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Likely future extirpation of another Asian river dolphin: The critically endangered population of the Irrawaddy dolphin in the Mekong River is small and declining

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ABSTRACT

The population of Irrawaddy dolphins that occupies the Mekong River in southern Lao People's Democratic Republic and Cambodia is classified as *Critically Endangered* by the IUCN. Based on capture-recapture of photo-identified individuals, we estimated that the total population numbered 93 ± SE 3.90 individuals (95% CI 86–101), as of April 2007. The combined photo-identification and carcass recovery program undertaken from 2001 to 2007 established that the Irrawaddy dolphin population inhabiting the Mekong River has reached a critical point with regards to its continued survival, where immediate research and management actions are required to greatly reduce adult mortality, and establish the cause of newborn mortality. In addition, community consultation is required to initiate, and evaluate, urgently required conservation measures. An ongoing well-designed combined program of abundance estimation (*i.e.*, photo-identification) and carcass recovery is required to monitor total population size and mortality rates, to inform and evaluate management initiatives. The conclusions of this paper are likely generic to river dolphin populations, particularly where photo-identification is possible.

Key words: Irrawaddy dolphin, *Orcaella brevirostris*, Mekong River, photo-identification, capture-recapture, abundance, mortality rates.

Habitat loss and fragmentation are widely regarded as major threats to the viability of wildlife populations as discussed extensively in the literature for terrestrial flora and fauna (Wilcove *et al*. 1986, Rolstad 1991, Fahrig and

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Merriam 1994, Wiens 1995) and some fish populations (Scheerer 2002). Habitat or landscape connectivity is the degree to which the landscape facilitates or impedes movement among resource patches (Taylor *et al.* 1993) and depends not only on specific landscape characteristics, but also on the species-specific movement capacity and behavior (Ferreras 2001, Bennet 2003). Fragmentation of river dolphin metapopulations by dams and irrigation barrages has been discussed for the Indus River dolphin, *Platanista gangetica minor* (Reeves *et al*. 1991, Smith *et al*. 2002, Braulik 2006), and briefly for the baiji, *Lipotes vexillifer* (Wu *et al.* 2003); although with current anthropogenic pressures, all river dolphin populations are likely experiencing a combination of landscape-specific and species-specific fragmentation.

In addition to a loss of connectivity for many river dolphin populations, their close proximity to communities in developing countries accentuates the difficulties of conservation. Challenges are often accentuated because community land rights are generally insecure, and/or uncertain, with a lack of tenure in many areas. Uncertain land tenure, in combination with increasing human population growth, catalyzes the "tragedy of the commons," where resources are often overexploited as people act in their own self-interest, regardless of long-term gain from conservation strategies (Hardin 1968, Kay 1997). Weak and ineffective governance and corruption are also major considerations in developing countries, which further accentuate the difficulty of conservation (Kaufmann 1997, Davis 2004, Ferraro 2005, Katzner 2005). In many parts of Asia, traditional subsistence fisheries are extensive, as are commercial fisheries in some areas. As a result of fisheries interactions, accidental bycatch in gill nets remains one of the most significant anthropogenic threats facing river dolphin populations, and other cetacean and marine megafauna worldwide (Lewison *et al.* 2004, Northridge and Hofman 1999, Read *et al*. 2006).

All Asian river dolphin populations are listed as either *Endangered* or *Critically Endangered* by the IUCN, apart from the baiji, which was recently listed as possibly extinct (Turvey *et al*. 2007, Smith *et al*. 2008). Asian river dolphin populations are primarily threatened by continuing anthropogenic threats and direct competition with humans for freshwater resources (Smith *et al*. 2007), with habitat loss and degradation being major factors of concern.

The Irrawaddy dolphin, *Orcaella brevirostris*, is found in coastal, lacustrine and riverine waters throughout Asia (Stacey and Arnold 1999). Freshwater Irrawaddy dolphins are found in three major river systems (Mahakam, Ayeyarwady, and Mekong Rivers) and two inland lakes (Songkhla and Chilka Lakes). All these populations, apart from Chilka Lake (which has not yet been formally assessed), have been listed as *Critically Endangered* by the IUCN (Kreb and Smith 2000; Smith 2004; Smith and Beasley 2004*a, b*). As a result of numerous anthropogenic threats facing all freshwater Irrawaddy dolphin populations, a comprehensive understanding of their population dynamics is required for effective long-term monitoring, and evaluation of implemented management strategies. Although research programs are currently being undertaken on all these populations, except Songkhla Lake, as a result of often-limited funds available for endangered species conservation, dedicated monitoring programs need to ensure that sampling methodology and effort are appropriate to achieve robust estimates of abundance, given regional limitations.

One of the most extensively studied river dolphin populations in Asia is the Irrawaddy dolphin population that inhabits the lower Mekong River (hereafter

Mekong dolphin population) of southern Lao People's Democratic Republic (hereafter Laos), Cambodia and Vietnam (Fig. 1). Attempts to conserve this population are an example of the challenge of conserving endangered species in complex economic, political and social situations (Beasley *et al*. 2009).

The Mekong dolphin population occurred historically throughout the lower Mekong River from Khone Falls (5 km north of the Laos/Cambodian border) south to the Vietnamese Delta (Mouhot 1966; Lloze 1973; Baird and Mounsouphon 1994, 1997; Tana 1995; Perrin *et al.* 1996; Baird and Beasley 2005; Beasley 2007). During the dry season (January–June), dolphins were reported to

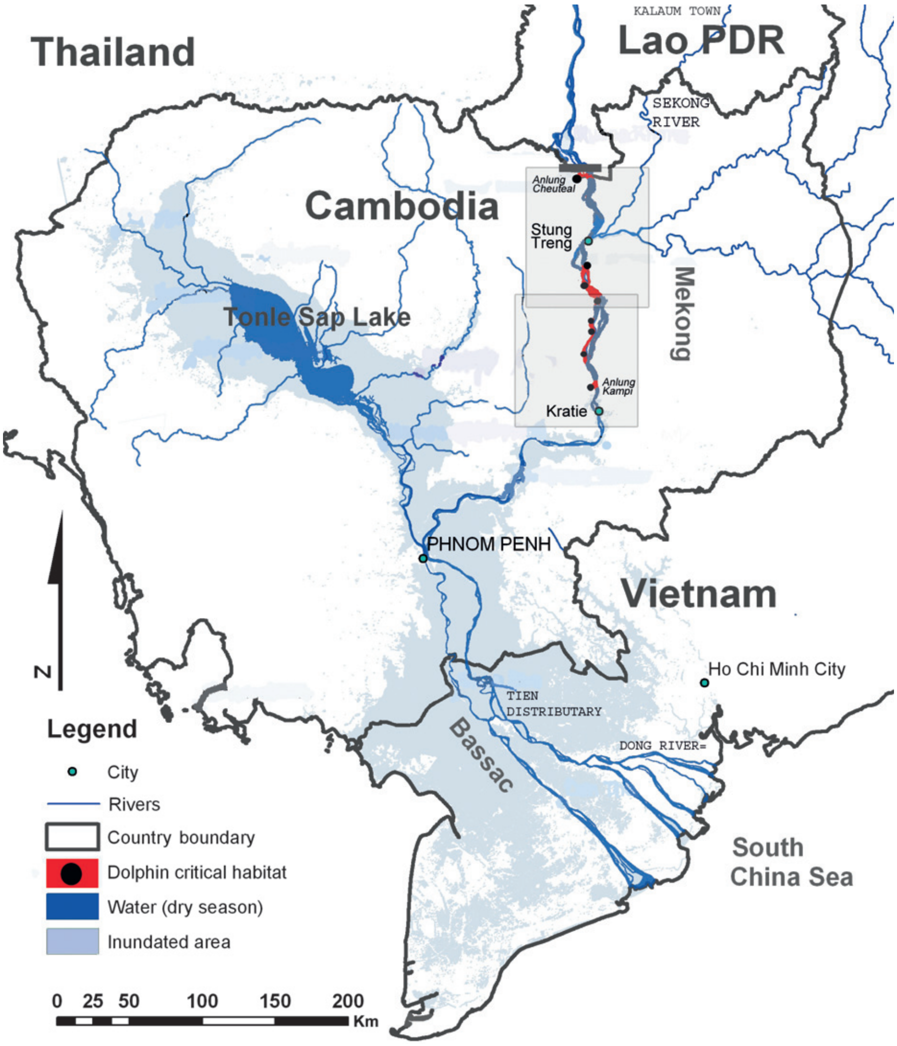

Figure 1. The study area in the lower Mekong River from the Laos/Cambodian border, south to the Vietnamese Delta. The highlighted river section (shaded boxes) is the Kratie to Khone Falls River section, which is the dolphins' primary habitat during the dry season.

primarily inhabit deep water pools north of Kratie to the Laos/Cambodian border, and occasionally some deep water areas in Tonle Sap Great Lake (Beasley 2007); however, large numbers of dolphins apparently moved downstream into Tonle Sap Great Lake at the start of the wet season (July–December) following large-scale fish migrations. Dolphins were, and continue to be, revered by Cambodian and Laoation villagers, where causing harm to a dolphin is considered bad luck as a result of folklores stating that dolphins were reincarnated from humans (Beasley *et al*. 2009).

Dolphins were found throughout the Mekong River prior to the Vietnamese War (1955–1975). By the late 1990s, a number of direct threats had apparently caused a significant decline in the Mekong dolphin population. Based on interviews with local fishers, Tana (1995), reported that during the Vietnamese War dolphins were often bombed directly, and indirectly, during air raids which occurred over southern Laos, and during the Pol Pot Regime numerous dolphins in Tonle Sap Great Lake were killed for their oil to be used as fuel for motorbikes and lamp oils. Additional interviews conducted by Beasley (2007) recorded that dolphins were also apparently shot for target practice by Vietnamese soldiers after the Pol Pot Regime, with Cambodian villagers reporting regular sightings of groups of dead dolphins floating downstream. After the Vietnamese withdrew from Cambodia in 1989, the Cham (Muslim) immigrants (who do not revere dolphins) were reported to have caught dolphins directly and indirectly using seine sets (often in the river stretch between Kratie and Phnom Penh) for food, oil in lamps, and medicine (Beasley 2007). As dolphin numbers declined and human fishing activity south of Kratie and within Tonle Sap Great Lake intensified after the Vietnamese War, dolphins reportedly became increasingly restricted to the Kratie to Khone Falls (Phakmitt Falls) River section, with the distances between subpopulations in this section becoming greater as dolphin numbers decreased. It is therefore virtually certain that the Mekong dolphin population is now significantly reduced compared to its pre-Vietnamese War population size.

Prior to 2000, only one Mekong dolphin population estimate of 200 individuals existed based on direct counts conducted in 1997, where 40 individuals were observed in the section of river from Kratie to Khone Falls (Baird and Beasley 2005). Beasley (2007) implemented a Mekong dolphin research and conservation program along the entire lower Mekong River (southern Laos, Cambodian and Vietnam) from 2001 to 2007. This research contributed to the Mekong dolphin subpopulation being listed as *Critically Endangered* by the IUCN in 2004 (Smith and Beasley 2004*a*). For this listing, known threats to the population were accidental entanglement in gill net fisheries, accidental death when fishers used illegal electric and dynamite fishing techniques, and pollutants from agriculture and gold-mining operations. There was therefore an urgent requirement to: (1) estimate abundance of the Mekong population and (2) investigate mortality rates and causes, to monitor population trends in order to quantify the risk of these known threats to the population.

In this paper we report on the absolute abundance of Irrawaddy dolphins in the Mekong River using photo-identification of individual dolphins (extrapolating capture-recapture estimates to total population size based on incorporation of "mark rate"), discuss mortality rates and causes, provide recommendations for future population monitoring and conservation strategies, and highlight the critical conservation situation now facing the Mekong dolphin population.

Methods

Study Area

Extensive boat and interview surveys were undertaken along the lower Mekong River from Khone Falls (5 km north of the Laos/Cambodian border) south to the Vietnamese Delta (including Tonle Sap Great Lake) from 2001 to 2005 and 2007 (no surveys were conducted during 2006) to investigate present-day distribution and abundance of Irrawaddy dolphins along the lower Mekong River (Fig. 1). During vessel surveys, dolphins were only sighted along the 190 km river segment from Kratie Township (Cambodia; *ca*. 750 km upstream from the Mekong Delta) north to Khone Falls (Baird and Beasley 2005, Beasley 2007, Beasley *et al.* 2009) (Fig. 2). Based on ranging patterns obtained from photo-identification resightings over six years, dolphins appear restricted to three main subpopulations within this river section: Kampi/Koh Pidau, Stung Treng, and Cheuteal (Fig. 2), with little, to no movement between these subpopulations, at least during the dry season. Individuals from Cheuteal and Stung Treng have never been photo-identified outside their respective areas, whereas there is some movement of individuals between the Kampi and Koh Pidau areas, particularly during the wet season. These areas and ranging patterns are described in more detail in Beasley (2007).

Photo-identification Methodology

Dorsal fins were targeted for photo-identification, which was undertaken in all months from January to June (dry season) during 2001–2004 but was limited to April in 2005, and April–May in 2007 for financial and logistical reasons. Some wet season surveys were also conducted from 2001 to 2005, however as a result of the difficulty in locating dolphin groups due to increased water levels, these data are excluded from further analysis in this paper. From January 2001 to December 2003, print photographs were taken using a Canon EOS 3 with a 200 mm (*f*/2.8) lens and converter (2×). In all subsequent years (2004, 2005, and 2007), photographs were taken using a Canon EOS 10D digital camera, with a 300 mm (*f*/2.8) lens and converter (2×). With the 1.6× digital camera conversion, this arrangement resulted in an effective focal length of 960 mm, which improved image quality substantially.

The dolphins' shy and erratic surfacing behavior and the turbidity of the river made photography difficult and time-consuming, particularly in the upper reaches of the Cambodian Mekong River (*i.e.*, Stung Treng). We worked to ensure that photographic effort was similar throughout the entire study area, and attempted to photograph every individual within each group, irrespective of whether dolphins appeared to have distinctive dorsal fin markings (Beasley 2007). As a result of the difficulty of photo-identifying Mekong dolphins, only one side of a recognizable dorsal fin was required for an individual to be positively photo-identified.

All photo-identification images were examined and graded according to: (1) image quality (poor, good, and excellent) and (2) presence/absence of identifiable features (unrecognizable, subtle markings, and recognizable). Unusable images were graded as "poor" and usable images (good lighting; dorsal fin in focus, completely visible and perpendicular to the image) were graded as "good" or "excellent." Only individuals with unambiguous, permanent marks (see Slooten

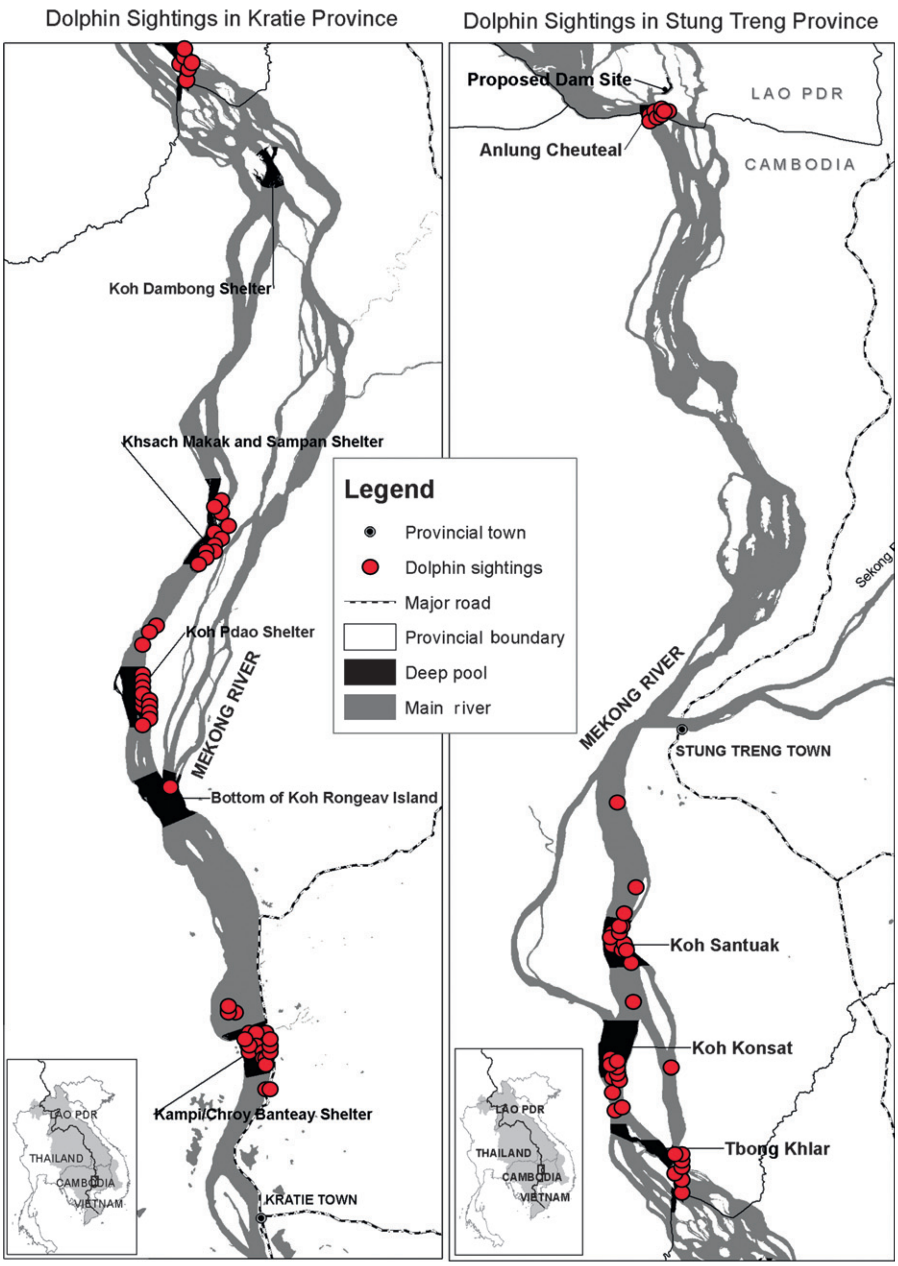

Figure 2. Map of the lower (left) and upper (right) Cambodian Mekong River from Kratie to Khone Falls. Major deep pools are designated by black and the red dots represent dolphin groups that were sighted. This map follows the format of Ryan *et al*. (2011) so a visual comparison of sighting locations between years can be made (*i.e.*, 2003–2007 and 2007–2010). Inset: Lower Mekong Basin.

et al. 1992) were categorized as "recognizable" in subsequent reexamination of the good or excellent images.

Capture-Recapture Assumptions

Throughout the study, bias was minimized through relevant photo-identification techniques, in order to address all model assumptions. Table 1 summarized our assessment of the robustness of the various capture-recapture assumptions in the context of our study.

Data Selection

Based on extensive boat and interview surveys throughout the entire lower Mekong River, one of our major assumptions is that the Mekong dolphin population is closed to immigration and emigration (but not to births and deaths) during the dry season (minimal movements south of Kratie have been reported to occur occasionally in the wet season: see Beasley 2007). Data excluded from the capture-recapture analysis were: (1) wet season sightings; (2) two individuals identified and recorded as calves from Cheuteal Pool, where the probability of capture was not independent from that of their mothers' (Wells and Scott 1990, Wilson *et al*. 1999); and (3) all photographs taken from 2001 to 2003 as a result of reduced quality and number of images obtained from film, when compared with digital technology. Only good and excellent quality photographs of recognizable individuals were included in the capture-recapture analysis.

To estimate the number of recognizable individuals in the population, robust capture-recapture models were analyzed using the program MARK 5.1 (White 2004). The robust design was considered most appropriate for this study as it used a combination of closed (within dry seasons) and open (between years) models. In addition to estimating abundance, a robust design allows estimation of survival, temporary emigration, and recruitment (Kendall *et al*. 1997, Kendall 2010). Survival estimation using the robust design is relatively insensitive to heterogeneity (Pollock 1982, Pollock *et al*. 1990, Kendall 2010).

Estimating Total Population Size

For analysis using the robust design, the annual sampling periods (2004, 2005, and 2007) were the primary sampling periods. The secondary sampling periods were January–March, April–May, and June–July (2004); 4–11 April and 17–23 April (2005); and 5–21 April and 23 April–2 May (2007). A robust design was analyzed using the 2004–2007 photo-identification data, where Stung Treng was separated from all other areas based on significantly reduced capture probabilities from that region. The small number of individuals inhabiting Cheuteal Pool/ Veun Nyang (hereafter Cheuteal Pool) on the Laos/Cambodian border (<10 individuals) made it inappropriate to use mark-recapture methodology to obtain a separate population estimate for the Cheuteal Pool subpopulation.

Robust Design—with Stung Treng separated from other areas—For unknown reasons, the dolphins in the Stung Treng river section were extremely difficult to approach and follow to obtain photo-identification images. To account for lower capture probabilities from individuals inhabiting the Stung Treng region, we used a robust

Table 1. The assumptions of mark-recapture in the context of this study. We assumed that recognizable and unrecognizable had the same detection probabilities and the same survival probabilities.

Assumption summary	Detailed capture-recapture assumption	Failure to address assumption?	Study methods	Potential for assumption violation
Mark recognition	A marked animal will be recognized with certainty if recaptured.	Over-estimation of abundance if poor quality photographs or ambiguous markings are used.	Only good and excellent quality photographs were used for analyses. Dolphins with subtle markings were excluded from capture-recapture analysis. A dolphin was not considered re-sighted, or a new individual, unless IB was certain about the decision – which was normally based on assessment of a number of photographs from different angles throughout the sighting. If there was any indecision, this individual was classified as unrecognizable but noted for future consideration.	Extremely unlikely

(Continued)

Behavioral responses	1. Marked animals have the same probability of being captured as unmarked animals. 2. The action of capture should not change the probability of recapture.	1. Over-estimation if dolphins stay away from the boat once marked and under-estimation if dolphins are attracted to the boat once marked. 2. Over-estimation if dolphins approach the boat and under-estimation if dolphins swim away from the boat before detection.	1. Photographs were taken of existing marks on the dorsal fin. Therefore, no physical interaction with the animal was involved to cause the dolphins to avoid the boat, once photographed. In addition, great care was taken not to disturb dolphin groups when taking photographs and the boat engine was always turned off during photo-identification attempts. 2. The boat always approached the group with care and the engine was stopped when photographing a dolphin group.	1. None 2. Unlikely

(Continued)

Table 1. (Continued)

Assumption summary	Detailed capture-recapture assumption	Failure to address assumption?	Study methods	Potential for assumption violation
Mark loss	Marks are not lost during the study.	Over-estimation if marks are lost during the study.	A combination of dorsal fin nicks, notches and cuts ("long lasting marks" *sensu* Wilson *et al.* 1999) were used to identify an individual. Scratches on the body were used as an additional feature to confirm identification, but were not the primary identification method. Unique pigmentation was not used as a primary identification feature. No deformities were evident on any individuals in the population, although two individuals had very distinctive fin shapes, recognizable over time.	Low

(Continued)

Geographical closure	1. An estimate of abundance that represents population size has limited value unless the population can be defined (Wilson *et al.* 1999) 2. The 'robust – separated by areas' model would be biased if Stung Treng individuals move to other primary areas	1 and 2. Inaccurate and imprecise estimate of population size if population is considered closed, when it is open, and *vice versa*.	1. Based on boat and interview surveys in other Mekong River segments of historical dolphin distribution, we concluded that the entire Mekong dolphin population is now restricted to the Kratie to Khone Falls river section during the dry season. 2. Based on photo-identification, Mekong dolphins are restricted to three main subpopulations which rarely, if ever interact (Stung Treng and Cheuteal individuals have never been sighted outside their primary areas: Beasley 2007 – Chapter 7); which facilitates the use of the 'robust – separated by areas' model.	1. Low, but possible 2. Unlikely

(Continued)

Table 1. (Continued)

Assumption summary	Detailed capture-recapture assumption	Failure to address assumption?	Study methods	Potential for assumption violation
Heterogeneity of capture probabilities	Within a sample, all individuals have the same probability of capture.	The presence of heterogeneity results in under-estimation of population size.	Attempts were made to photograph every individual encountered in a group and preferential photographing of any particular individual was avoided (Wilson *et al.* 1999). Also all possible habitat of the Mekong dolphin population in the Kratie to Khone Falls river section was surveyed to reduce the probability of missing animals inhabiting remote areas.	Minimized, but likely to be violated because of inherent differences in behavior of individuals.

design that separated the capture-recapture data into two attribute groups: (1) all individuals from Kampi, Koh Pidau and Cheuteal (similar capture probabilities) and (2) Stung Treng individuals (lower capture probabilities). This analysis resulted in separate capture probabilities and population size for both groups which were combined to obtained total population size. The survival rate and temporary emigration probabilities were obtained using the combined data set. The best model for this robust design was selected using the Akaike's Information Criterion (AIC) corrected for small sample bias ($AIC_{c.}$; Hurvich and Tsai 1989).

Estimating Mark Rate

Abundance estimates obtained through the capture–recapture analyses are only relevant to the recognizable individuals within the population and must be scaled by "mark-rate" in order to obtain an estimate of the total population size (Williams *et al*. 1993, Wilson *et al.* 1999, Chilvers and Corkeron 2003, Gormley *et al*. 2005, Parra *et al*. 2006). Assuming that recognizability was independent of the likelihood of dolphin's being within photographic range, and that photographic effort was uniform across individual animals during each encounter, we estimated the proportion of identifiable individuals in the total population by analyzing all excellent quality photographs from 2004 to 2007. The total number of photos with identifiable individuals was then divided by the total number of photographs in the sample, to provide an unbiased estimate of the proportion of identifiable individuals in the population (Gormley *et al*. 2005, Parra *et al*. 2006).

The average mark-rate ($\hat{Q}$) was obtained from 2004 to 2007 data only but assumed to be constant over the study period. The mark-rate did not change greatly from year to year, and the variance was assumed to be largely sampling error (Gormley *et al*. 2005). The estimate of mark-rate and variance is produced by:

$$\hat{Q} = I/T \tag{1}$$

$$\mathrm{var}(\hat{Q}) = \frac{\hat{Q}(1-\hat{Q})}{T} \tag{2}$$

where I is the number of photographs of individuals with recognizable marks, and T is the total number of photographs taken during the study period.

Estimating the Total Population Size

To include the unmarked portion of the population in the estimates, the population estimated obtained by MARK was scaled by the mark-rate to provide an estimate of total abundance ($\hat{N}$) and its variance as follows:

$$\hat{N}_j^* = \frac{\hat{N}_j}{\hat{Q}} \tag{3}$$

$$\mathrm{var}(\hat{N}_j^*) = \left(\frac{\hat{N}_j}{\hat{Q}}\right)^2 \left(\frac{\mathrm{var}(\hat{N}_j)}{\hat{N}_j^2} + \frac{\mathrm{var}(\hat{Q})}{\hat{Q}^2}\right) \qquad (4)$$

where j represents the sampling periods, $\hat{N}$ is the mark-recapture estimate, and $\hat{N}^*$ is the estimate of total abundance.

As recommended by Burnham and Anderson (1998), log-normal confidence intervals were constructed for abundance estimates, as standard confidence intervals often result in a lower limit below zero which is not realistic. Log-normal confidence intervals gave a lower limit of $\hat{N}_L^* = \hat{N}^*/r$, and an upper limit of $\hat{N}_L^* = \hat{N}^* \times r$. For 95% confidence intervals, r is given by:

$$r = \exp\left\{1.96\sqrt{Ln[1 + CV(\hat{N}^*)^2]}\right\} \qquad (5)$$

Estimating Temporary Emigration

The robust design allows the estimation of temporary emigration (Kendall *et al*. 1997, Kendall 2010). There are two models for temporary emigration, with the simpler one being called the random model and the more complex one the Markovian model. There are two parameters necessary to define the most general Markovian temporary emigration model because it allows for temporary emigration to depend on what happened in the previous period. The parameter γ_i' is the probability of being *outside* the study area, unavailable for capture during the primary sampling session at time (i) given the animal was *present inside* the study area during the previous primary sampling session ($i - 1$), and survives to primary sampling session (i); while the parameter γ_i'' is the probability of being *outside* the study area, unavailable for capture during the primary sampling session (i) given that the animal was *present inside* the study area during the previous primary sampling session ($i - 1$), and survives to primary sampling session (i). We also fitted random temporary emigration models by setting $\gamma' = \gamma''$, that is, the probability of moving between availability states between primary occasions (i) and ($i + 1$) is independent of the previous state of the system: Kendall 2010). Models with no temporary emigration allowed were fitted by setting γ' and $\gamma'' = 0$.

Survival and Mortality Estimation

We used two independent data sets to estimate mortality, a carcass recovery program (lowest mortality rate) and an estimate of survival, and therefore mortality, rate from the capture-recapture analysis (highest plausible mortality rate). Mortality estimates based on carcass recovery are almost certainly biased low, as a result of potentially under-reporting of dolphin carcasses (either through loss of carcasses in remote areas, or villagers afraid of reporting anthropogenic-caused deaths); whereas the mortality rates inferred from the capture-recapture survival rate estimates are likely biased high, as a result of the potential for true survival rates to be biased low.

To estimate the lower bound of mortality rates (of relevance to estimate the time required to detect a population trend), stranding data from 2003 to 2005 (see Gilbert and Beasley 2006, Beasley 2007) were used for analysis because an unknown number of dolphin carcasses likely went unreported prior to 2003 and all stranding data after 2005 were collected by a different agency. Only dolphins that were confirmed (*i.e.*, IB sighted the carcass, parts of the carcass, or a photograph of the carcass) were included in the analysis. The carcass recovery program also allowed mortality rate to be estimated by age class (*e.g.*, adult, juvenile, and calf).

We also estimated survival and mortality rates from the MARK capture-recapture output. If we consider $\varphi = SF$, the apparent survival rate φ is made up of true survival (S) and fidelity (F). If it is assumed that no emigration was possible (we have no evidence of permanent emigration), *i.e.*, $F = 1$, then the apparent survival is actually true survival (S). The annual mortality rate (M) is then $M = 1 - S$. An estimate of mortality from the capture recapture data can then be compared to the estimate of M from the carcass recovery program.

Results

A total of 11 surveys were undertaken along the Kratie to Khone Falls River section from January 2004 to May 2007. Each survey was conducted over 9–11 d. One hundred and ninety two groups (defined as 1 or >1 dolphin congregated together) were sighted over all surveys, ranging from 5 to 22 groups per survey. Mean group size was estimated to be 8 individuals (SD = 4.46), ranging from 1 to 34, with a modal group size of 8. Photo-identification was conducted successfully on 165 (86%) of the 192 groups encountered.

Abundance Estimation

Photo-identification effort and number of dolphins with recognizable marks—A total of 174 h of photographic effort was undertaken during the dry seasons from 2004 to 2007. Although photographic effort was proportionately similar between years, there was a significant difference in overall effort in each of the primary areas. Most photographic effort was conducted in the Kampi area (40.7%), close to where IB was based. Slightly less effort was conducted at Cheuteal (28.3%) and Koh Pidau (21.2%) areas. The remote Stung Treng area received the least effort (9.8%) because: (1) the exposed topography resulted in occasional high winds and wave action that made small boat surveys dangerous and (2) dolphins were particularly difficult to observe and approach in this area reducing opportunities for photo-identification (Beasley 2007). Unsuitable weather conditions were not a major consideration in any other primary area.

A total of 99 individual dolphins were identified from 2004 to 2007, with 8, 22, 28, and 41 individuals identified from the Cheuteal, Stung Treng, Koh Pidau, and Kampi areas, respectively. The discovery curve of identified individuals (based on number of groups sighted) was reaching a plateau by the end of 2004; however, substantially more dolphins were identified in 2005 and 2007. This increase in identified individuals was primarily attributable to new individuals being identified from the Stung Treng region. Individuals were sighted on 1–24 d during 2004–2007. Nineteen percent of individuals (n = 19) were sighted on only one day (most of these from the Stung Treng region). Of the 99 identified individuals in the population, 29% (29 individuals) were sighted in all three years.

Model selection and population size—The robust design consisted of seven secondary sampling occasions within three primary sampling occasions and two attribute groups. Based on the AIC_c values, the random model with γ' and γ'' constant best fit the data for this analysis (Table 2). The resulting estimate of the marked population was 76 ± SE 7.40 individuals (95% CI 66–09) as of April 2007 (Table 3).

A total of eight individuals were photo-identified in Cheuteal Pool from 2004–2007 (100% of adults were recognizable), however two of these individuals died in 2005/2006, resulting in six photo-identified individuals remaining in 2007. No juveniles inhabited the pool and two calves (both unidentifiable up to April 2007) were born in Cheuteal Pool in January 2004. Therefore, although a separate MARK population estimate was not available for Cheuteal Pool as a result of small sample size, only eight individuals (six adults and two unidentifiable 3 yr old juveniles; see Beasley 2007) remained in the pool, as of April 2007.

Between 2004 and 2007, a total of 592 excellent quality photographs were taken, of which 482 contained individuals that were recognizable. The proportion of dolphins identifiable in the Mekong River was 0.84 in 2004, 0.82 in 2005, and 0.78 in 2007. The overall mark-rate (0.81 ± 0.02) was applied to all years following Gormley *et al.* (2005). Using the "robust—separated by areas" design (two attribute groups), the number of recognizable individuals in the population was 76 ± SE 2.90 individuals (95% CI 66–109). Accounting for the number of unmarked dolphins in the population (Eq. 1, 2), the total population estimate of Irrawaddy dolphins inhabiting the Mekong River was 93 ± SE 3.90 individuals (95% CI 86–101) as of April 2007 (Table 2).

Based on the known number of individuals from Cheuteal Pool (*i.e.*, all adults identifiable and two known calves photo-identified in association with their mother since birth), total abundance for the three subpopulations as of April 2007 was 56 individuals in the Kampi/Koh Pidau subpopulation, 29 individuals in the Stung Treng subpopulation, and 8 individuals in the Cheuteal subpopulation.

Estimating temporary emigration—The "random model with temporary emigration constant" over time was the best model based on the AIC_c (Table 3). This indicated that $\gamma' = 0.10 \pm 0.063$, so that 10% of the animals were temporary emigrants in each period. However, we found that there was little difference

Table 2. The AIC values and associated statistics for the 'robust – separated by areas' population model used for Irrawaddy dolphins in the Mekong River. The photo-identification data were analyzed in MARK using three sampling occasions as outlined in Table 3 and two population groupings: (1) Stung Treng and (2) Cheuteal/Kampi/Koh Pidau.

Model	AIC_c	Delta AIC_c	AIC_c weight	Model likelihood	# of parameters	Deviance
Random $\gamma' = \gamma''(\cdot)$	−364.601	0.000	0.2821	1.000	22.000	64.174
Markovian $\gamma' = \gamma''(\cdot)$	−364.081	0.520	0.2175	0.771	23.000	62.381
No Movement $\gamma' = \gamma'' = 0$	−363.758	0.843	0.1852	0.656	21.000	67.314
Random $\gamma' = \gamma''(t)$	−362.479	2.122	0.0977	0.346	23.000	63.983

Table 3. Summary of sampling effort, the number of individuals identified in each year, in addition to population estimates of Irrawaddy dolphins in the Mekong River. min = minutes, n = the number of individuals identified in each sampling occasion, N = estimate of number of marked animals, SE = standard error, CV = coefficient of variation, CI = confidence interval, Proportion ID = proportion of identifiable animals.

Robust Model (7 Occasions, 2 Groups)

Year	Sampling occasions	Total dry season effort (min)	Total identified/year (n)	Group	Marked estimate $N \pm$ SE (95%CI)[a]	CV	Total population estimate $N \pm$ SE (95%CI)[b]
2004	January–March/ April–May/ June–July	4,947	78	Kampi/Koh Pidau/Cheuteal	61 ± 1.78 (59-68)	0.03	75 ± 5.29 (65-85)
				Stung Treng	27 ± 6.95 (21-54)	0.26	33 ± 11.10 (12-55)
				Total	**88 ± 2.95 (80-122)**	**0.03**	**108 ± 4.04 (101-116)**
2005	4–11 April/ 17–23 April	2,489	58	Kampi/Koh Pidau/Cheuteal	49 ± 2.02 (47-57)	0.04	60 ± 4.75 (51-70)
				Stung Treng	22 ± 8.13 (14-51)	0.36	28 ± 12.74 (3-52)
				Total	**71 ± 3.19 (61-108)**	**0.04**	**88 ± 4.04 (81-96)**
2007	15–21 April/ 23 April–2 May	2,975	64	Kampi/Koh Pidau/Cheuteal	52 ± 1.47 (51-60)	0.03	64 ± 4.11 (56-72)
				Stung Treng	24 ± 7.25 (16-49)	0.31	29 ± 11.44 (7-52)
				Total	**76 ± 2.95 (66-109)**	**0.04**	**93 ± 3.90 (86-101)**

[a]Robust Model = Random $\gamma' = \gamma''$ constant.
[b]Proportion ID = 0.81.

between the models, including the one allowing no temporary emigration in terms of AIC, which indicates that there is little temporary emigration occurring in this population. The results were insensitive to model uncertainty over the range of models considered.

Mortality and Growth Rate Estimation

From 2003 to 2005 a total of 46 dolphin carcasses (21 adults) were recovered and/or confirmed (Gilbert and Beasley 2006): 16 (11 adults) in 2003, 16 (5 adults) in 2004, and 14 (5 adults) in 2005. Fifty-four percent of all carcasses recovered were newborns (n = 25) and no juveniles were recovered (Table 4). It is assumed that no juveniles were recovered in the carcass recovery program because there is little, to no, recruitment of juveniles into the population because of the high newborn mortality. These results suggest that adult mortality was an average of seven dolphins/year, representing a mean minimum annual adult mortality rate of at least 8% of the population/year (based on 2005 robust model estimates of abundance). By contrast, based on the MARK capture-recapture output, the annual survival rate was 0.88, which resulted in an annual mortality rate of 0.12 ($M = 1 - S$) (which does assume that permanent emigration did not occur).

Although numerous live calves were sighted during both the dry and wet seasons along the Kratie to Khone Falls River section, we confirmed only two calves surviving more than three months between 2003 and 2005 (both from Cheuteal Pool on the Laos/Cambodian border). The pattern of mortalities indicates that most newborn calves sighted in the river died within 1–2 mo of birth (see Gilbert and Beasley 2006, Beasley 2007, and Dove 2009). The average number of known births that survived more than three months (study period to 2005) was 0.07 (Table 4); resulting in a mean minimum annual birth (and early survival) rate of 0.7%/yr for the population.

Based on these results, the estimated birth (and early survival) (*i.e.*, recruitment rate) averaged ~0.7%/yr and adult mortality averaged 8.0%/yr, suggesting that as of December 2005 the Irrawaddy dolphin population in the Mekong River was declining by approximately 7.3%/yr. Using both mortality rate estimates, population growth rates are estimated to be −0.073 (−0.08 + 0.007; carcass estimate) and −0.113 (−0.12 + 0.007; MARK estimate).

Table 4. Known minimum birth and mortality rates for Irrawaddy dolphin in the Mekong River from 2003–2005.

Year	Known surviving births (surviving more than 3 mo)	Confirmed adult mortalities	Confirmed juvenile mortalities	Confirmed newborn/calf mortalities	Total confirmed mortalities
2003	0	11	0	5	16
2004	2	5	0	11	16
2005	0	5	0	9	14
TOTAL	**2**	**21**	**0**	**25**	**46**
Annual mean (2003–2005)	0.7	7.0	0.0	8.3	15.3

Note: The ‘Annual mean’ represents the mean birth and mortality rates for 2003–2005.

Power Analysis to Inform the Design of Future Monitoring

Based on the capture-recapture estimate of 93 individuals (CV = 0.04), obtained using the robust analysis with two attribute groups (including the mark-rate), with a continuing decline of 7% per annum it would take an estimated three years to detect this decline, at which point the population would consist of only 76 individuals. This analysis suggests that by the time a trend in abundance is confirmed, the population will have decreased significantly.

Discussion

As of April 2007, our robust estimates suggest that 93 ± SE 3.90 Irrawaddy dolphins (95% CI 86–101) inhabited the Mekong River and that the population was declining at ~7%/yr. The decline is being driven primarily by unusually low recruitment and unusually high adult mortality, either of which on its own would drive the population to extinction. There is evidence that the already small Mekong population is separated into three subpopulations (Kampi/Koh Pidau = ~56 individuals; Stung Treng = ~29 individuals; and Cheuteal = ~8 individuals), with unknown levels of connectivity during the wet season. These results indicate that the status assessment of this population as *Critically Endangered* is correct and that without significant management intervention the population is heading towards local extirpation in the near future. Assuming a continuing exponential decline, the population would become less than two (and hence certainly locally extinct) in 53 yr. However, the actual time to reach the point of no return is likely to come much sooner because of small population factors that hasten decline, such as inbreeding depression and loss of social aspects critical to survival.

Based on the carcass recovery program, the current known, and high-risk, threats to the Mekong population are accidental entanglement in gill net fisheries and destructive fishing practices (*e.g.*, dynamite and electric fishing). There are strong indications based on Murphy *et al*. (2008) and Dove (2009) that disease, contaminants, and inbreeding depression are potentially high-risk threats, which would have a direct impact on individual survival. Other potential longer-term threats are dolphin-watching tourism boat harassment (causing habitat displacement and increased stress levels (Bejder *et al*. 2006, Beasley *et al.* 2010), reduced prey availability (causing starvation and reduced foraging success), and large scale dam and waterway construction (causing loss of habitat and further population fragmentation). Continued population monitoring is an important activity to assess whether conservation activities are successfully reducing mortality and increasing recruitment.

Implications for Monitoring

Through a combination of distance-sampling, direct count and photo-identification studies conducted from 2001 to 2005, Beasley (2007) determined that photo-identification was the most appropriate methodology to estimate abundance of the Mekong dolphin population. However, the dolphins' shy and evasive surfacing behavior proved to be a challenge for photo-identification in this study, particularly individuals from the Stung Treng region.

Given the restricted distribution of the Mekong dolphin population, fine-scale population changes (*e.g.*, mortalities) can potentially be monitored by a carcass recovery program, the success of which will be contingent on the continued cooperation of the local communities and government to recover and report carcasses (see Beasley *et al*. 2009). If such a program is successfully implemented (and our results indicate that this is achievable and provides robust mortality estimates), yearly capture-recapture abundance estimates are probably not required (particularly if finances are limited), because even with significant effort, trends in abundance are known to be difficult to detect in small populations (Taylor and Gerrodette 1993). Scarce resources could instead be directed towards conducting well-designed capture-recapture studies every second year (or at longer intervals), rather than suboptimal yearly estimates.

In addition to photo-identification for continued abundance, monitoring and movement studies, genetic studies to better document the extent of population fragmentation and potential inbreeding effects are essential to management efforts.

Demographic Parameters

The concordance between the estimates of the mortality rate based on (1) the carcass recovery program and (2) the MARK output were interesting, especially given that the two estimates are likely biased in opposite directions. As a result of these biases, the true mortality rate is thus likely to be between 8% and 12%/yr.

The apparently very low recruitment rate (0.07%/yr) and high adult mortality rate (8%–12%/yr; based on the carcass recovery program and MARK output, respectively) are of great concern, especially as these data are conservative for the carcass recovery program (based on confirmed numbers only); although non-conservative for the MARK program.

Between 2003 and 2008 there have been 88 confirmed dolphin deaths in the Mekong River, of which 56 (64%) were calves (Gilbert and Beasley 2006, Dove 2009). The high level of newborn mortality is of great concern. Conservation and management is urgently required to increase the probability of the population's survival by (1) reducing mortality (particularly of newborns to ensure recruitment into the existing population), (2) reducing human-induced stress on the population (such as from unregulated dolphin-watching tourism; Beasley *et al.* 2010), and (3) preserving critical habitats (particularly from large scale dam and waterway construction). Research on the cause of neonatal mortality is urgently required but the other actions should not wait until this cause is identified.

Mekong Dolphin Monitoring After 2007

From 2007 to 2010, WWF Cambodia program has continued photo-identification of the Mekong population, covering the same Kratie to Khone Falls study area as described in this paper. Dove *et al.* (2008) estimated 71 (95% CI = 66–86) "marked" individuals as of May 2007 using a closed capture-recapture model within the program MARK, however no estimate is provided on the proportion of "unmarked" individuals which constrains comparisons with this study. Ryan *et al.* (2011) estimated abundance of the Mekong population to be 85 individuals (95% CI = 78–91: including "unmarked" individuals) as of April

2010 using mark-resight models (McClintock and White 2009, McClintock *et al*. 2009). Despite some minor differences in abundance estimates, it is clear that the Mekong dolphin population now numbers <100 individuals, and is in urgent need of effective management.

Collaborative efforts to combine photo-identification data sets from 2004 to the present (currently underway) will be invaluable to investigate the long-term demography of the Mekong dolphin population and better estimate the magnitude of the apparent population decline (Ryan *et al*. 2011).

Risk of Small Populations and Population Fragmentation

Most, if not all freshwater Irrawaddy dolphin populations are small and declining, with continuing threats to their future survival (Smith *et al*. 2003, Beasley 2007). The risks of small population size to the long-term population viability of an endangered species are discussed by the IUCN Red Listing criteria (IUCN 2000). Based on photo-identification data, the Mekong dolphin population is small and now apparently fragmented into three subpopulations (*i.e.*, Cheuteal, Stung Treng, and Koh Pidau/Kampi) within the 190 km Kratie to Khone Falls river stretch (Fig. 2), which rarely, if ever, interact, at least during the dry season (Beasley 2007). The restricted range of the three subpopulations further reduces the potential for genetic mixing and increases the probability of extinction through stochastic perturbations (*i.e.*, demographic, environmental, genetic stochasticity, and natural catastrophes). Future photo-identification studies during the wet season, and genetic studies (*i.e.*, biopsy sampling[3]) will be essential to further elucidate the Mekong dolphin population structure, and establish levels of connectivity, if any, between subpopulations.

Of major conservation concern is the small subpopulation (<10 individuals) that inhabit Cheuteal Pool (pool size = 2 km^2) on the Laos/Cambodian border. This subpopulation is now separated by approximately 70 km from the Stung Treng subpopulation, and no interchange between subpopulations has been recorded using photo-identification during the dry season. Two calves were born in the pool in January 2004; however, apparently no calves have been sighted since (Ryan *et al*. 2011). There are therefore significant concerns for the long-term viability of this small subpopulation, particularly because management strategies to increase connectivity are limited as a result of the apparent high site fidelity and limited movements of Cheuteal individuals (*i.e.*, home range of a Cheuteal individual sighted 17 times from 2001 to 2005 was only 0.68 km^2, Beasley 2007).

In addition to fragmentation, a significant threat to the Cheuteal subpopulation is the proposed Don Sahong Hydropower Project (International Rivers 2011). This run-of-the-river dam is planned for the mainstream of the Mekong River in the Siphandone area of southern Laos (<2 km upstream of the Laos/Cambodian border), where the effects of blasting, construction, increased boat traffic, and subsequent alterations in prey dynamics would have a direct

[3]Biopsy sampling of such a small, critically endangered population should only be attempted after careful planning and assessment of potential risks, and only by experienced researchers who have developed their skills with other, less endangered populations of small cetaceans. Additionally, someone who knows the animals and their typical behavior in the area will need to be actively involved.

impact on the remaining dolphins in Cheuteal Pool, which is Lao's only remaining resident dolphin population (Ryan *et al.* 2011). As noted by Lusseau and Bejder (2007), it has been shown that anthropogenic impacts may alter vital rates (*i.e.*, survival, maturation, reproduction), which can lead to influences on the viability of populations (Slooten *et al*. 2000). These influences will depend on the resilience of the population's carrying capacity and therefore small, closed populations, such as the small group of dolphins inhabiting Cheuteal Pool, are highly likely to be more prone to extinction under these scenarios. As also mentioned by Ryan *et al*. (2011), this small group of dolphins should be high priority for future research and conservation initiatives.

Management Implications

Urgent and effective management actions are required if the Irrawaddy dolphin population is to survive in the Mekong River. The demonstrated decline found in this study makes additional trend research of secondary importance. The small population size means management actions are needed without delay.

Population fragmentation is a serious concern for the Mekong dolphin population, and the first step for management is to establish levels of connectivity between subpopulations through further photo-identification studies (particularly during the wet season), and genetic studies. Management that reestablishes connectivity is difficult, if not impossible, and becomes increasingly difficult as human activity increases along the river and Mekong dolphin population size continues to decrease. Reintroductions are unlikely to be successful given the precarious situation of the other small subpopulations, high site fidelity and strong social structure (*i.e.,* highly structured, with the majority of individuals having preferred, long-term associates: Beasley 2007), and difficulty to capture Irrawaddy dolphins without mortality (Tas'an and Leatherwood 1984).

As a result of continued threats facing the Mekong dolphin population, effective strategies are urgently required to reduce anthropogenic mortality to zero, while working in close cooperation with local communities to continue conservation initiatives. The conservation challenge will be difficult and complex because of the competing interests (*e.g.*, dolphin-watching tourism development *ca*. dolphin conservation efforts) (see Beasley *et al*. 2009, 2010).

Appropriate conservation actions need to be developed with the local communities in association with various levels of government and could include (1) development of Dolphin Conservation Zones (similar to the Fish Conservation Zones developed by Baird and Flaherty 2005), (2) continuation of Integrated Conservation Development Projects (Beasley 2007), and (3) initiation of microeconomic incentives to develop alternative livelihoods (Mandel *et al*. 2009). Conservation strategies need to be adapted and revised in a cycle of adaptive management. Continued research (*i.e.,* photo-identification) is also important, but it should only be conducted in parallel with management strategies, not as a replacement to management.

Conclusion

Extinction is a real possibility for endangered species such as river dolphins, and has apparently already occurred to the baiji that once inhabited the Yangtze

River of China (Reeves and Gales 2006, Turvey *et al.* 2007, Smith *et al.* 2008). The Mekong dolphin population occurs in a very limited 190 km river stretch of the lower Mekong River, where as a result of previous war and internal conflict, the habitat remains relatively intact supporting a wide variety of flora and fauna (particularly fisheries). Local communities revere dolphins and do not intentionally harm them; and are generally supportive of conservation measures (although recent gill net prohibitions may have alienated local communities from dolphin conservation efforts; Beasley *et al.* 2009). These factors have significant potential to assist conservation. However, the Mekong dolphin population has now reached a critical point with regards to its continued survival. Immediate management actions are required to greatly reduce adult mortality and research is required to establish the cause of newborn mortality. As stated by Taylor and Gerrodette (1993) "endangered populations leave little margin for recovery from incorrect management decisions," and the Mekong dolphin population is in this situation.

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