

NOTE

Model predicts catastrophic decline of common bottlenose dolphin (*Tursiops truncatus*) population under proposed land restoration project in Barataria Bay, Louisiana, USA

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The Barataria Bay Estuarine System (BBES) Stock is one of 31 identified stocks of common bottlenose dolphin (*Tursiops truncatus*) occupying the bays, sounds, and estuaries of the northern Gulf of Mexico (NOAA, 2019). The stock (hereafter “dolphin population”) is centered on Barataria Bay, a shallow (largely <2 m depth) estuarine system in Louisiana, close to the mouth of the Mississippi River (Figure 1). This area was heavily impacted by the *Deepwater Horizon* (DWH) oil spill in April 2010, and a population model was developed to quantify the impact on dolphin population abundance (Schwacke et al., 2017, 2022). As a result of the Natural Resources Damage Assessment arising from the DWH oil spill, many environmental restoration projects have been proposed, one of which is the Mid-Barataria Sediment Diversion (MBSD) project. The MBSD project proposes to build and operate a channel from the Mississippi River to the upper Barataria Basin (Figure 1) that would deliver seasonally varying quantities of fresh water, sediment, and nutrients in order to rebuild marsh and reduce land loss (U.S. Army Corps of Engineers, 2021). This fresh water will result in decreased levels of salinity in the basin. Prolonged exposure to low salinity has been linked to skin lesions and other pathologies in dolphins that can result in mortality (Booth & Thomas, 2021; Duignan et al., 2020). The potential extent of this mortality was examined in a recent report by the National Oceanographic and Atmospheric Administration (NOAA; Garrison et al., 2020). That report gave predictions of annual survival rates in four geographic regions (“strata”) within the Barataria Basin (Island, Southeast, Central and West; see Figure 1) under two scenarios presented in the Draft Environmental Impact Statement for the proposed project: the

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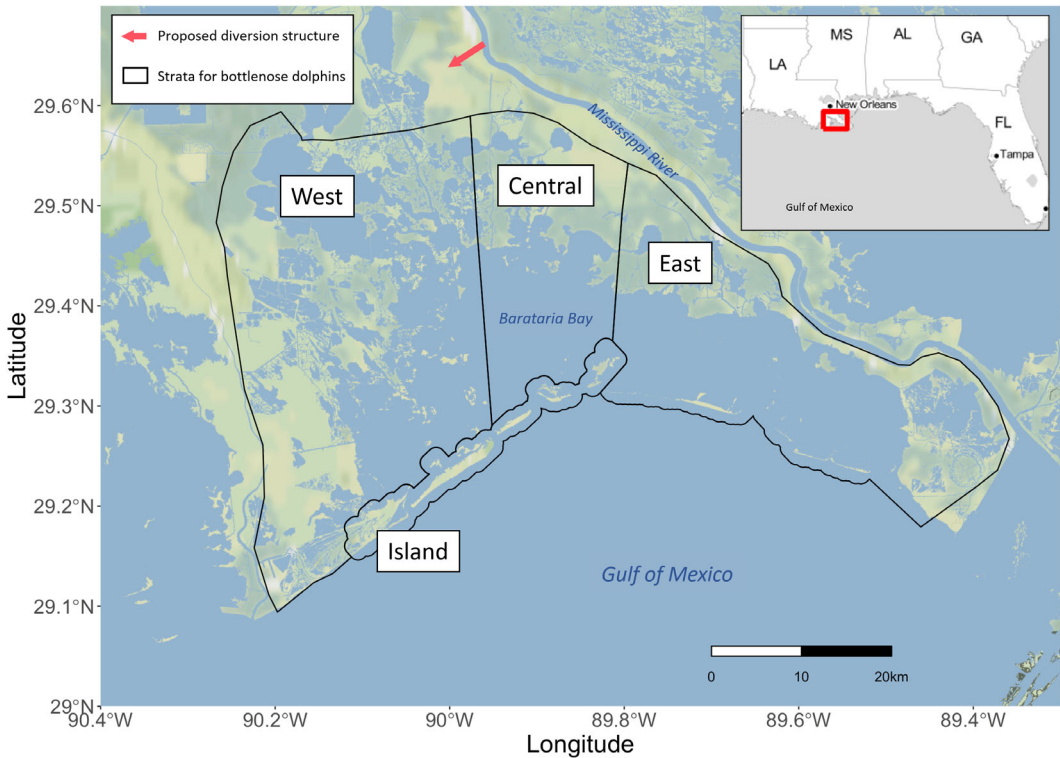


FIGURE 1 Map of Barataria Basin showing the location of the proposed sediment diversion structure (from U.S. Army Corps of Engineers, 2021) and the four geographic strata used for the bottlenose dolphin population analysis.

“Applicants Preferred Alternative” (hereafter “Diversion scenario,” DS), which assumes that the MBSD is constructed and begins operation in 2027, and the “No Action Alternative” (hereafter “No Diversion scenario,” NDS), which assumes that the MBSD is not constructed. Here, we integrate the annual survival of dolphins in each of the four strata from the two scenarios (DS and NDS) of Garrison et al. (2020) into the population model of Schwacke et al. (2022) and predict the consequences of the proposed MBSD project for the dolphin population.

The model of Schwacke et al. (2022) is an age- sex-structured discrete-time deterministic population model that includes population regulation through density-dependent fecundity. The model allows the cohort of animals exposed to the DWH oil spill to have lower survival and fecundity, and a proportion of these animals to recover over time. Animals born after the spill have baseline levels of survival and fecundity. The model accounts for scientific uncertainty in its input parameters by sampling from a distribution on each parameter and simulating one population trajectory for each sample, thereby giving a distribution of predictions. Input distributions are given in table 1 of Schwacke et al. (2022). We used 1,000 samples from this model as the basis to predict the possible effect of the proposed MBSD project (DS) on the dolphin population.

For each sample, we partitioned the BBES dolphin population ($N = 3,045$ in 2010, 95% CI [2,720, 3,611]) into the same four strata as Garrison et al. (2020), using estimates of the proportion of the population with home range centers in each of the four strata. These estimates come from a spatial capture recapture analysis (Glennie et al., 2021) that forms part of the inputs to the Schwacke model. For the purposes of this analysis, we assumed that each stratum is demographically independent, i.e., that dolphins in the BBES population do not move from one stratum to another. For each stratum, we ran the Schwacke model for 66 years (2010–2076) under two scenarios. In the first scenario, representing the NDS, we ran the Schwacke model without modification. In the second scenario, representing the DS, for each year after the proposed MBSD project begins in 2027 and until the last year of 50-year

TABLE 1 Summary statistics on predicted percentage difference in dolphin annual survival under the Diversion scenario (DS) relative to the No Diversion scenario (NDS). The second column is the median predicted percentage difference in survival between DS and NDS, the third is the percentage of replicates that predict a negative difference in survival between DS and NDS of 20% or more, and the fourth is the percentage of replicates that predict an increase in survival under DS relative to NDS.

Stratum	median % diff	% (diff < -20%)	% (diff >0)
Island	-2	10	1
Southeast	-14	40	24
Central	-68	97	0
West	-39	83	1

planning horizon in 2076, we adjusted the survival values from the Schwacke model by multiplying them by a random draw from the percentage difference in survival between DS and DNS, defined in the next paragraph. This sampling is equivalent to assuming that the factors driving uncertainty in survival difference between scenarios vary each year (see later discussion). The same multiplier was applied to all age- and sex-classes. We calculated the following metrics to summarize outcomes from 1,000 population model runs. (1) In the first year of operation of the MBSD (i.e., 2027–2028): (a) excess mortality—the total number of dolphins that are expected to die this year under the DS minus the number that are expected to die in the same year under the NDS; (b) change in population size under the DS and under the NDS; (c) percentage difference in population size in 2028 between the DS and NDS. (2) After 10 years of operation of the MBSD (i.e., in 2037): (a) probability of functional extinction, where functional extinction is defined as ≤ 1 animal; (b) percentage difference in population size between the DS and NDS. (3) In the final year of the MBSD operations planning horizon (i.e., 2076): (a) probability of functional extinction; (b) population size under the DS and under the NDS. In each case, we report the median value from the 1,000 samples from the population model, together with the lowest 2.5th and highest 97.5th percentile for each year—these latter values represent a pointwise 95% confidence interval (CI) on the prediction.

We obtained from NOAA 1,000 replicate predictions of estimated annual population-average survival under DS and NDS in each of the four strata, derived from the model of Garrison et al. (2020). The replicate predictions represent the range of scientific uncertainty on possible impacts, accounting for factors such as uncertainty on the salinity field for a given set of hydrographic conditions, uncertainty on animal movement and hence exposure, and uncertainty on the effect of low salinity on dolphin survival (see Garrison et al., 2020, for details). Note that all predictions are based on a single hydrograph for 1970 (Garrison et al., 2020), and so do not account for uncertainty or systematic trend in current or future hydrographic conditions (see later discussion). For each replicate prediction and stratum, we calculated the percentage difference in survival between the DS and NDS as follows:

$$\% \text{ difference in survival} = \frac{\text{survival under DS} - \text{survival under NDS}}{\text{survival under NDS}} \times 100$$

The resulting percentage difference in survival varies among strata (Table 1, Figure 2). For the Island stratum, the median prediction is of a 2% decline in survival under the DS relative to the NDS, although in 10% of replicates the predicted survival decline is $>20\%$. For the Southeast stratum, the median prediction is of a 14% decline in survival with 40% of replicates predicting a survival decline of $>20\%$. Note, however, that 24% of replicates in this stratum predict an increase in survival under the DS relative to the NDS. For the Central and West strata there is a predicted decline in survival of $>20\%$ in 97% and 83% of replicates, respectively.

Predicted population trajectories under DS and NDS scenarios are the same up until 2027, when proposed MBSD operations start (Figures 3 and 4). During this period (2010–2027) the populations are predicted to experience the negative effect of the DWH oil spill and, starting around 2020, to begin to recover. After 2027, under the NDS the populations are predicted to continue to recover and reach a steady state long before the end of

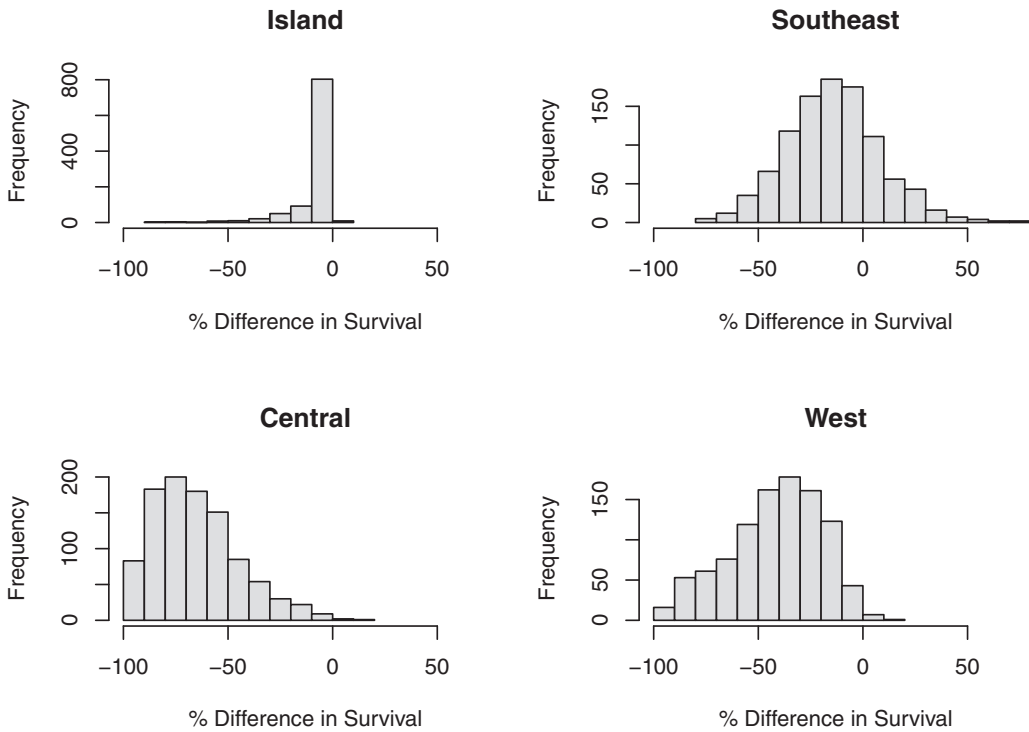


FIGURE 2 Predicted percentage difference in dolphin annual survival in four geographic strata under the Diversion scenario compared with the No Diversion scenario. One thousand predicted survival rates were provided by NOAA and were derived from the model of Garrison et al. (2020).

the modeled time period. Under the DS the median prediction for the Island stratum is of a steady decline, while the other strata are predicted on average to experience rapid declines to extinction (Figure 3). For the entire dolphin population, i.e., summing across strata, the population is predicted on average to decline after 2027, precipitously at first and then more gradually, reaching very low levels relative to the NDS by the end of the simulation time period (Figure 4).

Individual realizations of the population simulation show more erratic trajectories (Figure 5) than the averages over 1,000 simulations described previously. The part of the population in the Island stratum is predicted to experience occasional large decreases associated with years where there is a large decline in survival under the DS; in most years, however, there is predicted to be little or no decline. By the 50th year of operation, all realizations are predicted to have experienced an overall decline and none are at the level of the corresponding NDS. The part of the population in the Southeast stratum is predicted to experience frequent large decreases, but also occasional increases associated with survival increase under the DS. Nevertheless, by the 50th year of operation, all realizations are predicted to be at or close to zero. The parts of the population in the Central and West strata are predicted to experience rapid declines towards zero in all realizations.

In this first year of MBSO operation, the median predicted excess mortality under the DS is 537 dolphins with 95% CI [112, 1,400] (Table 2). This excess mortality represents a median of 26% of the population (95% CI [6, 63]) killed by the MBSO in its first year of operation. Predicted population size in 2027, before operation of the proposed MBSO, is 2,056 animals, 95% CI [1,408, 2,759]. In 2028 under the DS, this is predicted to be 1,529 animals, 95% CI [714, 2,270], a decline of 24%, 95% CI [3, 60] (Table 3). By contrast, under the NDS the population is predicted to increase by 3, 95% CI [1, 4] (Table 3). This increase is because the population is predicted to be still in recovery from the DWH oil spill. Therefore, by the end of the first year of MBSO operations, the population is predicted to be 26% smaller, 95% CI [6, 61] under the DS compared to the NDS (Table 3).

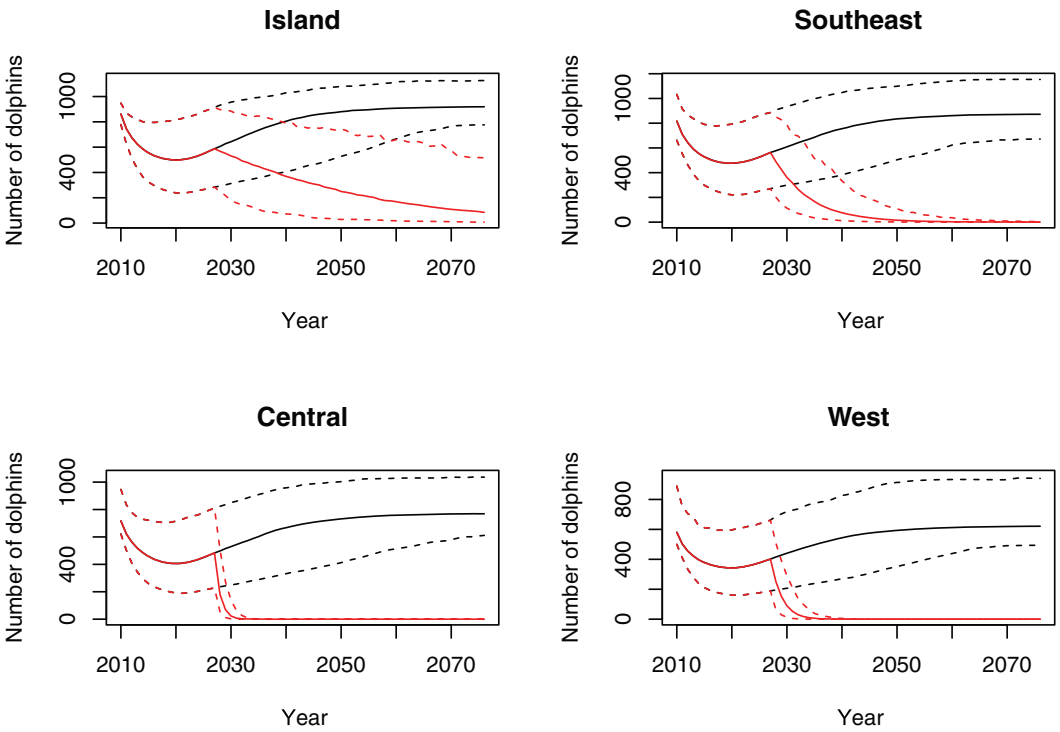


FIGURE 3 Summary of predicted population trajectories for bottlenose dolphin in Barataria Bay by geographic stratum under the Diversion scenario (red) and No diversion scenario (black). Solid line shows median; dashed lines show pointwise 95% confidence limits.

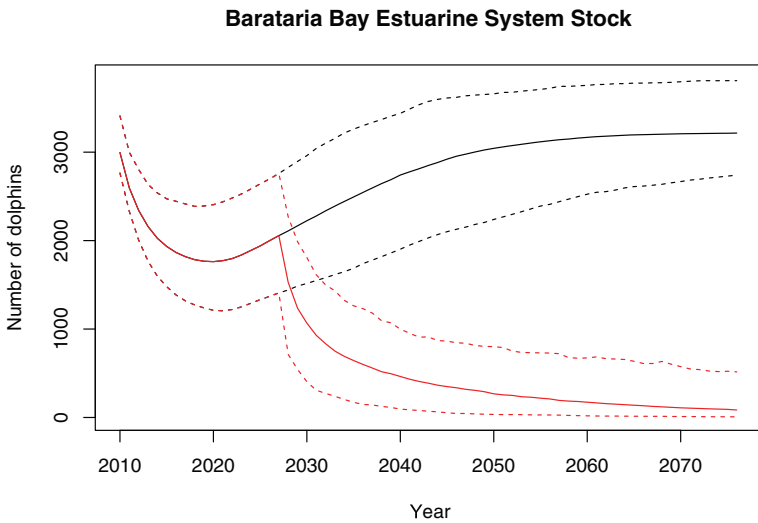


FIGURE 4 Summary of predicted population trajectory for bottlenose dolphin in Barataria Bay under the Diversion scenario (red) and No Diversion scenario (black). Solid line shows median; dashed lines show pointwise 95% confidence limits.

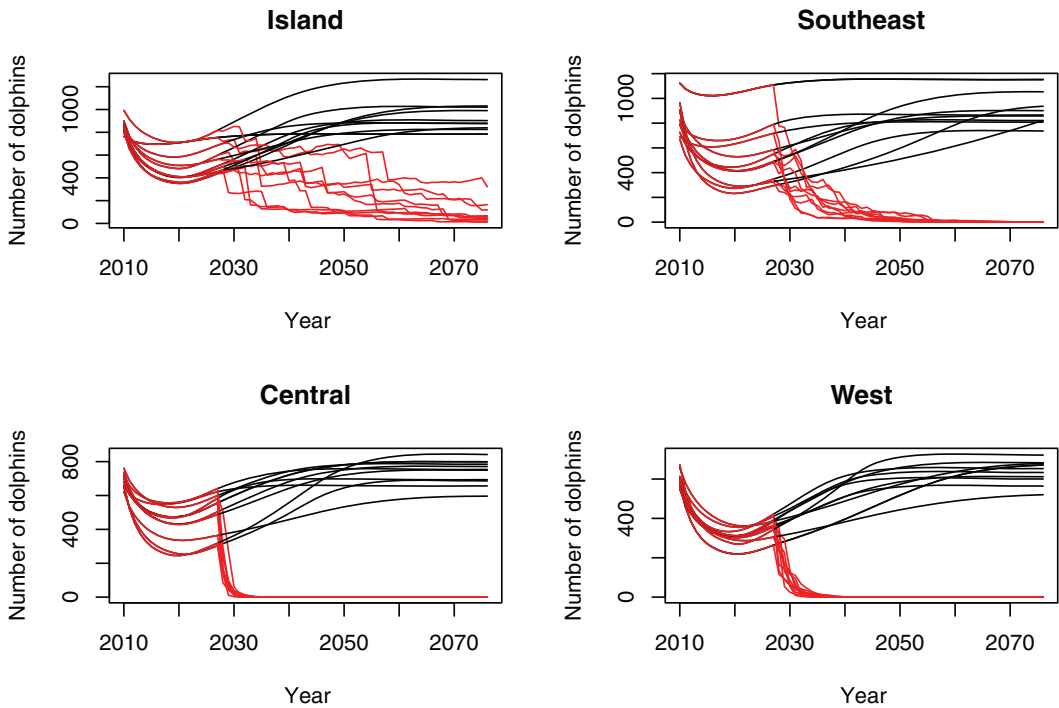


FIGURE 5 Ten example realizations of the population simulation for bottlenose dolphin in Barataria Bay under the Diversion scenario (red) and No Diversion scenario (black).

TABLE 2 Predicted dolphin mortality in 2027 under the Diversion scenario (DS) and No Diversion scenario (NDS). The last column shows excess mortality, i.e., mortality under DS minus mortality under NDS. Values are medians from the model simulations, with 95% confidence intervals in square brackets.

Stratum	DS mortality	NDS mortality	Excess mortality (DS – NDS)
Island	55 [24, 267]	40 [20, 63]	10 [0, 220]
Southeast	103 [0, 394]	39 [17, 61]	64 [–46, 342]
Central	313 [94, 655]	33 [15, 55]	282 [67, 602]
West	166 [42, 483]	28 [13, 48]	138 [20, 436]
Total	681 [24, 267]	140 [20, 63]	537 [112, 1,400]

Note: The median shown in the Total row is calculated by first aggregating the strata and then calculating the median. This calculation is not the same as simply summing the stratum medians. The same is true for the confidence limits. Similarly, median excess mortality is median (DS mortality – NDS mortality), which is not generally the same as median DS mortality – median NDS mortality.

After 10 years of operation of the MSBD, in 2038, substantial declines are predicted to have occurred in all strata (Table 4). Dolphins in the Central stratum are predicted to be functionally extinct (≤ 1 animal remaining) with probability 1, and in the West stratum with probability 0.37 (Table 5). The total population size is predicted to be 78% smaller, 95% CI [57, 94] under the DS than the NDS (Table 4).

In the last of the planned 50 years of operation, dolphins in the Central, West, and Southeast strata are predicted to be functionally extinct under the DS with probability 1, 1, and 0.85 respectively (Table 5). The number of dolphins in the Island stratum is predicted to be 91% lower, 95% CI [47, 99] under DS compared to NDS (Table 6). Overall, by the year 2076, the median predicted population size across all the Barataria Basin under the DS is

TABLE 3 Predicted number of dolphins in 2028 (after 1 year of operation of the diversion) under Diversion scenario (DS) and No Diversion scenario (NDS) scenarios, and percentage difference in number of dolphins between DS and NDS. Values are medians with 95% confidence intervals in square brackets.

Stratum	DS dolphins	NDS dolphins	% difference
Island	568 [249, 896]	605 [293, 932]	-2 [-39, 0]
Southeast	489 [202, 851]	578 [281, 908]	-12 [-50, 7]
Central	180 [54, 508]	498 [236, 823]	-62 [-87, -16]
West	251 [63, 508]	415 [195, 687]	-35 [-81, -6]
Total	1529 [714, 2,270]	2109 [1,442, 2,828]	-26 [-61, -6]

Note: The median shown in the Total row is calculated by first aggregating the strata and then calculating the median. This calculation is not the same as simply summing the stratum medians. The same is true for the confidence limits. Similarly, median percentage difference is median (DS dolphins – NDS dolphins), which is not generally the same as median DS dolphins – median NDS dolphins.

TABLE 4 Predicted number of dolphins in 2028 (after 10 years of operation of the diversion) under Diversion scenario (DS) and No Diversion scenario (NDS) scenarios, and percentage difference in number of dolphins between DS and NDS. Values are medians with 95% confidence intervals in square brackets.

Stratum	DS dolphins	NDS dolphins	% difference
Island	417 [89, 827]	766 [378, 1003]	-41 [-85, -10]
Southeast	120 [24, 458]	719 [353, 1020]	-82 [-96, -41]
Central	0 [0, 0]	634 [304, 933]	-100 [-100, -100]
West	2 [0, 19]	518 [250, 788]	-100 [-100, -97]
Total	559 [141, 1,181]	2,595 [1,779, 3,336]	-78 [-94, -57]

Note: The median shown in the Total row is calculated by first aggregating the strata and then calculating the median. This calculation is not the same as simply summing the stratum medians. The same is true for the confidence limits. Similarly, median percentage difference is median (DS dolphins – NDS dolphins), which is not generally the same as median DS dolphins – median NDS dolphins.

TABLE 5 Predicted probability of functional extinction, $p(\text{extinct})$, (i.e., ≤ 1 dolphin remaining) by stratum in 2037 (after 10 years of operation of the diversion under the Diversion scenario) and 2076 (final year of the planning horizon for the diversion project).

Stratum	$p(\text{extinct})$ in 2037	$p(\text{extinct})$ in 2076
Island	0.00	0.00
Southeast	0.00	0.85
Central	1.00	1.00
West	0.37	1.00

85 dolphins, 95% CI [7, 516] compared to 3,216, 95% CI [2,740, 3,080] under the NDS (Table 6). In other words, the population is predicted to be 97% smaller, 95% CI [84, 100] under the DS compared to the NDS.

The analyses presented here represent a case study in the use of population models to make quantitative predictions of the consequences of proposed management actions, including expressions of scientific uncertainty in the predictions. Outputs can be used alongside other information to weigh up alternative proposed actions. The scenarios considered in this case study have been relatively simplistic and so we briefly consider how more complex alternatives could affect the results.

TABLE 6 Predicted number of dolphins in 2076 (final year of the planning horizon for the diversion project) under Diversion scenario (DS) and No Diversion scenario (NDS) scenarios, and percentage difference in number of dolphins between DS and NDS. Values are medians with 95% confidence intervals in square brackets.

Stratum	DS dolphins	NDS dolphins	% difference
Island	84 [7, 515]	919 [776, 1,127]	-91 [-99, -47]
Southeast	0 [0, 4]	872 [672, 1,154]	-100 [-100, -99]
Central	0 [0, 0]	769 [611, 1,036]	-100 [-100, -100]
West	0 [0, 0]	621 [494, 941]	-100 [-100, -100]
Total	85 [7, 516]	3,216 [2,740, 3,808]	-97 [-100, -84]

Note: The median shown in the Total row is calculated by first aggregating the strata and then calculating the median. This calculation is not the same as simply summing the stratum medians. The same is true for the confidence limits. Similarly, median percentage difference is median (DS dolphins – NDS dolphins), which is not generally the same as median DS dolphins – median NDS dolphins.

We set a limit for “functional extinction” of one animal. To our knowledge there is no agreed threshold; other higher thresholds could have been used to indicate the point at which there are so few animals they no longer form a functioning part of the ecosystem. With higher thresholds, the probability of functional extinction under the DS would be higher. For example, if the threshold is raised to 30 animals, then probability of functional extinction in the Central stratum after 10 years of operation of the MSBD rises from 0.37 to 1.

The results presented here were generated by combining two separate analyses: the survival predictions from Garrison et al. (2020) and the population model of Schwacke et al. (2022). These use some overlapping information—the photo-ID surveys undertaken in Barataria Bay from 2010 to 2019. Hence it would be possible, with more modeling effort, to integrate the two more closely by building components of the Garrison et al. model into the population model. However, this more complex modeling is not expected to make a qualitative difference to the population predictions.

As noted earlier, sampling randomly each year from the replicate survival predictions of Garrison et al. (2020) is equivalent to assuming the factors driving uncertainty in predicted survival effects vary annually. While this assumption is correct for some sources of uncertainty (e.g., uncertainty in salinity field given hydrography, animal movement, and hence exposure), it is not fully correct for others (e.g., uncertainty on dolphin survival response given exposure). Ideally, the different components of uncertainty in the Garrison model would be separated and then we could sample as appropriate at the annual level or just once per population projection. This reduction in annual variability would be expected to produce a somewhat more positive population projection, particularly in the Island stratum. However, one very important source of annual variability, annual change in hydrography, was neglected in these simulations. The predictions we used from the Garrison model were based on a single annual hydrograph, from 1970 (cycle0; Garrison et al., 2020), when in reality hydrography is expected to vary substantially among years. This variability will mean that there are years of lower survival than predicted by Garrison and years of higher survival. The overall effect of this interannual variability on the dolphin population will be to produce a more negative trajectory, because years where survival is low produce large decreases in population size, but in years of good survival the population can only increase by a small amount as it is constrained by the birth rate. The population can decline by 25% in a bad year, but it cannot increase by 25% in a good year. Given this, we anticipate that addressing all the issues related to uncertainty discussed in this paragraph will lead to more negative population predictions overall.

Another issue with the use of a historical hydrograph is that it is unlikely to accurately reflect future hydrography, especially under climate change. This could affect the NDS if baseline levels of salinity, and related factors such as prey base, change over the long term. However, a much greater effect is anticipated under the DS, because the amount of freshwater released by the MBSD will be positively related to the flow rate of the Mississippi river, and the likelihood of high-flow years is predicted to increase (Garrison et al., 2020).

A further factor that makes our projections optimistic is that the population dynamics model is deterministic (Lande 2002). First, it does not account for the random nature of births and deaths, and also allows noninteger population counts. Incorporating demographic stochasticity in the model, and restricting population sizes to be whole numbers, will produce more negative predictions. The effect is stronger for smaller populations, and hence will affect the DS more than the NDS. Second, apart from sampling the annual survival effects, it does not include other external factors that cause demographic parameters to fluctuate over time, generally referred to as “environmental stochasticity.” This stochasticity tends to hasten extinction of small populations, and so again will affect the DS more than the NDS.

The analysis also assumed that the four strata are demographically independent. If dolphins move away from the three more affected strata into the Island stratum in response to low salinity, then the population-level effects may be lower. On the other hand, if dolphins disperse among strata without regard to salinity changes, then more animals will tend to move into the strongly affected strata from the less-affected Island stratum and the population-level effects may be greater. Genetic analyses have supported spatial structure within the BBES population and have identified genetically distinct dolphin groups in the Western, East/Central, and Island portions of the basin (Rosel et al., 2017). Tracking of Barataria Basin dolphin movement patterns via satellite-linked tags has shown multiyear site fidelity to small home ranges (Wells et al., 2017), and has not shown changes in movement that are coincident with fluctuating salinity (Takeshita et al., 2021).

The mortality estimates from freshwater exposure of Garrison et al. (2020) were based on a vertically integrated hydrographic model and hence did not account for the possibility that there may be patches of higher salinity water towards the bottom of deeper parts of the Barataria basin that dolphins could use as refugia. However, there are few deep-water channels within the basin and there is no evidence that dolphins move towards them during periods of low salinity (Takeshita et al., 2021). Further, bay, sound, and estuary bottlenose dolphins do not typically take long dives and must visit the water surface to breathe. In addition, the mortality estimates of Garrison et al. are conservative in that they only counted the single longest stretch of exposure to low salinity rather than attempting to determine the possible effect of multiple bouts of low salinity exposure in a single year. We cannot exclude the possibility that dolphins may adapt behaviorally or genetically to the low salinity, but behavioral adaptation to low salinity has not been documented previously and the rapid pace of decline combined with relatively small starting population size makes genetic adaptation unlikely.

In summary, under the assumptions of this model, there is predicted to be a catastrophic (97%, 95% CI [84, 100]) decline in population size caused by the MBSD under the Diversion scenario. The population is likely to become functionally extinct (≤ 1 individual) in three out of four strata and greatly reduced (91% lower, 95% CI [47, 99]) in the fourth. The declines are predicted to be greater than those caused by the DWH oil spill and would take place just as the population is starting to recover from the oil spill. While the population is predicted to recover fully from the DWH oil spill under the No Diversion scenario, this recovery is predicted not to happen under the Diversion scenario.

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AUTHOR CONTRIBUTIONS

Len Thomas: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing – original draft; writing – review and editing. **Tiago A. Marques:** Conceptualization; methodology; writing – review and editing. **Cormac Booth:** Conceptualization; methodology; writing – review and editing. **Ryan Takeshita:** Conceptualization; methodology; visualization; writing – review and editing. **Lori H. Schwacke:** Conceptualization; methodology; writing – review and editing.

DATA ACCESSIBILITY STATEMENT

All data and R code used to produce these results are available at the repository <https://github.com/TiagoAMarques/CARMMHApapersSI>. This repository includes code for the population model of Schwacke et al. (2022). A shortcut to the summary page for this Note is https://htmlpreview.github.io/?https://github.com/TiagoAMarques/CARMMHApapersSI/blob/master/FolderArchitecture2runCode/Diversion_ElectronicSupplements.html

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