

# Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging, and environmental variables within a highly urbanised estuary

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**Abstract** Coastal areas, and thus coastal species, are at increasing risk from human activities. Sections of the coastline of Western Australia are undergoing intense coastal development to fulfil commercial, industrial, and recreational requirements. Multiple populations of bottlenose dolphins (*Tursiops aduncus*) occur around this coastline; however, small community sizes and limited genetic exchange rates make them susceptible to anthropogenic pressure. This study investigated the occupancy of dolphins within the Swan–Canning Rivers, an urbanised estuary, with regard to (1) presence/absence, (2) abundance, and (3) duration in terms of time spent in the area. These response variables were related back to environmental conditions (tidal state, tidal height, salinity, temperature), vessel traffic, and dredging activities using generalised additive modelling. Theodolite tracking data revealed high levels of boat traffic at the two sites considered; however, dolphin occurrence was only negatively affected by vessel density at one of these sites. Dolphin occupancy was also significantly influenced by temperature, with possible seasonal effects. No dolphins were sighted on days when backhoe

dredging was present; however, low sample sizes limited statistical interpretation. These results highlight the need to consider context in behavioural response studies, in terms of habitat type studied, explanatory variables considered, and response variables selected.

**Keywords** Animal occupancy · Theodolite tracking · Anthropogenic activities · GAMs

## Introduction

Coastal habitats are among marine areas most at risk from the impacts of human activities (McIntyre, 1999; Moore, 1999). As a result, threats to coastal species, such as Indo-Pacific bottlenose dolphins (*Tursiops aduncus*; Ehrenberg, 1832), are among those in need of management to reduce their impacts (Thompson et al., 2000; DeMaster et al., 2001; Ross, 2006; Allen et al., 2012). Due to their acoustic specialisations, bottlenose dolphins are vulnerable to noise and disturbance from human activities, which are widespread throughout their coastal range (Hastie et al., 2003; Lusseau, 2003a; Buckstaff, 2004; Lusseau, 2005; Morisaka et al., 2005; Bejder et al., 2006; Nowacek et al., 2007; Tyack, 2008; Jensen et al., 2009; Steckenreuter et al., 2012; Guerra et al., 2014; May-Collado & Quiñones-Lebrón, 2014; Pirodda et al., 2015; Heiler et al., 2016).

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Sections of the Western Australian coastline are currently undergoing intense development in the form of port maintenance and expansion, marine construction, and increasing tourism. These activities can have detrimental effects on the marine environment (e.g. habitat destruction, chemical contamination, littering, underwater noise, loss of food sources; Clark, 2001) which can lead to impacts on local fauna. Multiple local populations of Indo-Pacific bottlenose dolphins occur around the coast of Western Australia. These dolphins occupy a diversity of habitat types, having adapted to unique environments such as inshore bays, riverine, and semi-enclosed estuaries. Although the species itself is widely distributed, many live in small communities with limited genetic exchange outside of their social network (Holyoake et al., 2010). These attributes, in combination with their near-shore distribution, make bottlenose dolphin communities vulnerable to environmental changes and anthropogenic pressures (Wilson et al., 1999; Ross, 2006; Chabanne et al., 2012). Additionally, strong site fidelity to small, defined areas makes some dolphin communities particularly vulnerable to anthropogenic pressures, as they are exposed to the repeated and cumulative effects of such stressors (Finn, 2005; Ross, 2006).

The Swan–Canning River system, flowing through the Western Australian state capital of Perth, is an urban estuary subjected to several forms of human activity. Within this system are an industrial port, commercial ferry channels, jetski and powerboat race areas, shoreline construction works, and thousands of recreational vessels. As a result, sections of the river have been reported to experience considerable anthropogenic noise (Salgado Kent et al., 2012; Marley et al., 2016). In spite of this, the river system is also home to a resident community of bottlenose dolphins (*Tursiops aduncus*), composed of approximately 18 adults and several juveniles/calves (Chabanne et al., 2012; Swan River Trust, 2015). These animals are distributed heterogeneously within the river system, with some particular areas acting as dolphin “hotspots”, based on nearest neighbour hierarchical clustering analyses to determine which areas have a higher number of dolphin sightings (Moiler, 2008).

Despite these animals inhabiting a noisy, urbanised environment, limited work has been done for investigating any potential disturbance from human activities. The only existing behavioural response study involving this community of dolphins focused on pile-driving

within the Fremantle Inner Harbour located at the mouth of the river system. The study found that dolphin detections decreased during pile-driving activity associated with harbour deepening (Salgado Kent et al., 2012; Paiva et al., 2015). Reduced detections may have reflected the following: increased absences of dolphin groups from the study area, reduced number of dolphins using the site, or decreased occupancy time within the harbour (Paiva et al., 2015).

The most ubiquitous anthropogenic activity in the Swan–Canning River system (and indeed the majority of marine systems) is vessel traffic, which has been shown to induce a range of behavioural responses in cetaceans. These range from relatively subtle effects, such as changes to inter-breath intervals, inter-animal distances, breathing synchrony, travel heading, and speed (Williams et al., 2002; Hastie et al., 2003; Lusseau, 2006; Nowacek et al., 2007; Weilgart, 2007), to more obvious reactions, such as termination of activities or displacement from the impacted area (Cosens & Dueck, 1988; Morton & Symonds, 2002; Lusseau, 2003a, b; Constantine et al., 2004; Bejder et al., 2006; Nowacek et al., 2007; Christiansen et al., 2010). Over 97,000 recreational vessels are registered within Western Australia, approximately 53,000 of which are registered within the Perth metropolitan area (J. Nunn; personal communication, 21st January 2014). A study investigating underwater noise at a site within the Swan River found vessel noise to be present in 52% of hourly acoustic recordings (Marley et al., 2016). Furthermore, parts of the river system have also experienced dredging activities for the maintenance and expansion of vessel channels. Dredging has the potential to impact cetaceans through acoustic masking, behavioural changes, or changes to prey availability (Erbe, 2002; Clark et al., 2009; Todd et al., 2015). For example, both probability of occurrence and time spent in the area by bottlenose dolphins (*T. truncatus*) within Aberdeen Harbour (an urbanised foraging patch) declined during higher intensities of dredging, despite high baseline levels of disturbance from vessel traffic and the importance of the area as a foraging site (Pirota et al., 2013). The small size of the Swan–Canning River resident dolphin community makes it inherently vulnerable to human impacts (Chabanne et al., 2012). Thus, vessel traffic and dredging (and their cumulative effects) are activities which warrant investigation with regard to their potential effects on this dolphin community.

Describing patterns of animal occurrence and occupancy in a particular area can provide important information on the status of mobile cetacean species in an area of interest (Durban et al., 2000). “Occurrence” typically connotes frequency of an event, whereas “occupancy” connotes that the event occurs at least once (Lele et al., 2013). Therefore, how a species occupies a particular area can be measured in various ways, such as presence/absence, relative abundance, or time spent in an area (MacKenzie & Nichols, 2004; Efford & Dawson, 2012; Lele et al., 2013; Latif et al., 2016). Although these are all assessing animal occupancy, such response variables each provide different levels of context to behavioural response studies. For example, an impact study may see no change in the overall daily presence/absence of a species in the impact area—but animals may still be spending less time in the area. Alternatively, the number of minutes with animals present in the study area may not change—but only because one individual is spending hours circling the area, when pre-impact there were multiple individuals passing through. Monitoring animal occupancy in a variety of forms can thus provide deeper perspective to behavioural response studies. Such information can also help identify critical areas within a population’s range for conservation management strategies (Ingram & Rogan, 2002).

This study aims to investigate whether vessel density and dredging activities are related to dolphin occupancy. The study did not aim to test the effects of anthropogenic sources on behaviour, spatial distribution, or broad seasonal occurrence. To achieve the aims of this study, two sites were selected for monitoring: Perth Waters and the Fremantle Port. Land-based theodolite tracking was used to ensure no disturbance from the presence of the research team. Patterns of vessel traffic were described for both sites, and dolphin occupancy in these areas was assessed in terms of their (1) presence/absence, (2) relative abundance, and (3) duration of time spent in the areas. Continuous tracking of dolphin groups ensured that ‘new’ sightings in the study area were indeed novel and not due to the same individual moving in and out of the area; this observation method also allowed calculation of duration of time spent in the study area by each group. These data were related back to environmental conditions, as well as the density of vessels and (in the case of the Perth Waters site)

dredging activities. Environmental conditions were included to ensure that any observed changes to occupancy were indeed due to anthropogenic activities, rather than other environmental processes. Additionally, environmental variables could be related to key occupancy drivers such as prey availability.

## Materials and methods

### Study site

The Swan–Canning River system flows through the centre of metropolitan Perth, a city of over 1.4 million people. The Swan and Canning Rivers are 72 and 110 km long, respectively; together, these form an extensive river system composed of narrow channels, large shallow basins, and riverine upper reaches. The river system was originally partially closed, due to a large sand bar at the river mouth, making the river mostly fresh and brackish. The bar was dredged in the late 1800s to allow development of the Fremantle Port, which also allowed increased intrusion of oceanic water (Hodgkin & Hesp, 1998). This considerably altered the salinity of the river system and opened it to tidal influences. The estuary now experiences low-amplitude diurnal tides (Robson et al., 2008). This area also shows larger water-level variations which coincide with the passage of atmospheric pressure systems; water levels rise in response to low barometric pressure, which is linked with variations in water column salinity (Hamilton et al., 2001). Furthermore, there are seasonal changes to sea level as a result of the Leeuwin Current, which are reflected within the estuary (Thomsen et al., 2001). The river system experiences a strong seasonal inflow of freshwater with most rain (approximately 70%) falling in austral winter, when saline estuarine water is flushed from the upper estuary. Almost no river flows occur during the austral summer to autumn months (Hamilton et al., 2001; Thomsen et al., 2001). As a result of these features, estuarine salinity levels vary within and between years, depending on the balance of tidal diffusion and mean water flow (Thomsen et al., 2001). However, typically salinity varies seasonally due to the low tidal amplitude and strong seasonal rainfall (Kurup et al., 1998). The estuary can thus be described as a micro-tidal system with strong hydrological dependence on seasonal river inflows (Robson et al., 2008).

The resident community of bottlenose dolphins uses this river system on a daily basis, with hotspots of dolphin sightings in particular areas of the lower and upper reaches of the estuary (Moiler, 2008; Beidatsch, 2012; Chabanne et al., 2012). However, the dolphins also range far into the upper reaches of both the Swan and Canning Rivers, using the entirety of the river including the two sites which were the focus of this study—Perth Waters and the Fremantle Inner Harbour.

Perth Waters is a 1-km-wide bay in the upper reaches of the Swan River. It is a relatively shallow area, most of which is only 1 m deep, with several dredged ferry channels (approximately 5 m deep). Perth Waters is also the site of the Elizabeth Quay development, a new waterfront facility which was under construction at the time of this study, involving terrestrial landscaping, jetty reconstruction, and dredging to create deeper vessel access channels. A high number of recreational boats use this area, in addition to transport and commercial ferries, contributing significantly to the underwater soundscape (Marley et al., 2016). This area appears to be used by dolphins moving between the upper and middle reaches of the Swan River (Beidatsch, 2012).

The Fremantle Inner Harbour is situated at the mouth of the river system. The Fremantle Port is situated within the Inner Harbour and is the state's biggest general cargo port and Australia's fourth largest container port ([www.fremantleports.com.au](http://www.fremantleports.com.au)). The Fremantle Inner Harbour also experiences high use by recreational vessels, transiting the area between the Swan–Canning River and the Indian Ocean. As a result, it experiences high levels of anthropogenic noise from vessel traffic, wharf maintenance, and traffic passing over nearby train and traffic bridges (Salgado Kent et al., 2012). Despite this, it appears to be a seasonal dolphin hotspot, primarily used for foraging (Moiler, 2008). The harbour depth is 13 m (dredged to accommodate ship movements), but at the eastern-most edge the river channel is 5 m deep, forming a sill known as the “Wangara Shoal”.

These two sites were selected partly due to their use by dolphins (based on previous modelling works by Moiler (2008), Beidatsch (2012) and Paiva et al. (2015)) and also due to their significance for anthropogenic activities. Furthermore, adjacent vantage points of significant height (>30 m) allowed theodolite tracking to be employed and reduced observational bias.

## Theodolite tracking

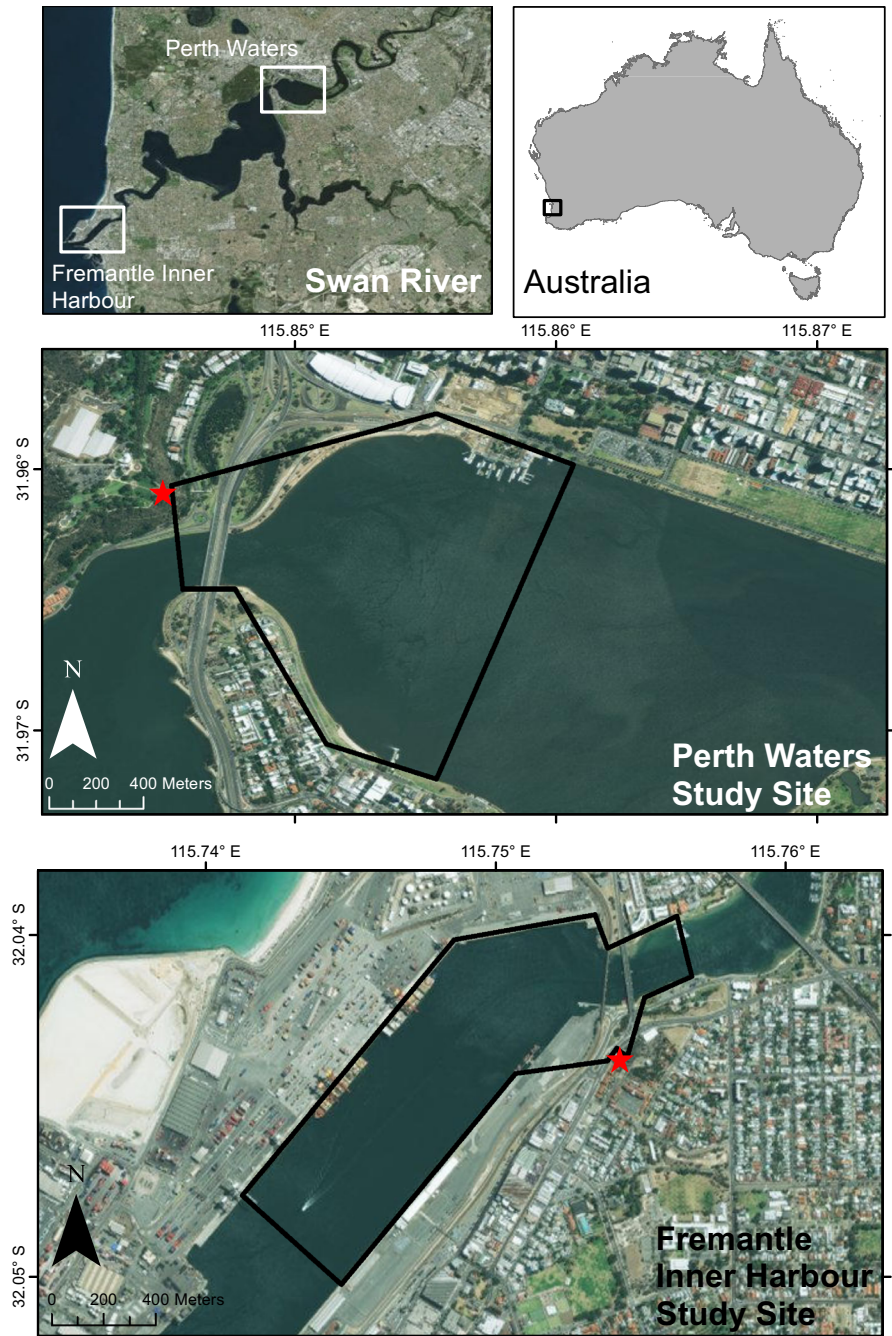
Land-based observations were conducted from two elevated locations (Fig. 1): one overlooking the western side of Perth Waters in the vicinity of Elizabeth Quay (31.960901°S, 115.844951°E; 63 m height) and another overlooking the east end of the Fremantle Inner Harbour (32.043634°S, 115.754284°E; 32 m height). Fieldwork occurred over two years between January and June (Table 1).

A surveyor's theodolite (TopCon GTS-603 AF Electronic Total Station) was used to obtain the position of dolphin groups, vessels, and dredgers. Data were collected by a team of 3–4 trained observers and recorded in real-time using Vadar (vr 2.00.01b) software (E. Kniest, University of Newcastle). Fieldwork at each location was limited to single 4-h surveys per day conducted in good weather conditions (high visibility, Beaufort <3, low glare, temperatures <35°C) to ensure accurate data and avoid observer fatigue.

Observers scanned the study area using 7 × 50 mm binoculars. If dolphins were sighted, an initial position was taken with the theodolite and the group size was noted. For the purposes of this study, a ‘group’ was defined as ‘dolphins observed in apparent association, moving in the same direction and often, but not always, engaged in the same activity’ (Shane, 1990). The dolphins were tracked until they left the study area, were lost from sight, or until conditions deteriorated sufficiently to justify ending the survey. A ‘track’ was defined as a series of theodolite positions taken of the same dolphin group. Tracks were therefore considered independent of each other.

Vessels were tracked continuously during their time in the study area via the same theodolite used for dolphin positioning. Vessels were tracked even if no dolphins were present in the study area. The identity of each vessel was noted based on either the name or a physical description of the vessel (colour, crew, distinguishing features, etc.). This enabled continual tracking of each vessel, regardless of how many vessels were present in the study area, with points taken in turn over a short period of time to reflect the entrance, exit, and movement of vessels within the study area. Vessels were categorised according to types, as defined in Table 2. If a vessel was conducting a transit through the area, a minimum of three theodolite shots were deemed acceptable to determine average speed and course. However, if the vessel was

**Fig. 1** Theodolite tracking of dolphins, vessels, and dredging occurred at Perth Waters and Fremantle Port in the Swan–Canning Rivers. Theodolite stations are marked with a star. *Map Source:* ESRI ([www.esri.com](http://www.esri.com))



milling or using the area for recreational activities (e.g. fishing), then theodolite shots were taken whenever the vessel appeared to have significantly changed its position. The vessel behaviour was also noted, either as stationary, milling, or travelling in one of the four directions (north, east, south, or west).

Elizabeth Quay experienced dredging activities in January–May 2014. The theodolite team was able to observe the dredging platform from their hill station, and recorded when dredging occurred. Dredging was deemed to be occurring when the bucket was in motion and the pontoon being filled with sediment. In some

**Table 1** Overview of observation effort at the Perth Waters and Fremantle Inner Harbour field sites, with information on number of dolphin and vessel sightings, and surveys with dredging activity

	Survey effort				Observations			
	Year	Study period	No. of shifts	Effort (h)	Shifts with dolphins	No. of dolphin sightings	No. of vessel sightings	Shifts with dredging
Perth Waters	2014	12th Jan–14th Jun	46	130	10	24	1,547	12
	2015	12th Jan–3rd Apr	32	100	8	28	1,297	0
Fremantle Inner Harbour	2014	19th Feb–13th Jun	35	106	32	229	1,820	0
	2015	13th Apr–23rd Jun	23	71	23	180	1,192	0

**Table 2** Vessel types and their descriptions

Vessel type	Description
Barge	Flat-bottomed vessels mainly used for transporting heavy material or goods. While some are self-propelled, those in this study were not self-propelled and needed to be towed
Cargo	An ocean-going bulk carrier or tanker. Only observed within the Fremantle Inner Harbour
Charter	Displacement hull with an inboard motor. Equipped with extensive deck space, fully-enclosed cabin, and entertainment facilities for tourism
Crayboat	Large commercial fishing vessel with an inboard motor. Large rear deck space and an enclosed front cabin
Dredger	Backhoe dredger mounted on a spud-stabilised pontoon. Uses a hydraulic excavator to dredge material, but is not self-propelled
Ferry	Commercial transport vessel, operating for both tourism and public transport within the Swan–Canning Rivers
Jetski	Personal water craft which is jet-propelled
Kayak	Light, canoe-like boat with a watertight frame in which a paddler sits with legs forward, using one paddle with two blades
Large Rec	Fibreglass-hulled boat with either inboard or large outboard motor. Equipped with either partially or fully enclosed cabin; designed to stay on the water for days at a time
Motoryacht	Typically 12 m or above with powerful inboard engines. Ample deck and cabin space; designed to stay on the water for days or weeks at a time
Pilot	Work boat used to transport maritime pilots between land and in- or outbound ships. Medium to large vessels with inboard motors. Only observed within Fremantle Inner Harbour
Sailboat	Small yacht with both sail and inboard engine capabilities. At the two study sites considered, they were always under motor
Small Rec	Small, fibreglass or aluminium hulled boat with an outboard motor. Open top with forward controls or a centre console; designed to stay on the water for short periods of time (i.e. day trips)
SUP	Stand-up paddleboard. Propelled by paddling by rider using one paddle with one blade
Tinny	Small, aluminium hulled boat with a tiller-steered outboard motor. Open top, no cabin space. Also commonly referred to as a 'dingy'
Tug	Work boat used to manoeuvre vessels by pushing or towing them. Medium to large, powerful inboard motors

instances, the dredger was present but not operational; in such cases, dredging was considered as being absent. Dredging works utilised a backhoe dredger, a common stationary type of dredger where the dredging operation is performed by a hydraulic excavator,

mounted on a pontoon stabilised usually by means of spuds. All dredging works were enclosed by a silt-net to minimise environmental impact due to sediment plumes. Support vessels towed barges into position for collection and removal of dredged material.

## Data analysis

Use of these sites by dolphins was measured in three ways: (1) the occupancy of dolphins based on their presence/absence, (2) the relative abundance of dolphins, and (3) the duration of time dolphins spent in the study area. To investigate the relationship between site occupancy and vessel density, separate models with environmental covariates were fitted for each of these response variables. Due to the influence of tides, salinity, and seasons described above, it was deemed prudent to include environmental variables in addition to anthropogenic variables. Responses were investigated at a daily scale, i.e. the presence/absence, relative abundance, and total duration of time dolphins spent in an area in a day were considered as a single observation. The two sites themselves were not directly compared due to the daily timing of field work surveys (mornings in Fremantle Inner Harbour versus afternoons in Perth Waters), the seasonality of observations (not concurrently monitored in year two), and the different station heights at the two sites potentially resulting in dissimilar detection probabilities.

The explanatory variables initially considered for inclusion in each model were vessel density, dredging presence/absence (for Perth Waters), year, tidal state, tidal height, water salinity, water temperature, and maximum air temperature. Vessel density was calculated as the average number of vessels per hour effort for each survey (with a single survey undertaken per day), while the occurrence of dredging was recorded as a binary factor over the entire survey. Although year can be classed as a continuous variable, in this instance, it was included as a factor to reflect that only two levels existed. Tidal state and height data were inferred from tidal charts available on the Department of Transport website ([www.transport.wa.gov.au](http://www.transport.wa.gov.au)).

Tidal state was defined as a categorical variable with four levels (low, rising, high, and falling tide). The ‘high slack’ was defined as a period  $\pm 1.5$  h centred on the time of high water; ‘low slack’ was similarly defined for the time of low water. Consequently, a tidal state was defined as *high* if at least 50% of the survey overlapped with the ‘high slack’ period. Similarly, the tidal state was deemed *low* if at least 50% of the survey overlapped with the ‘low slack’ period. If a survey did not sufficiently overlap with

either of these periods, it was categorised as either *falling* or *rising*, which, respectively, indicated if the tidal state was moving towards or away from the ‘low slack’ period.

Tidal height varies according to the ‘Rule of Twelfths’, a rule of thumb for estimating the height of the tide at any time given the time of day and height of high/low water (Pearson, 2007). Tidal height for each survey in this study was calculated for the median time of the survey. The Rule of Twelfths was used to calculate the start/end time of each tidal ‘twelfth’, as well as the start/end tidal height for each of these twelfths. The start/end time of each twelfth period was then matched with the corresponding median tidal height for that period. Finally, tidal height data were taken from the twelfth period which matched the median survey time, to give one tidal height value per survey.

While water-quality (salinity, water temperature, pH, dissolved oxygen) data are collected by the Department of Water (Western Australia), daily data were not available for these sites. Models used the weekly (Perth Waters) or fortnightly (Fremantle Inner Harbour) water-quality data available. Water salinity and temperature were selected as measures of interest.

Due to the low resolution of water quality sampling, we investigated whether maximum daily air temperature could be used as a proxy for water temperature. This was justified by performing a Spearman’s Rank correlation, using days on which water quality sampling was performed and investigating the relationship between recorded water temperature and the maximum air temperature recorded for that day. The correlation was applied to each study site independently.

Generalised additive models (GAMs) were used to model the presence/absence, abundance, and duration of dolphins in the study sites. A GAM is an extension of a generalised linear model (GLM), which allows estimation of relationships between predictor and response variables using non-parametric functions, without making assumptions regarding the nature of such relationships (Zuur et al., 2009; Waples et al., 2013). GAM allows smoothing functions to be fitted to predictor variables, which generate curves that can flow more freely than a straight line for describing the data. For analyses using GAMs, explanatory variables were fitted in different combinations (i.e. smoothers, linear terms, and factors) for each response variable.

As not all surveys were equal in duration, the natural logarithm of survey effort was used as an offset variable in each model.

GAMs assume that model errors are independent. To verify their independence, model residuals were checked to ensure that there was no temporal autocorrelation using semi-variograms of the standardised residuals (Zuur et al., 2009). Additionally, for each model, the absence of concurvity (i.e. the non-parametric analogue of multi-collinearity) between these explanatory variables was confirmed using variance inflation factors (VIFs; Zuur et al., 2010). Overdispersion is commonly encountered in count data, meaning that data may vary more than expected compared to data following a Poisson distribution. Overdispersion was investigated using the sum of squared Pearson residuals divided by sample size, minus the number of parameters. QQ-Plots, histograms, residuals versus fitted values, fitted values versus observed values, and the percentage of deviance explained were used to quantify each model's goodness of fit (Zuur et al., 2009; Zuur & Ieno, 2016).

To assess the occupancy of dolphins, firstly the presence/absence of dolphins during each survey was investigated using a binomial GAM with a logit-link function. Secondly, the abundance of dolphins was originally investigated using a GAM with a Poisson distribution and a log-link function to model the number of dolphins sighted in each survey at Perth Waters; however, overdispersion in the Inner Fremantle Harbour data resulted in this model being fitted with a negative binomial distribution. Finally, the duration of time dolphins spent in the study area was investigated at both sites using a negative binomial GAM with a log-link function to model the number (counts) of minutes (rounded to the nearest minute) in each survey in which dolphins were present. A negative binomial distribution was selected to account for overdispersion of the data (Zuur et al., 2009; O'Hara & Kotze, 2010; Linden & Mantyniemi, 2011).

Model selection was conducted based on the maximum likelihood, considering the Akaike's Information Criterion corrected for small sample sizes (AICc; Burnham & Anderson, 2004). This approach stipulates that the lower the AICc the better the fit of the model, and is equally applicable to larger sample sizes as AICc converges with AIC in such cases. In addition, the difference between the AICc of each model and the lowest observed AICc of all models (i.e.

$\Delta\text{AICc}$ ) was calculated. Models with  $\Delta\text{AICc} < 2$  are equally plausible as the best model to explain the observed patterns in the data (Burnham & Anderson, 2004). To account for this, the Akaike's Information Criterion weight (wAICc) was calculated for models with similar plausibilities under the AICc. The wAICc expresses the relative contribution of the model to explain the observed patterns (Burnham & Anderson, 2004). In cases where the wAICc scores were identical for multiple models, the most parsimonious model was selected (Richards, 2008; Richards et al., 2011).

All analysis was conducted in R (R Core Team, 2015), using the following packages: *car* (Fox & Weisberg, 2011); *lattice* (Sarkar, 2008); *MASS* (Venables & Ripley, 2002); *mgcv* (Wood, 2006); *MuMIn* (Barton, 2016); and *stats* (R Core Team, 2015).

## Results

Across the 2-year study period, approximately 222 and 168 h of observation effort were invested in the Perth Waters and Fremantle Inner Harbour study sites, respectively. The exact breakdown of these hours and the resulting dolphin sightings are summarised in Table 1.

An investigation of the relationship between water temperature and maximum air temperature returned a positive correlation for both study sites (Perth Waters:  $r_s = 0.72$ ,  $P < 0.001$ ; Fremantle Inner Harbour:  $r_s = 0.81$ ,  $P < 0.01$ ). Thus, the decision to use maximum air temperature (hereafter 'temperature') as a proxy for water temperature was considered justified, given the high resolution of the former data compared to the latter.

Survey day was removed as a potential explanatory variable, due to concurvity issues with maximum air temperature and water salinity. Given the spread of surveys over several months and that an increase in survey day for each year corresponded with a decrease in temperature and an increase in water salinity, these variables appeared to show seasonal patterns. To avoid temporal confounding, survey day was thus removed from analysis.

### Summary of vessel activity

At the Perth Waters site, a total of 2,656 vessels were sighted and tracked across the 2-year study period,



resulting in a vessel density of approximately 12 vessels per hour of effort. The maximum observed vessel density was 43 vessels per hour effort. The majority of these were small recreational vessels (44%), followed by ferries (15%) and tinnies (10%; Fig. 2a). Approximately 72% of vessels spent 15 min or less in the study area (Fig. 2b), illustrating its use as a transit area. However, this site is also used over longer periods (up to several hours) by recreational fishers, day-trippers utilising the public moorings, jetskis using the personal watercraft area, and transport ferries which cross the river at regular intervals. As a result of the wide range of activities available for boat users, there is no one vessel category which stands out as spending a long time in the area, on average; yet there are a few vessel categories which spend either little or no time in this area (Fig. 2c).

Primarily afternoon-based visual observations were conducted at this site. This was a result of the orientation of the hill station, which forced observers to look due east, consequently causing extreme glare if surveys were conducted in the morning. Thus, afternoon surveys generally occurred between 2:00 pm and 6:00 pm; during this time, Perth Waters experienced the highest levels of vessel traffic between 4:00 pm and 6:00 pm, when approximately 60% of vessel activity occurred (Fig. 2d). This is believed to reflect the evening ‘rush hour’ of recreational vessels heading home. However, as boat ramps and pens exist both up- and down-river of this site, there is no clear directional movement (Fig. 2e). Additionally, two transport ferries operate during this time to meet the demands of city commuters crossing the river, as opposed to regular day-time service involving just one transport ferry. Approximately 76% of vessels were travelling at <8 knots while using the Perth Waters area (Fig. 2f). Jetskis and small recreational vessels had higher average speeds than other vessel types (Fig. 2g).

At the Fremantle Inner Harbour site, a total of 2,601 vessels were tracked across the two-year study period—equivalent to a vessel density of approximately 16 vessels per hour effort. The maximum observed vessel density was 56 vessels per hour effort. The majority of these were small recreational vessels (46%), followed by large recreational vessels (18%; Fig. 2a). Approximately 91% of vessels spent 15 min or less in the study site (Fig. 2b), which also implies that the Inner Harbour is primarily a transit zone. Those vessels which had a longer duration were

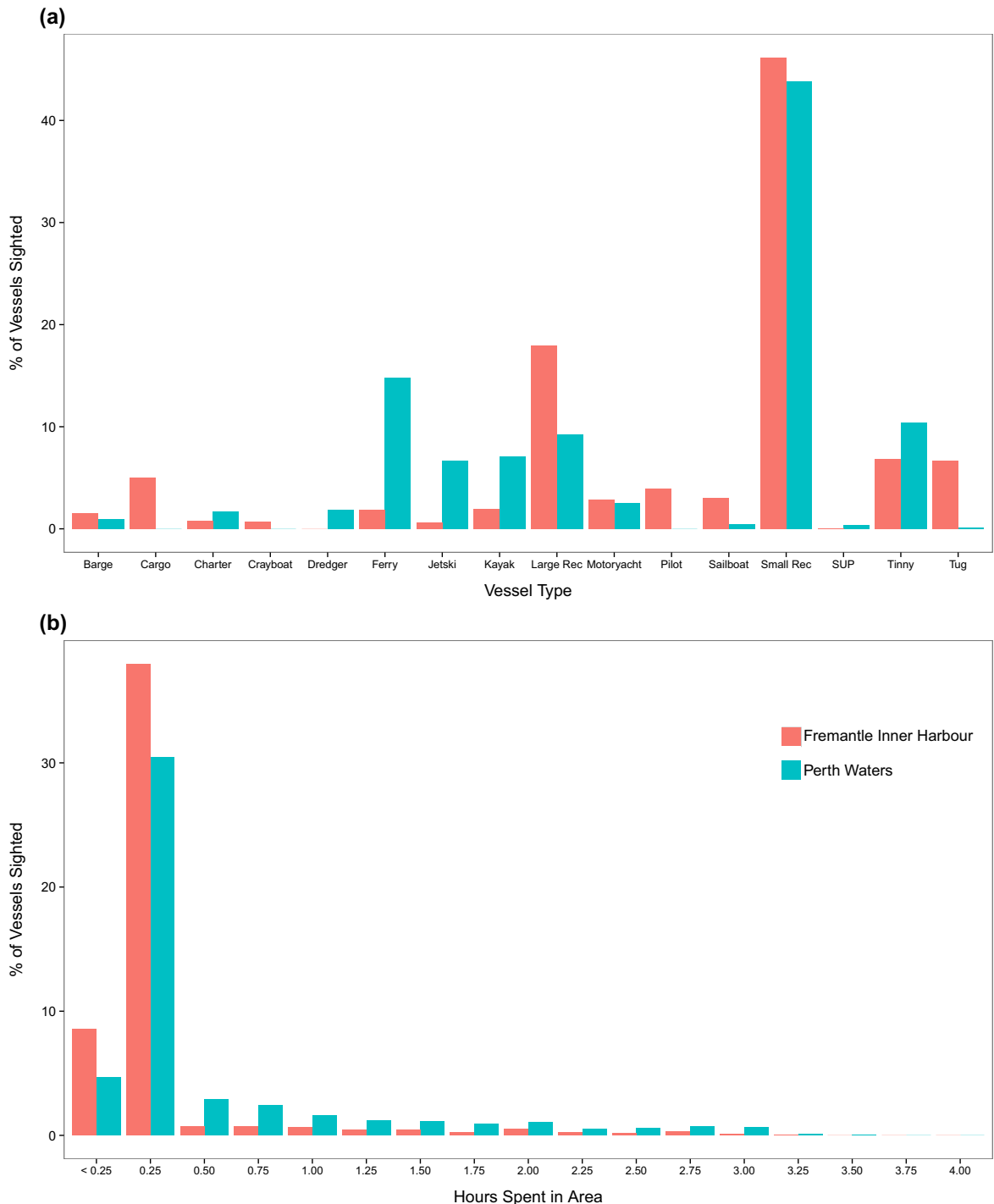
typically port work boats, such as barges, pilot vessels, or tugs (Fig. 2c).

Primarily morning-based visual observations were conducted at this site, as observers were positioned facing due west and thus experienced extreme glare during the afternoon. As a result, morning surveys generally occurred between 7:00 am and 10 am. During these hours, the Inner Harbour typically experienced the highest levels of vessel traffic between 8:00 am and 10:00 am, when approximately 66% of vessel activity occurred (Fig. 2d). This is believed to reflect the morning ‘rush hour’ of recreational vessel users heading out for the day, and is substantiated by the observation that the majority of vessels were travelling down-river (i.e. away from boat ramps/pens and out to sea) (Fig. 2e). Approximately 69% of vessels had average speeds <8 knots (14.8 km/h) within the Fremantle Inner Harbour; however, this varied with vessel type (Fig. 2f, g).

#### Dolphin occupancy within Perth Waters

At the Perth Waters site, dolphins were present in 23% (18 of 78) of surveys conducted. The maximum number of dolphins sighted during a survey at Perth Waters was eight sightings, with an average of 0.23 dolphin sightings per hour effort. The maximum of eight dolphins sighted in one survey is a true sighting and not a re-sighting of the same animals. Two groups were sighted during this survey: the first comprised four adults and one calf, while the second comprised three juvenile dolphins. The comparison of group compositions between ‘new’ groups and groups previously sighted during that survey allowed counts of dolphin sightings to be made with relative confidence. Across 13,306 min of observational effort, dolphins were present for a total of 383 min (approximately 1.72 min per hour effort), with a maximum duration time of 93 min in any one survey.

Due to the low sample size, modelling was not appropriate for this dataset; instead, the number of dolphin sightings was visually represented in relation to each potential explanatory variable (Fig. 3). From these, overall dolphin sightings were more numerous when vessel density was low. No dolphins were sighted at vessel densities above 20 vessels per hour; however, there were few surveys conducted at these high densities. Dredging was directly observed on 12 days. No dolphins were sighted on days when the dredger was operating. A peak in dolphin sightings



**Fig. 2** Summary of observed vessel traffic in Fremantle Inner Harbour (red) and Perth Waters (blue): **a** Percentage of vessel types sighted; **b** Duration of time vessels spent in the area; **c** Average duration of time spent in the area by different vessel types; **d** Number of vessels per hour effort present in the area by hour of day; **e** Frequency of vessel behaviours observed;

**f** Frequency of vessel speeds recorded; and **g** Average speed recorded for each vessel type. See Table 2 for definition of vessel types. Note that the surveys generally occurred from 7:00 to 10:30am (Fremantle Inner Harbour) and 2:00 pm to 6:00 pm (Perth Waters), with some exceptions

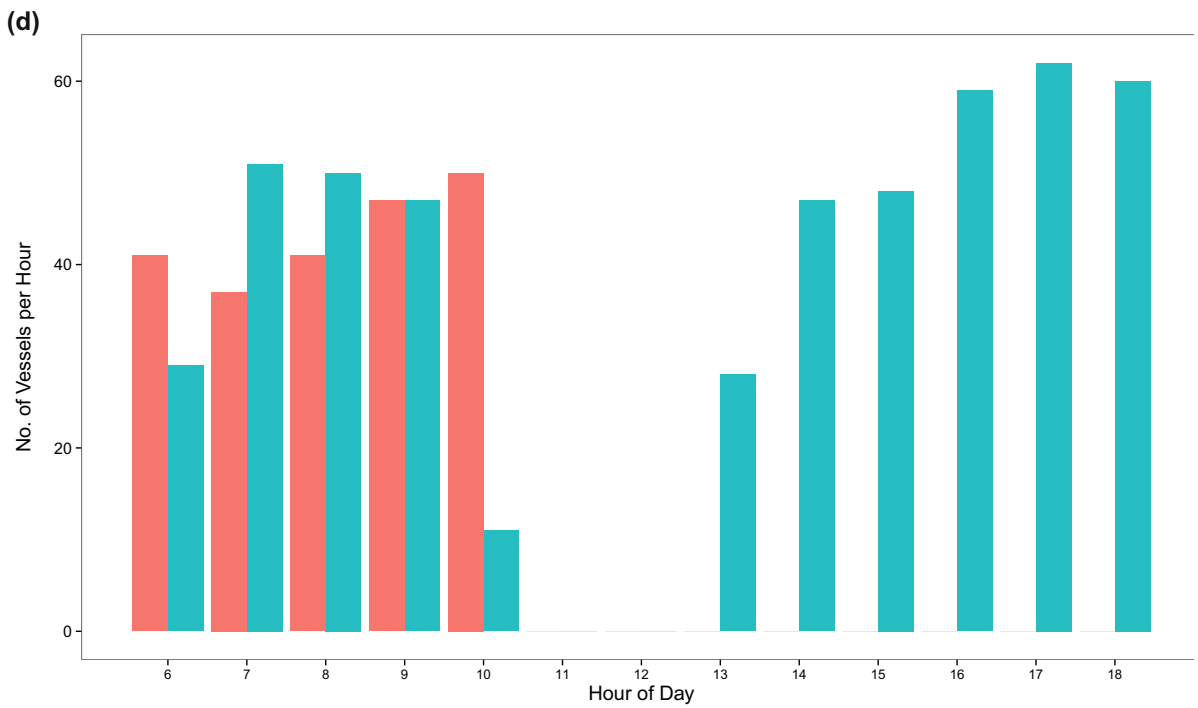
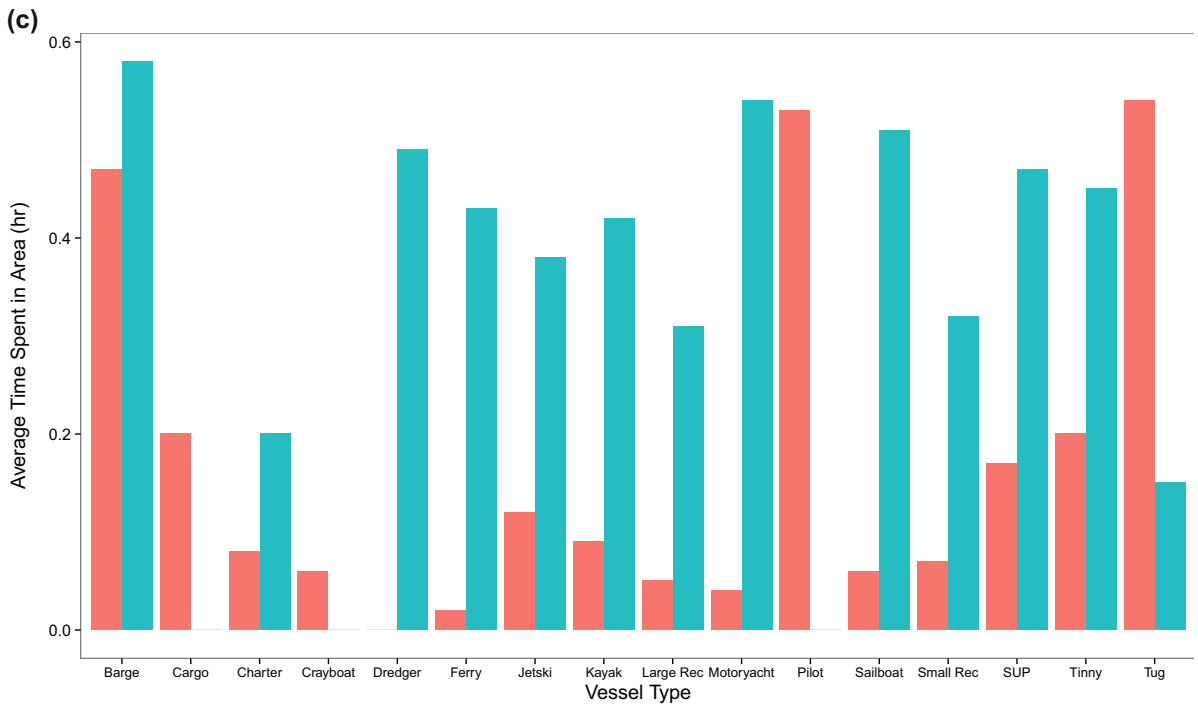


Fig. 2 continued

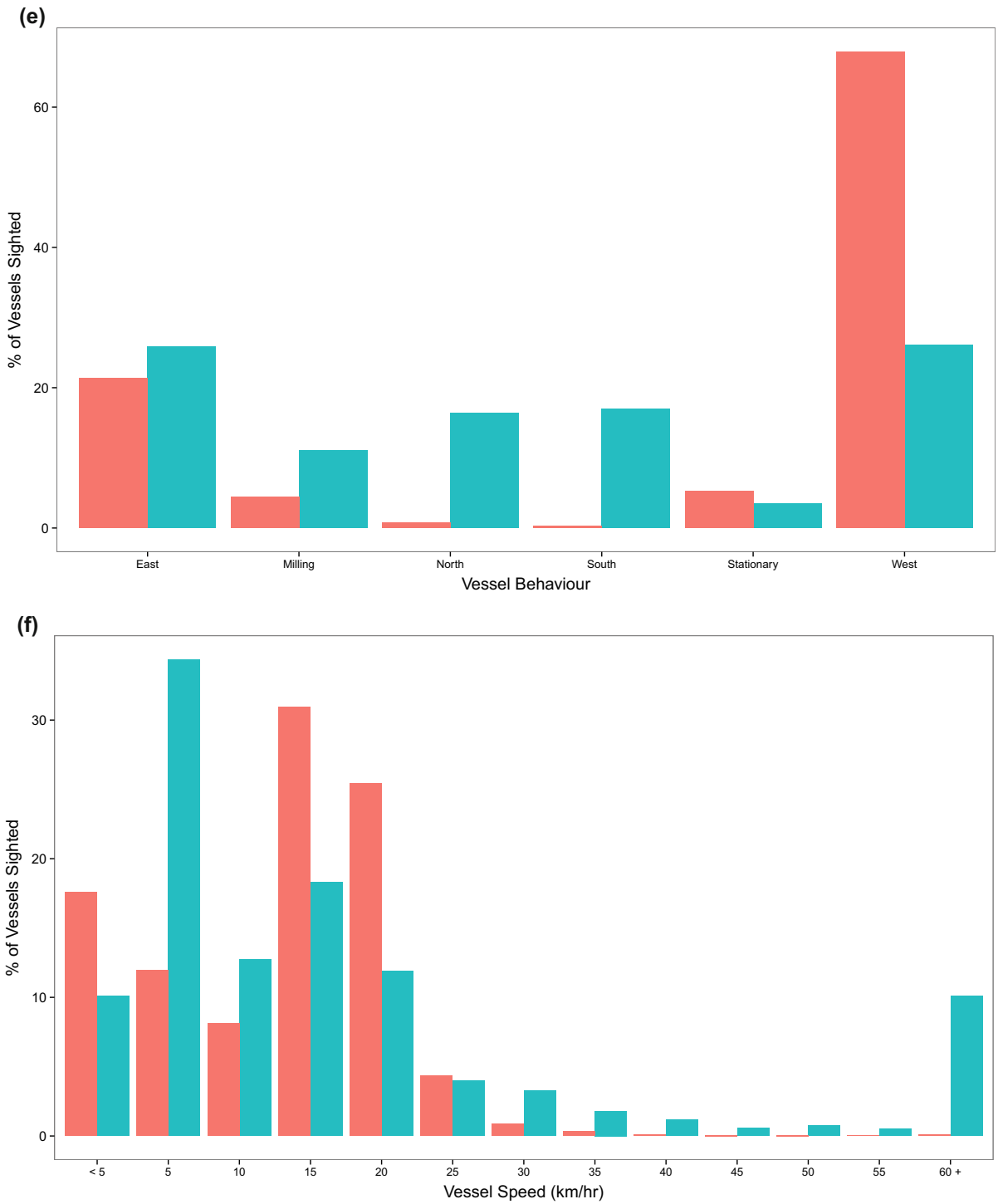
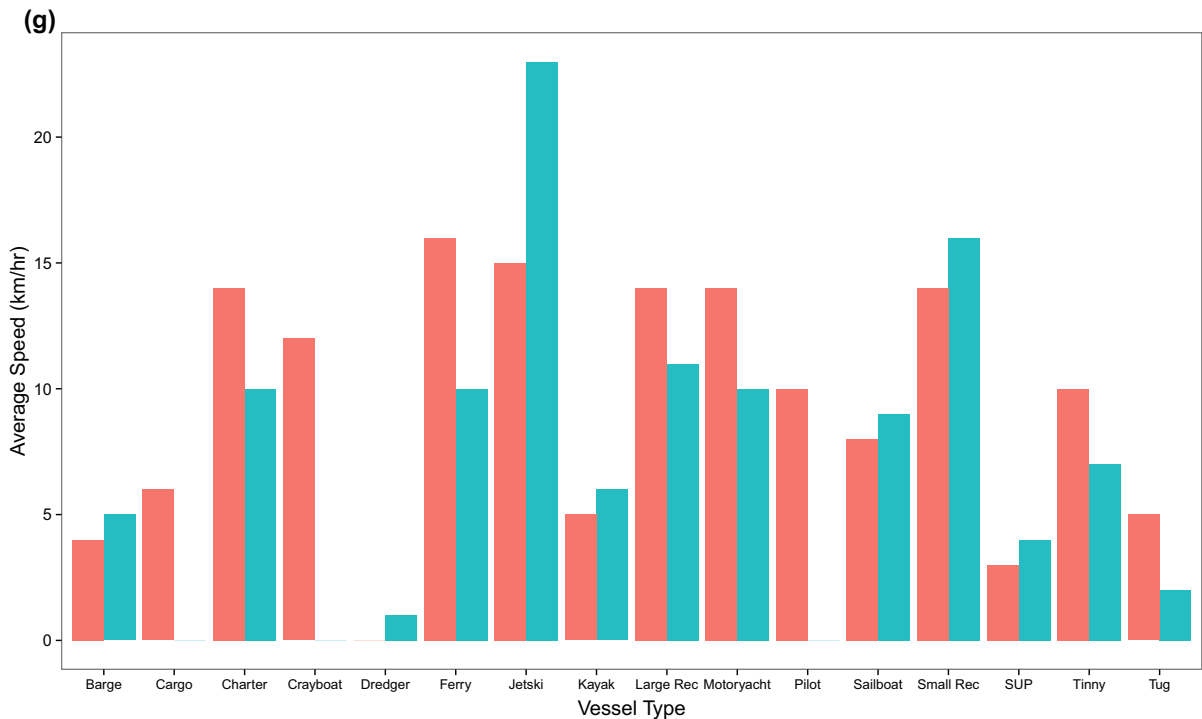


Fig. 2 continued



**Fig. 2** continued

occurred in the middle temperature ranges. Relatively high numbers of dolphin sightings were made during low or falling tidal state in comparison to high or rising tidal states. Numbers of dolphin sightings were also greater with increased tidal height and water salinity.

To determine the presence of any seasonal patterns, the number of dolphin sightings was also plotted by Julian Day in association with each potential explanatory variable for each of the two study years (Fig. 4). Both temperature and water salinity display seasonal patterns, reflecting the change from austral summer to winter during the study period. Low or falling tidal states were more commonly observed later in the study period. Dolphin sightings appear less abundant in the austral summer months at Perth Waters, suggesting a seasonal pattern to their occupancy at this site.

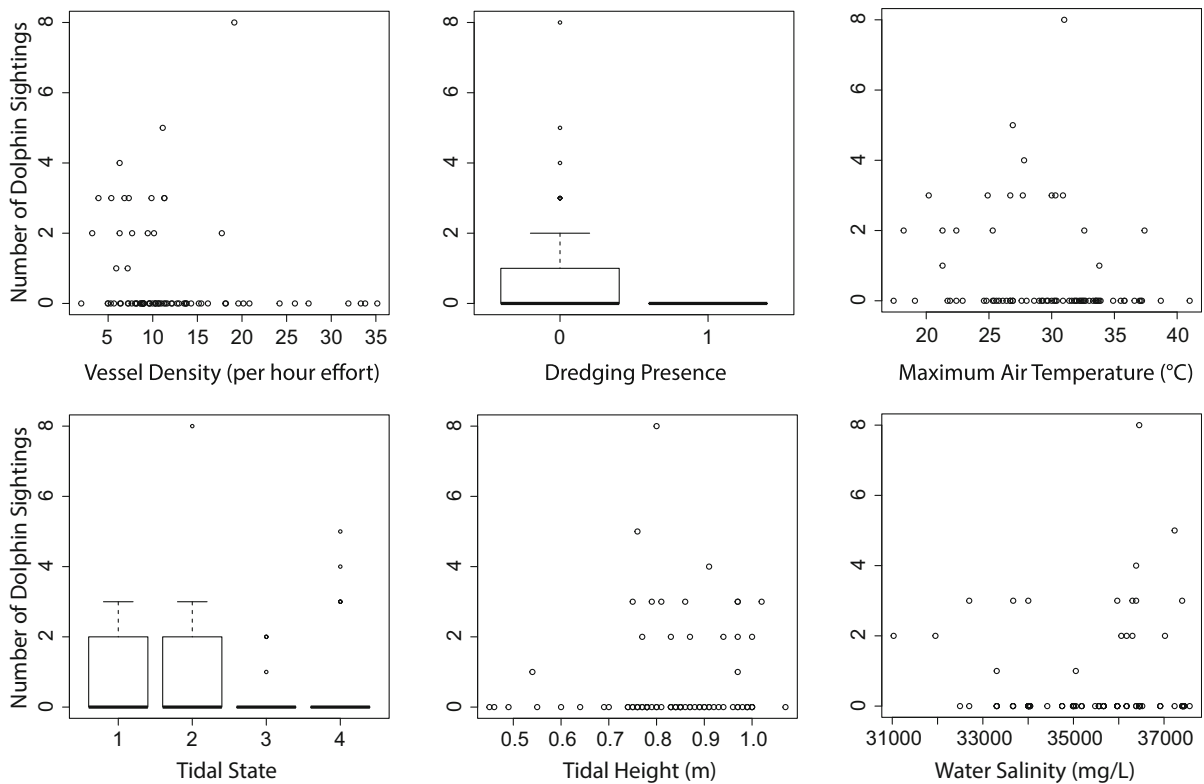
#### Dolphin occupancy within the Fremantle Inner Harbour

Within the Fremantle Inner Harbour site, dolphins were present in 55 of the 58 surveys conducted (95%). Given the low number of absences, modelling of dolphin presence/absence was not attempted. Thus, it

appears that dolphins are present in the Fremantle Harbour independent of vessel densities, temperature, tidal state, tidal height, or water salinity.

The maximum number of dolphins sighted within the Fremantle Inner Harbour across a single survey was 27 sightings; the average was 2.30 dolphin sightings per hour effort. Model selection retained temperature as being a significant predictor for the number of dolphins sightings in the study area ( $X^2 = 17.52$ ,  $df = 2.605$ ,  $P < 0.001$ ; Fig. 5a; Tables 3, 4). The final model explained 27.2% of deviance.

Across 10,049 min of observational effort at the Fremantle Inner Harbour, dolphins were present for a total of 4,705 min (approximately 28.09 min per hour effort), with a maximum duration time of 181 min in any one survey. Model selection with AICc and wAICc identified multiple possible models; thus, the most parsimonious model was selected. This retained temperature as having a significant negative relationship with the amount of time dolphins spent in the study area ( $X^2 = 6.786$ ,  $df = 0.893$ ,  $P = 0.005$ ; Fig. 5b; Tables 3, 4), but only explained 9.0% of deviance. This suggests that additional, as yet



**Fig. 3** Number of dolphin sightings in Perth Waters in association with potential explanatory variables. It is worth noting that the maximum of eight dolphins sighted in one survey (which skews some perceived patterns, so may initially be

thought an outlier) is a true sighting and not a re-sighting of the same animals. Two groups were sighted during this survey: the first comprised four adults and one calf, while the second comprised three juvenile dolphins

unidentified, covariates could further explain the response data.

site environmental factors influenced occupancy rather than vessel traffic.

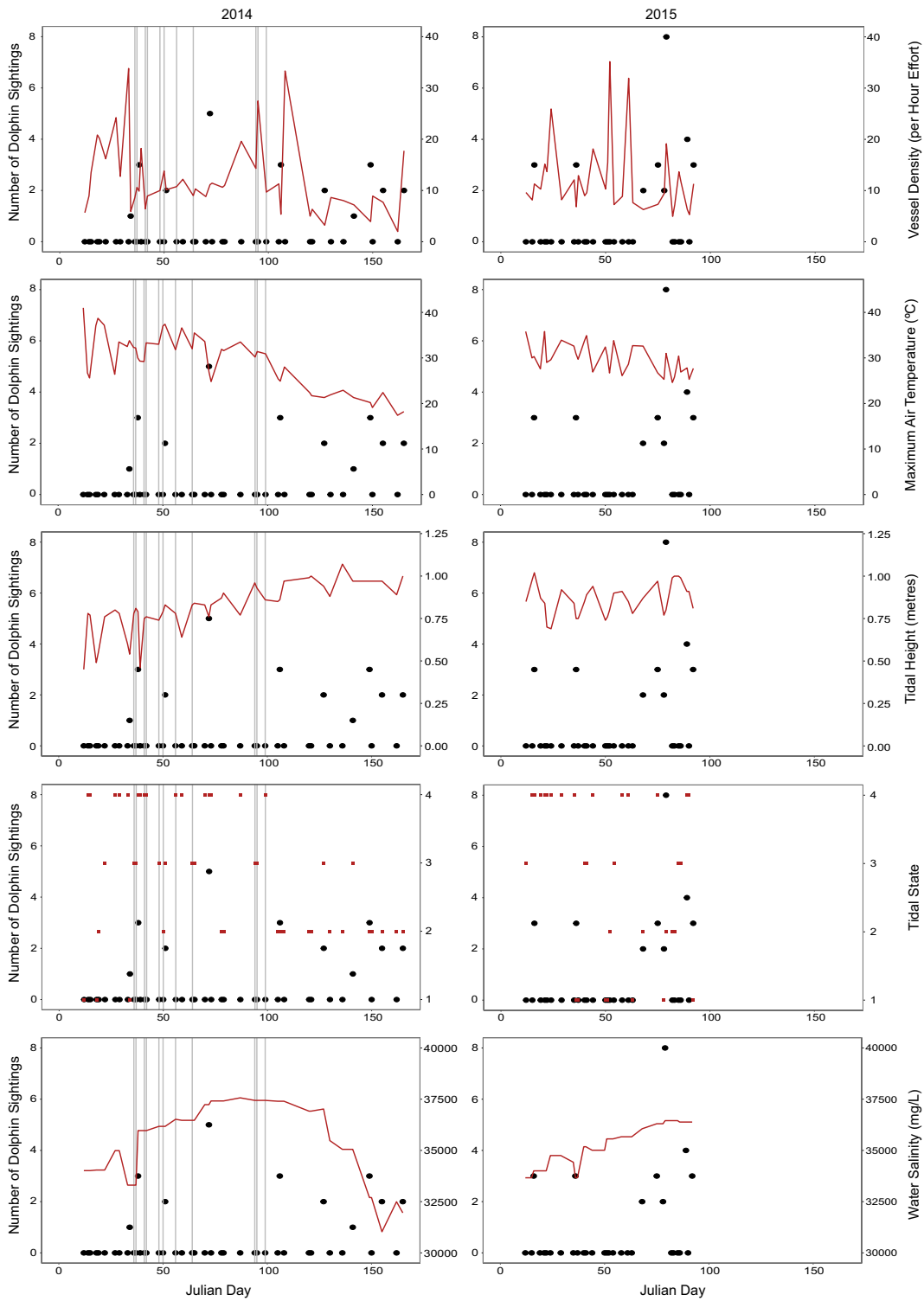
## Discussion

In this study, dolphins were sighted much more often in the Fremantle Inner Harbour than at the Perth Waters site. At Perth Waters, there were fewer overall sightings of dolphins when vessel densities were high. Additionally, of the relatively few sightings at Perth Waters, dolphins were never sighted on days when backhoe dredging was underway. However, within the Fremantle Inner Harbour, statistical analyses indicated that dolphins remained using the site despite high levels of vessel traffic. Instead, temperature showed a significant negative association with both the number of dolphin sightings and the duration of time dolphins spent in the study area. These results suggest that dolphins use sites differentially, and at the preferred

## Vessel traffic

At Perth Waters, number of dolphin sightings appeared more frequent when vessel density was low. However, at the Fremantle Inner Harbour, dolphin occupancy displayed no observable change relative to vessel density. Despite reaching a maximum of 34 vessels per hour effort, dolphins continued to be present in almost all surveys and showed no response in either the number of dolphin sightings or the duration of time spent by dolphins in this area.

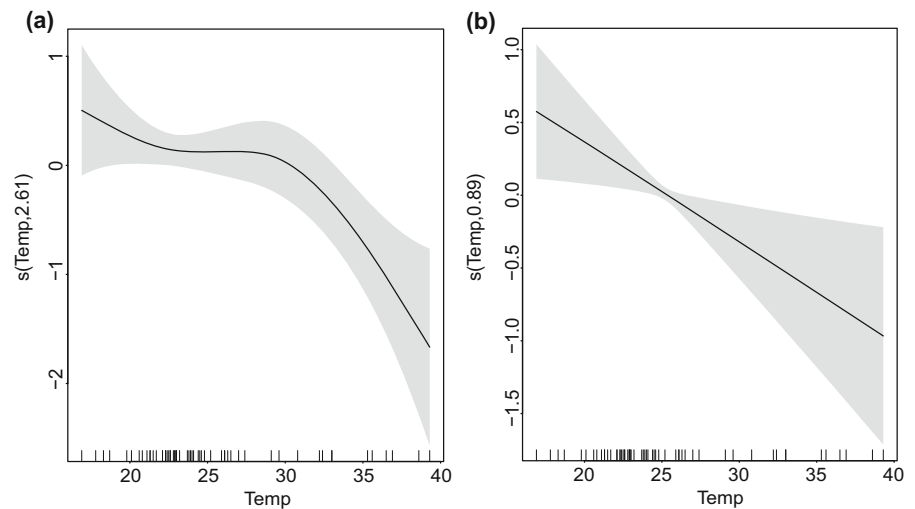
Both Perth Waters and Fremantle Inner Harbour experienced relatively high levels of vessel traffic throughout the study period. A variety of vessel types were observed within the Swan River; however, the majority of vessels at both sites were small recreational vessels, indicating the high use of these areas



**Fig. 4** Number of dolphin sightings in Perth Waters in association with Julian Day and potential explanatory variables. Points represent number of dolphin sightings, red lines/points

represent variation in explanatory variable, and grey vertical bars represent days when dredging was present

**Fig. 5** Results of the negative binomial GAMs for the Fremantle Inner Harbour dataset, showing **a** number of dolphin sightings in association with maximum air temperature, and **b** duration of time dolphins were present in association with maximum air temperature



by recreational boaters. Boats at both locations typically spent less than 15 min in the site, suggesting that the majority of vessel traffic is merely transiting through these areas. Peaks in vessel traffic were observed at both sites, occurring in the early morning and late evening. This corresponds with acoustic studies in parts of the Swan River, which have observed daily peaks in the presence of vessel noise hypothesised to represent “rush hour” as vessels head out shortly after sunrise and return home shortly before nightfall (Marley et al., 2016). Visual observations from the present study detailing the time, duration, and direction of vessel movements confirm this theory.

However, despite the low temporal presence of the majority of individual vessels, many vessels were recording travelling at high speeds. Two speed zones exist within Perth Waters. A large shallow area constitutes the majority of this site and is restricted to 8 knots (14.8 km/h), while the remaining area is “non-speed restricted”. Similarly, a legal speed limit of 8 knots also applies within the Fremantle Inner Harbour. Ferries, small recreational vessels, and jetskis typically had an average speed above this limit, although it appears that all vessel categories bar kayaks and SUPs had instances where the 8-knot level was breached. Additionally, despite a prohibition of fishing within the Fremantle Inner Harbour (for safety reasons), there were two days when dozens of recreational vessels were observed to stop and commence this activity within the site. This was due to the presence of large bait balls moving into the Inner Harbour from the ocean. Furthermore,

throughout the study period, a number of vessels were also observed to trail fishing lines behind them while transiting the Inner Harbour, although this was not quantified due to the difficulty of consistently observing fishing line from the hilltop station.

Despite these similarities in vessel activity, Perth Waters and the Fremantle Inner Harbour were used differentially by dolphins. The Fremantle Inner Harbour is known to be a foraging site for this dolphin community (Moiler, 2008), whereas Perth Waters appears to be primarily used as a transit area to reach different parts of the river system. It may be that the value of the Inner Harbour as a foraging site outweighs its cost as an area of high vessel traffic. In comparison, as a transit area, the presence of dolphins in Perth Waters would depend on the value of the habitat they are attempting to reach balanced with the cost of high vessel densities.

Sensitivity to vessel density may also reflect physical environmental features. Perth Waters is a large, shallow bay with an average depth of 1 m; in comparison, the Fremantle Inner Harbour is 13 m deep. Dolphins have been shown to avoid shallow areas as a predator-avoidance response (Heithaus & Dill, 2002). This is hypothesised to reflect the riskiness of shallow habitats, due to the reduced efficiency of echolocation in shallow waters (a result of clicks scattering off the surface and bottom) and existence of fewer potential escape routes in shallow water compared to deeper habitats (Heithaus & Dill, 2002). Although no predation of dolphins by sharks has been observed within the Swan–Canning Rivers, high vessel traffic has been seen to invoke



**Table 3** Model selection was conducted based on the Akaike’s Information Criterion corrected for small sample sizes (AICc)

	Model	Explanatory variables considered	AICc	R2	% Deviance explained	wAICc
Number of dolphin sightings	<i>Null</i>	1	335.4	0	0	–
	<i>Mod_1</i>	VD, AT, TS, TH	323.7	0.214	35.4	0.136
	<i>Mod_2</i>	VD, AT, TS	323.7	0.214	35.4	0.136
	<i>Mod_3</i>	AT, TS	323.0	0.201	34.1	0.190
	<i>Mod_4</i>	AT	322.8	0.160	27.2	0.204*
	<i>Mod_5</i>	VD, AT, TS, WS	323.7	0.214	35.4	0.136
	<i>Mod_6</i>	AT, TH	322.9	0.188	29.0	0.199
Duration of time dolphins present	<i>Null</i>	1	626.9	0	0	–
	<i>Mod_1</i>	VD, AT, TH, WS	622.7	0.162	8.98	0.125
	<i>Mod_2</i>	AT, TH, WS	622.7	0.162	8.98	0.125
	<i>Mod_3</i>	VD, AT, TH	622.7	0.162	8.98	0.125
	<i>Mod_4</i>	VD, AT, WS	622.7	0.162	8.98	0.125
	<i>Mod_5</i>	AT, WS	622.7	0.162	8.98	0.125
	<i>Mod_6</i>	VD, AT	622.7	0.162	8.98	0.125
	<i>Mod_7</i>	AT, TH	622.7	0.162	8.98	0.125
	<i>Mod_8</i>	AT	622.7	0.162	8.98	0.125*

Models with  $\Delta AICc < 2$  were compared using Akaike weights (wAICc). In cases where the wAICc scores were identical for multiple models, the most parsimonious model was selected. The final model selected for each dataset is indicated by an ‘asterisk’. Explanatory variables: Vessel Density (VD); Maximum Air Temperature (AT); Tidal State (TS); Tidal Height (TH); Water Salinity (WS)

**Table 4** Results from negative binomial GAMs with log-link functions investigating the number of dolphin sightings and duration of time spent by dolphins within Fremantle Inner Harbour

Number of dolphin sightings				
	Estimate	SE	Z-value	P value
Intercept	–3.32943	0.08779	–37.92	$<2e^{-16}$ ***
	Chi-squared	d.f.	P value	
Temperature	17.52	2.61	0.000111***	
Duration of time dolphins present				
	Estimate	SE	Z-value	P value
Intercept	–0.8199	0.1511	–5.427	$<5.75e^{-08}$ ***
	Chi-squared	d.f.	P value	
Temperature	6.786	0.8926	0.00527**	

Significance level:  $\leq 0.0001 = \text{‘***’}$ ;  $\leq 0.001 = \text{‘**’}$ ;  $\leq 0.01 = \text{‘*’}$ ;  $\leq 0.05 = \text{‘.’}$

predator-avoidance responses in bottlenose dolphins from other populations (Frid & Dill, 2002; Lusseau, 2003b; Lusseau & Higham, 2004; Lusseau, 2006). If

this occurs in the Swan–Canning dolphin community, then the Fremantle Inner Harbour would offer superior detectability and avoidance strategies compared to Perth Waters, facilitating the use of the former despite high vessel densities.

Furthermore, the majority of vessel traffic in the Fremantle Inner Harbour typically transits through the centre channel. If dolphins forage primarily outside of this channel, they may avoid the more detrimental aspects of vessel traffic (e.g. risk of collision, intense underwater noise, disturbance of prey species). Consistent levels of vessel traffic may even alter the distribution of prey species within the Inner Harbour, forcing them to utilise refuges around the harbour periphery. If this is the case, there may be relatively little overlap in fine-scale spatial use of the Inner Harbour between dolphins and the majority of vessel traffic.

Temperature and seasonality

Previous studies have found possible seasonality in the use of the Fremantle Inner Harbour, where dolphins may occupy this area more often or for longer periods than other sites within the river system (Moiler, 2008). A study investigating spatial and temporal patterns of

dolphin habitat use in the Swan River found the highest abundance of dolphins occurred in the Fremantle Port, with greater numbers of dolphins observed in the austral autumn (Moiler, 2008). A similar pattern was indicated in a later study, but was confounded by the presence of pile-driving (Paiva et al., 2015). It was suggested that this pattern was influenced by seasonal variation and abundance/migration of prey species, induced by seasonal water temperature changes (Moiler, 2008). The present study also found temperature to be a significant explanatory variable, negatively affecting both the number of dolphin sightings and the duration of time dolphins spent within the Fremantle Inner Harbour.

If the Fremantle Inner Harbour is subject to seasonal use by dolphins in response to seasonal availability of prey species (potentially driven by seasonal water temperature changes), the limited temporal availability of food in this area could increase the importance of this location as a foraging site. Bait balls were observed during this study, lending some additional support to theories relating to prey availability within the Inner Harbour. This may also contribute to explaining why dolphin occupancy does not appear to change in response to vessel density at this site. Dolphins may tolerate high levels of vessel traffic in order to maximise intake of seasonal prey present within the Fremantle Inner Harbour. Although no prey data were available for this study, previous research has shown dolphin hotspots to be linked to foraging (Hastie et al., 2004), and detailed foraging-related studies could be worthwhile at this site in the future. However, given the relatively low deviance explained by the models, there may be additional, as yet unconsidered, covariates which could further explain dolphin occupancy within the Fremantle Inner Harbour.

There could have been patterns in dolphin occupancy associated with temperature and water salinity at the Perth Waters site. However, it was not possible to fully interpret any relationships due to limited sample size. Dolphin groups were generally seen travelling through this area, with foraging presumably occurring elsewhere; no bait balls or indicators of prey availability were observed. If Perth Waters has low significance as a foraging site, this may concur with the above theory that it is worth staying in busy areas if prey availability is high, explaining why dolphin sightings here were clustered around surveys of low vessel density.

## Dredging

No dolphins were ever sighted during a survey in which dredging was also present. However, confident interpretation of the potential effects of dredging cannot be made as there was a relatively small number of days of observed dredging (15% of all Perth Waters surveys) compared with days with no dredging. Additionally, there was a relatively low overall sighting rate of dolphins at this site regardless of whether dredging was occurring or not. It was not possible to extend monitoring sufficiently after cessation of dredging activities, due to logistical constraints.

The most likely impact on cetaceans elicited by dredging is linked to underwater noise. Dredging generally produces continuous, broadband sound with main energy below 1 kHz. However, noise levels can vary according to dredger type, operational stage, or environmental conditions. Backhoe dredging (as used here) is one of the quietest forms of marine dredging compared to cutter suction dredgers or trailing suction hopper dredgers (Todd et al., 2015). The available literature has few studies on the effects of dredging activities on cetacean species (see Todd et al., 2015 for review). Only one other study has investigated the influence of dredging on bottlenose dolphin occupancy. Dolphins were displaced by dredging works in Aberdeen Harbour, an important foraging site (Pirotta et al., 2013). Unfortunately, the authors did not indicate what type of dredging was used during their study, limiting the potential for comparisons. A study on the effects of a trailing suction hopper dredger found harbour porpoises (*Phocoena phocoena*) to exhibit short-term avoidance at ranges of 600 m (Diederichs et al., 2010). However, the majority of other dredging studies appear to be inconclusive, with many observing the study species both in proximity to operating dredgers while also showing an overall decline in numbers and possible avoidance (e.g. bowhead whales, *Balaena mysticetus*) (Richardson et al., 1985, 1987, 1990). In many reports, it is also difficult to separate the effects of dredging and of vessel traffic, as these activities often occur concurrently (Anderwald et al., 2013). In the present study, the need to quantify vessel traffic was imperative, as vessels were present in all surveys; however, this also provided the opportunity to separate the potential effects of this activity from those of dredging.

## Conclusion

It appears that although the Swan–Canning dolphin community is frequently exposed to vessel traffic, the dolphins may not have become fully habituated to this activity. Dolphins may tolerate relatively high levels of vessel traffic in some areas, but not in others. Reasons for this most likely reflect differences in the quality of those areas and their importance as sites for vital life processes. Seasonal presence of prey species at specific sites may account for tolerance of anthropogenic activities in order to maximise limited prey availability.

Therefore, beyond considering the occupancy of dolphins with regard to vessel traffic, future studies could consider the effect of this anthropogenic activity at a finer resolution by examining the following: what spatial overlaps exist; the role that vessel type, speed, and behaviour may play in dolphin behavioural responses; and how dolphin behavioural budgets may be affected by changes in vessel density. It may be that dolphins have specific strategies for coping with such busy environments. Studies investigating the availability of dolphin prey species within areas of the Swan–Canning Rivers would also contribute to our understanding of dolphin spatial use within this system. In conclusion, to determine whether vessel traffic invokes a more subtle behavioural response, it is recommended that future work focusses on fine-scale changes to dolphin movement patterns, activity states, individual behaviours, and vocalisation patterns. These results provide managers and stakeholders with information on dolphin occupancy and vessel traffic, and also highlight the importance of considering multiple response variables and habitat characteristics.

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