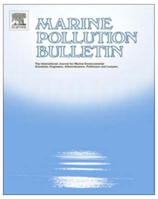
Marine Pollution Bulletin 75 (2013) 168–173

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul



Does boat traffic cause displacement of fish in estuaries?

Alistair Becker[a,*], Alan K. Whitfield[a], Paul D. Cowley[a], Johanna Järnegren[b], Tor F. Næsje[a,b]

[a] *South African Institute for Aquatic Biodiversity, Private Bag 1015, Grahamstown 6140, South Africa*
[b] *Norwegian Institute for Nature Research, P.O. Box 5685 Sluppen NO-7485, Trondheim, Norway*

ARTICLE INFO

Keywords:
Urbanisation
Disturbance
South Africa
Estuaries

ABSTRACT

Estuaries are increasingly under threat from a variety of human impacts. Recreational and commercial boat traffic in urban areas may represent a significant disturbance to fish populations and have particularly adverse effects in spatially restricted systems such as estuaries. We examined the effects of passing boats on the abundance of different sized fish within the main navigation channel of an estuary using high resolution sonar (DIDSON). Both the smallest (100–300 mm) and largest (>501 mm) size classes had no change in their abundance following the passage of boats. However, a decrease in abundance of mid-sized fish (301–500 mm) occurred following the passage of boats. This displacement may be attributed to a number of factors including noise, bubbles and the rapidly approaching object of the boat itself. In highly urbanised estuarine systems, regular displacement by boat traffic has the potential to have major negative population level effects on fish assemblages.

1. Introduction

Urbanisation is a rapidly increasing feature of coastal regions around the world which coincides with human population levels three times greater in this zone than the global average (Small and Nicholls, 2003). Coastal population growth has been directly linked to increases in commercial and recreational boating activity, particularly in more affluent areas of the world (Widmer and Underwood, 2004; Davenport and Davenport, 2006).

Detrimental effects of boating on marine fauna has recently been recognised, and linked to noise levels (Codarin et al., 2009; Slabbekoorn et al., 2010). Other effects may include strikes from propellers (Killgore et al., 2011; Balazik et al., 2012) or pollution from outboard exhaust (Situ and Brown, 2013). Noise from boats may increase stress levels of fish (Smith, Kane & Popper, 2004) while the passage of boats may break up schools and cause increased activity and energy expenditure due to the movement away from the disturbance. Animals living within estuaries are particularly vulnerable to potential adverse effects of recreational boating because, relative to open coastal regions, they are often spatially restricted in terms of depths and width, especially during the ebb tide. This problem may be exacerbated in countries like South Africa where coastal boating is largely restricted to estuaries because of the often hostile conditions along the open coast. Despite this, field studies on the effects of boats on fish are rare, with studies conducted in estuaries, where boat traffic perceivably could have the greatest impact, being overlooked.

Boats may affect the abundance of fish within a particular location at different temporal scales. Firstly, the passing of a boat may cause a 'flight' response, leading to a rapid change in localised fish abundance as individuals are displaced away from the passing boats. Secondly, fish may avoid areas of high boat traffic, leading to longer term variations in abundance (Gutreuter, Vallazza & Knights, 2006) and altered trophic functioning within the system. These observations highlight the need to continue to expand laboratory studies into field based observational or manipulative research.

Direct observation of the effect of passing boats on fish is difficult. Underwater cameras or direct observation by divers offer a potential solution, but estuaries are often turbid, meaning such approaches are unpractical. The advent of high definition acoustic cameras (DIDSON), which produce near video quality footage in dark and turbid waters, offers a potential solution that has proved useful in a range of fisheries and ecological studies (Boswell, Wilson & Cowan, 2008; Becker et al., 2011; Handegard et al., 2012).

This study aims to investigate whether boat traffic influences the local abundance of estuarine fish at two temporal scales, namely short term effects (immediately before and after passing boats) and long terms effects (high traffic days versus low traffic days). We predict a reduction in abundance of fish in the main navigational channel of a permanently open estuary immediately after the passage of a boat. Secondly, we predict that fish abundance in the same channel will be lower on days of high boat traffic compared to days with little or no boat traffic.

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[*] Corresponding author. Current address: School of Biological Earth and Environmental Science, University of New South Wales, Sydney, NSW 2052, Australia. Tel.: +61 2 9385 8322.

E-mail address: a.becker@saiab.ac.za (A. Becker).

http://dx.doi.org/10.1016/j.marpolbul.2013.07.043

2. Methods

2.1. Site description

The Bushmans Estuary (33°41′14″S, 26°39′39″E) is a permanently open system located in the warm-temperate region of South Africa. Tides in estuaries along this section of the coast are microtidal (vertical range < 2 m) although they can still penetrate approximately 30 km up the Bushmans system. As a result of catchment river abstraction, this estuary is freshwater deprived, with salinities in the lower reaches almost permanently similar to seawater (Whitfield, 2005).

As this project formed part of a broader research program, work was conducted at a single site approximately 3 km from the estuary mouth. The estuary at this location is characterised by large shallow mud-flats with a single deep (≈2 m) approximately 20 m wide channel which runs close to the south-western shoreline (Fig. 1). This allowed us to position the DIDSON so it captured a cross section of the entire channel. Another advantage of this site was the morphology of the channel and mud-flats meant all boat traffic had to pass along the channel through the field of view of the DIDSON (Fig. 1).

2.2. Field methods

Fieldwork was conducted between the 9th and 18th March 2011. A standard DIDSON 300 unit was attached to a bottom weighted vertical metal stand via a dual ball and socket system which allowed for fine adjustments in the position and tilt angle of the sonar. The sonar was orientated with the beams angled slightly below horizontal, aiming through the water column and avoiding 'digging' them into the substrate (Maxwell and Smith, 2007). Once an optimal position was obtained, providing a clear view across the channel, the sonar was not moved for the duration of the study.

The DIDSON was operated with a window length (range) of 20 m, thus encompassing the entire width of the channel. Water depth at the position of the DIDSON varied with the tide, ranging between 1.25 and 1.95 m. The DIDSON was set to 'film' continuously throughout the study and observers noted the exact time boats passed through the area covered by the DIDSON beams. All boat traffic consisted of small vessels (<6 m total length), with most fitted with outboard engines of between 20 and 80 horsepower. Boat traffic is required to slow to 5 knots at the filming location, and this was respected by almost all boat operators.

2.3. Analysis of footage

DIDSON footage was manually processed using the Soundmetrics DIDSON software V5.25.24. Fish were grouped into one of three size classes (100–300 mm, 301–500 mm, >500 mm) using the measurement tool in the DIDSON software. Fish less than 100 mm could not be accurately counted due to the window length settings used for this particular study. Size classes were delineated into broad fish guilds based upon published literature of estuary-associated fish species within the region (Whitfield, 1998), as well as comprehensive netting surveys (gill and seine nets) on the Bushmans Estuary (T.D. Harrison unpublished data). The 100–300 mm TL size class would most likely consist of the various non-piscivorous taxa common within South African estuaries (Whitfield, 1998), including juvenile mugilids, sparids and monodactylids. The intermediate size class (301–500 mm) was most likely dominated by juvenile piscivores such as *Argyrosomus japonicas*, subadult zoobenthivores such as *Pomadasys commersonnii* and, to a greater extent, larger adult detritivores such as *Liza tricuspidens* in the Bushmans Estuary. The largest size class (>500 mm TL) was established so that it would include principally large piscivorous species occupying the top trophic position within the estuary (e.g. *A. japonicus* and *Lichia amia*).

The relative abundance of the three size classes (100–300 mm, 301–500 mm, >500 mm) was calculated using the MaxN method (Cappo, Speare & De'ath, 2004; Becker et al., 2013), where relative abundance is defined as the maximum number of individuals

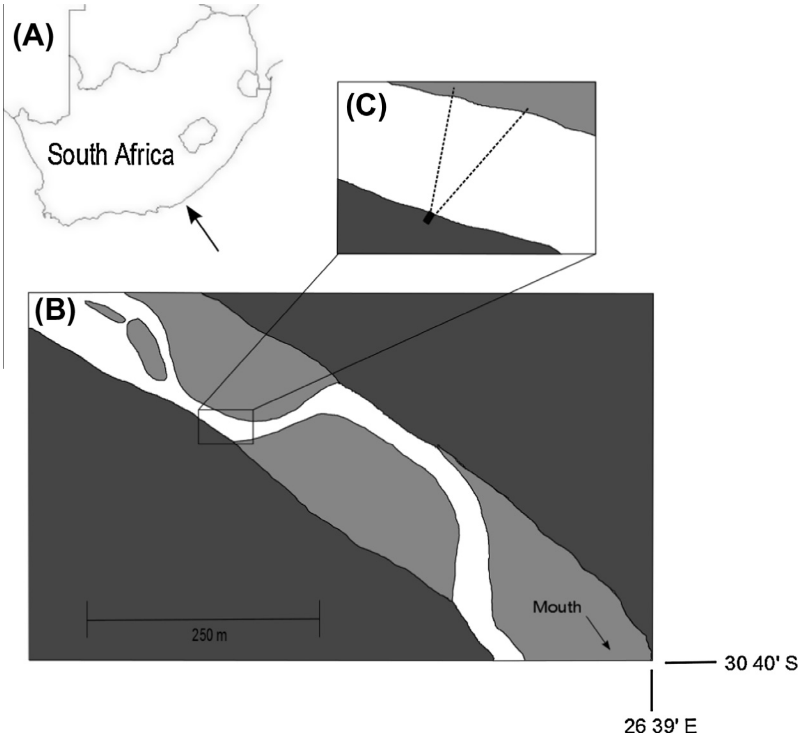

Fig. 1. (A) Map of South Africa with an arrow showing the location of the Bushmans Estuary. (B) The study site showing the deep navigation channel in white, intertidal mud banks in light grey and the shore in dark grey. (C) Insert showing the field of view of the DIDSON (dashed lines).

present in the field of view at the same time. This widely adopted approach does not attempt to produce an accurate count but rather a relative abundance measure and eliminates the chance of repeatedly counting the same fish over a selected period. Separate MaxN estimates were made for each size class.

For the short-term effects experiment, a symmetrical 'Beyond BACI' (Before/After and Control/Impact) design was developed consisting of multiple controls and impacts (Underwood, 1993). Because the study was restricted to a single site, the usual spatial factor 'Locations' which would typically include control and impacted areas required modification. We overcame this shortcoming by including a temporal factor called 'Event'; where an event equated to a 40 min period of video that was assigned as either a 'Control' or 'Disturbed' and can be considered analogous to 'Locations' in a standard spatial experimental design of Beyond BACI. Exactly halfway through 'Disturbed Events' a boat travelled within the DIDSON field of view, thereby creating a 20 min 'Before' section and a 20 min 'After' section. 'Control Events' were similarly 40 min long, but consisted of periods during which no boat had passed for at least 3 h. Following the Beyond BACI convention, these were also broken into a 20 min 'before' and 20 min 'after' sections. The study included 10 disturbed and 10 control Events.

During each Event, a MaxN abundance estimate was taken over three randomly selected 1 min periods during both the 20 min 'Before' and 'After' sections, thus creating six observations per Event. Because fish may hear or sense an approaching boat, no MaxN calculations were made in the final five minutes of the 'Before' section of Events (i.e. 5 min prior to the passage of a boat). Because MaxN calculations were made separately for each of the three fish size classes, different frames were usually selected for each class.

The long term response study consisted of selecting footage from two replicate 'busy' days and two 'quiet' days. Observers recorded 33 and 43 boat passes between 07h00 and 17h00 during the two busy days, while only two and one boat passages occurred through the DIDSON field of view on quiet days. Boat passes during the night were rare, occurring only three times; therefore nocturnal observations were not included in the study. From the footage collected during each of the four replicate days, five separate 30-minute time periods were selected from between 07h00 and 17h00 (roughly corresponding to daylight hours), resulting in 10 time periods during both busy days and quiet days. To provide independence from potential short term effects of boats, no boats passed through the site during the selected 30-min time period (or 10 min before or 5 min after the time period).

Over a 30-min period a single MaxN value could provide misleading data on the abundance of fish during that time (Becker et al., 2011, 2013). This issue occurs when few fish are observed during most of the time period except for the rapid brief passage of a large school. In this case, a single MaxN value is not a true representation on the abundance of fish over the majority of that time period. The problem can be simply overcome by taking the mean MaxN of multiple randomly selected shorter (1 min) time intervals spread over the 30-min period. We therefore selected six 1-min subsamples and calculated a separate MaxN for each. The mean of these six subsamples was then calculated and defined as the 'mean' MaxN (hereon referred to as mMaxN) and was used as an estimate of relative abundance for each of the 30-min periods for the long term study.

2.4. Statistical analysis

The short term response study was analysed using factorial ANOVA based upon our modified 'Beyond BACI' design. The model consisted of three factors Control/Disturbed (2 levels; fixed); Event (10 levels; random) and Before/After (2 levels; orthogonal and fixed). When the lowest interaction term was non-significant ($P > 0.25$), it was pooled post hoc with the residual to allow a more powerful test of individual factors (Underwood, 1997). With this model, a significant impact by boat traffic would lead to a change in abundance after the passing of boats in the disturbed Events. This would be identified by a significant interaction term for the Control/Disturbed and Before/After factors. Post Hoc Student–Newman–Keuls (SNK) tests were performed for significant sources of variation to determine differences relevant to hypothesis of interest. Prior to analysis, data was tested for departures from homogeneity of variance with Cochran's C test, subsequently data for the 301–500 mm size class required a square root transformation to meet this assumption.

The long term response study was analysed using a two factor ANOVA. The first factor was Traffic Conditions (2 levels: Busy and Quiet; fixed), the second factor was Days and related to the two replicate busy days and two quiet days (2 levels; fixed nested in Traffic Conditions).

3. Results

In total, 122 boat passes were recorded at the sampling location over the 10 days of filming. The most traffic recorded in a single day was 43 passes and was included as one of the 'Busy' days for the long term study while during four days, three or less boats were recorded. More traffic was recorded during the weekend (average 30 passes) compared to weekdays (average four passes) and reflects the recreational nature of boat traffic within the Bushmans Estuary. Boats could easily be observed within the DIDSON footage as the hull and propeller passed through the field of view. Normally a plume of bubbles was evident in the minutes following the passing boat (Fig. 2).

For the short term response study there was a significant main effect for Event which influenced the relative abundance (MaxN) for the 100–300 mm size class (Table 1). Events themselves were a random factor for which we had no specific hypothesis, with no interaction occurring between the 'Before/After' and 'Control/Disturbed' factors this outcome can be interpreted as no effect of boats on fish abundance.

An interaction between the factors 'Control/Disturbed' and 'Before/After' was observed for the 301–500 mm size class. Post Hoc pairwise comparisons showed no difference between 'Before/After' for the *Control Events* but there was an effect of 'Before versus After' in the *Disturbed Events* with fish abundances lower following the passage of boats ($P < 0.01$). A clear drop in relative abundance (MaxN) can be observed while control treatments remain constant over the Event time period (Fig. 3). This can be interpreted as boats having a significant effect on localised fish abundance (MaxN) for this size class. No significant results were recorded for the 500+ mm size class, indicating boats have no short term effects on the localised abundance of these fish (Fig. 3).

The long term study showed there was no difference in relative abundance (mMaxN) between 'Days' nested within 'Traffic Conditions', or between 'Traffic Conditions' themselves (Table 2). This was consistent across each of the three fish size classes and showed that there was no significant difference in relative fish abundance between busy and quiet days.

4. Discussion

We have shown that the disturbance caused by the passage of boats in an estuary can decrease the local abundance of certain fish size classes as they are displaced away from the impacted area. Interestingly, this was only observed for the 301–500 mm size class. The most likely explanation for this is that the species which

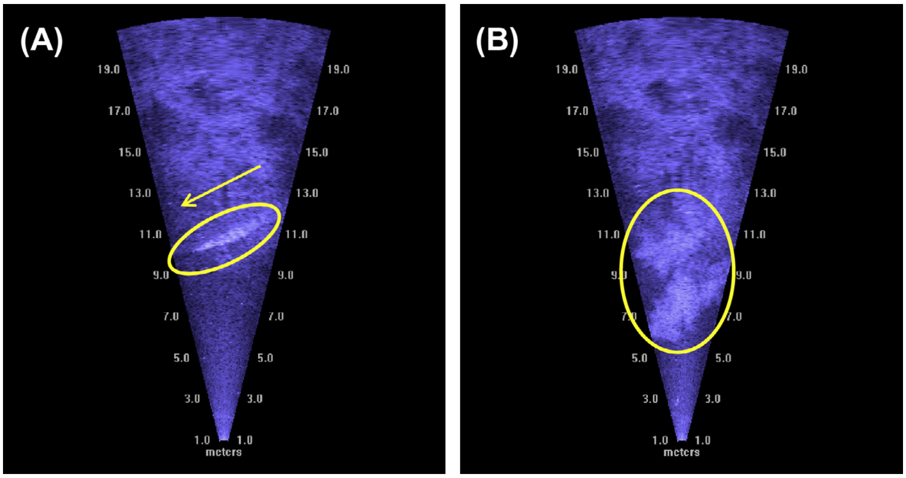

Fig. 2. Still frames from the sonar videos, with the DIDSON field of view being as seen from above. (A) The propeller passing through the field of view can be seen (yellow oval), with the direction of boat movement shown by the yellow arrow. (B) The bubble plume left by the passing boat is clearly visible in the centre of the picture (yellow oval). Image (B) was taken 1 min after image (A). The scale on the image is in meters and highlights the horizontal distance away from the DIDSON sonar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
ANOVA comparing relative abundance (MaxN) for Control and Disturbed Events, Before and After the passage of boats within the Bushmans Estuary for each of the three size classes.

100–300 mm size class	d.f.	MS	*F*	*P*
Control/Disturbed = (C/D)	1	60.21	0.73	0.403
Event (Control/Disturbed) = (Ev)	18	81.96	11.78	**0.001**
Before/After = (B/A)	1	2.41	0.35	0.558
C/D × B/A	1	10.21	1.47	0.229
B/A × Ev*	18	5.01		
Residual*	80	7.39		
Total	119			
Pooled data	98	6.95		
301–500 mm size class				
Control/Disturbed = (C/D)	1	1.06	1.7	0.209
Event (Control/Disturbed) = (Ev)	18	0.62	3.81	**0.000**
Before/After = (B/A)	1	0.66	4.08	**0.046**
C/D × B/A	1	0.97	5.98	**0.016**
B/A × Ev*	18	0.15		
Residual*	80	0.17		
Total	119			
Pooled data	98	0.16		
501 mm + size class				
Control/Disturbed = (C/D)	1	1.01	0.89	0.359
Event (Control/Disturbed) = (Ev)	18	1.14	1.63	0.067
Before/After = (B/A)	1	2.41	3.45	0.066
C/D × B/A	1	0.08	0.11	0.744
B/A × Ev*	18	0.43		
Residual*	80	0.76		
Total	119			
Pooled data	98	0.70		

[*] Denotes tests which were performed against pooled data, adjusted degrees of freedom (d.f.) and means squared (MS) are shown in the table. Significant results are shown in bold.

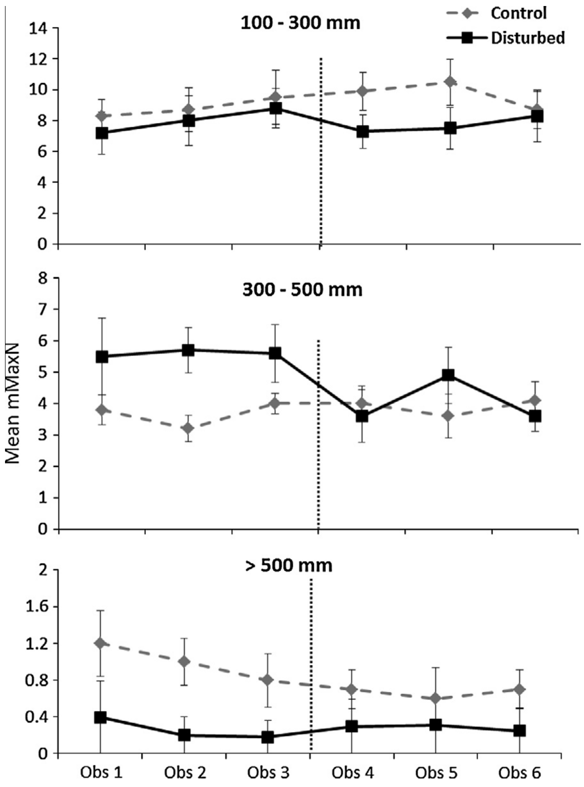

Fig. 3. Mean relative abundance (mMaxN ± s.e.) of fish during each of the six consecutive observations made for each of the Control Events (dashed grey line) and Disturbed Events (solid black line). Vertical dashed line shows time of boat passes during Disturbed Events. 'Obs' 1–6 refer to the six consecutive observations made during each 40 min Event.

make up this size class are more reactive to the disturbance caused by passing/moving boats, rather than simply relating the result to the size of the fish. Within temperate South African estuaries, this size class would largely consist of the subadults and adults of various mugilid species and juvenile piscivores such as *L. amia* (Whitfield, 1998, 1999), which school higher in the water column and therefore show a greater reaction to boats than more benthic associated species such as sparids in the smaller size class or larger piscivores within the largest size class (Becker, Cowley & Whitfield, 2010). The exact height in the water column of these fish is difficult to determine as the footage is in 2D format. However, acoustic shadows cast by these fish often indicated that they were not near the substratum. Species specific responses to boat traffic have previously been recorded in systems such as the Mississippi where species such as toothed herring and channel catfish abundance decreased with increasing boat traffic while other species abundances appear unaffected (Gutreuter, Vallazza & Knights, 2006). A final explanation for the lack of response for the largest size class may simply be a lack of power in the test due to overall low

Table 2
ANOVA comparing relative abundance (mMaxN) between 'busy' and 'quiet' Traffic Conditions and Days nested within Traffic Conditions in the Bushmans Estuary for each of the three size classes.

100–300 mm size class	d.f.	MS	*F*	*P*
Traffic condition	1	2.45	0.67	0.4987
Day (Traffic condition)	2	3.65	0.72	0.5006
Residual	16	5.05		
Total	19			
301–500 mm size class				
Traffic condition	1	0.8	0.32	0.6286
Day (Traffic condition)	2	2.5	1.67	0.22
Residual	16	1.5		
Total	19			
501 mm + size class				
Traffic condition	1	0.45	1.8	0.3118
Day (Traffic condition)	2	0.25	0.71	0.5045
Residual	16	0.35		
Total	19			

abundances of fish of this size. While not uncommon, MaxN values rarely exceeded two for this size class.

The exact reason for the movement of these fish from the disturbed area of the channel is difficult to determine but may result from a combination of factors, including a fleeing response associated with a rapidly approaching large object, noise, bubbles and the emission of gaseous pollutants by the outboard engines. While noise has long been suspected as disrupting marine mammals (e.g. Ellison et al., 2011), recent research has focused on the effect of noise emitted by boats and ships on fish in both laboratory and field based studies (Popper, 2003; Purser and Radford, 2011; Bracciali et al., 2012). This showed that noise reduced attention in fish and affected foraging performance. Furthermore, noise caused a breakdown in schooling behaviour by bluefin tuna (Sara et al., 2009) while noise also affected communication among fish within a Marine Protected Area in the Mediterranean (Codarin et al., 2009).

A plume of bubbles following the passing of the boat was also clearly evident in the DIDSON footage, and at times it took up to five minutes for these bubbles to fully dissipate. The effect of artificial bubbles on fish behaviour has received some research attention (Sager and Hocutt, 1987) and indeed combinations of bubbles and other stimuli have been investigated as a potential method of deterring fish from areas such a power station intakes (Perry et al., 2012). While the response of fish to bubbles alone has produced mixed results (e.g. Sager and Hocutt, 1987), Welton, Beaumont & Clake (2002) found that a combination of bubbles and sound elicited avoidance behaviour among Atlantic salmon smolts. Given that the bubbles were suspended in the upper part of the water column, this may provide further evidence why mid-water or surface schooling fish in the 301–500 mm size class showed the only response to boat passes.

Boat traffic is likely to be highest around urban areas and these are also places most likely to be affected by other detrimental effects of urbanisation (Nixon and Fulweiler, 2012). In a system containing lots of available habitat, fish displacement by boats may not cause any real consequences for the maintenance of healthy populations (Gill, Norris & Sutherland, 2001). However, one of the first effects of urbanisation on estuarine and coastal systems is a rapid and dramatic loss of habitat (Lui et al., 2012). In such a situation, displacement of fish by boat traffic may have an increased effect on the population, as alternative habitats in low traffic areas may be located some distance away or destroyed due to urbanisation and/or pollution. Additionally, loss of habitats combined with displacement would also lead to greater competition for increasingly scarce habitat resources. This may be particularly evident on days of high traffic such as weekends when regular sustained boat passes continually disrupt the natural distribution of fish within an estuarine system. Regular sustained displacement may also cause the dispersal of schooling fish, thus leading to them becoming more susceptible to predation (Sumpter, 2006).

We found no evidence that localised abundances of fish altered on days of high traffic compared to days with little or no traffic. This finding differs from other studies that found decreased fish abundance was associated with increased boating activities (Gutreuter, Vallazza & Knights, 2006; Huckstorf et al., 2011). It must be noted these studies did not find consistent results across all species investigated, with Gutreuter, Vallazza & Knights (2006) suggesting that species which have a narrow niche breadth may be more affected by boat traffic when compared to generalists. There is also the possibility that boat traffic on the Bushmans Estuary, even on busy days, was relatively light when compared to that on highly developed urban estuaries with large numbers of boats present. Alternatively, the location of our study may have represented a particularly important channel habitat so that, despite high traffic volumes, fish chose to continue to return to this location. This issue can only be fully answered with a more detailed spatially replicated study in a variety of estuaries with different levels of boat activity and includes more replicate days for each treatment.

It is important to highlight that this study was focused solely on the changes in fish abundance associated with boat disturbance. No attempt was made to categorise the behaviour of fish as we believe this is beyond the realistic interpretation of our footage. Despite this, it must be acknowledged that some behaviour (e.g. feeding), which boat traffic has been found to interrupt (Bracciali et al., 2012), may have occurred but was impossible for us to confidently detect.

In conclusion, due to their restricted spatial dimensions, estuaries represent systems in which the effects of commercial and recreational boating are most likely to impact fish. Combined with habitat loss, which characterises many urbanised estuarine landscapes, fish in these systems may be particularly vulnerable to displacement caused by boat traffic. Consistent with previous studies, our research shows that responses to boat traffic by fish are species and/or size specific and that this response is probably due to a combination of an innate flight response to an approaching large object, the noise and bubbles generated by the outboard engines, all of which would have the greatest impact on mid-water or surface swimming species. We suggest that regular displacement of fish by boats in already stressed estuarine systems may pose a threat at the population level to certain species, particularly pelagic groups.

Acknowledgements

A Claude Leon Post-Doctoral Fellowship was provided to A.B. Further financial support was provided by the South African Institute for Aquatic Biodiversity (SAIAB), through the National Research Foundation (NRF), and the Norwegian Institute for Nature Research (NINA). We are grateful to Noell and Thane of the Sandbar Floating Restaurant for their hospitality and support during the fieldwork phase of the project. Victoria Cole is thanked for her advice on the design of statistical procedures. Field support was provided by Frikkie van der Vyver, Victoria Cole, Bruce Ellender, Bruce Mostert, Charles von der Meden, Christine Coppinger and Rhett Bennett.

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