A Sampling Design for Long-Term Monitoring of Dolphin Populations in Darwin Harbour

Report to Northern Territory Department of Natural Resources, Environment, the Arts and Sport

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Introduction

Background

a) As part of the environmental approvals under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 and the Northern Territory Environmental Assessment Act 1982 for the INPEX Ichthys Gas Field Development project, a monitoring program for coastal dolphins is required for Darwin Harbour. The stated aim of the program is to detect change, beyond natural spatial and temporal variation, in marine mammal abundance and distribution during near shore Project construction activities in Darwin Harbour. The monitoring program will include pre- and post-construction phase monitoring.

b) In December 2010, Northern Territory Cabinet announced additional funding to boost monitoring and research to improve management and protection of Darwin Harbour’s wealth of aquatic wildlife. This announcement represents the Government’s response to the Darwin Harbour Strategy prepared by Darwin Harbour Advisory Committee and endorsed by Government earlier this year. The funding includes ongoing monitoring of coastal dolphin populations in the Harbour by the Northern Territory Department of Natural Resources, Environment, the Arts and Sport, extending the existing program based on dolphin photo identification and capture-recapture analysis to determine population dynamics.

c) In order to monitor and assess the impact of construction activities associated with the INPEX Ichthys Development Project, INPEX Browse Ltd. (INPEX) and Northern Territory Department of Natural Resources, Environment, the Arts and Sport (NRETAS) have agreed that an integrated monitoring programme will be implemented.

This document

This document specifies a sampling design for long-term monitoring of dolphin populations in Darwin Harbour. As reported by Palmer (2010), three species of dolphin (Orcaella heinsohni, Sousa chinensis and Tursiops aduncus) and other marine mammal species are known to occur in Darwin Harbour.

The proposed research is to employ capture-recapture statistical models based on the capture histories of individuals identified by photographs of their dorsal fins in repeated sampling. Analyses
of existing data (Palmer et al. in prep.) reported here indicate that, while there were too few data to estimate the numbers of *Orcaella*, local populations include approximately 160 *Sousa* and 60 *Tursiops*.

The research plan is to survey Darwin Harbour and two adjacent sites in Shoal Bay and Bynoe Harbour. As briefly discussed here, these sites may be part of the local Darwin Harbour habitat system (particularly Shoal Bay), may be used by dolphins displaced from Darwin Harbour by construction activity, or provide an informal reference for natural seasonal or other temporal variation in habitat use (particularly Bynoe Harbour).

We describe the Robust Design (RD) capture-recapture model (Pollock 1982, Kendall and Pollock 1992, Kendall et al. 1995, 1997), its advantages over alternative models and its relevance to the proposed research. Analyses of the existing data for *Sousa* and *Tursiops* are reported and the estimates of abundance and capture probability are employed to define ‘true’ models for simulation of data, similar to what might be expected from the proposed sampling scheme. Models were fitted to the simulated data to estimate the precision of the abundance estimates which would result from their analysis. This information was used in conjunction with a ‘practical’ effort limit of 4 boats per day in Darwin Harbour specified in the sampling design.

A sampling scheme based on the Robust Design model is recommended with two primary sampling periods per year, one in the dry season (May to November) and one in the wet season (December to April). Within each Primary Period, a secondary sampling session composed of 9 days is undertaken at each of the 3 sites. Survey effort includes 4 boats sampling Darwin Harbour, 3 sampling Bynoe Harbour and 1 sampling Shoal Bay. With favorable weather conditions the Secondary Sampling could be completed in 18 days.

Maps of the 3 survey sites are shown with suggested transect lines and comments made on access to the suggested transects given tidal states. Brief comment is made on the potential for spatial analysis.

The Robust Design capture-recapture model

The Robust Design (RD) capture-recapture model (Pollock 1982, Kendall and Pollock 1992, Kendall et al. 1995, 1997) follows a sampling scheme structured into relatively widely separated Primary Periods within each of which a set of relatively closely adjacent Secondary sampling is nested. Often population closure may be assumed to apply over the Secondary Samples session within each Primary Period. This justifies fitting models based on closed population models that allow for
unequal capture probabilities due to trap response or individual heterogeneity and thus reduces bias in population size estimates. The longer intervals between primary samples allow for simultaneous estimation of apparent survival which is quite robust to heterogeneity. More recent developments of the model also allow temporary emigration between primary samples to be estimated (Kendall et al. 1995, 1997), and for estimation of movements among multiple states, such as sites that some of the animals may visit (the multistate RD; Schaub et al. 2004).

The parameters estimated by the RD (without multiple states) are:

1. $S_j$ apparent survival to primary session $j$ for $j>1$,
2. $\gamma_j$ probability of temporarily emigrating prior to session $j$ given presence at $j-1$ for $j>1$,
3. $\gamma_j'$ probability of temporarily emigrating prior to session $j$ given absence at $j-1$ for $j>2$,
4. $p_{ij}$ probability of first capture in sample $i$ of session $j$ for $i \geq 1$,
5. $c_{ij}$ probability of recapture in sample $i$ of session $j$ for $i > 1$,
6. $N_j$ population sizes obtained as derived estimates.

There are several advantages to the RD model including:

1. Estimates of $p_{ij}$ and thus $N_j$ and recruitment are less biased by heterogeneity in capture probability (specifically, if heterogeneity within primary samples is modeled),
2. Temporary emigration can be estimated assuming completely random or Markovian (temporally structured) availability for capture,
3. If temporary emigration does not occur, abundance, survival, and recruitment can be estimated for all time periods (whereas, in a 4-period study, half the parameters are inestimable using the JS method),
4. Precision of estimates is usually better than for other open models.

The RD and the Darwin Harbour dolphin populations

Members of the Darwin Harbour dolphin populations may have different patterns of habitat use such that some may occupy relatively small home ranges and others may range more widely. This would result in the dolphins with more closely defined home ranges (greater fidelity) having a higher probability of capture than those that range more widely. This is heterogeneity of capture probabilities which, over relatively short time scales, can be modeled in the closed part of the RD model (the Secondary Sampling within sessions) eliminating the downward bias in population size estimates that would otherwise occur. If variation in home range and habitat usage occurs over longer time scales, or has a seasonal pattern, it can be modeled as temporary emigration in the open part of the RD model (Primary Periods), increasing the accuracy of the estimated capture.
probabilities and separating temporary emigration from apparent survival estimates. The authors have observed seasonal patterns in the presence of dolphins in coastal waters near Bunbury, WA (manuscript under review) and there are several reports of seasonal movements of dolphin species (e.g., Karczmarski et al. 1999, Rayment et al. 2010). Dolphins may also move in response to disturbance which, if they move back when the disturbance abates, may be also be modeled as temporary emigration and distinguished from apparent survival.

Three sites, Darwin Harbour, Shoal Bay and Bynoe Harbour, are proposed for long term monitoring. To the extent that dolphins move to and from these sites in response to temporal patterns of disturbance, the multistate version of the RD may be used to model these movements as transition probabilities. While natural movements between Darwin Harbour and Shoal Bay have been observed (Palmer reports having identified 12 Tursiops and 4 Sousa in both Darwin Harbour and Shoal Bay, pers. com.), Bynoe Harbour has not previously been surveyed. Natural movements may also occur between Darwin Harbour and Bynoe Harbour or among all three sites. If Bynoe Harbour is not part of a local system regularly used by the Darwin Harbour dolphins but is habitat for relatively discrete populations, the survey there may serve to provide information on seasonal movements in the absence of disturbances due to large scale construction activities.

In sum, the Robust Design model is highly informative and very flexible, and represents the optimal model for long term monitoring of the Darwin Harbour dolphin populations.

**Summary of key findings from existing photographic identification data for Darwin Harbour**

A coastal dolphin research program was recently undertaken in Darwin Harbour in which photographic identification data on 3 species of coastal dolphins (*Orcaella heinsohni*, *Sousa chinensis* and *Tursiops aduncus*) were collected from March 2008 until November 2010. An interim report (Palmer 2010) summarised data collected from March 2008 to February 2010. Preliminary capture-recapture analyses of the complete data sets (March 2008 to November 2010) are being undertaken (Palmer et al. In Prep.). The daily sighting data were summarized into two nominal seasons per year for analysis - dry (D, May to November) and wet (W, December to April) seasons and the “super population” (POPAN) parameterisation of the Jolly Seber model (Crosbie and Manly 1985, Schwarz and Arnason 1996) for open populations was employed for the analyses. The available data were limited, confidence intervals around the estimates were wide and interpretation is tentative.

**Ability to estimate population sizes**
While there were too few data on *Orcaella* to support capture-recapture modelling, initial estimates were made of the population sizes of *Sousa* and *Tursiops*. The proportions of images that represented markable individuals were 0.84 for *Sousa* and 0.79 for *Tursiops* (Palmer et al. In Prep.).

**Small population sizes**

The size of the markable proportion of the resident population of *Sousa* was estimated to vary around 139 between 133 and 145 individuals over 6 seasons, indicating that approximately \(139/0.84 = 165\) individual *Sousa chinensis* regularly use Darwin Harbour.

The size of the markable proportion of the resident population of *Tursiops* was estimated to vary around 47 between 42 and 54 individuals over 5 seasons, indicating that approximately \(47/0.79 = 60\) individual *Tursiops aduncus* regularly use Darwin Harbour.

**Low capture rates**

The estimated capture probability for *Sousa* was 0.03 per 4 days of sampling. The estimated capture probability for *Tursiops* was 0.12 per 4 days of sampling.

**Emigration/immigration**

From the size and seasonal variation in the estimates of the apparent survival and new entries probabilities, it appears that there may be slightly greater immigration and emigration (more recruitments into and losses from) for the resident *Sousa* population between wet and dry than between dry and wet seasons.

Conversely, for the resident *Tursiops* population it appears that there may be slightly greater emigration (more losses) between dry and wet than between wet and dry seasons, and slightly greater immigration (gains) between the wet and dry than between dry and wet seasons. This apparent movement of *Tursiops* out of Darwin Harbour between dry and wet and into the Harbour between wet and dry seasons is in contrast to *Sousa* which appears to move more, both into and out of the resident population between wet and dry than between dry and wet seasons.

**Estimated capture probabilities for a 4 boat days sample based on the 2008-2010 data**

As reported subsequently, data were simulated and models fitted to estimate the precision of estimates from models built on data similar to what might be expected from the proposed study. The simulations required prior estimates of abundance and capture probability. Estimates of abundance were obtained from the analysis of the existing 2008–2010 data reported above. These
analyses also yielded estimates of capture probabilities as functions of daily sampling effort which were employed to estimate the expected capture probabilities based on 4 days sampling by a single boat or 1 days sampling for 4 boats. While increasing capture probability increases the precision of estimates, 4 boats and crews working simultaneously represents a considerable commitment of resources. The estimated capture probability of *Sousa* for 4 boat days sampling (0.03) was extremely low and attention must focus on how best to maximise the capture probability for this species.

The capture probabilities were estimated from POPAN models and are the apparent capture probabilities given that a proportion of animals may have temporarily emigrated and been unavailable for capture at any time. The ‘true’ capture probability $p^*$ is related to the apparent capture probability by the relation $p = (1 - \gamma) p^*$ where $\gamma$ is the probability of being absent and unavailable for capture (Kendall *et al.* 1997). In the Robust Model, the ‘true’ capture probability, estimated will be greater than the apparent capture probability depending on the size of $\gamma$.

The capture probability may also increase slightly with 4 boats sampling simultaneously as animals that may move to avoid one boat are sampled by another boat.

**Simulations**

Simulation was employed to estimate the precision of estimates from models built on data similar to what might be expected from the proposed study.

Parameter estimates were obtained for 48 sets of 100 models each. For each of the 48 sets of models, the 100 sets of replicated data were simulated from true models with parameters around the estimates obtained from analysis of the existing data for *Sousa chinensis* and *Tursiops aduncus*. All simulations were for closed population models with 9 capture occasions. This number of occasions was chosen to provide for optimal precision of estimates while allowing for fitting complex heterogeneity models and a systematic pattern for employment of 4 boats in the 3 sites in a relatively short period of secondary sampling in each primary session. Further comment is made on this in the subsequent discussion of transect design.

Population sizes for *Sousa chinensis* were specified as 125, 150, and 175; and for *Tursiops aduncus* as 25, 50, and 75. These assumed population sizes are spread around the estimated sizes of the ‘markable’ portions of the populations from the models on the existing data.
For models without heterogeneity, capture probabilities for *Sousa chinensis* were specified as 0.025, 0.050, 0.075, and 0.010; and for *Tursiops aduncus* as 0.075, 0.100, 0.125 and 0.150. Half of the simulation sets were defined without and half with heterogeneity of capture probabilities.

Models with heterogeneity were specified for 75% of the population with a higher (p1) and 25% with a lower (p2) capture probability such that the average or nominal overall capture probabilities matched those employed for the non-heterogeneity models; for nominal p = 0.025, p1 = 0.030 and p2 = 0.010; for p = 0.050, p1 = 0.060 and p2 = 0.020; for p = 0.075, p1 = 0.09 and p2 = 0.03; for p = 0.010, p1 = 0.120 and p2 = 0.040; for p = 0.125, p1 = 0.15 and p2 = 0.05; for p = 0.150, p1 = 0.180 and p2 = 0.060.

For each of the sets of simulated data, relative standard errors of the estimated population sizes [RSE(N-hat)] were estimated as the beta estimates from regression through the origin of the estimated standard errors of the population sizes on the estimated population sizes. Extreme (outlier) estimates were identified in plots and removed prior to analysis. As would be expected, there were more extreme estimates in models built on data simulated for lower capture probabilities and population sizes.

The estimated RSE(N-hat) are plotted by true model p and N in Figure 1. The nominal true model p is shown for the heterogeneity models.

Overall, RSE(N-hat) differs little between comparable models with and without heterogeneity except where the capture probability is very low and the population size is relatively small, specifically for *Sousa chinensis* when p = 0.025, and N = 125. Despite the larger estimated population size of this species, the relative standard errors of both the heterogeneity and non heterogeneity models are unacceptably high for p = 0.025 and barely acceptable at about 30% for p = 0.050. While it may not be possible to increase the capture probability of this species using 4 boat days, estimates of 0.03 beyond 0.050, yield an increase to 0.075 and would result in an acceptable relative standard error of about 20%. For *Tursiops aduncus* however, with a currently estimated capture probability of 0.12, this level of RSE(N-hat) is achieved despite their relatively smaller estimated populations size.

To provide some reference for the effect of the RSE(N-hat) on the precision of N-hat, it might be noted that 95% confidence intervals are approximately $\hat{N} \pm 2RSE_{N} \hat{N}$. In the case of *Sousa chinensis*, with an estimated population size of 140, the 95% confidence interval is 84:196 with RSE(N-hat) = 0.2 and 56:244 with RSE(N-hat) = 0.3. In the case of *Tursiops aduncus*, with an estimated population size of 47, the 95% confidence interval is 28:66 with RSE(N-hat) = 0.2 and
19:75 with RSE(N-hat) = 0.3. A RSE(N-hat) = 0.15 may be possible for this species, yielding a 95% confidence interval of 33:61.

The key message here is that models built on data with capture probabilities < 0.050 provide very imprecise information about population size and attention must be devoted to increasing the capture probability for Sousa chinensis hence the increase in the sampling effort. Culik (2010, p.3) reports that “The species is usually quite difficult to approach and tends to avoid boats by diving and reappearing some distance away in a different direction. They rarely permit a close approach before diving, splitting up into small groups or single animals.”

As described above, these estimates may be lower than the ‘true’ capture probabilities that would be obtained in a Robust Design model which estimates d temporary emigration; they were derived under the simple assumption that capture probability was time invariant. That may not be the case with real data and this would tend to decrease the precision. Some thought needs to be given to time-varying variables that may be measured at each sampling occasion and may be related to and serve as covariates on capture probability. Use of such covariates may make it unnecessary to model time-varying capture probabilities and improve the precision of the estimates. Sea state, ambient light, and water turbidity may be suitable candidates for covariates on capture probability.
Figure 1. RSE(N-hat) by true model p and N for closed models without and with heterogeneity for Sousa chinensis and Tursiops aduncus

Proposed sampling design
As previously described on p.4 Darwin Harbour, Shoal Bay and Bynoe Harbour, are proposed for long term monitoring. To the extent that dolphins move to and from these sites in response to temporal patterns of disturbance, the multistate version of the RD may be used to model these movements as transition probabilities. While natural movements between Darwin Harbour and Shoal Bay have been observed (Palmer reports having identified 12 Tursiops and 4 Sousa in both Darwin Harbour and Shoal Bay, pers. com.), Bynoe Harbour has not systematically been surveyed. Natural movements may occur between Darwin Harbour and Bynoe Harbour or among all three sites. If Bynoe Harbour is not part of a local system regularly used by the Darwin Harbour dolphins but is habitat to relatively
discrete populations, the surveys there may serve to provide information on seasonal movements in the absence of disturbances due to large scale construction activities.

We propose a sampling design of 2 Primary Periods (sessions) per year each composed of 9 Secondary Samples at each site. Although the precise timing of the primary sampling sessions can be flexible to some extent (to accommodate variation in weather patterns and periods of more intense construction activity), we propose a dry season session around October and a wet season session around March each year. In typical circumstances, these times should provide suitable weather for undertaking surveys and, as we’ve commented previously, there may be natural seasonally-structured movements which would be advantageous to model.

A Secondary Sample is defined as a complete set of transects through a site. The estimates of capture probabilities around which our capture-recapture model simulations were constructed were based on 4 days’ sampling in Palmer’s (2010) study. Palmer reports (pers. com.) that, under suitable conditions, she was able to cover approximately 50 km of transect per day. This means that the capture probabilities assumed in our simulations resulted from surveying approximately 200 km of transect in Darwin Harbour. We assume that 150 km and 50 km should yield comparable capture probabilities in Bynoe Harbour and Shoal Bay respectively because they include smaller areas of suitable habitat than Darwin Harbour. To cover these lengths of transect in one day per site would require 4 boats surveying Darwin Harbour, 3 boats surveying Bynoe Harbour and 1 boat surveying Shoal Bay.

While the set of Secondary Samples in each Primary Period should be completed as quickly as possible in order to increase the probability of population closure, sufficient samples are required in each session to fit heterogeneity models and to allow for adequate parameter precision. Nine secondary samples per session are sufficient to derive estimates from mixture-type, maximum likelihood heterogeneity models (Pledger 2000), to provide the levels of precision identified from our simulations and to facilitate a rational scheme using 4 boats for sampling at Darwin Harbour, 3 boats at Bynoe Harbour and 1 boat at Shoal Bay in closely adjacent periods. This structure is presented in Table 1 which shows the number of boats by site by day per session. While an alternative structure is possible in which the 9 Darwin Harbour samples were completed before moving to Bynoe Harbour and Shoal Bay, the proposed structure is more appropriate should multistate models be required as these assume simultaneous sampling in each of the sites.
Table 1. Within session sampling scheme: number of boats by site by day per session

<table>
<thead>
<tr>
<th>Site</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>7</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<td>4</td>
<td>4</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>SB</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

In accordance with the principle that a sample is defined as a complete set of transects through a site, interruptions due to poor weather or other factors should be managed by either separating out data as “off effort” data if only a small proportion of transects were completed before interruption and beginning the sample again, or completing the set of transects on the following day and combining the data into a single sample. Some flexibility might be afforded in the case of repeatedly rough seas in the central Darwin Harbour transects, or in the case of ongoing poor access. The transects completed in each sample should be reported in all cases along with the values of such environmental variables as might account for variation in capture probabilities.

**Transect locations and comments on access to transects given tidal state**

Approximate transect locations and lengths are plotted in Figures 2, 3 and 4 for Darwin Harbour, Shoal Bay and Bynoe Harbour respectively. Table 2 reports the approximate transect lengths (km), provides comments on access, and serves as reference to Figures 2, 3 and 4.
Figure 2. Map of Darwin Harbour showing the approximate locations and lengths of transects.
Figure 3. Map of Shoal Bay showing the approximate locations and lengths of transects.
Figure 4. Map of Bynoe Harbour showing the approximate locations and lengths of transects.
Table 2. Transect description, approximate length (km) and comments on access

<table>
<thead>
<tr>
<th>Area</th>
<th>Transect</th>
<th>Length</th>
<th>Who</th>
<th>Tidal access</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darwin Harbour</td>
<td>DH1</td>
<td>6</td>
<td>INPEX</td>
<td>mid to high beware intertidal zone</td>
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<tr>
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<td>DH2</td>
<td>11</td>
<td>INPEX</td>
<td>any tide except for upper reaches</td>
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<td>DH3</td>
<td>17</td>
<td>INPEX</td>
<td>any tide with care (watch reefs)</td>
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<td>DH4</td>
<td>25</td>
<td>NTG</td>
<td>high tide intertidal otherwise any tide</td>
</tr>
<tr>
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<td>DH5</td>
<td>6</td>
<td>NTG</td>
<td>any tide with care</td>
</tr>
<tr>
<td>Darwin Harbour</td>
<td>DH6</td>
<td>33</td>
<td>NTG</td>
<td>any tide except for upper reaches</td>
</tr>
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<td>28</td>
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<td>any tide except for upper reaches</td>
</tr>
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<td>DH9</td>
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<td>mid to high tide with care</td>
</tr>
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<td>21</td>
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</tr>
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<td></td>
<td>199</td>
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<tr>
<td>Bynoe Harbour</td>
<td>BH1</td>
<td>21</td>
<td>INPEX</td>
<td>mid to high</td>
</tr>
<tr>
<td>Bynoe Harbour</td>
<td>BH2</td>
<td>34</td>
<td>INPEX</td>
<td>all tides but upper reaches mid to high</td>
</tr>
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<td>30</td>
<td>INPEX</td>
<td>mid to high with upper reaches close to high tide</td>
</tr>
<tr>
<td>Bynoe Harbour</td>
<td>BH4</td>
<td>28</td>
<td>INPEX</td>
<td>all tides with care (beware depth on intertidal areas)</td>
</tr>
<tr>
<td>Bynoe Harbour</td>
<td>BH5</td>
<td>25</td>
<td>INPEX</td>
<td>mid to high tide (beware depth on intertidal areas)</td>
</tr>
<tr>
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<td>23</td>
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<td>mid to high with care</td>
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<td>INPEX</td>
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<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>46</td>
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</table>

Spatial analysis

Dolphins may move permanently or temporarily completely out of the local area either naturally or in response to disturbance. As previously described, if permanent, such movements are modeled in the RD as a component of the apparent survival estimate (with demographic survival) and, if temporary, as the temporary emigration estimates. They may also move between the Darwin Harbour, Shoal Bay and Bynoe Harbour sites, again either naturally or in response to disturbance. These movements can be modeled together with temporary emigration in the Multistate version of the RD which would be viable given sufficient observed movements to estimate the ‘transition’ probabilities.

Dolphins may also change their spatial patterns of habitat usage within sites, particularly in Darwin Harbor where considerable construction activity and increased shipping traffic will occur, but also
potentially in Shoal Bay in response to increased turbidity from material dredged from Darwin Harbour and deposited nearby. While such within site movements are not subject to modeling in the RD, they can be externally modeled given GPS records of the locations of individual captures or school sightings.
References


