



THEME SECTION

# Foraging behaviour of little penguins *Eudyptula minor* in an artificially modified environment

Tiana J. Preston<sup>1</sup>, Yan Ropert-Coudert<sup>2</sup>, Akiko Kato<sup>3</sup>, André Chiaradia<sup>1,4</sup>,  
Roger Kirkwood<sup>4</sup>, Peter Dann<sup>4</sup>, Richard D. Reina<sup>1,\*</sup>

<sup>1</sup>School of Biological Sciences, Monash University, Clayton, Victoria 3800, Australia

<sup>2</sup>Institut Pluridisciplinaire Hubert Curien, UMR 7178 DEPE, 23 rue Becquerel, 67087 Strasbourg, France

<sup>3</sup>National Institute of Polar Research, 1-9-10 Kaga, Itabashi-ku, Tokyo 173-8515, Japan

<sup>4</sup>Research Department, Phillip Island Nature Parks, PO Box 97, Cowes, Victoria 3922, Australia

**ABSTRACT:** We investigated the 3-dimensional foraging behaviour of little penguins *Eudyptula minor* breeding on an artificially constructed breakwater near dredged shipping channels in Port Phillip Bay, southern Australia. Breeding penguins were fitted with either satellite trackers or time-depth recorders during the 2006–2007 breeding season to record foraging locations and diving behaviour, which were then compared with local bathymetry. Diving appeared to be both mid-water and demersal, and on 1 d trips penguins reached a mean maximum distance from the colony of 13.8 km. Penguins were recorded in locations containing artificially constructed shipping channels, and examination of their diving profiles suggests that they probably forage within these channels. Little penguins at this urban colony have benefited from anthropogenic alterations in the terrestrial environment, but their location exposes them to many potential anthropogenic threats in their marine environment, including a large-scale dredging operation to deepen the existing shipping channels.

**KEY WORDS:** Anthropogenic · Dredge · Satellite · Foraging · Dive · *Eudyptula minor*

Resale or republication not permitted without written consent of the publisher

## INTRODUCTION

Anthropogenic alteration of the natural environment is a widespread and obvious phenomenon. There are numerous examples of the deleterious effect of artificial habitat changes on wildlife, such as the reduction in species diversity caused by dam constructions (Pringle 2000, Gehrke et al. 2002) or the range of animals affected by land-clearing (see examples in Vos & Chardon 1998, Crooks 2002, Lehman et al. 2006). However, a few animal populations are capable of adapting to and benefiting from anthropogenic changes, such as peregrine falcons *Falco peregrinus* nesting in high rise buildings (Gilbert 1989, Cade & Bird 1990).

The effects of human activities in the marine environment are less conspicuous than on land, but they

are often extensive, particularly in coastal areas. While the local influence of anthropogenic habitat modification can be readily assessed for sessile organisms such as algae, seagrass and coral (e.g. Richmond 1993, Nyström et al. 2000, Duarte 2002), the effect on mobile marine animals is more difficult to determine. Ongoing miniaturisation of remote monitoring tools, such as satellite transmitters and diving loggers, is providing increased opportunities to identify how highly mobile animals use the marine environment (Ropert-Coudert & Wilson 2005) and to examine the influence of human alterations on them.

The little penguin is an ideal model for studying local oceanic alterations because it is part of a relatively short food chain (Cullen et al. 1992) and has a restricted foraging range during the chick-rearing phase

\*Corresponding author.  
Email: richard.reina@sci.monash.edu.au

of the breeding season (Collins et al. 1999). Little penguins are capable of acquiring only local resources at this time because they need to return regularly to their terrestrial nest site to feed their chicks (Chiaradia et al. 2007). This central place foraging behaviour facilitates the attachment and removal of data loggers, which allow their at-sea behaviour to be studied.

Although considered common, little penguins have been adversely affected by human settlement and activities in some places. Introduced mammalian predators and habitat loss have been the major causes of decline in this species on Phillip Island and south-eastern Tasmania in Australia, and the Otago region of New Zealand (Dann 1992a,b, Stevenson & Woehler in press). Other potential threats of anthropogenic origin also exist at sea, such as oil spills, over fishing, gill-netting, introduction of diseases to prey populations and dredging (Dann 1992b, Dann et al. 2000, Goldsworthy et al. 2001, Stevenson & Woehler in press).

A colony of little penguins resides on a breakwater wall constructed at St Kilda, 5 km from the centre of the city of Melbourne, Australia. The colony is close to both marine and terrestrial urban developments. This is the only established little penguin colony within Port Phillip Bay, which seems otherwise largely unsuitable for the establishment of penguin populations due to a lack of appropriate nesting sites, terrestrial threats from introduced predators and on-land habitat distur-

bance. Although extensive habitat alteration and other anthropogenic effects occur within this colony's foraging range, the population has grown to approximately 1000 individuals (Z. Hogg unpubl. data) since the first breeding pairs were discovered in 1974 (Eades 1975). Population growth is attributed to the proximity of food resources in northern Port Phillip Bay, within 20 km of the colony (Cullen et al. 1996), but is also likely to be due in part to the general absence of predators. A secure fence prevents access to the breakwater by roaming dogs and foxes, which may otherwise decimate the colony.

We investigated the 3-dimensional foraging behaviour of little penguins at the St Kilda colony during the 2006–2007 breeding season in order to examine how penguins use a highly modified marine habitat. Using satellite transmitters and time-depth recorders, we assessed whether the penguins have adapted their foraging strategy to use bathymetric variations of the sea floor (including dredged shipping channels) that are present within their foraging range.

## MATERIALS AND METHODS

**Study site.** The diving behaviour and foraging zone occupancy of little penguins were examined at St Kilda, Melbourne, Australia ( $37^{\circ} 51' S$ ,  $144^{\circ} 57' E$ , Fig. 1)

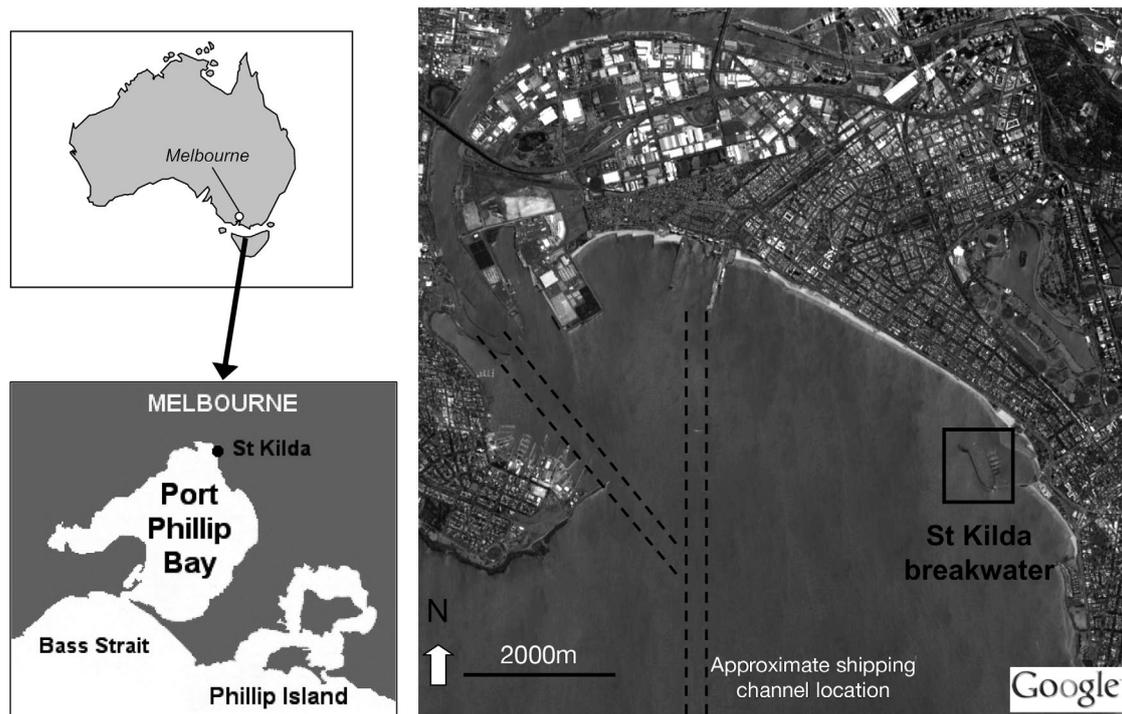


Fig. 1. Location of St Kilda penguin colony inside Port Phillip Bay, relative to Melbourne and Phillip Island. Satellite image taken from Google Earth™

during November and December of the 2006–2007 breeding season. Penguins were monitored in their nests 3 times  $\text{wk}^{-1}$  to determine their stage of breeding and were permanently identified by either a passive integrated transponder (Trovan<sup>®</sup>) or a flipper band.

At St Kilda, penguins forage inside Port Phillip Bay (Cullen et al. 1996), a bay of 1950  $\text{km}^2$ , with an average depth of 13 m and a maximum depth of 24 m (although some trenches at the entrance extend deeper). Several large shipping channels exist in the north and west of Port Phillip Bay, as well as the south where Port Phillip Bay joins Bass Strait (Fig. 1). The shipping channel ranges between 12–17 m depth and 180–240 m width.

**Deployment of satellite trackers and time-depth recorders.** Satellite tracking and time-depth recording devices were deployed separately on penguins. Although data from both devices on single birds could have proved useful, we considered the encumbrance resulting from their deployment together too great for a 1 kg bird. Only 1 penguin (O53F) was fitted with both devices, the time-depth recorder during incubation and satellite transmitter during chick-guard.

Satellite tracking was conducted on 13 birds from the chick-guard stage (chicks up to 2 wk old) using platform transmitter terminals (PTT, KiwiSat model 202 by Sirtrack, 60 × 31 × 20 mm, cross-sectional area 514  $\text{mm}^2$ , mass in air 43 g, antenna 18 cm spring mounted at 60°). In parallel, miniature time-depth recorders (TDR, M190-DT by Little Leonardo 49 × 15 mm, cross-sectional area 177  $\text{mm}^2$ , mass in air 14 g) were fitted to 14 penguins, 9 at the egg incubation stage and 5 at the chick-guard stage. Little penguins typically make trips of up to 3 consecutive days at sea during egg incubation and just 1 day at sea during the chick-guard stage, but the duration may increase during poor breeding seasons (Chiaradia & Nisbet 2006). TDRs collected data every 1 s in the 0–190 m depth range with a 12-bit resolution and 0.1 m accuracy.

All devices were attached to the penguins' feathers using waterproof tape (Tesa<sup>®</sup> 4651) (Wilson et al. 1997) along the mid-line of the lower back to minimise drag (Wilson & Culik 1994). We applied a thin strip of adhesive compound (Mastic, Denso) between the feathers and the device, to reduce friction and prevent loosening. All devices and adhesives were removed from the penguin upon its return to the colony after a foraging trip. Attachment and removal each took <5 min. Penguins were weighed to the nearest 20 g using a spring balance (Pesola 42500) before and after instrumentation.

**Data analysis.** Penguin locations from the PTTs and the accuracy of these locations were provided by CLS Argos and plotted using Elsa Pro software (CLS Argos, 2005). Only locations where accuracy was 1 km or better (Classes 1, 2 and 3) were included in the analysis. We filtered the locations in the R statistical program

(R Development Core Team 2005) using TimeTrack, a custom designed software package (Sumner 2006). TimeTrack uses the algorithms described by McConnell et al. (1999) to filter out locations that result from unreasonable speeds for a particular species. Using the maximum swimming speed of 3.3  $\text{ms}^{-1}$  reported by Bethge et al. (1997), none of the Class 1, 2 or 3 locations were eliminated. Time-in-area analysis was calculated by interpolation of locations at 10 min intervals between the predicted locations, assuming straight-line travel at an even speed between the 2 locations (Austin et al. 2003), and assigning time spent to 1  $\text{km}^2$  grid-squares.

Bathymetry contours (at 5 m depth intervals) of Port Phillip Bay (provided by D. Ball, Primary Industries Research Victoria) were plotted using ArcView GIS version 3.0 (Environmental Systems Research Institute, 2004) and overlain with the time-in-area data.

G Power analysis (Faul et al. 2007) was used *a posteriori* to calculate the power of our sample size in describing the foraging area at 95% confidence interval. We used the number of grid-squares visited per penguin and conducted 50 permutations of adding the data from each penguin sequentially and in a random order. In this way, we derived a curve for the cumulative increase in grid-squares visited with each additional penguin. We then used the mean and standard deviations of the data to calculate the power of our sample size.

Diving data were downloaded from TDRs and analyzed (surface-align and dive detection) using IGOR Pro version 5.0 (Wavemetrics). Based on the relative accuracy of the logger, we adopted a dive threshold of 1 m. Diving activity was defined by the following parameters: maximum depth, dive duration, bottom phase (calculated as the period in the dive between when vertical speed first drops below and last rises above 0.25  $\text{m s}^{-1}$  vertical speed), depth amplitude within bottom phase (the difference between the maximum and minimum depths reached during the bottom phase), descent and ascent rates, and number of undulations in the dive profile (Kato et al. 2006, Ropert-Coudert et al. 2006). For analysis of these diving parameters, we filtered data to exclude dives without a bottom phase (15.4%). Predominately, they were shallow (86.5% were  $\leq 5$  m deep) and were likely to be dives performed during travel. Dive shapes were analyzed using Multi-Trace Dive (Jensen Software Systems), excluding only dives <1 m. Based on observation of the dive profiles, demersal dives generally had descent rates  $\geq 0.8 \text{ ms}^{-1}$  and were performed at depths  $\geq 6$  m.

We conducted all other statistical analysis in SYSTAT Version 10 (SPSS). The statistical threshold was set at 0.05 and the values are presented as means with 1 SD.

## RESULTS

### Satellite tracking

The 13 penguins fitted with PTTs made either 1 or 2 d foraging trips and the total number of unfiltered locations of all classes was 279. After filtering, this was reduced to 11 penguins tracked from 98 Class 1, 2 or 3 locations, 10 of which performed single day trips and 1 (penguin O53F) performed a 2 d trip. By interpolating between satellite data, we calculated that the penguins spent time in 222 different 1 km<sup>2</sup> grid-squares within Port Phillip Bay. Time spent in each square ranged from 1 to 668 min.

Little penguins making 1 d trips from St Kilda remained in the north of the bay within 22 km of the colony (Fig. 2). They headed out in a south-westerly direction from St Kilda that included and crossed the shipping channels. Mean maximum distance from the colony on 1 d trips was  $13.8 \pm 4.1$  km. Our sample size of 10 penguins had a power of 0.95 at 95% confidence interval to represent the foraging area within 1 d trip at the chick-guard stage.

On average, penguins on 1 d trips spent 10.8% of their time in the 1 km<sup>2</sup> grid-squares containing the shipping channels and 31.5% of their time <2 km from the northern shipping channel (i.e. the 1 km<sup>2</sup> grid-squares containing, and on either side of, the shipping channel). These grid-squares accounted for 9.3 and

22.5%, respectively, of all grid-squares visited on 1 d trips. The penguin that performed a 2 d trip travelled in waters <15 m deep to the western channel achieving a maximum distance from the colony of 51 km.

### Dive behaviour

We retrieved TDRs from all penguins after 1 or 2 trips, except for 1 penguin at the incubation stage and 3 at the guard stage; these penguins had abandoned their nests. We do not think that nest abandonment was related to device attachment, because 57% of the monitored nests in the colony were abandoned prior to chick fledging, whether the birds had been part of this study or not. Reproductive success of the colony as a whole was poor during the 2006–2007 breeding season (T. J. Preston unpubl. data). Trip durations for retrieved dive loggers ranged from 1 to 11 d, with a total of 48 foraging days and 32 690 dives from 10 birds (Table 1).

Diving was exclusively diurnal, with dive depths being greatest during the middle of the day. Excluding dives <1 m, the total number of dives for an individual ranged from 422 to 6321 (Table 1). The maximum depth recorded was 26.5 m and the maximum dive duration was 79 s. Penguins dived to a mean depth of  $8.4 \pm 1.8$  m, with a mean diving duration of  $28.5 \pm 3.8$  s. Most (82.7%) dives were to depths of between 2 and 13 m (Fig. 3). Just under half ( $44.3 \pm 4.6\%$ ) of all dives were made to a depth  $\pm 1$  m of the previous dive.

Analysis of dives with a bottom phase (84.6%) found that the bottom phase accounted for almost half ( $49.7 \pm 7.3\%$ ) of each dive time (Table 1). In  $60.7 \pm 7.0\%$  of dives, at least half of the bottom phase occurred in the lowest depth quartile and these dives had either flat bottoms, several small undulations (<1 m amplitude) or ragged shapes (Fig. 4).

As location and diving data was collected separately, it was not possible to identify definitively which dives were made inside the shipping channels. However, penguins in the present study did exhibit some unusual dive profiles that contained a flat bottom phase usually followed, but sometimes preceded, by a rapid change in depth (Fig. 5). Many of these dives appeared to be made mid-water, as indicated by the surrounding dives and low descent rates, but 248 were considered demersal. Of these, 180 correspond with the depth profile of the shipping channels (outside channel

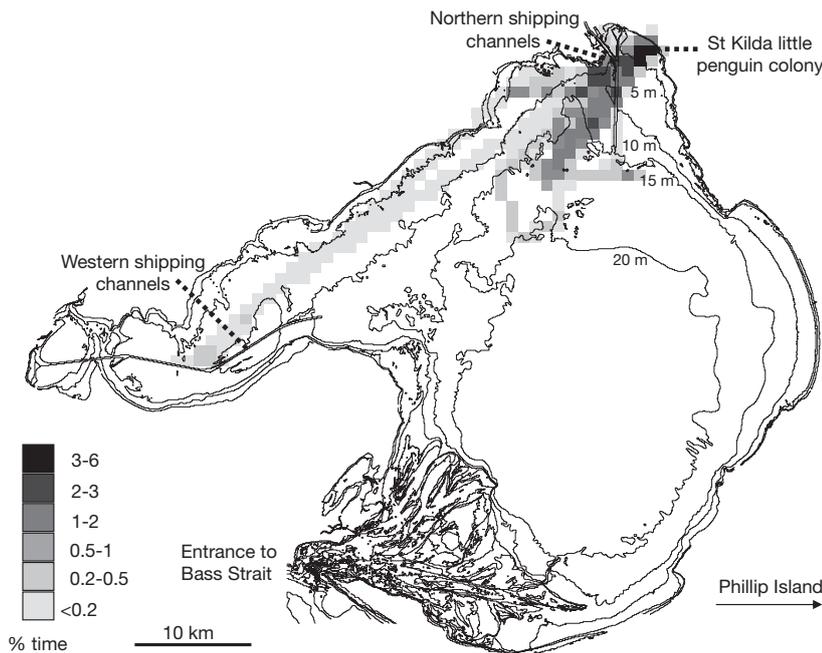


Fig. 2. Bathymetry contours and dredged shipping channels in Port Phillip Bay, and foraging areas of little penguins at the chick-guard stage from the St Kilda colony. Areas were determined from satellite tracking with shading indicating the relative amount of time penguins spent within 1 km<sup>2</sup> areas

Table 1. *Eudyptula minor*. Trip and diving information (mean  $\pm$  SD) for penguins fitted with time-depth recorders. F: female; M: male

Penguin	Breeding stage	Trip duration (d) <sup>a</sup>	Total no. of dives	Diving depth (m)	Dive duration (s)	Bottom phase duration (s)
B14M	Incubation	1, 7	5533	8.1 $\pm$ 3.9	25.1 $\pm$ 11.7	46.7 $\pm$ 19.9
B33M	Incubation	1	561	7.9 $\pm$ 4.6	26.3 $\pm$ 14.5	47.0 $\pm$ 20.9
C93F	Incubation	7	5365	9.9 $\pm$ 4.6	34.0 $\pm$ 13.5	48.9 $\pm$ 17.4
I53F	Incubation	6	3532	9.7 $\pm$ 5.2	29.2 $\pm$ 13.8	43.8 $\pm$ 19.7
O53M	Incubation	6	4116	8.5 $\pm$ 4.6	27.8 $\pm$ 15.3	46.6 $\pm$ 21.6
O63M	Incubation	11	6321	11.0 $\pm$ 5.8	31.4 $\pm$ 16.0	39.3 $\pm$ 19.3
L24F	Incubation	1	422	8.0 $\pm$ 4.2	33.0 $\pm$ 15.1	53.3 $\pm$ 18.9
O53F	Incubation	4, 1	3800	5.4 $\pm$ 3.1	23.1 $\pm$ 12.5	56.2 $\pm$ 20.0
O03F	Chick-guard	1	922	5.6 $\pm$ 2.8	24.5 $\pm$ 9.8	65.7 $\pm$ 17.0
O74M	Chick-guard	2	2118	10.0 $\pm$ 4.4	31.1 $\pm$ 15.1	49.9 $\pm$ 19.1

<sup>a</sup>Two values denote 2 trips made by the same penguin

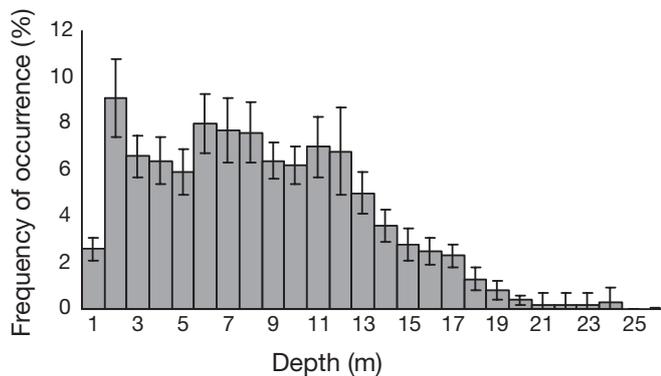


Fig. 3. *Eudyptula minor*. Frequency of occurrence and maximum depth of dives with bottom phase ( $n = 32\,690$ ,  $\pm 1$  SE)

6–10 m, inside 11–17 m, depth between outside and inside  $\geq 3$  m). These dives could have been made by the penguins entering or leaving the shipping channels. The remaining dives were deeper and all made by penguins on trips  $>1$  d that may have travelled to deeper trenches at the mouth of the bay.

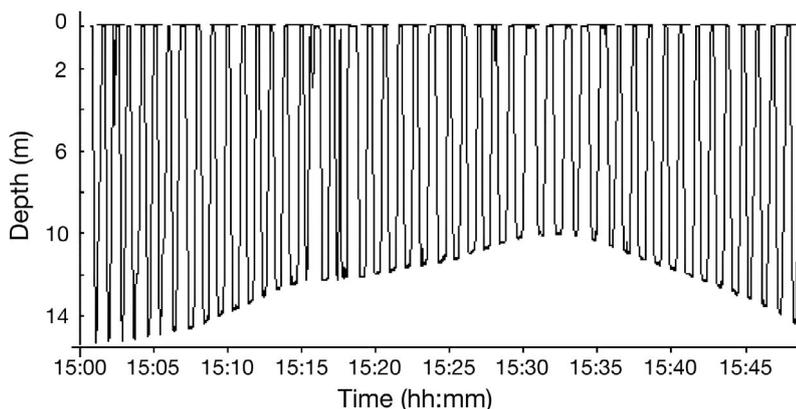


Fig. 4. *Eudyptula minor*. Flat bottom dives indicate demersal diving. This series of dives suggests that penguins follow the topography of the sea floor

## DISCUSSION

Many studies of penguin behaviour at sea now combine both location and diving information for the same bird (e.g. Pütz et al. 1998, Charrassin et al. 2004, Ryan et al. 2004, Sokolov et al. 2006, Mattern et al. 2007); this allows direct correlation between behaviour of the animal and bathymetry of the area. Unfortunately, the instruments required to combine this information are still too large to be deployed on little penguins. Accordingly, our data on location and diving behaviour were collected separately. We have no reason to believe, however, that over a comparable time-frame the penguins fitted with TDRs foraged in different areas to those fitted with PTTs. The foraging area of all PTT carrying birds on 1 d trips were similar and the diving depths recorded by TDRs on single day trips were within the ranges of depths over which PTT-bearing birds foraged. Time spent at sea is a determining factor in how far penguins can travel from the colony, and those penguins at sea for  $>1$  d may have travelled further than the 1 d foraging area described.

Attachment of external devices to penguins is known to affect their foraging performance (Wilson et al. 1986). Decreasing the device size and judicious placement on the lower back minimises the effects (Ropert-Coudert et al. 2007). In the present study, we used the smallest devices available to us. The difference in cross-sectional area between the TDRs and PTTs, as well as the presence of an aerial (cf. Wilson et al. 2004), may have resulted in differences in diving capabilities, but it is unlikely that this will lead to a difference in foraging area used by penguins fitted with PTTs compared with those fitted with TDRs. Aban-

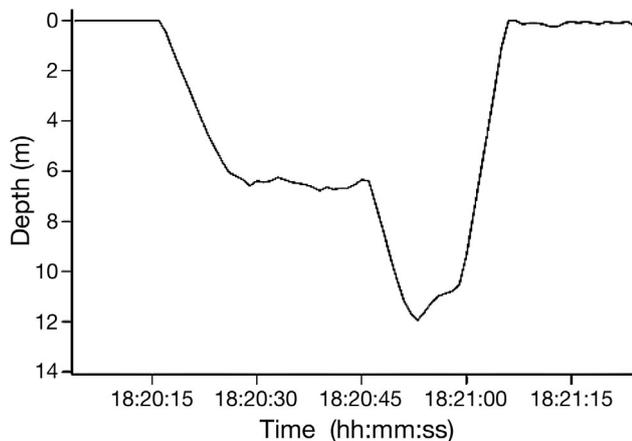


Fig. 5. *Eudyptula minor*. Example of a dive thought to be made into the shipping channel. Flat bottom phase is equivalent to the depth of the sea floor outside the shipping channel, while sharp increase in depth corresponds with the shipping channel wall

donment of nests during the 2006–2007 breeding season was high (57%) for all breeding pairs in the colony. Interestingly, though, the breeding success of birds that carried devices was actually higher than the colony average (colony 29.5%, TDR or PTT carried by at least 1 parent on 1 trip: 38.0 and 44.5%, respectively).

The distribution of tracked penguins at the chick-guard stage from St Kilda was concentrated in the north of Port Phillip Bay, similar to the non-breeding distribution recorded by radio tracking (Cullen et al. 1996). This foraging area is inclusive of the northern shipping channels that lie to the west of the colony. The limited foraging range of little penguins caring for young chicks was reflected in the low maximum distance travelled from the colony, which was slightly lower than the value reported for little penguins on 1 d trips from Phillip Island (Collins et al. 1999).

The west of Port Phillip Bay was used by 1 penguin in our study that spent 2 d at sea and travelled between shipping channels in the north and west. Little penguins from Phillip Island (Fig. 1) are known to occur in both the north and west of Port Phillip Bay (Collins et al. 1999), which suggests high prey availability and highlights the importance of these areas to both populations. Penguins have also been observed in the central part of Port Phillip Bay, but it was not identified whether they came from St Kilda, Phillip Island or elsewhere (Port of Melbourne Corporation 2007). We can expect that little penguins from St Kilda, if not restricted in their foraging trip duration, might also sometimes forage in the west of the bay.

Little penguins commonly dive to mid-levels of the water column (Bethge et al. 1997, Chiaradia et al.

2007), but demersal diving has also been reported in this species (Ropert-Coudert et al. 2006). Penguins in the present study appeared to use both mid-water and demersal diving strategies, as suggested by the length and shape of dive profiles (Fig. 4, Table 1). Penguins dived to  $\pm 1$  m of the previous dive depth on a mean of 44.3% of occasions, comparable with rockhopper penguins *Eudyptes chrysocome* employing a mixture of benthic and pelagic dives, to within  $\pm 10\%$  of the previous dive depth around 53% of the time (Tremblay & Cherel 2000). Given the shallow nature of Port Phillip Bay and reasonable natural variations in the sea floor topography, we considered that a threshold of  $\pm 1$  m was more appropriate than  $\pm 10\%$  for this study.

The mean bottom phase duration of penguins from St Kilda was similar to that reported for demersal diving little penguins from Penguin Island, Western Australia (Ropert-Coudert et al. 2006). In contrast, little penguins from other colonies that engage primarily in mid-water or shallow-water diving spend less time in the bottom phase of the dive (Chiaradia et al. 2007). Penguins in present study could move from the shallow area around their colony (<5 m) to the deepest part of the bay (>20 m), a distance of approximately 20 km, in around 3 h (based on average swimming speed, Bethge et al. 1997). Subsequently we saw frequent changes in the depth profile throughout the day, which makes differentiation between demersal and mid-water dives difficult.

Little penguins from St Kilda have an unusual monospecific diet of anchovy (*Engraulis australis*; A. Chiaradia unpubl. data), with apparently few supplementary or alternative prey species in the diet (T. J. Preston unpubl. data). Anchovy is generally regarded as a shallow water pelagic species, occurring in the top 20 m of the water column (Kailola et al. 1993). Penguin species including the Humboldt *Spheniscus humboldti* and African *Spheniscus demersus* that feed on pelagic schooling fish, including anchovy, have been found to seize prey from below, as the fish are easier to locate as a silhouette rather than from the side or above (Wilson & Duffy 1986, Wilson et al. 1989), and this is likely to be the case for penguins at St Kilda that feed almost exclusively on anchovy.

Little penguins from St Kilda had some unusual dive profiles that displayed a sharp increase in depth during the bottom phase (Fig. 5). Unpublished accounts of these types of dives in Snares *Eudyptes robustus* (T. Mattern pers. comm.) and Magellanic penguins *Spheniscus magellanicus* (R. Wilson pers. comm.) suggest that these dives are made mid-water, as do the characteristics of many of the dives made in this study. However, benthic diving yellow-eyed penguins *Megadyptes antipodes* are also known to make dives of similar shape (T. Mattern pers. comm.). The surrounding dives to consistent depth and the high

descent rates of a number of the unusual dives made by the little penguins in the present study indicated that they were demersal, and probably reflect penguins following changes in the sea floor topography. To precisely determine the location of these dives requires simultaneous collection of these data from an individual bird, but this currently presents significant technical challenges for animals of small size. However, from our knowledge of bathymetry in the area, the shipping channels are the most likely place for these dives to occur and some of the recorded dive profiles probably represent penguins diving into or out of the channels. It is possible that the penguins use both the sea floor and the 3-dimensional structure of the shipping channels to trap their prey, a foraging strategy similar to that suggested for the little penguins at Penguin Island (Ropert-Coudert et al. 2006). Although numerous studies exist on the benthic and demersal diving patterns of various marine birds and mammals (see Tremblay & Chérel 2000 for review), this is the first reported instance where anthropogenic features in the sea floor are probably being used by a species for foraging, and may benefit them by reducing the prey escape field.

Physical modifications to both the marine and terrestrial environments seem to have benefited this population of little penguins, but their exploitation of these modifications has consequently placed them in close proximity to a large human settlement and associated potential threats. One such potential threat is the current proposal to deepen the shipping channels in the north and south of Port Phillip Bay by dredging.

The proposed dredging to increase the depth of shipping channels by approximately 3 m is much larger in scale than the routine dredging that has taken place since the channels were first constructed in the 1860s. The main immediate potential effect of the dredging on little penguins in the vicinity will be the increased water turbidity, the extent and concentration of which are likely to vary at any one time and place. In all, the dredging will produce suspended sediment above  $5 \text{ mg l}^{-1}$  that is predicted to spread over an area approximately 4 km wide and 18 km long before it settles, immediately surrounding and east of the shipping channels in the north of Port Phillip Bay (Port of Melbourne Corporation 2007). This area overlaps approximately 30% of the penguin foraging range described in this study and is situated between the penguin colony and their main foraging area to the west of the shipping channels. The reactions of little penguins to turbidity are unknown, but they are considered visual predators (Cannell & Cullen 1998, Ropert-Coudert et al. 2006) and as such it is unlikely that they will be able to forage within highly turbid areas of the suspended sediment plume,

particularly in the area of the channels where the suspended sediments originate from the sea floor. Whether the penguins will travel across the densest areas of the plume or swim around them in order to reach clear foraging areas is not known.

Much of the recruitment biology and spawning dynamics of the anchovy inside Port Phillip Bay is uncertain, but the north of the bay, including areas to be affected by the dredging plume, has been identified as a spawning ground for this species in several studies (Blackburn 1950, Jenkins 1986, Neira & Tate 1996). Spawning takes place from September to March, peaking in January (Jenkins 1986), which coincides with the scheduled dredging in the north of the bay (Port of Melbourne Corporation 2007). The foraging behaviour of anchovy may be affected by the turbidity plume, as they are generally regarded as visual predators (Chiappa-Carrara & Gallardo-Cabello 1993). Physiological effects of the suspended sediment on anchovy, particularly eggs and larvae, may result in high levels of mortality (Wilber & Clarke 2001), decreasing recruitment and ultimately leading to a decline in the population size. Reduction of available cape anchovy *Engraulis capensis* has been implicated in the breeding failure of African penguins *Spheniscus demersus* (Crawford & Dyer 1995, Crawford 1998), and a widespread decline of pilchards *Sardinops sagax* was associated with high levels of adult mortality and very low breeding success in little penguins from Phillip Island (Dann et al. 2000). Similar levels of breeding failure and adult mortality may be expected for the St Kilda little penguin colony if there was a significant reduction or an absence of anchovies and alternative food sources as a result of the dredging. The population of >52 000 little penguins at Phillip Island may also be affected by the channel dredging, as radio-tracking has determined that they use Port Phillip Bay extensively in winter and spring (Collins et al. 1999) and anchovy is a major prey component of their diet (Cullen et al. 1992).

The St Kilda colony of little penguins appears to have adapted to and benefited from some artificial environmental modifications in the past; construction of a breakwater wall provided a suitable nesting habitat and shipping channels reduced the prey escape field. However, this adaptation to artificial environmental modifications now puts little penguins in a precarious position where significant changes in their spatially limited marine habitat, such as the proposed dredging, have the potential to severely affect this population.

*Acknowledgements.* We thank E. Buik, T. Shaw, Z. Hogg and volunteers of Earthcare St Kilda for field assistance. We also thank M. Sumner for kindly providing advice and assistance with analysing satellite data. D. Ball from Primary

Industries Research Victoria, Queenscliff, provided the bathymetry data for Port Phillip Bay. Funding for satellite tracking was provided by Toyota Australia, The Penguin Foundation and Dan Costa. Diving study was supported by a grant from BHP-Billiton. The study site was accessed with permission from Parks Victoria and the St Kilda Breakwater Wildlife Management Co-operative Area committee. Research was conducted under animal ethics permit BSCI/2006/12 from the Monash University AEC and wildlife permits 10003374 and 10003848 from the Department of Sustainability and Environment, Victoria. Picture in Fig. 1 accessed from Google Earth™.

#### LITERATURE CITED

- Austin D, McMillan JI, Bowen WD (2003) A three-stage algorithm for filtering erroneous Argos satellite locations. *Mar Mamm Sci* 19:371–383
- Bethge P, Nicol S, Culik BM, Wilson RP (1997) Diving behaviour and energetics in breeding little penguins (*Eudyptula minor*). *Zool Soc Lond* 242:483–502
- Blackburn M (1950) A biological study of the anchovy, *Engraulis australis* (White) in Australian waters. *Aust J Mar Freshw Res* 1:3–84
- Cade TJ, Bird DM (1990) Peregrine falcons *Falco peregrinus* nesting in an urban environment: a review. *Can Field Nat* 104:209–218
- Cannell B, Cullen JM (1998) The foraging behaviour of little penguins *Eudyptula minor* at different light levels. *Ibis* 140:467–471
- Charrassin JB, Park YH, Le Maho Y, Bost CA (2004) Fine resolution 3D temperature fields off Kerguelen from instrumented penguins. *Deep-Sea Res I* 51(12):2091–2103
- Chiappa-Carrara X, Gallardo-Cabello M (1993) Feeding behavior and dietary composition of the northern anchovy, *Engraulis mordax* Girard (Pisces: Engraulidae), off Baja California, Mexico. *Cienc Mar* 19:285–305
- Chiaradia A, Nisbet I (2006) Plasticity in parental provisioning and chick growth in little penguins *Eudyptula minor* in years of high and low breeding success. *Ardea* 94:257–270
- Chiaradia A, Ropert-Coudert Y, Kato A, Mattern T, Yorke J (2007) Diving behaviour of little penguins from four colonies across their whole distribution range: bathymetry affecting diving effort and fledging success. *Mar Biol* 151:1535–1542
- Collins M, Cullen JM, Dann P (1999) Seasonal and annual foraging movements of little penguins from Phillip Island, Victoria. *Wildl Res* 26:705–721
- Crawford RJM (1998) Responses of African penguins to regime changes of sardine and anchovy in the Benguela System. *S Afr J Mar Sci* 19:355–364
- Crawford RJM, Dyer BM (1995) Responses by four seabird species to a fluctuating availability of cape anchovy *Engraulis capensis* off South Africa. *Ibis* 137:329–339
- Crooks KR (2002) Relative sensitivities of mammalian carnivores to habitat fragmentation. *Conserv Biol* 16:488–502
- Cullen JM, Montague TL, Hull C (1992) Food of little penguins *Eudyptula minor* in Victoria: comparison of three localities between 1985 and 1988. *Emu* 91:318–341
- Cullen, M, Blake, N, Bickham, M (1996) Urban penguins. *Nature Australia* Winter:22–28
- Dann P (1992a) Breeding distribution, abundance and nest-sites of blue penguins *Eudyptula minor* in Otago. *Notornis* 41:157–166
- Dann P (1992b) Distribution, population trends and factors influencing the population size of little penguins *Eudyptula minor* on Phillip Island, Victoria. *Emu* 91:263–272
- Dann P, Norman FI, Cullen JM, Neira FJ, Chiaradia A (2000) Mortality and breeding failure of little penguins, *Eudyptula minor*, in Victoria, 1995–96, following a widespread mortality of pilchard, *Sardinops sagax*. *Mar Freshw Res* 51:355–362
- Duarte CM (2002) The future of seagrass meadows. *Environ Conserv* 29:192–206
- Eades D (1975) Fairy penguins (*Eudyptula minor*) breeding on St Kilda Pier. *Bird Observer* 519:12
- Faul F, Erdfelder E, Lang AG, Buchner A (2007) G\*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods* (in press)
- Gehrke PC, Gilligan DM, Barwick M (2002) Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. *River Res Appl* 18:265–286
- Gilbert OL (1989) The ecology of urban habitats. Chapman & Hall, London
- Goldsworthy S, He X, Tuck GN, Lewis M, Williams R (2001) Trophic interactions between the Patagonian toothfish, its fishery, and seals and seabirds around Macquarie Island. *Mar Ecol Prog Ser* 218:283–302
- Jenkins G (1986) Composition, seasonality and distribution of ichthyoplankton in Port Phillip Bay, Victoria. *Aust J Mar Freshw Res* 37:507–520
- Kailola P, Williams M, Stewart P, Reichelt R, McNee A, Grieve C (1993) Australian fisheries resources. Bureau of Rural Science and Fisheries Resource Development Corporation Publication, Canberra
- Kato A, Ropert-Coudert Y, Gremillet D, Cannell B (2006) Locomotion and foraging strategy in foot-propelled and wing-propelled shallow-diving seabirds. *Mar Ecol Prog Ser* 308:293–301
- Lehman SM, Rajaonson A, Day S (2006) Lemur responses to edge effects in the Vohibola III Classified Forest, Madagascar. *Am J Primatol* 68:293–299
- Mattern T, Ellenberg UA, Houston DC, Davis LS (2007) Consistent foraging routes and benthic foraging behaviour in yellow-eyed penguins. *Mar Ecol Prog Ser* 343:295–306
- McConnell BJ, Fedak MA, Lovell P, Hammond PS (1999) Movements and foraging areas of grey seals in the North Sea. *J Appl Ecol* 36:573–590
- Neira FJ, Tate S (1996) Ichthyoplankton survey in Port Phillip Bay, Victoria, 1995–1996: preliminary results. Marine and Freshwater Resources Institute, Queenscliff
- Nystrom M, Folke C, Moberg F (2000) Coral reef disturbance and resilience in a human-dominated environment. *Trends Ecol Evol* 15:413–417
- Port of Melbourne Corporation (2007) Supplementary Environmental Effects Statement, Channel Deepening Project. Port of Melbourne Corporation, Melbourne
- Pringle (2000) Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. *Bioscience* 50(9):807–823
- Pütz K, Wilson RP, Charrassin JB, Raclot T and others (1998) Foraging strategy of king penguins (*Aptenodytes patagonicus*) during summer at the Crozet Islands. *Ecology* 79:1905–1921
- R Development Core Team (2005) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Richmond RH (1993) Coral reefs: present problems and future concerns resulting from anthropogenic disturbance. *Am Zool* 33:524–536
- Ropert-Coudert Y, Wilson RP (2005) Trends and perspectives

- in animal-attached remote sensing. *Front Ecol Environ* 3:437–444
- Ropert-Coudert Y, Kato A, Wilson RP, Cannell B (2006) Foraging strategies and prey encounter rate of free-ranging little penguins. *Mar Biol* 149:139–148
- Ropert-Coudert Y, Knott N, Chiaradia A, Kato A (2007) How do different data logger sizes and attachment positions affect the diving behaviour of little penguins? *Deep-Sea Res II* 54:415–423
- Ryan PG, Petersen SL, Peters G, Grémillet D (2004) GPS tracking a marine predator: the effects of precision, resolution and sampling rate on foraging tracks of African. *Mar Biol* 145:215–223
- Sokolov S, Rintoul SR, Wienecke B (2006) Tracking the Polar Front south of New Zealand using penguin dive data. *Deep-Sea Res I* 53:591–607
- Stevenson C, Woehler EJ (in press) Population decreases in little penguins *Eudyptula minor* in southeastern Tasmania, Australia, over the past 45 years. *Mar Ornithol*
- Sumner MD (2006) TimeTrack. University of Tasmania, Hobart
- Tremblay Y, Cherel Y (2000) Benthic and pelagic dives: a new foraging behaviour in rockhopper penguins. *Mar Ecol Prog Ser* 204:257–267
- Vos CC, Chardon JP (1998) Effects of habitat fragmentation and road density on the distribution pattern of the moor frog *Rana arvalis*. *J Appl Ecol* 35:44–56
- Wilber D, Clarke D (2001) Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. *N Am J Fish Manag* 21:855–875
- Wilson R, Culik B (1994) Hydrodynamic aspects of design and attachment of a back-mounted device in penguins. *J Exp Biol* 194:83–96
- Wilson RP, Duffy DC (1986) Prey seizing in African penguins (*Spheniscus demersus*). *Ardea* 74:211–214
- Wilson RP, Grant WS, Duffy DC (1986) Recording devices on free-ranging marine animals: Does measurement affect foraging performance? *Ecology* 67:1091–1093
- Wilson RP, Wilson MP, Duffy DC, Araya B, Klages N (1989) Diving behaviour and prey of the Humboldt penguin (*Spheniscus humboldti*). *J Ornithol* 130(Suppl):75–79
- Wilson RP, Putz K, Peters G, Culik BM, Scolaro JA, Charrassin JB, Ropert-Coudert Y (1997) Long-term attachment of transmitting and recording devices to penguins and other seabirds. *Wildl Soc Bull* 25:101–106
- Wilson RP, Kreye JA, Lucke K, Urquhart H (2004) Antennae on transmitters on penguins: balancing energy budgets on the high wire. *J Exp Biol* 207:2649–2662

*Editorial responsibility: Rory Wilson, Swansea, UK*

*Submitted: September 13, 2007; Accepted: November 6, 2007  
Proofs received from author(s): November 20, 2007*