinsed with deionised water and dried with clean paper towels. All specimens were handled with clean nitrile gloves.

Carapace length was measured using Vernier callipers (to the nearest 0.1 mm) from the tip of the rostrum to the mid dorsal posterior edge of the carapace. Total length was obtained by measuring from the tip of the rostrum to the tip of the telson (to the nearest 0.1 mm). Individuals were blotted dry with clean paper towel and weighed to the nearest 0.01 g. Individuals were sexed according to the presence of a petasma (male) or thelycum (female).

Whole prawn composite samples (n = 23) consisted of seven unshelled whole prawns to provide enough material for analysis. Prawn tail composite samples (n = 20) were collected in 2015 only and consisted of 12 unshelled prawn tails removed using a ceramic knife. Care was taken to ensure no internal organs were damaged when the tails were removed so that internal fluids did not contact the targeted tissue. The weight of each tail was recorded to the nearest 0.01 g. To ensure composites were representative of the prawn population susceptible to capture by

recreational fishers, both sexes and specimens caught at the same site on different sampling days were distributed randomly throughout the composites (noting that females were not retained in 2014). All samples were rinsed in deionised water and blotted dry using clean paper towel before being placed in a clean, food-grade polyethylene bag. Samples were stored at -20°C until being transported frozen to the laboratory for analysis. The composition of each composite including the sex, mean length and weight of the specimens is provided in the appendix (Table A1 and A2).

Samples were provided to a National Association of Testing Authorities (NATA) accredited laboratory and tested for the suite of metals and organic contaminants detailed in Table 1, and lipid content. Samples were homogenised and material subsampled for each analytical group. In all cases, the lowest limit of reporting achievable was employed to ensure that a non-detect did not result in an unacceptable uncertainty in the consumption guidance (Table 1).

Metals (mg/kg) were determined using the following methods:

- iASIN1BTVG – Arsenic (inorganic) in biota by selective extraction VG-AAS based on the methods of Øeygard, Lundebye, and Julshamn (1999)
- iMET1BTICP - Metals in biota by microwave digestion and ICPAES (EN 13805:2002/USEPA 3052 modification)
- iMET1BTMS - Metals in biota by mixed acid microwave digestion and ICPMS (EN 13805:2002/USEPA 3052 modification)
- OrgTin-B – Tributyltin and metabolites in biota by solvent extraction and LC-MS

Organic contaminants (mg/kg), *i.e.* organochlorine (OC) and organophosphorus (OP) pesticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and selected other herbicides, were determined using the following methods:

- RCS-OM-05B: OC and OP pesticides, PCBs, Diuron, Metolachlor and Simazine in biota based on USEPA 8081 and USEPA 8141
- RCS-OM-20-B: PAHs in biota based on USEPA 8270

Lipid contribution (% dry weight) was determined following the method:

- Vet10 (Folch): Lipids in biota based on the methods of Folch, Lees, and Sloane Stanley (1957)

*Table 1. The suite of analytes tested for in western school prawn (*M. dalli*) collected from the Swan Canning Estuary in 2014 and 2015, the limit of reporting for each analyte and the available consumption guidance parameters*

	LOR (mg/kg)	ADI (mg/kg-d)	Authority	CSF[1] $(mg/kg\text{-}d)^{-1}$
Metals				
Aluminium	2	0.14	FAO/WHO	-
Arsenic (total)	0.01	-	-	-
Arsenic (inorganic)	0.1	0.0003	USEPA	1.5 (A)
Cadmium	0.001	0.001	FAO/WHO,USEPA	(B1)
Cobalt	0.001	-	-	-
Chromium (total)	0.05	0.003[2]	USEPA	(D)
Copper	0.01	0.2	DHA	(D)
Iron	5	0.8	FAO/WHO	-
Mercury (total)	0.01	0.0006	FAO/WHO	(D)
Mercury (methyl)		0.0001	FAO/WHO	(D)
Manganese	0.05	0.14	USEPA	(D)
Molybdenum	0.01	-	-	-
Nickel	0.01	0.02	USEPA	-
Lead	0.005	0.0036	FAO/WHO	(B2)
Selenium	0.01	0.005	USEPA	(D)
Zinc	1	0.3	USEPA	-
PAHs				
Acenaphthene	0.1	0.06	USEPA	-
Acenaphthylene	0.1	-	-	(D)
Anthracene	0.1	0.3	USEPA	(D)
Benz(a)anthracene	0.1	-	-	(B2)
Benzo(a)pyrene	0.1	-	-	7.3 (B2)
Benzo(e)pyrene	0.1	-	-	-
Benzo(b)&(k)fluoranthene	0.1	-	-	(B2)
Benzo(ghi)perylene	0.1	-	-	(D)
Chrysene	0.1	-	-	(B2)
Dibenzo(ah)anthracene	0.1	-	-	(B2)
Fluorene	0.1	0.04	USEPA	(D)
Fluoranthene	0.1	0.04	USEPA	(D)
Indeno(1,2,3-cd)pyrene	0.1	-	-	(B2)
Naphthalene	0.1	0.02	USEPA	C
Perylene	0.1	-	-	-
Phenanthrene	0.1	-	-	(D)
Pyrene	0.1	0.03	USEPA	(D)
PCBs				
Aroclor 1016	0.001	0.00007	USEPA	-
Aroclor 1221	0.001	-	-	-
Aroclor 1232	0.001	-	-	-
Aroclor 1242	0.001	-	-	-
Aroclor 1248	0.001	-	-	-
Aroclor 1254	0.001	0.00002	USEPA	2 (B2)[3]
Aroclor 1260	0.001	-	-	-
Lipids				
Fat (Folch)	0.005%	-	-	-

	LOR (mg/kg)	ADI (mg/kg-d)	Authority	CSF $(mg/kg\text{-}d)^{-1}$
OC Pesticides				
Aldrin	0.001	0.00003	USEPA	17 (B2)
Chlordane	0.001	0.0005	DHA,EC,FAO/WHO,USEPA	0.35 (B2)
trans-Chlordane	0.001	-	-	-
cis-Chlordane	0.001	-	-	-
p,p'-dichlorodiphenyltrichloroethane (DDT)	0.001	0.0005[4]	USEPA	0.34 (B2)
p,p'-dichlorodiphenyldichloroethylene (DDE)	0.001	-	-	0.34 (B2)
p,p'-dichlorodiphenyldichloroethane (DDD)	0.001	-	-	0.24 (B2)
Dieldrin	0.001	0.00005	USEPA	16 (B2)
Endosulphan	0.001	0.006	USEPA	-
Endosulphan sulphate	0.001	0.006	FAO/WHO	-
α-Endosulphan	0.001	0.006	FAO/WHO	-
β-Endosulphan	0.001	0.006	FAO/WHO	-
Endrin	0.001	0.0002	DHA,FAO/WHO	(D)
α-Hexachlorocyclohexane	0.001	-	-	6.3 (B2)
β-Hexachlorocyclohexane	0.001	-	-	1.8 (C)
δ-Hexachlorocyclohexane	0.001	-	-	(D)
Lindane (γ-HCH)	0.001	0.0003	USEPA	-
Heptachlor	0.001	0.0001	EC,FAO/WHO	4.5 (B2)
Heptachlor epoxide	0.001	0.000013	USEPA	9.1 (B2)
Hexachlorobenzene	0.001	0.0008	USEPA	1.6 (B2)
Methoxychlor	0.001	0.005	USEPA	(D)
OP pesticides				
Bromophos-ethyl	0.01	0.003	EC,FAO/WHO	-
Chlorfenvinphos	0.01	0.0005	EC,FAO/WHO	-
Chlorpyrifos	0.01	0.003	DHA	-
Chlorpyrifos-methyl	0.01	0.01	EC,FAO/WHO	-
Diazinon	0.01	0.0002	EC	-
Ethion	0.01	0.0005	USEPA	-
Fenchlorphos	0.01	0.01	FAO/WHO	-
Fenitrothion	0.01	0.002	DHA	-
Malathion	0.01	0.02	USEPA	-
Methidathion	0.01	0.001	EC,FAO/WHO,USEPA	-
Mevinphos	0.01	0.0008	EC,FAO/WHO	(C)
Parathion	0.01	0.0006	EC	(C)
Parathion-methyl	0.01	0.0002	DHA	-
Tetrachlorvinphos	0.01	0.03	USEPA	-
Other Herbicides				
Diuron	0.1	0.002	USEPA	-
Metolachlor	0.1	0.08	DHA	(C)
Simazine	0.1	0.005	DHA,USEPA	-
Antifoulants				
Tributyltin oxide (as Sn)	0.001	0.00025[5]	EC	(D)
Bibutyltin (as Sn)	0.001			

LOR = Limit of Reporting; **ADI** = Acceptable Daily Intake; **Authority** = issuing authority of the most conservative ADI; **CSF** = Cancer Slope Factor; **DHA** = Department of Health and Ageing, Australia; **EC** = European Commission; **FAO/WHO** = Food and Agriculture Organisation / World Health Organisation; **USEPA** = United States Environmental Protection Agency; **A** = human carcinogen; **B1/B2** = probable human carcinogen; **C** = possible human carcinogen; **D** = not classifiable to human carcinogenicity.

[1] Issuing authority for CSFs is USEPA. Carcinogenic characterisation based on oral routes of exposure only (USEPA 2018).

[2] ADI employed for Chromium (total) is the more conservative value for Chromium VI

[3] CSF is for PCB mixtures and is based on carcinogenicity assessment of Aroclors 1260, 1254, 1242 and 1016 (USEPA 2018).

[4] ADI is for Total DDT (sum of 4,4'- and 2,4'- isomers of DDT, DDE and DDD; USEPA 2018).

[5] ADI is for a group of organotin compounds (sum of tributyltin, dibutyltin, triphenyltin and di-n-octyltin).

2.2.1 Data analysis

Multivariate approaches were applied to the analyses of the dataset to investigate: 1) a comparison of tissue types (tails vs whole prawns in 2015) and; 2) interannual differences (whole prawns 2014 vs 2015). For those analytes that were detected in some, but not all, samples, *i.e.* Cd, Ni, TBT, Dieldrin, DDE, DDD and Aroclor 1254, a conservative approach, consistent with that of the (United States Environmental Protection Agency, 2000b), was employed whereby non-detects were treated as half of the limit of reporting for that analyte. Data were normalised ($(n - \bar{x})/\sigma$) to remove the effect of enormous differences in concentration of the different contaminants. A Euclidean Distance resemblance matrix was constructed. To statistically test for differences the between years (2014 and 2015) or tissue types (whole prawns and prawn tails) ANOSIM was conducted followed by SIMPER analysis to further explore the data and determine the contaminant(s) driving the major difference between years or tissue types. Nonmetric multidimensional scale (MDS) analysis was performed to visually explore the comparisons. All statistical analysis was conducted using PRIMERe (Version 6).

2.3 Consumption guidance determination

This study extends the work completed by Hoeksema (2015) by analysing *M. dalli* for the same list of contaminants (listed in Table 1) which were selected based upon extensive review of the literature including previous studies investigating contaminants in biota and the environment in the Swan Canning Estuary (Table 2). In addition, contaminants were also selected where exceedances of relevant environmental guidelines, *i.e.* Australian Water Quality Guidelines (ANZG, 2018) marine or freshwater 95% ecosystem protection trigger values and low interim sediment quality guidelines, at any site in the Swan Canning Estuary on any occasion during contaminant investigations between 2006 and 2013.

Of the 79 contaminants analysed in this study 54 have an Acceptable Daily Intake (ADI) guideline assigned by a national or international human health authority (Table 1). An ADI represents the level of intake of a chemical that can be ingested daily over an entire lifetime (*i.e.* 70 years) without an appreciable risk to human health. The most conservative ADI available was always employed when calculating the consumption guidance.

In addition, 20 of the analytes in this study have been identified as known or probable human carcinogens, of which 17 have been assigned Cancer Slope Factors (CSFs). The CSF represents the increased likelihood of developing cancer or cancer related illness from the daily ingestion of a known or probable human carcinogen over a lifetime (USEPA 2000a, 2000b).

Other considerations applied to the data include;

- Inorganic arsenic was detected at very low levels in the whole prawns and not detected in the prawn tails. Inorganic arsenics is frequently not detected in environmental samples due to the laboratory detection limits being approximately 10 times higher than total arsenic, in such cases a conversion factor applied to the total arsenic can be used (i. e. United States Environmental Protection Agency, 2003). However in this study inorganic arsenic was detected, the measured values were used to calculate the consumption guidance in accordance with the method applied by Food Standards Australia New Zealand (2019) which resulted in no guidance calculated for the prawn tails.
- The (USEPA 2000a, 2000b) recommends that total mercury is analysed and the conservative assumption be made that all mercury is present as the toxic methylmercury and,
- The ADI for the group of organotin compounds (Tributyl tin (TBT) and dibutyltin (DBT)) when expressed as the tin (Sn) content (European Food Safety Authority, 2004) is the most conservative approach and has been adopted in this study.
- Chromium VI is recognised as a carcinogen, however carcinogenic effects are noted only for inhalation exposure and not ingestion (USEPA, 2018).

Consumption guidance was based on the mean concentration (C_m) of each metal or organic contaminant detected above the limit of reporting in at least one sample of composite whole and tails of *M. dalli*. The mean concentration was calculated from all 23 whole composite samples and 20 tail composite samples and for the purposes of this report, was considered representative of *M. dalli* in the entire Swan Canning Estuary rather than of a specific site or region.

For purpose of comparison with future studies the lipid adjusted concentration for organic contaminants was provided, using the equation:

$LC = C / (L_{\%} / 100)$

where LC = the lipid adjusted concentration (mg/kg lipid), C = the concentration of the organic contaminant (mg/kg), and $L_{\%}$ = the percentage of lipid to the total sample weight.

To determine chronic, non-carcinogenic effects an ADI value was employed to calculate the number of standardised meals of *M. dalli* that could be consumed daily over an entire lifetime without an appreciable increase in such effects. Relevant ADI's have been provided in the Table 1 with the prescribing authority listed adjacent. Following the methods of the USEPA (2000b) consumption guidance was calculated by firstly, determining a daily consumption limit (CR_{lim}):

CR_{lim} (kg d^{-1}) = ADI x BW / C_m (USEPA, 2000b)

Where ADI = the acceptable daily intake (mg/kg-bw; see Table 1), BW = a standardised body weight (kg) of the consumer (males and females combined) and C_m = the mean concentration of the substance in the sample (mg kg^{-1}). The standardised body weight employed in this guidance was 79.4

kg, based on an average weight of an Australian male (18 years and over) of 87.0 kg and of a female of 71.8 kg (Australian Bureau of Statistics, 2018).

An acceptable number of meals that could be consumed per month without causing adverse non-carcinogenic effects was then calculated by employing the daily consumption limit:

CR_{mm} (meals/month) = CR_{lim} x T_{ap} / MS (USEPA, 2000b)

Where CR_{mm} = meal consumption limit, T_{ap} = the number of days in the selected period, *i.e.* 30.44 days for a month, and MS = a standardised meal size of 0.150 kg. A standardised meal size for *M. dalli* of 0.075 kg consistent with Food Standards Australia New Zealand (2007) in the assessment of contaminants in prawns.

If the CR_{mm} is >16 meals /month then consumption of the seafood is considered to be unrestricted (USEPA, 2000b).

The risk posed by carcinogenic substances is determined through the calculation of a lifetime risk level (RL) and a comparison of this risk level to a designated acceptable risk level (ARL). The ARL employed in this guidance is consistent with the USEPA recommendation of 1 in 100, 000 and is considered protective of human health. This means that if a lifetime of exposure to the contaminant increases a person's risk of carcinogenic effects by more than 1 in 100 000, (0.00001%) the risk is not acceptable. The RL posed by the concentration of carcinogenic substances in the edible portion of *M. dalli* was determined and assessed using the modified (United States Environmental Protection Agency, 2000b) equation:

$RL = (CR_{lim} \times CSF \times C_m) / BW$

where RL = risk level, CR_{lim} = daily consumption limit (kg d^{-1}), CSF = Cancer Slope Factor ($(mg/kg\text{-}d)^{-1}$; see Table 1), C_m = the mean concentration of the substance in both raw, composite whole prawns and composite prawn tail (mg kg^{-1}) and BW = a standardised body weight (kg) of the consumer (males and females combined), *i.e.* 79.4 kg.

Following the recommendations of the USEPA, when an assessment of the potential non-carcinogenic effects of a known or probable human carcinogen does not restrict consumption, CR_{lim} is to be determined by the average rate of consumption of the specified commodity by the local population. Consumption rate of *M. dalli* in the Swan and Canning Estuary was not known, consequently the current consumption guidance employed the national rate of mollusc and crustacea consumption by Australians 17 years and older of 0.0038 kg day^{-1} (Food Standards Australia New Zealand, 2011).

2.3.1 Caveats

This consumption guidance aims to provide a guidance only and has several important caveats. It should be noted that the consumption guidance in the current study accounts for exposure to metals and organic contaminants only through the consumption of whole or tails of *M. dalli* caught from the Swan Canning Estuary and does not account for contaminant exposure from other sources nor does it account

for potential antagonistic, synergistic or additive effects of multiple contaminants in a single or multiple source. It is also recommended that pregnant and postnatal women consider the current consumption guidance with caution and seek independent dietary advice from a physician before consuming *M. dalli* from the Swan Canning Estuary. Additionally, consumption guidance for children has not been determined in this document. It is acknowledged that there are regions of the estuary where contaminants are higher than others (see Nice 2009), however this consumption guidance does not distinguish the prawns from different regions, instead combines data from multiple sites to characterise the contaminant concentration of the whole estuary.

Table 2. Previous investigations of metals and organic contaminants in fish, crustaceans and molluscs in the Swan Canning Estuary that have potential implications for health. Table modified from Hoeksema (2015).

Investigation	Analytes	Target Species	Sample size	Analysed	Detected analytes	Limitations
Marks, Plaskett, Potter, and Bradley (1980)	Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn.	Black bream, Yellowtail grunter, Perth herring, Sea mullet, Yelloweye mullet.	41, 61, 103, 95, 47.	Fillet.	Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn.	Metals only; bioaccumlation focus rather than human health; NHMRC guidelines employed no longer available.
Shute (2007)	As, As (inorganic), Cd, Cr, Cu, Hg, Ni, Pb, Zn, TBT.	Mussels.	6 (10-15 per composite).	Edible portion.	TBT.	Metals only (organic and inorganic); limited sample size; FSANZ guidelines applied to wild-caught seafood (excluding TBT).
DoH (unpub. data)	Al, As, As (inorganic), Cd, Hg, methyl-Hg, Ni, Pb, Se, Sn, Zn, TBT.	Black bream, Blue swimmer crabs, Mussels, Prawns.	30, 14, 26 (15 per composite), 6.	Edible portion.	Al, As, As (inorganic), Cd, Hg, methyl-Hg, Ni, Pb, Se, Sn, Zn, TBT.	Metals only (organic and inorganic); FSANZ guidelines applied to wild-caught seafood.
Shute (2008)	TBT.	Black bream	13	Fillet.	TBT.	TBT only; not all fish >MLL; limited sample size.
K. A. Smith (2010)	Aldrin, trans-Chlordane, cis-Chlordane, oxy-Chlordane, DDT, DDE, DDD, Dieldrin, Endosulphan sulphate, α- and β-Endosulphan, Endrin, Endrin Aldehyde, Endrin Ketone, α-, β- and δ-HCH, Lindane (ɣ-HCH), Heptachlor, Heptachlor epoxide, HCB, Methoxychlor, PCB congener 8, 18, 28, 44, 52, 66, 77, 101, 105, 118, 126, 128, 138, 153, 169, 170, 180, 187, 195, 206 and 209, PCBs (total).	Black bream, Sea mullet, Perth herring, Blue swimmer crabs.	50, 20, 4, 12.	Edible portion, fillet, eviscerated carcass, whole fish, viscera.	DDT (total), Dieldrin, PCBs (total), Heptachlor / Heptachlor epoxide.	Study focus both dolphin and human health; organic contaminants only; not all fish >MLL; multiple samples from same individual; inconsistent portion analysed; limited sample sizes for edible portion; different laboratories used; FSANZ or APVMA guidelines applied to wild-caught seafood.
Nice and Fisher (2011)	Al, As, Cd, Cr, Co, Cu, Hg, Mn, Pb, Zn, petroleum hydrocarbons, Acenaphthene, Acenaphthylene, Anthracene, Benz(a)anthracene, Benzo(a)pyrene, Benzo(b)&(k)fluoranthene, Benzo(ghi)perylene, Chrysene, Dibenzo(ah)anthracene, Fluorene, Fluoranthene, Indeno(1,2,3-cd)pyrene, Naphthalene, Phenanthrene, Pyrene, Aldrin, Chlordane, DDT, DDE, DDD, Dieldrin, Endosulphan sulphate, α- and β-Endosulphan, Endrin, HCH (total), Lindane (ɣ-HCH), Heptachlor, Heptachlor epoxide, HCB, Methoxychlor.	Mussels	6 (196 - 297 per composite).	Edible portion.	Al, As, Cd, Cr, Co, Cu, Mn, Pb, Zn, DDT, Dieldrin.	Bioaccumulation focus rather than human health; FSANZ guidelines applied to wild-caught seafood.
Hoeksema (2015)	Al, As, As (inorganic) Cd, Cr, Co, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, Zn, Acenaphthene, Acenaphthylene, Anthracene, Benz(a)anthracene, Benzo(a)pyrene, Benzo(e)pyrene, Benzo(b)&(k)fluoranthene, Benzo(ghi)perylene, Chrysene, Dibenzo(ah)anthracene, Fluorene, Fluoranthene, Indeno(1,2,3-cd)pyrene, Naphthalene, Perylene, Phenanthrene, Pyrene, Aldrin, Chlordane, trans-Chlordane, cis-Chlordane, DDT, DDE, DDD, Dieldrin, Endosulphan sulphate, Endosulphan, α- and β-Endosulphan, Endrin, HCH (α, β and δ), Lindane (ɣ-HCH), Heptachlor, Heptachlor epoxide, HCB, Methoxychlor, Bromophos-ethyl, Chlorfenvinphos, Chlopyrifos, Chlopyrifos-methyl, Diazinon, Ethion, Fenchlorphos, Fenitrothion, Malathion, Parathion, Parathion-methyl, Tetrachlorvinphos, Diuron, Metolachor, Simazine, Tributyltin oxide, dibutyltin, Aroclor 1016, Aroclor 1221, Aroclor 1232, Aroclor 1242, Aroclor 1248, Aroclor 1254 and Aroclor 1260	Black bream	32 fish	Fillet.	As, Cd, Co, Cu, Pb, Mn, Hg, Ni, Se, Zn, TBT, Dieldrin, DDE, DDD, 1254, 1260	Pilot study assessment of a method to determine consumption guidelines. Determined safe limits for the consumption of black bream.

Al = aluminium; **As** = arsenic; **Cd** = cadmium; **Co** = cobalt; **Cr** = chromium; **Cu** = copper; **Fe** = iron; **Pb** = lead; **Mn** = manganese; **Hg** = Mercury; **Ni** = nickel; **Se** = selenium; **Sn** = tin; **Zn** = zinc, **TBT** = Tributyltin; **DDT** = p,p' -dichlorodiphenyltrichloroethane; **DDE** = p,p' -dichlorodiphenyldichloroethylene; **DDD** = p,p' -dichlorodiphenyldichloroethane; **α-, β- & δ-HCH** = α-, β- & δ-Hexachlorocyclohexane; **ɣ-HCH** = Lindane (ɣ-Hexachlorocyclohexane); **HCB** = Hexachlorobenzene; **PCB** = Polychlorinated Biphenyl; **NHMRC** = National Health and Medical Research Council; **FSANZ** = Food Standards Australia New Zealand; **APVMA** = Australian Pesticides and Veterinary Medicines Authority; **MLL** = Minimum Legal Length.

3 Results

3.1 Analytical results

Of the 79 analytes tested, 22 were detected in the composite whole prawns and 20 were detected in the composite prawn tails (Table 3). No polycyclic aromatic hydrocarbons (PAHs), organophosphate pesticides, diuron, metolachlor or simazine were detected in this study. Of the organochlorine pesticide suite, dieldrin, aldrin, endrin, DDT and its metabolites DDE and DDD were detected in at least one sample. Aldrin, endrin, DDE were detected in the whole prawns only and DDT and DDD were detected in the prawn tails only. Dieldrin was detected 14 times (from 43 samples), 12 of these were in whole prawns and two in the prawn tails (Table 3). Of the seven polychlorinated biphenyl (PCBs) mixtures included in this study only Aroclor 1254 was detected, 30 times in the 43 samples, 14 times in whole prawns and 16 times in prawn tails (Table 3). The length, weight and sex composition of the composite samples is included in appendix 1.

All metals examined in this study were detected in both whole prawns and prawn tail composite samples, except inorganic arsenic which was only detected in whole prawns (Table 3). Of the organotin compounds, tributyl tin (TBT) was detected 16 times in whole prawns and twice in prawn tails. The metabolite of TBT, dibutyl tin (DBT) was detected in 18 times in whole prawns and six times in prawn tails.

The comparison of contaminants between tissue types (whole prawns vs prawn tails) collected in 2015 showed a highly significant difference (ANOSIM, R = 0.686, p= 0.001). The SIMPER derived % contribution and squared distance/SD ratio suggest the contaminants largely driving the difference between the tissues were copper, selenium and inorganic arsenic (Table 4). Ordination in nMDS indicates a clear separation between the two tissue types (Figure 2) based on contaminant composition. All metals detected were more highly concentrated in the whole prawn samples (Table 3) and only the organic contaminants; DDT, DDD and Aroclor 1254 were higher in the tails, albeit at very low levels (Table 3).

The comparison of interannual variability of contaminants in the whole prawns revealed a significant difference in contaminant concentration and composition between the sampling years analysis, (ANOSIM, R = 0.428, p = 0.001). The difference is apparent in the nMDS, which despite the moderate stress (0.13) clearly indicates the separation between years. Of the contaminants largely driving the difference between years (based on % contribution and the Squared dist/SD ratio) mercury, nickel and dieldrin were greater in 2014 than 2015 and zinc and copper were greater in 2015 than 2014 (Table 5).

Table 3. A summary of the mean contaminant concentration (Cm) and standard error (Cse) in whole prawn composites, prawn tail composites, and for comparative purposes black bream fillets (from Hoeksema 2015). The number samples where each contaminant was detected (Detects (n)) is also shown. The light shading depicts where contaminant concentrations in the edible portions (bream fillets vs prawn tails) were greater. The dark shading depicts the overall highest concentrations observed in the two studies.

	Whole prawns (n=23)			Prawn tails (n=20)			Bream fillet (n=32)		
	C_m (mg/kg)	Detects (n)	C_{SE} (mg/kg)	C_m (mg/kg)	Detects (n)	C_{SE} (mg/kg)	C_m (mg/kg)	Detects (n)	C_{SE} (mg/kg)
Al	12.87	23	1.06	3.65	11	1.27	-	0	-
As	8.94	23	0.42	7.30	20	0.16	3.5	32	0.3
As (inorg)	0.074	11	0.0053	-	0	-	-	0	-
Cd	0.043	23	0.0047	0.013	14	0.0034	0.0005	2	0.00002
Co	0.078	23	0.0051	0.009	20	0.0007	0.005	32	0.0004
Cr	0.188	23	0.0251	0.067	10	0.0111	-	0	-
Cu	107.2	23	3.22	50.85	20	0.68	0.33	32	0.01
Fe	52.83	23	3.22	26.75	20	1.16	-	0	-
Pb	0.111	23	0.014	0.043	20	0.0044	0.003	2	0.0002
Mn	13.11	23	0.75	8.23	20	0.34	0.15	32	0.01
Hg	0.018	17	0.0023	0.007	3	0.0010	0.03	32	0.002
Mo	0.14	23	0.011	0.038	20	0.0024	-	0	-
Ni	0.24	14	0.054	0.096	5	0.0461	0.008	4	0.002
Se	2.47	23	0.05	1.44	20	0.03	0.50	32	0.01
Zn	65.22	23	2.30	57.55	20	0.60	8.5	32	0.2
TBT	0.0013	16	0.0002	0.001	2	0.00004	0.0006	2	0.00005
DBT	0.0029	18	0.0006	0.001	6	0.0002	-	0	-
Aldrin	0.0008	1	0.0003	-	0	-	-	0	-
Dieldrin	0.0036	12	0.0007	0.0026	2	0.0015	0.001	5	0.0005
Endrin	0.0005	1	0.00002	-	0	-	-	0	-
DDT	-	0	-	0.0011	2	0.0005	-	0	-
DDE	0.0005	1	0.00002	-	0	-	0.0010	7	0.00002
DDD	-	0	-	0.0011	3	0.0003	0.0005	1	0.0002
1254	0.0027	14	0.0006	0.0113	16	0.0023	0.0021	24	0.0003
1260	-	0	-	-	0	-	0.0005	1	0.00002

*Table 4. SIMPER output from the analysis of contaminant concentrations in the whole prawns and the prawn tails collected in 2015. Note the means are the mean concentration of normalised data. Positive values represent the higher concentrations. * denotes key contaminants as identified by the highest Sq.dist/SD ratio.*

Variable	WP-mean	PT-mean	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%
Cu	1.32	-0.662	4.21	1.96*	6.41	6.41
Co	1.24	-0.618	4.04	1.07	6.15	12.56
Se	1.28	-0.641	4.04	1.69*	6.15	18.71
Mo	1.18	-0.588	3.92	0.87	5.97	24.68
Mn	1.12	-0.56	3.72	1.05	5.66	30.34
Zn	1.03	-0.513	3.63	0.9	5.52	35.86
Asinorg	0.983	-0.492	3.63	1.22*	5.52	41.38
Fe	1.1	-0.548	3.61	1.07	5.49	46.87
Pb	0.79	-0.395	3.23	0.63	4.92	51.79
Cd	0.853	-0.426	3.18	0.61	4.85	56.64
TBT	0.524	-0.262	3.05	0.39	4.65	61.29
DBT	0.555	-0.277	3.05	0.47	4.64	65.93
Aldrin	0.365	-0.183	3	0.33	4.57	70.5

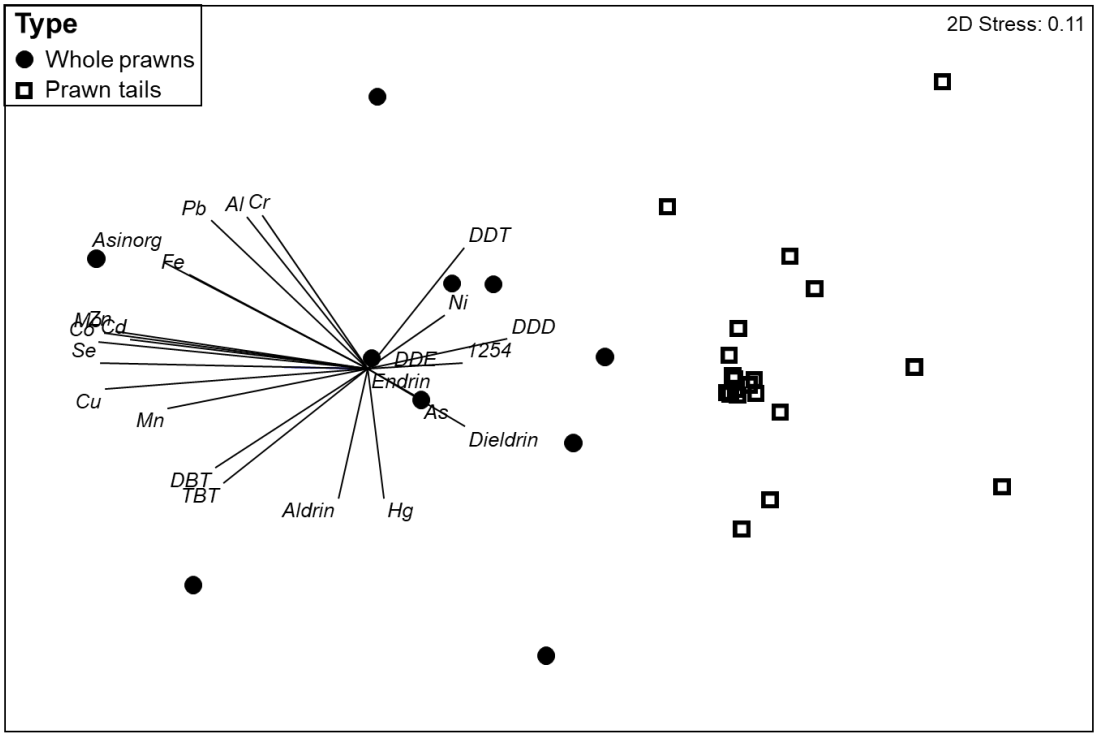

Figure 2. nMDS plot of the concentrations of contaminants detected in each composite sample of whole prawns and prawn tails. The vectors demonstrate the directional influence of the compounds on the position of the data points.

*Table 5. SIMPER output from the analysis of contaminant concentration in the whole prawns between 2014 and 2015. Note the means are the mean concentration of normalised data. Positive values represent the higher concentration. * denotes key contaminants as identified by the highest Sq.dist/SD ratio.*

Variable	2014-mean	2015-mean	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%
Hg	0.76	-0.988	3.43	1.47*	6.16	6.16
Ni	0.677	-0.88	3.06	0.72	5.51	11.67
Dieldrin	0.668	-0.869	3.03	1.17*	5.44	17.11
Zn	-0.598	0.777	3.01	0.88*	5.41	22.52
Cu	-0.544	0.707	2.86	0.8	5.13	27.66
As	0.607	-0.789	2.83	0.86	5.08	32.74
Mo	-0.46	0.598	2.67	0.5	4.8	37.54
Mn	-0.467	0.607	2.59	0.78	4.65	42.18
Cr	0.453	-0.589	2.38	0.65	4.27	46.45
Co	-0.286	0.371	2.34	0.48	4.2	50.66
Cd	-0.227	0.295	2.31	0.47	4.15	54.81
Aldrin	-0.209	0.271	2.3	0.33	4.13	58.94
1254	-0.225	0.293	2.27	0.77	4.07	63.01
Se	0.32	-0.416	2.25	0.82	4.05	67.06

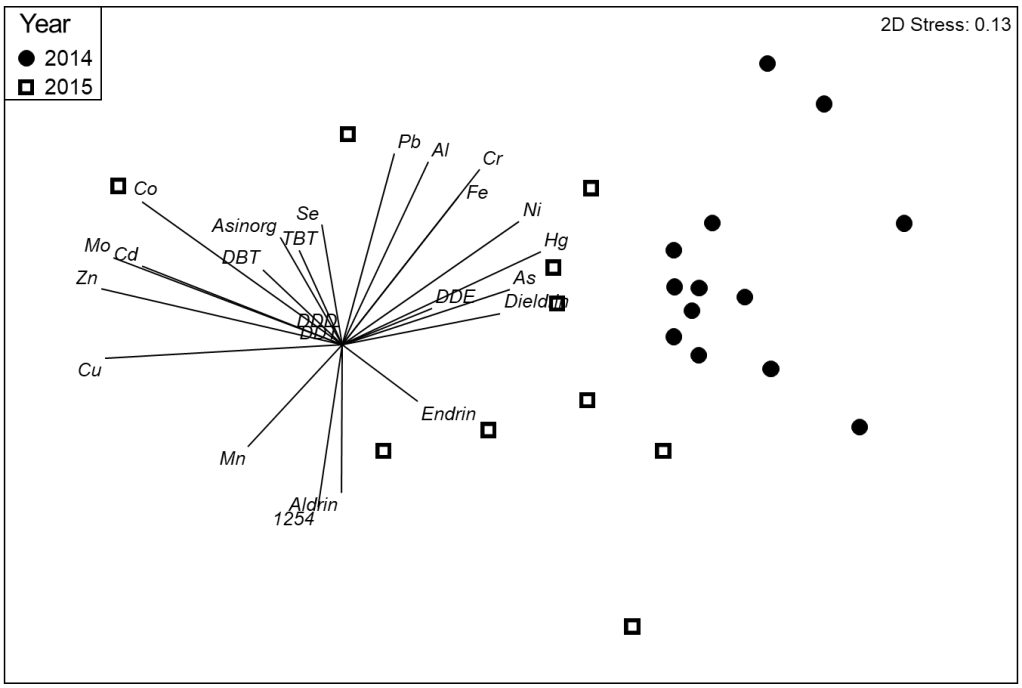

Figure 3. nMDS plot showing the similarities between years based on all contaminants detected. The vectors demonstrate the directional influence of the compounds on the position of the data points.

3.1.1 Comparison to black bream study

The companion study to the current study determined the concentrations of the same suite of contaminants in the fillets of black bream (Hoeksema 2015) and thus it is of interest to compare the concentrations detected in these two studies. In the current study 22 contaminants were detected in the whole prawn composites, 20 in the prawn tails and in the black bream study 16 were detected in the skin-on fillets (Table 3). The concentration of most contaminants found in fish were exceeded by prawns (either whole or tails) and particularly metal contaminants including nickel, cadmium, copper and lead were an order of magnitude higher. Only the organic contaminants DDE, mercury and Aroclor 1260 were higher in the fish.

3.2 Consumption guidance

Based on the average tissue concentration (C_m) of the contaminants detected, and the relevant ADI, none of the metals, OC pesticides or Aroclor 1254 in the current study restricted consumption of *M. dalli* whole prawns or tails caught from the Swan Canning Estuary (Table 6). The average meal consumption limit (CRmm) for all detected contaminants exceeded the USEPA restriction criteria of 16 meals/month (Table 6). In the whole prawns, chromium was the most restrictive with a CR_{mm} of 51. This means a consumer would need to ingest greater than 51 standard meals of whole prawns every month over their lifetime to be at an increased risk of adverse non carcinogenic health effects. In the prawn tails the PCB mixture, Aroclor 1254 resulted in the most restrictive consumption with a CR_{mm} of 57.

Eight of the metals and organic contaminants detected in the study have been identified as known or probable carcinogens and assigned a cancer slope factor (CSF), with the exceptions of cadmium (Cd) and lead (Pb) (Table 1). Based on the mean concentration for arsenic (As), dieldrin, DDE, DDD, and Aroclor 1254, none of these analytes increased the potential lifetime probability of an individual developing cancer or cancer related illness beyond the acceptable risk level (ARL) of 10^{-5} or 1 in 100,000 people (Table 6). For example, the average concentration of inorganic arsenic in whole prawns presented the greatest potential risk of any analyte in the current investigation, yet only resulted in a risk level (RL) of 5.37×10^{-6} or 1: 186, 326 people.

Table 6. The average concentration (and standard error) of metal and organic contaminants in composite samples of western school prawns (whole prawns and prawn tails) collected from the Swan Canning Estuary in 2014 and 2015 and the associated consumption guidance.

			Al	As	As (inorg)	Cd	Co	Cr	Cu	Fe	Pb	Mn	Hg	Mo	Ni	Se	Zn	TBT	DBT	Aldrin	Dieldrin	Endrin	DDT	DDE	DDD	1254
	ADI	**(mg/kg-d)**	0.14	0.0003[1]	0.0003	0.001	-	0.003[2]	0.2	0.8	0.0036	0.14	0.0001[3]	-	0.02	0.005	0.3	0.0001[4]	-	0.00003	0.00005	0.0002	0.0005[5]	-	-	0.00002
	CSF	**(mg/kg-d)$^{-1}$**			1.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	16	16	0.34	0.34	0.24	2[6]
Whole Prawns	**C_m**	**(mg/kg)**	12.87	8.94	0.074	0.043	0.078	0.188	107.2	52.83	0.111	13.11	0.018	0.14	0.24	2.47	65.22	0.0013	0.0029	0.0008	0.0036	0.0005	-	0.0005	-	0.0027
	C_{SE}	**(± mg/kg)**	1.06	0.42	0.0053	0.0047	0.0051	0.0251	3.22	3.22	0.014	0.75	0.0023	0.011	0.054	0.05	2.30	0.0002	0.0006	0.0003	0.0007	0.00002	-	0.00002	-	0.0006
	LC_m	**(ug/g lipid)**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0312	0.0675	0.0214	0.0837	0.0125	-	0.0125	-	0.0622
	LC_{SE}	**(± ug/g lipid)**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0044	0.0132	0.0096	0.0170	0.0006	-	0.0006	-	0.0144
			Consumption Guidance - Whole Prawns																							
	CR_{lim}	**(kg-d)**	**0.864**	**0.278**	**0.322**	**1.86**	**-**	**1.27**	**0.148**	**1.202**	**2.573**	**0.848**	**0.445**	**-**	**6.60**	**0.161**	**0.37**	**1.89[7]**	**-**	**3.04**	**1.11**	**30.44**	**76.1[8]**	**-**	**-**	**0.594**
	CR_{mm}	**(meals/month)**	**351**	**113**	**131**	**756**	**-**	**515**	**60**	**488**	**1,044**	**344**	**181**	**-**	**2,678**	**65**	**148**	**766[7]**	**-**	**1,235**	**119**	**12,353**	**30,883[8]**	**-**	**-**	**241**
	ARL	**-**	**-**	**-**	**5.31E-06**	**-**	-	-	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**6.4E-07**	**2.7E-06**	**4E-07**	-	**8.5E-09**	**-**	**2.56E-07**
Prawn Tails	**C_m**	**(mg/kg)**	3.65	7.30	-	0.013	0.009	0.067	50.85	26.75	0.043	8.23	0.007	0.038	0.096	1.44	57.55	0.001	0.001	-	0.0026	-	0.0011	-	0.0011	0.0113
	C_{SE}	**(± mg/kg)**	1.27	0.16	-	0.0034	0.0007	0.0111	0.68	1.16	0.0044	0.34	0.0010	0.0024	0.0461	0.03	0.60	0.00004	0.0002	-	0.0015	-	0.0005	-	0.0003	0.0023
	LC_m	**(ug/g lipid)**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0146	0.0240	-	0.0689	-	0.0348	-	0.0339	0.2879
	LC_{SE}	**(± ug/g lipid)**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0015	0.0042	-	0.0427	-	0.0170	-	0.0120	0.0557
			Consumption Guidance - Prawn Tails																							
	CR_{lim}	**(kg-d)**	**3.05**	**3.265**	**-**	**6.16**	**-**	**3.55**	**0.312**	**2.38**	**6.72**	**1.35**	**1.18**	**-**	**16.59**	**0.277**	**0.414**	**5.17[7]**	**-**	**-**	**1.56**		**17.84[8]**			**0.141**
	CR_{mm}	**(meals/month)**	**1,236**	**1,325**	**-**	**2,498**	-	**1,443**	**127**	**964**	**2,727**	**549**	**477**	**-**	**6,731**	**112**	**168**	**2,099[7]**	**-**	**-**	**632**		**7,242[8]**			**57**
	ARL	**-**	**-**	**-**	**-**	**-**	-	-	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2E-06**		**1.8E-08**		**1.3E-08**	**1.08E-06**

ADI = Acceptable Daily Intake; **CSF** = Cancer Slope Factor;
Al = aluminium; **As** = total arsenic; **As (inorg)** = inorganic arsenic; **Cd** = cadmium; **Co** = cobalt; **Cr** = chromium; **Cu** = copper; **Fe** = iron; **Pb** = lead; **Mn** = manganese; **Hg** = mercury (total); **Mo** = molybedium; **Ni** = nickel; **Se** = selenium; **Zn** = zinc;
TBT = Tributyltin as tin (Sn); **DBT** = Dibutyltin as tin (Sn); **DDT** = p,p'-dichlorodiphenyltrichloroethane; **DDE** = p,p' -dichlorodiphenyldichloroethylene; **DDD** = p,p' -dichlorodiphenyldichloroethane; **1254** = Aroclor 1254;
C_m = average concentration of a metal or organic contaminant in composite sample; **C_{SE}** = standard error of C_m; **LC_m** = average concentration of an organic contaminant in the lipid component of composite sample; **LC_{SE}** = standard error of LC_m;
CR_{lim} = Daily Consumption Limit; **CR_{mm}** = Average Meal Consumption Limit; **ARL** = Acceptable Lifetime Risk Level.
[1] = ADI and CSF are for As (inorganic); [2] = ADI is for Cr VI; [3] = ADI is for methyl-Hg; [4] = ADI is for a group of organotin compounds (sum of tributyltin, dibutyltin, triphenyltin and di-n-octyltin);
[5] = ADI is for Total DDT (sum of 4,4'- and 2,4'- isomers of DDT, DDE, DDD; USEPA 2018); [6] = CSF is for PCB mixtures and is based on an assessment of Aroclor 1254, 1260, 1242 and 1016 (USEPA 2018);
[7] = CR_{lim} and CR_{mm} were calculated from the the average of summed TBT and DBT concentrations; [8] = CR_{lim} and CR_{mm} were calculated from the average of summed DDT, DDD and DDE concentrations.

CR_{lim}, CR_{mm} and ARLs provided do not account for potential antagonistic, synergistic or additive effects of multiple contaminants in a single species diet, i.e. western school prawns.
Consumption guidance does not account for contaminant exposure from other sources, including other fish species.

4 Discussion

None of the metals or organic contaminants detected in this study were at high enough concentrations to restrict the consumption, by adults, of *M. dalli* caught from the Swan Canning Estuary. There are however a number of caveats to this calculation and include: The calculation of the consumption guidelines, however, did not make allowances for the synergistic, additive or antagonistic effects of the contaminants studied and the consumption guidelines do not consider any other exposure sources or impacts to children or pregnant women. Nor does the consumption guidance take into account changes that may occur during cooking. Finally, the study did not attempt to determine effect of different locations in the estuary on prawn contaminant concentrations.

Historical land uses and current activities have resulted in the widespread distribution of contaminants (e.g. metals, organic pesticides, hydrocarbons) in the sediment and surface water of the Swan Canning Estuary and its catchment (Foulsham et al., 2009; Nice, 2009, 2013b; Nice et al., 2009). The suite of contaminants detected in the body tissues of *M. dalli* largely reflect those previously detected in the sediment of the estuary (Nice, 2009). Interestingly, organochlorine pesticides were detected in a number of composite samples, but haven't previously been found in sediments above detection limits in the vicinity of where the prawns samples were collected, i.e. Matilda Bay and Canning Estuary (sites 14 and 17 in Nice (2009)) suggesting either rapid movement of the prawns between regions or the accumulation of very low levels of these contaminants into the body tissues of the prawns. Polychlorinated biphenyls have not been widely studied in the Swan Canning Estuary until a small scale study around the Claisebrook Cove detected PCBs in sediments (Nice, 2013a). The prevalence of the PCB Aroclor 1254 in the body tissues suggests that prawns were exposed to low levels of the contaminants in the estuary and further investigations of sediment contaminants using sufficiently low limits of reporting may indicate potential regions of contamination.

No reliable, comparative studies of contaminants in *M. dalli* could be found in the literature despite the significant national and international geographic distribution. This may reflect the lack of any major commercial or artisanal fishery within its range. To gain some context of how the concentrations detected in this study compare globally, a comparison of contaminant concentrations in species of the same genus have been identified (M. ensis - Ip, Li, Zhang, Wong, & Zhang, 2005; M. bennetae - Lewtas et al., 2014). In these examples prawns were collected in regions known to have significant sediment and surface water contamination including the Pearl River Delta in China (Ip et al., 2005), and Sydney Harbour and Port Hacking Estuary in Australia (Lewtas et al., 2014). In each of these systems, concentrations of metals detected in prawns were comparable or higher than that observed in this study. Despite the concentration of contaminants, both species were consumed regularly in these locations. While the above studies occurred in estuaries known to be contaminated, the study by Dincer and Aydin (2014) investigated the metal concentration of *Metapenaeus affins* in the Mediterranean. Concentrations of metals

in that study were orders of magnitude less than those recorded in the current study, suggesting that the contaminants detected in this genus likely reflect environmental exposure.

While the comparison of contaminant studies across taxa may be informative, caution must be applied in any interpretation of such comparisons as the uptake rates, storage and depuration rates of different taxa can vary widely even under exposure to the same contaminant concentration (Cresswell et al., 2014; Rainbow, 2002). In the Cresswell et al. (2014) study, three congeneric prawn species (*Macrobrachium*) were experimentally exposed to consistent concentrations of cadmium, zinc, copper, lead and arsenic. Despite the exposure to the same metal concentrations, the mean body tissue concentration varied between the species from 50% higher to nearly an order of magnitude higher. The variation in that study was suggested to be a result of different metabolic requirements of each species (Cresswell et al., 2014).

Many of the metals detected in this study are physiologically essential metals for the species and would naturally occur and accumulate within the body tissues. Prawns, like most organisms have a significant ability to regulate the concentrations of these essential metals within their body tissues (Rainbow, 2002). Such essential metals include copper, selenium, zinc and iron and all, particular copper and selenium, were metals that distinguished the whole prawns from the prawn tails in the current study. In crustaceans (and molluscs), copper is an essential metal used in hemocyanin to transport oxygen in the blood. Decapods have an enormous ability to regulate copper concentrations despite elevated or low concentrations of copper in the environment (Rainbow, 2002). One study identified that a prawn species (*Palaemon elegans*) regulated copper concentrations in its body at approximately 110 µg/g while dissolved concentrations remained below and up to this level, and when dissolved concentrations where 75 times higher (7500 µg/L), the copper concentration in the body of the prawns was only 6 times higher (~600 µg/g) (White & Rainbow, 1982). Interestingly the normal body copper concentration reported by White and Rainbow (1982) is similar to that observed in *M. dalli* in the current study. It is only when the uptake of metabolically available metals from the environment exceed the ability of the organisms to regulate the substance that toxic effects may be observed (Rainbow, 2002). These factors explain the higher concentration of contaminants in the whole prawns in comparison to the tails.

A significant finding on the current study was a much higher concentration of most contaminants in whole *M. dalli* than prawn tails. This finding is consistent with previous work on contaminant partitioning in the congenic *M. bennettae* where observed tissue concentrations were in order of highest to lowest; gills, hepatopancreas, exoskeleton and tail muscle (Lewtas et al., 2014). Cresswell et al. (2015) also found that metals accumulated in the cephalothorax (gills and hepatopancreas) and very low concentrations were detected in the abdominal muscle tissue. The accumulation of metals in the cephalothorax was primarily due to the uptake of contaminants through the gills, and ingestion and then storage in the hepatopancreas. The hepatopancreas is a known site of contaminant regulation, break down and storage (Rainbow, 2002).

Furthermore, different exposure pathways for contaminants can influence their distribution in the body tissue, for example, ingestion is a dominant pathway for some metals (i.e. arsenic and lead), while dissolved metal exposure through the gills maybe the dominant exposure pathway for others (i.e. cadmium and zinc) (Cresswell et al., 2015). Uptake pathways of organic contaminants can also have a significant effect on the way these contaminants are metabolised. Kwong, Yu, Lam, and Wang (2008) found that DDT absorbed through dietary exposure was more rapidly transformed than through aqueous exposure through the skin and gills of a species of bream (A*canthropagrus schlegeli*). In addition, of the major DDT metabolites, DDD is eliminated by the body much faster than DDE which was generally retained. In the current study DDT and its metabolites were rarely detected, however when they were, DDE was observed in a single whole prawn composite sample and both DDT and DDD were associated with the prawn tails. The detections of DDT and metabolites were very close to the laboratory limits of reporting and so it is difficult to draw any substantial conclusions on any partitioning patterns in *M. dalli*. The organochlorine pesticide dieldrin, was detected many times in the current study, almost exclusively in whole prawn samples. In another species of prawn (*Macrobrachium faustinum*) Robinson, Henry, and Mansingh (2002) found that dieldrin accumulates in the cephalothorax tissue in much higher concentrations than in the muscle tissue. Interestingly, in the same study dieldrin was demonstrated to depurate very quickly, 50% reduction after eight days in clean water (Robinson et al., 2002). On a further note, aldrin was detected in one whole prawn sample. Aldrin rapidly breaks down to dieldrin in the environment and body (Jorgenson, 2001) and so the detect of aldrin may suggest the disturbance of previously confined legacy sources or the potential but highly unlikely recent use of the chemical.

Interannual differences in contaminant concentrations were detected for whole prawns in this study. Of the contaminant identified as significantly contributing to the difference, mercury, nickel and dieldrin were all higher in 2014. Annual and seasonal variation in contaminant concentration has long been known for many species (Luoma, Dagovitz, & Axtmann, 1990) and one hypothesis put forward is that seasonal changes in water quality may be responsible (Beldi, Gimbert, Maas, Scheifler, & Soltani, 2006). It is possible that this may be a mechanism for the differing concentration between years in *M. dalli* observed in this study. The rapid growth and annual life cycle of this species (Broadley et al., 2017; Tweedley et al., 2017) would suggest the contaminant load of the species may reflect exposure to contaminants in the water and sediment at this time. Alternatively, *M. dalli* use different habitat over a 12-month period, overwintering in deep areas of the river, moving into shallower nearshore areas during the spring and summer months, importantly the time they spend in the deeper or shallow regions varies annually (Poh et al 2019). Poh et al (2019) found that in spring and summer 2014-15 *M. dalli* was more abundant for a longer period in the shallow nearshore areas than in 2013-2014. The residency in different regions of the estuary may affect contaminant exposure risk and uptake. Finally, the sex composition of the composite samples should be considered. In 2014 samples comprised of all males while in 2015 females were also retained (see appendix 1). Differences in toxicant accumulation can vary with sex in different species and different contaminants (e.g. Lafontaine et al., 2017;

Mohamed Harris, Vinobaba, Kularatne, & Kankanamge, 2019). It is unknown how/if toxicants will accumulate differently in males and females in *M. dalli,* however there if likelihood that difference in sample composition may have partly contributed to the differences observed between 2014 and 2015.

This study, by analysing *M. dalli* for the same suite of contaminants competed on black bream in the earlier study (Hoeksema 2015), provides an opportunity to compare the contaminant load of two different species, which occupy different niches in the Swan Canning Estuary. Black bream (*Acanthopagrus butcheri*) is a generalist and is known as an opportunistic predator of *M. dalli* (Sarre, Platell, & Potter, 2000) while consuming a mix other crustaceans, bivalves, gastropods and macrophytes (Tweedley et al., 2017). Given more than half the diet is live prey it would be reasonable to expect that the concentration of contaminants would be higher in *A. butcheri* if they biomagnify. The concentrations of three known biomagnifying substances, mercury, DDE and Aroclor 1260 were all higher in *A. butcheri* than *M. dalli*. However, the other known biomagnify substances, Aroclor 1254, DDT, DDD and selenium were all higher in *M. dalli*. Additionally, there were more contaminants detected in *M. dalli* (22 in whole prawns, 20 in prawn tails and 16 in black bream fillets) and the concentrations of those contaminants were generally higher.

The accumulation of contaminants in different species will be influenced by dietary exposure pathways. For example a study by Hu et al. (2010) conducted food web comparisons of organochlorine pesticides in a freshwater lake and found that organochlorine pesticides (DDT and metabolites, and HCH and metabolites) varied in concentration among a large number of species from arrange of feeding guilds and these difference were largely attributed to trophic level. Additionally, they were able to use the ratio of OC pesticides metabolites to infer feeding habitats, for example a high ratio of DDD:DDE would imply exposure in anoxic environments versus low DDD:DDE ratio. The accumulation of contaminants within *M. dalli* is a likely result of feeding behaviour and physical position within the water column. Like most prawns, *M. dalli* is a detritivore and grazes by sifting through sediment ingesting small particles of organic and inorganic material. If those sediments were contaminated, then the dietary pathway is likely to be a significant mechanism for accumulation of contaminants. In addition, *M. dalli* is known to spend a substantial portion of a diurnal period on or buried in the sediment (Bennet, 2014). The preferential selection by *M. dalli* to bury in sediment with finer sediment particle size (Bennet, 2014) could, if the sediment is contaminated, result in significant exposure across the gills and skin.

While determining the impact of contaminants on the biological health of *M. dalli* was not the primary objective of this study, a discussion on the potential effects is of interest. In a comprehensive assessment of sediment contamination throughout the Swan Canning Estuary, Nice (2009) determined that zinc, copper, mercury, lead, dieldrin and DDE exceeded the Low Interim Sediment Quality Guideline (ANZECC & ARMCANZ, 2000) and zinc exceeded the High guideline. The majority of exceedances occurring in the historical industrial area of the lower Middle Swan Estuary, in the Claisebrook to Belmont reach. The exceedance of the guidelines indicate that adverse effects to biota may occasionally occur (Low guideline) or are

likely to occur (High guideline) (Long, Macdonald, Smith, & Calder, 1995). During surveys of the *M. dalli* population in the Swan Canning Estuary, consistently high (relative to other sites) abundances were observed in the lower Middle Swan Estuary (Poh et al., 2019) suggesting a potential for a higher exposure risk for *M. dalli*. However, it is inherently difficult to determine the biological effects of a given contaminant load of an individual. Different contaminants can interact and cause a range of antagonistic, synergistic or additive effects (e.g. Rodea-Palomares, Leganés, Rosal, & Fernández-Piñas, 2012). Additionally, climate change impacts, such as warmer temperatures are also indicated to change the way contaminants impact biota (Letcher et al., 2010). In addition, long term, multigenerational exposure to organic contaminants has been known to cause genetic changes in fauna which may result in an increased resilience to the effects of the contaminant/s (Medina et al. 2007). While these changes may appear to be beneficial, it was proposed that they also come with a cost, which may manifest in a reduced resilience to other environmental stressors (Medina, Correa, & Barata, 2007) such as temperature increases, salinity or toxic algal blooms.

5 Conclusions and recommendations

The current study has established a consumption guidance for the recreational fishing species, western school prawn (*M. dalli)*. It has identified that none of the contaminants were high enough to present a health risk to people from the consumption of wild caught *M. dalli* in the Swan Canning Estuary and thus a restriction on consumption is not recommended, within given caveats. Additionally, it has provided an evaluation of the prevalence of contaminants in *M. dalli* within the Swan Canning Estuary which constitutes the first investigation of this type on this species. The contaminant suite identified within the body tissues of *M. dalli* broadly reflect that found in the sediments of the estuary established by previous contaminant investigations. The concentration and contribution of contaminants did vary between years which may reflect seasonal life history movements of the species or sex differences in contaminant accumulation. It was not within the scope of this study to determine the potential impact on contaminants on *M. dalli* and this remains a knowledge gap.

It should be noted that the samples were collected in 2014-2015 and may not reflect impacts from exposure to new or emerging contaminants. As a result, the consumption guidance provides a general overview of the safety of *M. dalli* for human consumption however this information will need to be revised through the health authorities as new information is made available.

Per- and polyfluorinated compounds have recently been detected in surface and ground waters throughout the Swan Canning Estuary and its catchment. There was no knowledge of the presence of these compounds within the system at the time of sampling and thus were not included as an analyte in this study. A comprehensive investigation into the prevalence of PFAS within the estuary and biota has been completed (Novak and Hoeksema in prep). A human health risk assessment completed by the Department of Health had found that there is negligible risk from PFAS to human health from the consumption of wild caught fish and crabs from the Swan and Canning Estuary.

This study was not intended to address site specific loading of biota due to contaminants. Previous environmental investigations have identified priority areas of contaminant concern within the Swan Canning Estuary, such as adjacent to historical heavy industry and yacht clubs (e.g. Nice, 2013b; Shute, 2007). Given the movement of fish and crustaceans into and out of these regions and the ability of organisms to rapidly accumulate contaminants, an understanding of site specific/ regional contaminant information may improve understandings of the mechanism for uptake of contaminants and mobilisation into the food web.

Appendices

Biological results and composite sample composition

The mean length and weight were consistent among the majority of samples (Table A1 and A2). The whole prawn composites collected in 2014 comprised all males, due to need of the restocking program to retain all ovigerous females as broodstock or return them at the site of capture. In 2015 the restocking program was well established and females were retained, resulting in a mix of males and females (Table A1). Those samples containing a greater number of females tended to have larger mean length and weight, given the larger size of females (Table A1 and A2). The prawn tail composites were comprised largely of males with 1-4 females, except sample CE-15-16 which was all females.

Table A1. Biological information (mean and SE) for each whole prawn composite showing total length, carapace length, weight and the number of males and females. Sample code is explained as follows, CE (Canning Estuary) or SCE (Lower Swan Canning Estuary), 14 or 15 = year of sampling (2014 or 2015) and the sample number.

Whole prawns	Total length (mm)		Carapace length (mm)		Weight (g)		Sex	
Sample ID	Mean	SE	Mean	SE	Mean	SE	M	F
CE-14-1	87.50	1.01	30.27	0.67	4.85	0.14	7	0
CE-14-2	86.92	0.76	30.49	0.31	4.80	0.13	7	0
CE-14-3	87.58	1.58	29.96	0.53	4.97	0.24	7	0
CE-14-4	88.19	1.53	30.67	0.74	5.00	0.24	7	0
CE-14-5	86.78	1.25	30.36	0.65	4.84	0.17	7	0
CE-14-6	85.25	1.15	29.81	0.57	4.82	0.15	7	0
CE-14-7	85.56	0.93	30.21	0.46	4.90	0.15	7	0
CE-14-8	87.17	0.85	30.51	0.59	5.25	0.14	7	0
CE-14-9	86.15	0.88	30.46	0.37	5.08	0.16	7	0
CE-14-10	85.29	1.18	30.59	0.51	4.98	0.16	7	0
CE-14-11	84.80	1.23	29.17	0.31	4.90	0.19	7	0
CE-14-12	87.96	1.27	30.74	0.72	5.52	0.20	7	0
CE-15-39	98.73	2.46	38.22	1.40	7.79	0.62	1	6
CE-15-40	94.72	2.34	35.60	1.41	6.87	0.58	3	4
CE-15-41	92.40	2.00	33.79	1.29	6.18	0.44	5	2
CE-15-42	89.75	1.82	32.76	1.17	5.74	0.36	5	2
CE-15-43	87.21	1.72	31.75	0.84	5.56	0.36	3	4
SCE-14-13	87.71	0.98	30.64	0.50	5.52	0.13	7	0
SCE-15-34	84.54	1.80	30.79	1.11	5.05	0.38	5	2
SCE-15-35	85.07	1.43	30.19	0.95	4.88	0.21	4	3
SCE-15-36	84.04	1.88	29.93	1.03	4.62	0.28	5	2
SCE-15-37	84.36	1.88	29.40	0.95	4.70	0.29	7	0
SCE-15-38	90.02	3.50	29.62	0.78	6.09	0.75	6	1
Total	**87.42**	**0.49**	**31.13**	**0.23**	**5.27**	**0.10**	**135**	**26**

Table A2. Mean biological data for each prawn tail composite showing; weight, total length, carapace length and the number of males and females. Sample code is explained as follows, CE (Canning estuary) or SCE (lower Swan and Canning Estuary), 14 or 15 = year of sampling (2014 or 2015) and the sample number.

Prawn tails	Total length (mm)		Carapace length (mm)		Weight (g)		Tail weight* (g)		Sex	
Sample ID	Mean	SE	Mean	SE	Mean	SE	Mean	SE	M	F
CE-15-16	107.02	1.95	40.88	1.01	10.32	0.63	5.42	0.32	0	12
CE-15-17	83.99	1.64	29.97	0.62	4.63	0.26	2.80	0.20	10	2
CE-15-18	85.23	1.83	29.97	0.62	4.93	0.28	2.74	0.15	11	1
CE-15-19	84.82	1.58	30.14	0.62	4.71	0.22	2.76	0.13	11	1
CE-15-20	84.55	1.27	29.88	0.59	4.65	0.21	2.80	0.11	11	1
CE-15-21	83.16	1.62	29.80	0.67	4.61	0.23	2.74	0.15	10	2
CE-15-22	85.43	1.74	30.29	0.64	5.02	0.25	2.81	0.14	10	2
CE-15-23	84.91	1.18	30.26	0.54	4.80	0.19	2.67	0.10	9	3
CE-15-24	85.13	1.55	30.13	0.61	4.88	0.22	2.88	0.14	2	9
CE-15-25	85.46	1.91	30.18	0.64	4.87	0.28	2.84	0.15	12	0
CE-15-26	85.11	1.42	30.09	0.55	4.88	0.22	2.70	0.14	11	1
CE-15-27	85.43	1.62	30.33	0.52	4.99	0.28	2.80	0.14	10	2
CE-15-28	84.33	1.57	29.70	0.58	4.71	0.24	2.71	0.14	11	1
CE-15-29	83.61	1.34	30.08	0.51	4.70	0.18	2.71	0.09	8	4
CE-15-30	85.08	1.21	30.07	0.43	4.81	0.17	2.72	0.09	11	1
CE-15-31	85.16	1.03	30.10	0.43	4.84	0.14	2.69	0.10	9	3
CE-15-32	86.47	0.93	30.77	0.43	5.02	0.16	2.90	0.10	11	1
CE-15-33	87.79	0.77	31.05	0.33	5.47	0.22	3.09	0.18	11	1
SCE-15-14	85.83	0.66	30.37	0.26	4.74	0.10	2.78	0.08	12	0
SCE-15-15	87.14	1.15	30.81	0.43	5.13	0.16	2.89	0.11	11	1
Total	**86.27**	**0.44**	**30.73**	**0.20**	**5.13**	**0.10**	**2.92**	**0.05**	**191**	**48**
* Tail weights were obtained from thawed specimens										

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