Mortality Estimates of Invertebrates and Early Life Stage Fish, and Other Injury Metrics in the Upper Mixed Layer of the Water Column during the *Deepwater Horizon* Oil Spill

Technical Report

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August 31, 2015

SC14006

1. Introduction

As the surface oil slick from the *Deepwater Horizon* (DWH) incident moved across the Gulf of Mexico (GoM), fish and invertebrates in the upper water column were exposed to toxic levels of polycyclic aromatic hydrocarbons (PAHs). The scale of the DWH spill made it impossible to fully characterize exactly where and when these toxic exposures occurred. However, multiple researchers collected hundreds of water column samples from beneath the slick, and there is a significant body of biological data describing the types of organisms that might have been present. We assumed that these water column and biological data represented random samples of what could have been present during the course of the spill, and we estimated the exposure to PAHs for organisms using a repeated random sampling (Monte Carlo) approach. We then estimated the toxicity to the exposed organisms based on toxicity testing results for Gulf species, and developed an estimate of the percent mortality from this exposure. The percent mortality of larval fish and invertebrates was used by the Trustees to evaluate injuries in the upper water column as a result of the DWH oil spill.

In this report we describe the methods we used to estimate mortality of biota in the upper water column, and we present the resulting estimates. We discuss two other metrics used to estimate injury in the upper water column: the spatial extent of the surface oil slick over time, and the volume of water affected by the surface oil slick. We also describe methods we used to assess these metrics over space and time during the DWH spill, and again we present the resulting estimates.

2. Methods

This section describes how we combined data on the areal extent of surface oil, water quality data, estimated distributions of fish embryos and invertebrates in the upper water column, and toxicity testing results to estimate the fraction of embryonic fish and invertebrates killed by the DWH oil spill.

2.1 Areal Extent of Surface Oil during the DWH Spill

During the DWH oil spill, a large volume of oil rose rapidly from the wellhead and spread out on the ocean surface. The areal extent and cumulative number of days in which oil was observed on the ocean surface was determined by the analysis of satellite images (Garcia-Pineda et al., 2015; Graettinger et al., 2015). This analysis showed that a surface oil slick was present from at least April 23 through August 11, 2010, with a cumulative areal extent of 112,100 km^2 (43,300 mi^2). At its peak on June 19, 2010, oil covered more than 39,600 km^2 (15,300 mi^2) of the sea surface (ERMA, 2015) – an area nearly one-third the size of the State of Mississippi.

We estimated the areal extent of the surface slick in offshore, shelf, and estuarine waters for the 113 days oil was present on the water based on the synthetic aperture radar (SAR) image analysis from Graettinger et al. (2015) and Garcia-Pineda et al. (2015). Offshore waters were defined as areas with depths greater than 200 m, and shelf areas were defined as waters less than 200-m deep (Figure 1), and we based the extent of estuarine waters on the National Wetland Inventory (Cowardin et al., 1979). Using ArcGIS, we estimated the spatial overlap of the SAR images with these different water column zones, and calculated the areal extent of oil within each area for each day SAR images were available.

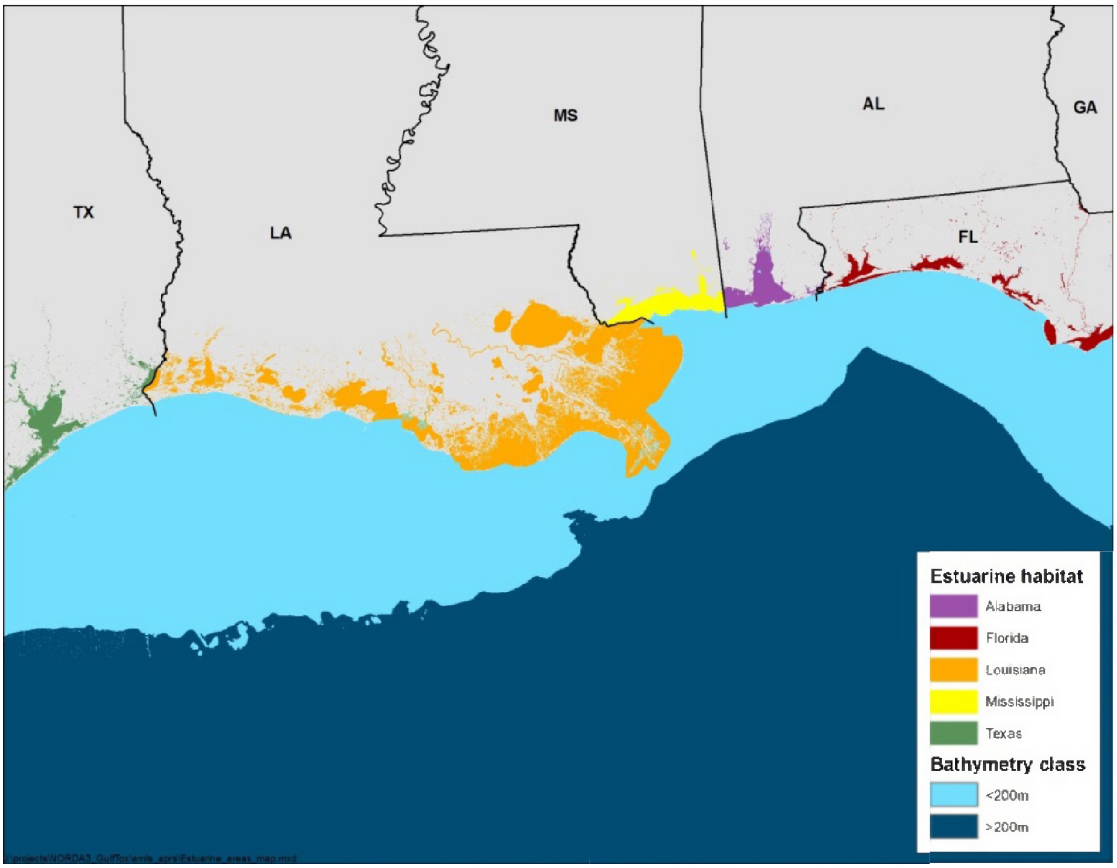

Figure 1. Areal extent of estuarine waters, by state, as defined by the National Wetland Inventory for the northern GoM. Estuarine waters from Cowardin et al. (1979); land modified in Louisiana using Couvillion et al. (2011). Bathymetry adapted from NOAA (2006) and (2010).

SAR image analyses included separate examinations of oil on the open ocean (Garcia-Pineda et al., 2013) and oil in nearshore estuaries (Garcia-Pineda et al., 2015). The data showed oil on the ocean surface on April 23, 2010, when the first SAR image of DWH oil was collected. It took several days for oil to move across the Gulf and reach coastal waters, arriving in estuarine waters by early May 2010.

SAR images were not available for every day between April 23 and August 11, 2010, and on some days, SAR imagery covered only a portion of the oil slick in the northern GoM. For days without SAR images, we used a linear interpolation between data for the day before and the day after to estimate the missing daily oil extent. For days with only partial image coverage, we used only the available data, knowing that it underestimated the surface oiling on that day. Figure 2 shows the estimated areal extent of surface oil detected in the offshore, shelf, and estuarine waters by day; Figure 3 provides the oil extent for estuarine waters only.

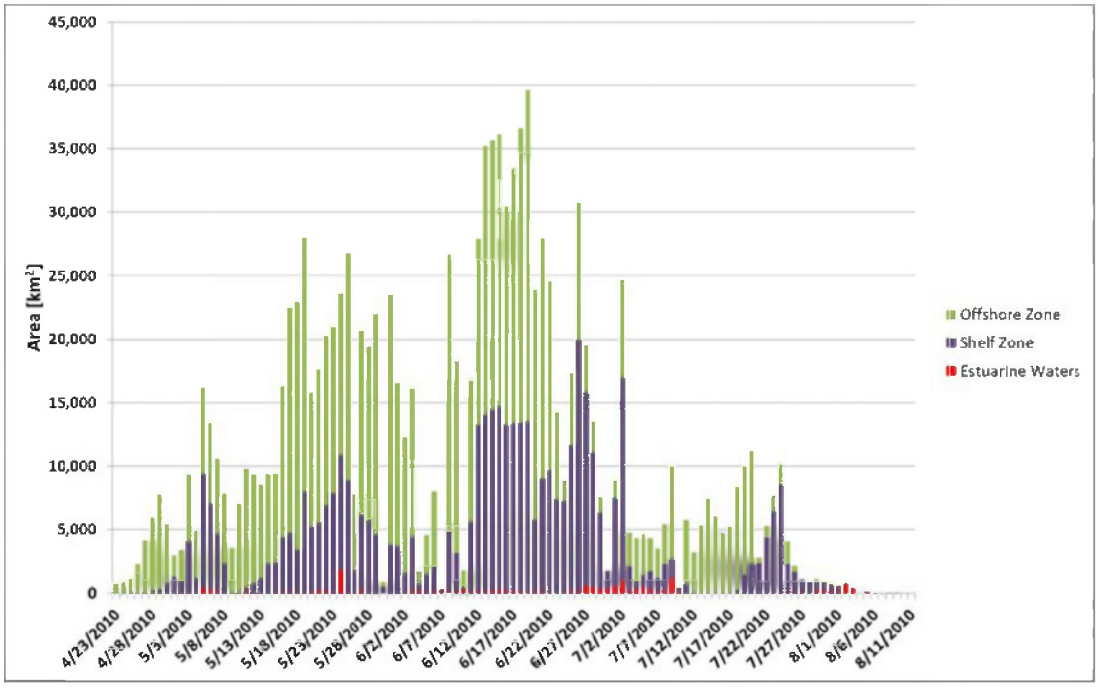

Figure 2. Estimated areal extent of surface oil during the DWH spill in offshore, shelf, and estuarine waters.

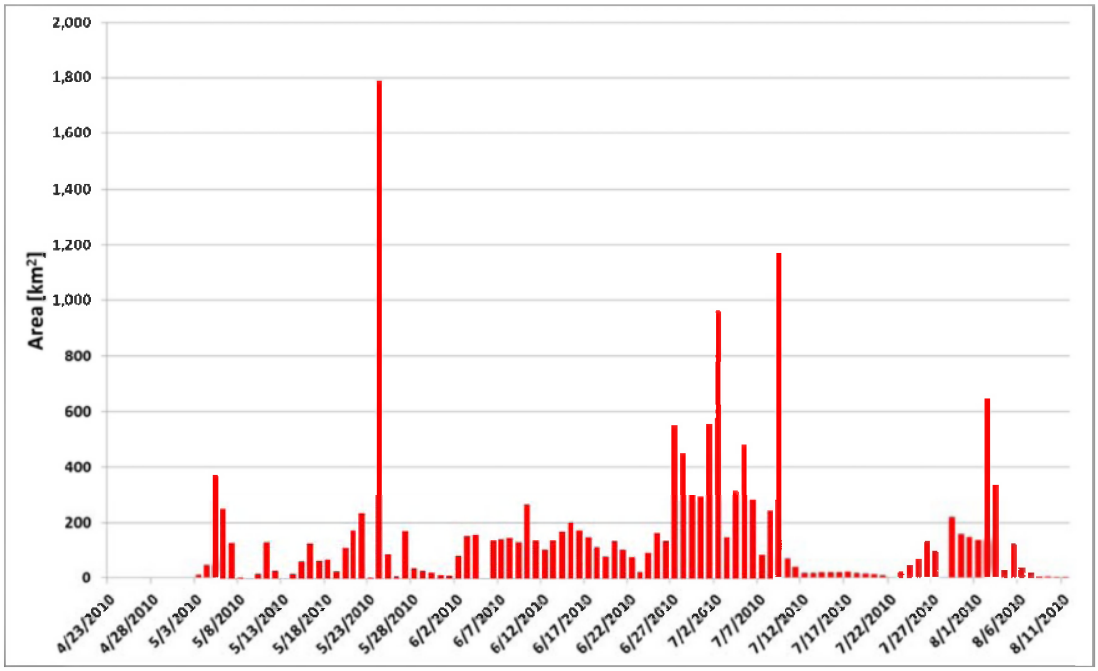

Figure 3. Estimated areal extent of surface oil during the DWH spill in estuarine waters.

2.2 PAH Concentrations beneath the Surface Slick

Multiple researchers collected water samples at different depths to assess water column oil concentrations. To assess exposures of biota to oil in the upper mixed layer of the water column, we used a dataset compiled from multiple sources, including Trustee Natural Resource Damage Assessment (NRDA) data, BP NRDA data, response data, and BP public data, available on NOAA's data management system, DIVER (2015).

The DWH NRDA toxicity testing program generally reported effect concentrations in terms of the sum of 50 PAHs (TPAH50; Forth et al., 2015a; Morris et al., 2015a). Consequently, for comparison of toxicity test results, we also used TPAH50 to describe oil concentrations. Travers et al. (2015) developed a regression that described the TPAH50 in the upper 20 m of the water column for samples collected within the estimated surface oil slick "footprint" based on the SAR analysis. In general, TPAH50 concentrations decreased with depth (see Figure 4). Approximately 19% of samples had no detectable PAHs (i.e., TPAH50 = 0 µg/L), and this percentage was relatively constant with depth.

This distribution of TPAH50 in the upper water column was used to estimate the exposure of biota as described below.

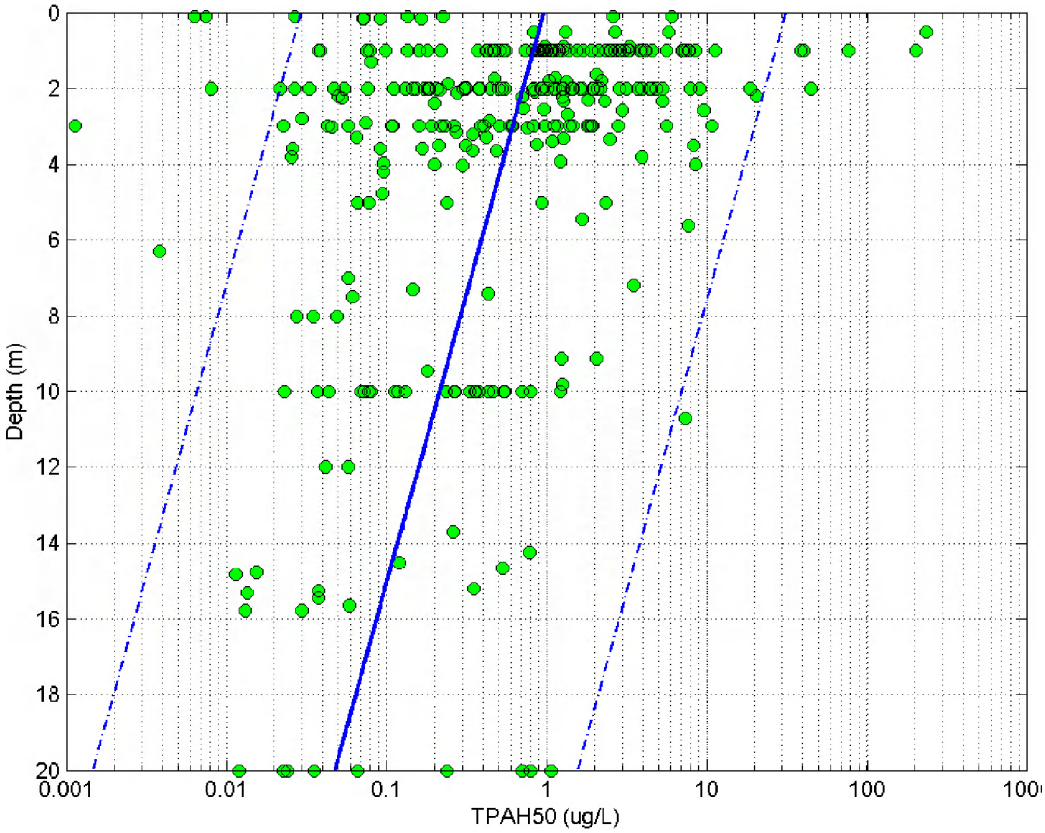

Figure 4. Empirical TPAH50 data for water column samples collected beneath surface slicks over the course of the spill (green dots), along with log-linear fit to the data (solid blue line) and 2σ range (dashed blue lines). Only samples with PAHs above the detection limit appear on this plot. Approximately 19% of all samples had no detectable PAHs.

2.3 Vertical Distribution of Eggs

The vertical distribution of eggs in the upper water column is a function of the diameter and density of the eggs, and the upper ocean turbulence. Larger egg diameters and lower egg densities increase overall egg buoyancy and tend to increase the relative concentration of eggs near the surface, whereas a more turbulent upper ocean increases dispersion and tends to distribute eggs more evenly over the upper water column (Sundby, 1991, 1997). To quantify the vertical distribution of fish eggs as a function of turbulence, egg diameter, and egg buoyancy, we used the VertEgg toolbox (Ådlandsvik, 2000), which solved the equations for the steady-state

egg distribution as a function of depth. Wobus et al. (2015) conducted these simulations in the upper 20 m of the water column for offshore and shelf areas, and for an average depth of 2.5 m for estuarine waters.

2.4 Toxicity of PAHs in the Water Column

2.4.1 Oil entrained into the water column

During oil spills, organisms are generally exposed to oil droplets and dissolved oil in the upper mixed layer of the water column. To calculate a range of potential toxicity to the ichthyoplankton and zooplankton that were exposed to DWH oil, we chose two species of fish and two species of invertebrates that represented the range of sensitivity observed across a range of taxa tested for the DWH NRDA (Morris et al., 2015b). For water column exposures, we used results from our bioassays conducted with water accommodated fractions (WAF; Morris et al., 2015a), where some mixing of oil into water was simulated in the laboratory (Forth et al., 2015b).

The Trustees' aquatic toxicity testing program investigated photo-induced toxicity on GoM early life stage (ELS) fish and invertebrates and determined that ultraviolet (UV) light can greatly enhance the toxicity of DWH oil on ELS organisms. In fact, the average amount of UV light measured in the GoM during the spill could have increased the toxicity of DWH oil by 10 to 100 times over the course of a single day (Lay et al., 2015a). Therefore, we derived a correction factor to apply to the dose response curves for the several species we tested and chose those that represented the range of sensitivities to oil in the presence of UV light (Lay et al., 2015a). We used this correction factor to adjust the inflection point of the sigmoidal dose-response curve for a given UV dose. We generated separate UV corrections for fish and invertebrates as discussed in Lay et al. (2015a).

The species that we chose to represent the low and high end of the range of sensitivity for photo-induced toxicity of oil for ELS fish in the upper water column (0–20 m) were bay anchovy (*Anchoa mitchilli*) and mahi-mahi (*Coryphaena hippurus*), respectively (Table 1; Lay et al., 2015a; Morris et al., 2015b). Additionally, the low- and high-sensitivity invertebrate species for oil toxicity in the presence of UV light were copepod (*Arcartia tonsa*) and blue crab (*Callinectes sapidus*; Table 1; Lay et al., 2015a; Morris et al., 2015a, 2015b), respectively. We conducted all the tests used to generate the dose response relationships using one of two weathered oils (Slick A or Slick B) collected from slicks in the Gulf (Forth et al., 2015b; Morris et al., 2015a).

Table 1. LC50 values for fish and invertebrates showing adjustment for phototoxicity. Toxicity increased (i.e., lower LC50s) in ambient UV.

Species	Oil	WAF	Bioassay duration (h)	LC50 µg/L TPAH50	
				No UV	UV-adjusted
Ichthyoplankton					
Bay anchovy	B	HEWAF	48	1.4	0.1
Speckled sea trout	B	HEWAF	72	24.7	0.2
Red drum	A	HEWAF	72	27.1	0.2
Bay anchovy	A	HEWAF	48	3.9	0.2
Speckled sea trout	A	HEWAF	72	30.3	0.2
Red drum	B	HEWAF	60	30.9	0.2
Mahi-mahi	A	HEWAF	96	8.8	0.6
Zooplankton					
Copepod	A	HEWAF	96	64.4	2.4
Blue crab	B	HEWAF	48	79.0[a]	2.9

a. For blue crab, we used the LC50 from a 10% UV treatment as none of the indoor HEWAF tests produced reportable LC50.

2.4.2 Surface oil slick exposures

In addition to exposure to oil mixed into the water, organisms may also have been exposed to floating oil in the form of surface slicks or sheens. The Trustees also determined the toxicity of thin surface oil sheens (~ 1 µm) in the presence of varying levels of UV light (Morris et al., 2015a, 2015c). We assessed the mortality of biota exposed to the integrated average dose of UV light in the GoM over the course of the spill (1,550 mWs/cm^2 at 380 nm; Lay et al., 2015b). In the presence of this UV light, exposure to thin Slick A sheens result in high mortality rates of 85%, 89%, 100%, and 100% for red snapper (embryo), bay anchovy (embryo), speckled sea trout (embryo), and mysid shrimp (juvenile), respectively (Morris et al., 2015a, 2015c). We used these mortality estimates when exposing our representative species to the surface slick zone in our model. We averaged the estimates for red snapper, bay anchovy, and speckled sea trout and used a value of 91% mortality for our two fish species (bay anchovy and mahi-mahi). We used 100% mortality for our two invertebrate species, copepod and blue crab.

For the purposes of estimating injury to biota in the upper water column, we assumed that biota were exposed to surface slicks, as well as to entrained and dissolved oil beneath the slick. For estuarine areas, below-slick data were too sparse to characterize water concentrations (Travers et al., 2015); thus, for estuarine waters we assessed only toxicity related to exposure to surface oil slicks.

2.5 Mortality Estimates in Shelf and Offshore Areas

2.5.1 Fish egg model simulations

We used a Monte Carlo simulation approach (Robert and Casella, 1999) to estimate the exposure of fish eggs and invertebrates to water column concentrations of TPAH50. For fish eggs, we randomly selected an egg from the distribution of egg depths from the VertEgg model simulations (Wobus et al., 2015). We then selected an exposure concentration from the modeled distribution of TPAH50 values at that depth (Figure 4; Travers et al., 2015), accounting for the estimated 19% of samples below detection limits in the random sampling. Figure 5 shows a pseudorandom sample of 10,000 egg depths and TPAH50 concentrations generated by our Monte Carlo framework. For each randomly selected egg, we calculated a UV dose assuming average incident UV at the water surface (1,550 mWs/cm^2 for 380 nm wavelength), and an extinction coefficient of 0.06 m^{-1} (Lay et al., 2015b). We then used each combination of TPAH50 and UV to calculate the percent mortality, using the UV-adjusted dose-response curves for sensitive (bay anchovy) and less sensitive (mahi-mahi) embryos. This yielded a distribution of percent mortality for the full set of 10,000 randomly selected eggs.

To provide a check on the TPAH50 distribution model, we also conducted the Monte Carlo simulations by randomly sampling from the observed TPAH50 concentrations (a total of 378 samples), binned by depth. Because there were more data available in the upper bins, data were binned into 1-m bins for the upper 5 m, and then into 5-m bins from 5 to 20 m. After an egg was randomly selected, an observed TPAH50 concentration was selected within the depth bin for that egg. Use of the observed TPAH50 data rather than the modeled distribution of TPAH50 yielded similar estimates of mortality for eggs.

The assumption inherent in this approach is that once a PAH exposure concentration was "assigned" to each representative organism, the organism would theoretically move with the parcel of water that contained the "assigned" PAH concentration during the organism planktonic lifecycle. This assumption is reasonable given that surface oil slicks and planktonic organisms in the upper water column are subject to many of the same physical transport processes near the ocean surface. Therefore, the model does not explicitly invoke a duration of PAH exposure but assigns a probability of exposure to a water parcel with a certain PAH concentration. The only portion of the model that does have an explicit duration associated with it is the amount of UV light the organisms are exposed to at each depth, which is based on the integrated daily average UV light the GoM received during the spill (Lay et al., 2015a). As such our model implicitly assumes at least a one-day exposure to both PAH and UV, consistent with field toxicity tests (e.g., Lay et al., 2015a, 2015b).

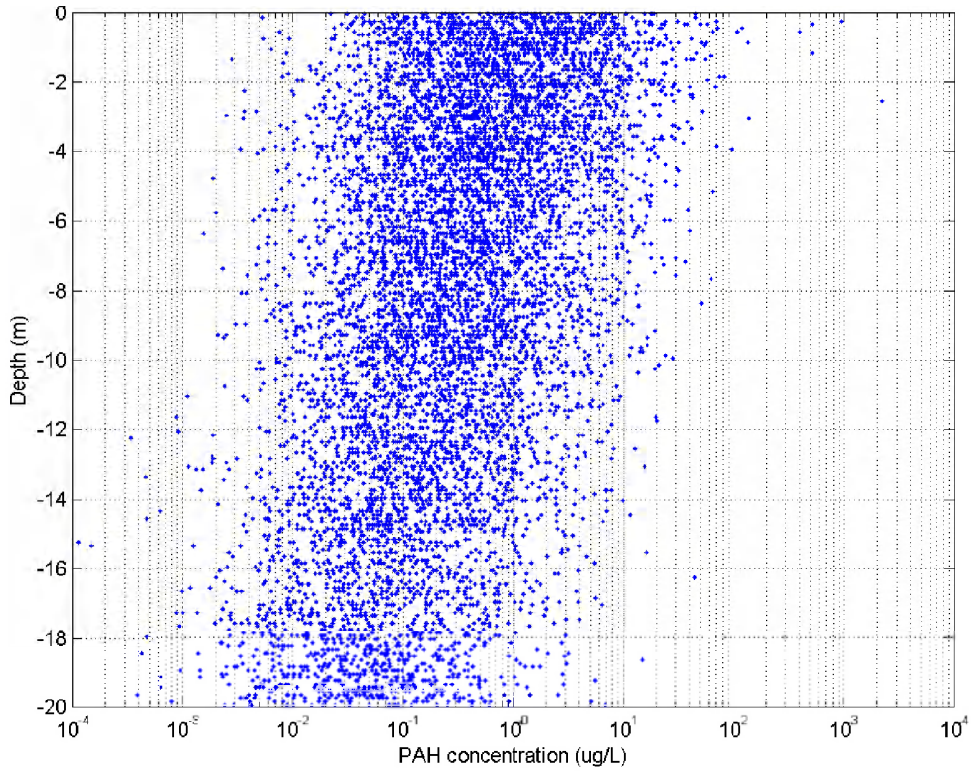

Figure 5. Example of 10,000 randomly selected depth-PAH combinations from the VertEgg and TPAH50 model fits.

In addition to exposure to oil entrained in the water column, we considered the mortality associated with exposure to the surface oil slick. For these evaluations, we assumed that all eggs and invertebrates within a threshold distance of the slick would have sufficient exposure to the slick that the slick toxicity test results, rather than the WAF exposure test results, would be the most appropriate toxicity metric to apply. Because we did not know the exact depth over which organisms might have been exposed to the surface slick in the offshore and shelf environments, we conducted a sensitivity analysis and varied the threshold distance between 0.1 and 1 m. For these sensitivity analyses, we varied the depth of the upper 1 m over which we applied surface slick toxicity results vs. WAF exposure results. Applying the WAF exposure toxicity results in the upper 1 m results in large estimated mortality because of the high estimated TPAH50 concentrations and UV light dose. As described above, application of the slick exposure tests also resulted in high mortality. Because application of both types of toxicity tests result in high mortality in the upper meter, we found that the assumed depth of influence of the surface oil slick over this range made almost no difference in the estimated mortality of fish embryos in the upper water column of offshore and shelf waters. Since the mortality results were insensitive to

this parameter choice, we selected a depth of 0.2 m for the simulations for consistency with the estuarine analysis.

2.5.2 Invertebrate model simulations

For invertebrates, we used a similar Monte Carlo approach as described for fish eggs. However, available data were insufficient to describe variability in the vertical distribution of invertebrates in the water column. Thus, for offshore and shelf areas, we assumed that invertebrates were uniformly distributed within the upper 20 m of the water column. We again selected exposure concentrations randomly from the distribution of water column TPAH50 values (Figure 4), but in contrast to the egg exposure model, this selection was not weighted by a higher proportion of organisms in the uppermost water column.

2.6 Mortality Estimates in Estuarine Waters

For the estuarine waters, the Trustees evaluated exposure only to the surface slick. Although PAHs were detected in water beneath or in the vicinity of the surface oil slicks, TPAH50 concentrations were generally low – at or below 0.6 µg/L. In addition, the estuarine waters generally contained high concentrations of sediment, and UV light does not penetrate deeply in turbid waters. In this analysis, oil slick toxicity was estimated only to 0.2 m, the depth where 10% of incident UV light remained, based on Barataria Bay light attenuation measurements (Lay et al., 2015b). To estimate mortality to fish and invertebrates in this 0.2-m interval, we used the average of the slick mortality at the surface (i.e., 100% of ambient UV) and mortality estimated at 0.2 m below the surface (i.e., 10% of ambient UV) for each of our three fish species and our invertebrate species for which we had surface slick UV toxicity data. The mortality at the surface was calculated using full-incident daily integrated UV estimates (1,550 mW-s/cm^2; Lay et al., 2015b), and the mortality at a depth of 0.2 m was estimated using 10% of the daily incident UV (155 mW-s/cm^2). The average mortality over the upper 0.2 m was calculated as an average of the calculated mortality at the surface and the calculated mortality at a depth of 0.2-m (Table 2).

2.6.1 Eggs and larval fish

For larval fish, the average mortality for less-sensitive fish (represented by bay anchovy) and sensitive fish (represented by red snapper) in the upper 0.2 m was 50% and 70%, respectively (Table 2; Morris et al., 2015a). The VertEgg model results indicated that 8.7% of the eggs were present in the upper 0.2 m. Thus, the estimated percent mortality for fish eggs was 4–6% in estuarine waters.

Table 2. Model estimates of mortality for fish and invertebrates exposed to a thin (~ 1 µm) surface sheen of Slick A oil and different amounts of UV light. Representing average UV light in the GoM during the DWH oil spill or 10% of average UV light.

			Modeled mortality[a] with UV light		
Species	**Test ID**	**Life stage**	**% mortality under 155 mW-s/cm^2**	**% mortality under 1,550[b] mW-s/cm^2**	**% average mortality**
Red snapper	962	Embryo	55	85	70
Bay anchovy	959	Embryo	10	89	50
Speckled sea trout	643	Embryo	25	100	63
Mysid shrimp	666	Juvenile	21	100	61

a. See Morris et al. (2015c) for details on surface slick UV toxicity modeling and toxicity testing results.
b. Average daily UV light (380 nm) in the GoM during the spill was 1,550 mW-s/cm^2 (Lay et al., 2015b).

2.6.2 Invertebrates

For invertebrates, we used an estimated mortality based on a surface slick/UV exposure using juvenile mysid shrimp (Morris et al., 2015c). The mysid shrimp tests showed 100% mortality at a UV of 1,550 mW-s/cm^2 and an estimated 21% mortality at a UV of 155 mW-s/cm^2. We assumed no mortality below 0.2 m. Thus the total mortality over the upper 0.2 m of the water column was 61% (Table 2). Using the 61% total mortality for the upper 0.2 m and no mortality below 0.2 m, and assuming the invertebrates were evenly distributed in the water column, we estimated that invertebrate mortality in estuarine waters (average depth of 2.5 m; see Wobus et al., 2015) was 5% of the total invertebrates present.

2.7 Results: Water Column Injury Metrics

2.7.1 Summary of estimated mortality in offshore, shelf, and estuarine waters

The estimated percent mortality for ELS fish ranged from 21% to 45%, compared with 4–6% for invertebrates in offshore/shelf areas (Table 3). The offshore/shelf values represent percent mortality estimates for only those biota present in the upper 20 m of the water column. The estuarine values were 4–6% mortality for ELS fish and 5% mortality for invertebrates (Table 3), representing the percent mortality for all biota in the water column, which is typically only a few meters in depth.

Table 3. Estimated percent mortality for biota exposed to floating and entrained oil during the DWH oil spill. Offshore/shelf values represent the percentage of biota present in the upper 20 m. Estuarine values represent the biota in the entire water column, with average depth of 2.5 m.

Category	Offshore/shelf	Estuarine
Eggs and larval fish		
Higher sensitivity	45%	6%
Lower sensitivity	21%	4%
Invertebrates		
Higher sensitivity	6%	5%
Lower sensitivity	4%	5%

2.7.2 Areal extent of surface oil

Based on the SAR analyses, oil was present on the surface of the Gulf from at least April 23, 2010 through August 11, 2015 (Appendix A). We estimated the maximum and average daily extent of oil in estuarine, shelf, and offshore waters (Table 4). In addition, we summed the estimated area of surface oil slicks for each day to provide an estimate of the total area of the Gulf affected. This estimate appears in units of area and time (km^2-days).[1]

Table 4. Summary of areas of the Gulf affected by surface oil slicks during the DWH oil spill

	Estuarine	Shelf (< 200-m depth)	Offshore (> 200-m depth)	All areas[a]
Maximum daily (km^2)	1,790	19,840	26,160	39,660
Average daily (km^2)	140	3,870	7,060	11,080
Total cumulative (km^2-days)	15,630	429,820	784,000	1,229,450

a. The maximum daily extent of surface oil for all water depths is not equal to the sum of the maximum oil extents in the estuarine, shelf, and offshore areas, because these maxima occurred on different dates.

1. A km^2-day is a compound unit that means one square kilometer for one day, in any combination of area and time. For example, 100,000 km^2-days could mean 1,000 km^2 for 100 days, 10,000 km^2 for 10 days, or 100,000 km^2 for 1 day.

2.7.3 Estimated volume of affected water

Using the estimated areal extent of surface oil and water chemistry data, we also estimated the volume of water affected by the surface oil slicks during the spill (Appendix B). As described above, we calculated the total areal extent of surface oil for each day that oil was present on the water, using areas obtained from SAR image analysis. For offshore and shelf waters, we multiplied the daily areal extent of surface oil by the estimated affected volume of water beneath the oil as described below.

In offshore and shelf waters, we used the vertical distribution of TPAH50 to estimate the depth of impacts from entrained and dissolved surface oil. Travers et al. (2015) used upper water column samples collected under surface oil with detectable TPAH50 concentrations to fit a linear regression model to estimate log(TPAH50) as a function of sample depth. Although we used dose-response curves and not a single threshold value to estimate mortality of biota, to estimate the volume of affected water, we needed to select a concentration. For these estimates, we selected a TPAH50 concentration of 0.5 µg/L, a concentration sufficient to cause adverse effects to sensitive biota in the presence of UV light (Morris et al., 2015c; Lay et al., 2015a). Using the linear regression relationship, the probability of water samples exceeding a TPAH50 concentration of 0.5 µg/L was 0.26 over the upper 20 m beneath the oil slick (Travers et al., 2015). We used the probability of exceeding this concentration, in conjunction with the extent of the oil slicks, to estimate a volume of injured water.

The daily maximum and average volume of upper mixed layer water exceeding 0.5 µg/L from April 23, 2010 to August 11, 2010 were 2.1×10^{11} m^3 and 5.7×10^{10} m^3, respectively (Table 5). Summing the daily volume that exceeded this TPAH50 concentration for each day of the spill resulted in 6.3×10^{12} m^3-days.[2]

Table 5. Estimated volume of water exceeding 0.5 µg/L from April 23, 2010 to August 11, 2010 in the upper mixed layer in offshore/shelf areas during the DWH oil spill

	Areal extent of floating oil in shelf and offshore waters	Volume of water exceeding 0.5 µg/L
Maximum daily	39,580 km^2	2.1×10^{11} m^3
Average daily	10,940 km^2	5.7×10^{10} m^3
Total cumulative	1,213,810 km^2-days	6.3×10^{12} m^3-days

2. A m^3-day is a compound unit that means one cubic meter for one day, in any combination of area and time. For example, 100,000 m^3-days could mean 1,000 m^3 for 100 days, 10,000 m^3 for 10 days, or 100,000 m^3 for 1 day.

To provide some context for this volume, we compared the volume of water exceeding 0.5 µg/L TPAH50 as the result of surface oil slicks during the DWH spill to the flow in the Mississippi River. The average annual discharge from the Mississippi River at New Orleans is 600,000 cfs (NPS, 2015), or 1.5 x 10^9 m^3/day. The estimated average daily average volume of the upper water column exceeding a TPAH50 of 0.5 µg/L during the DWH spill was 5.7 x 10^{10} m^3. Thus, the volume of water exceeding this concentration in the upper mixed layer was approximately 40 times the average daily discharge in the Mississippi River.

For estuarine waters, we estimated the volume of water affected by the surface slicks using the areal extent of the oil (Table 4), and an assumed depth of 0.2 m based on the penetration depth of UV light in these turbid waters (see Section 2.6). We estimate that the daily maximum and average volume of affected estuarine water was 3.6 x 10^8 m^3 and 3.1 x 10^7 m^3, respectively. In addition, the sum of the daily volumes of estuarine water affected by surface oil slicks is 3.1 x 10^9 m^3-days.

2.8 Summary

We evaluated three metrics of injury in the upper mixed layer of the water column resulting from the DWH spill: (1) mortality estimates for fish embryos and planktonic invertebrates, (2) the areal extent of surface oil slicks, and (3) the volume of water affected by the surface oil slicks. The estimated percent mortality for ELS fish ranged from 21% to 45%, compared with 4–6% for invertebrates in the upper 20 m of the water column in offshore/shelf areas. The estuarine values were 4–6% mortality for ELS fish and 5% mortality for invertebrates. Surface oil covered a daily maximum of 39,660 km^2 and an average of 11,080 km^2 of the surface of the Gulf. We estimate that the surface oil slicks affected a maximum daily volume of water of 2.1 x 10^{11} m^3, and an average daily volume of water of 5.7 x 10^{10} m^3. These metrics were used by the Trustees to assess injuries in the water column.

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A. Areal Extent of Oil during the *Deepwater Horizon* Oil Spill

Date	Areal extent of oil				
	Estuarine (km^2)	Shelf < 200 m depth (km^2)	Offshore > 200 m depth (km^2)	Shelf + offshore (km^2)	Total estuarine, shelf, and offshore (km^2)
4/23/2010	0	37	738	775	775
4/24/2010	0	*52*	*929*	*981*	981
4/25/2010	0	66	1,121	1,187	1,187
4/26/2010	0	4	2,267	2,271	2,271
4/27/2010	0	*101*	*4,019*	*4,120*	4,120
4/28/2010	0	*199*	*5,771*	*5,970*	5,970
4/29/2010	0	297	7,528	7,825	7,825
4/30/2010	0	*798*	*4,599*	*5,396*	5,396
5/1/2010	0	1,298	1,669	2,967	2,967
5/2/2010	0	921	2,488	3,409	3,409
5/3/2010	13	4,042	5,253	9,295	9,308
5/4/2010	46	1,085	3,807	4,892	4,939
5/5/2010	372	9,000	6,805	15,804	16,176
5/6/2010	*250*	*6,769*	*6,384*	*13,153*	13,403
5/7/2010	*128*	*4,539*	*5,963*	*10,502*	10,630
5/8/2010	6	2,303	5,541	7,844	7,849
5/9/2010	2	55	3,493	3,548	3,550
5/10/2010	20	105	6,892	6,997	7,017
5/11/2010	129	305	9,393	9,698	9,827
5/12/2010	31	742	8,536	9,278	9,309
5/13/2010	3	1,140	7,393	8,534	8,536
5/14/2010	18	2,294	7,064	9,358	9,376
5/15/2010	61	2,341	7,062	9,403	9,464
5/16/2010	127	4,232	11,948	16,181	16,307
5/17/2010	64	4,683	17,784	22,467	22,531
5/18/2010	68	3,334	19,521	22,856	22,924
5/19/2010	28	8,001	19,974	27,975	28,003
5/20/2010	111	5,049	10,653	15,702	15,813

Date	Areal extent of oil				
	Estuarine (km^2)	Shelf < 200 m depth (km^2)	Offshore > 200 m depth (km^2)	Shelf + offshore (km^2)	Total estuarine, shelf, and offshore (km^2)
5/21/2010	172	5,338	12,095	17,433	17,605
5/22/2010	232	6,681	13,363	20,045	20,277
5/23/2010	7	*7,870*	*13,085*	*20,955*	20,962
5/24/2010	1,788	9,058	12,807	21,865	23,654
5/25/2010	87	8,755	17,947	26,702	26,789
5/26/2010	10	1,740	6,037	7,777	7,787
5/27/2010	170	5,983	14,544	20,527	20,697
5/28/2010	38	5,633	13,709	19,341	19,379
5/29/2010	*30*	4,585	17,396	21,981	22,011
5/30/2010	*22*	474	393	868	890
5/31/2010	*15*	3,733	19,732	23,465	23,479
6/1/2010	13	3,611	12,974	16,584	16,597
6/2/2010	*82*	1,501	10,730	12,231	12,313
6/3/2010	151	4,255	11,725	15,980	16,131
6/4/2010	156	554	1,058	1,612	1,768
6/5/2010	0	1,469	3,088	4,557	4,557
6/6/2010	137	1,900	5,986	7,886	8,023
6/7/2010	*141*	167	18	185	326
6/8/2010	144	4,710	21,847	26,557	26,702
6/9/2010	130	3,018	15,171	18,189	18,319
6/10/2010	265	199	1,287	1,486	1,751
6/11/2010	136	5,454	11,241	16,695	16,831
6/12/2010	105	13,120	14,644	27,764	27,869
6/13/2010	*136*	13,912	21,171	35,083	35,219
6/14/2010	*168*	*14,210*	*21,302*	*35,512*	35,680
6/15/2010	199	14,508	21,433	35,941	36,140
6/16/2010	*174*	13,130	17,193	30,323	30,496
6/17/2010	148	*13,229*	*20,177*	*33,406*	33,554
6/18/2010	*113*	*13,328*	*23,162*	*36,490*	36,603
6/19/2010	78	13,428	26,155	39,583	39,661
6/20/2010	134	5,599	18,253	23,852	23,986
6/21/2010	*105*	8,904	18,952	27,856	27,962

Date	Areal extent of oil				
	Estuarine (km^2)	Shelf < 200 m depth (km^2)	Offshore > 200 m depth (km^2)	Shelf + offshore (km^2)	Total estuarine, shelf, and offshore (km^2)
6/22/2010	76	9,617	14,867	24,484	24,560
6/23/2010	26	7,334	6,904	14,237	14,264
6/24/2010	*94*	7,146	1,591	8,737	8,832
6/25/2010	163	11,508	5,675	17,184	17,346
6/26/2010	134	19,839	10,800	30,638	30,772
6/27/2010	549	15,247	3,725	18,972	19,521
6/28/2010	449	*10,638*	*2,489*	*13,127*	13,576
6/29/2010	298	*6,029*	*1,252*	*7,281*	7,579
6/30/2010	293	1,406	12	1,418	1,711
7/1/2010	554	6,895	1,444	8,339	8,893
7/2/2010	960	16,012	7,691	23,703	24,663
7/3/2010	147	1,925	2,668	4,592	4,740
7/4/2010	*313*	608	3,382	3,991	4,304
7/5/2010	480	901	3,315	4,216	4,696
7/6/2010	*282*	1,421	2,617	4,039	4,321
7/7/2010	85	1,098	2,303	3,401	3,486
7/8/2010	240	2,029	3,146	5,176	5,416
7/9/2010	1,173	1,501	7,333	8,834	10,007
7/10/2010	71	351	14	365	436
7/11/2010	41	677	5,000	5,677	5,718
7/12/2010	19	44	3,132	3,176	3,195
7/13/2010	*20*	*29*	*5,260*	*5,290*	5,309
7/14/2010	*20*	15	7,388	7,403	7,423
7/15/2010	*21*	*15*	*6,014*	*6,028*	6,049
7/16/2010	*22*	14	4,639	4,654	4,675
7/17/2010	*22*	0	5,247	5,247	5,269
7/18/2010	*20*	232	8,131	8,363	8,383
7/19/2010	*17*	1,424	8,598	10,022	10,039
7/20/2010	*14*	2,296	8,868	11,164	11,179
7/21/2010	12	2,341	446	2,788	2,799
7/22/2010	1	*4,381*	*862*	*5,243*	5,243
7/23/2010	*23*	*6,420*	*1,277*	*7,698*	7,721

Date	Areal extent of oil				
	Estuarine (km^2)	Shelf < 200 m depth (km^2)	Offshore > 200 m depth (km^2)	Shelf + offshore (km^2)	Total estuarine, shelf, and offshore (km^2)
7/24/2010	*46*	8,466	1,694	10,160	10,206
7/25/2010	69	2,196	1,797	3,993	4,062
7/26/2010	133	1,536	468	2,004	2,137
7/27/2010	98	949	28	977	1,074
7/28/2010	3	*853*	*73*	*927*	930
7/29/2010	220	*758*	*119*	*877*	1,096
7/30/2010	159	663	164	827	985
7/31/2010	*147*	*513*	*146*	*658*	805
8/1/2010	136	362	127	490	625
8/2/2010	648	131	0	131	779
8/3/2010	*339*	*66*	*0*	*66*	404
8/4/2010	29	0	0	0	29
8/5/2010	124	25	0	25	149
8/6/2010	38	21	0	21	59
8/7/2010	21	*16*	*4*	*20*	40
8/8/2010	5	*11*	*8*	*19*	24
8/9/2010	7	6	12	18	24
8/10/2010	*5*	0	0	0	5
8/11/2010	4	1	0	1	5
Grand total (km^2-days)	15,633	429,820	784,000	1,213,810	1,229,453
Max (km^2)	1,788	19,839	26,155	39,583	39,661
Average (km^2)	155	3,872	7,063	10,935	11,076
Grand total (mi^2-days)	6,036	165,954	302,704	468,654	474,694
Max (mi^2)	690	7,660	10,099	15,283	15,313
Average (mi^2)	60	1,495	2,727	4,222	4,277

Notes: Values in italics indicate SAR image not available on date; values estimated by interpolation from previous and following days.
Totals may not sum due to rounding.

B. Volume of Water Affected by Surface Oil during the *Deepwater Horizon* Oil Spill

Date	Estuarine (m^3)	Offshore and shelf (m^3)	Total estuarine, shelf, and offshore (m^3)
4/23/2010	0.0E+00	4.0E+09	4.0E+09
4/24/2010	0.0E+00	5.1E+09	5.1E+09
4/25/2010	0.0E+00	6.2E+09	6.2E+09
4/26/2010	0.0E+00	1.2E+10	1.2E+10
4/27/2010	0.0E+00	2.1E+10	2.1E+10
4/28/2010	0.0E+00	3.1E+10	3.1E+10
4/29/2010	0.0E+00	4.1E+10	4.1E+10
4/30/2010	0.0E+00	2.8E+10	2.8E+10
5/1/2010	0.0E+00	1.5E+10	1.5E+10
5/2/2010	0.0E+00	1.8E+10	1.8E+10
5/3/2010	2.6E+06	4.8E+10	4.8E+10
5/4/2010	9.3E+06	2.5E+10	2.5E+10
5/5/2010	7.4E+07	8.2E+10	8.2E+10
5/6/2010	5.0E+07	6.8E+10	6.8E+10
5/7/2010	2.6E+07	5.5E+10	5.5E+10
5/8/2010	1.1E+06	4.1E+10	4.1E+10
5/9/2010	4.9E+05	1.8E+10	1.8E+10
5/10/2010	4.0E+06	3.6E+10	3.6E+10
5/11/2010	2.6E+07	5.0E+10	5.0E+10
5/12/2010	6.2E+06	4.8E+10	4.8E+10
5/13/2010	5.3E+05	4.4E+10	4.4E+10
5/14/2010	3.7E+06	4.9E+10	4.9E+10
5/15/2010	1.2E+07	4.9E+10	4.9E+10
5/16/2010	2.5E+07	8.4E+10	8.4E+10
5/17/2010	1.3E+07	1.2E+11	1.2E+11
5/18/2010	1.4E+07	1.2E+11	1.2E+11
5/19/2010	5.6E+06	1.5E+11	1.5E+11
5/20/2010	2.2E+07	8.2E+10	8.2E+10
5/21/2010	3.4E+07	9.1E+10	9.1E+10

Date	Estuarine (m^3)	Offshore and shelf (m^3)	Total estuarine, shelf, and offshore (m^3)
5/22/2010	4.6E+07	1.0E+11	1.0E+11
5/23/2010	1.4E+06	1.1E+11	1.1E+11
5/24/2010	3.6E+08	1.1E+11	1.1E+11
5/25/2010	1.7E+07	1.4E+11	1.4E+11
5/26/2010	2.1E+06	4.0E+10	4.0E+10
5/27/2010	3.4E+07	1.1E+11	1.1E+11
5/28/2010	7.6E+06	1.0E+11	1.0E+11
5/29/2010	6.0E+06	1.1E+11	1.1E+11
5/30/2010	4.5E+06	4.5E+09	4.5E+09
5/31/2010	2.9E+06	1.2E+11	1.2E+11
6/1/2010	2.6E+06	8.6E+10	8.6E+10
6/2/2010	1.6E+07	6.4E+10	6.4E+10
6/3/2010	3.0E+07	8.3E+10	8.3E+10
6/4/2010	3.1E+07	8.4E+09	8.4E+09
6/5/2010	2.5E+04	2.4E+10	2.4E+10
6/6/2010	2.7E+07	4.1E+10	4.1E+10
6/7/2010	2.8E+07	9.6E+08	9.9E+08
6/8/2010	2.9E+07	1.4E+11	1.4E+11
6/9/2010	2.6E+07	9.5E+10	9.5E+10
6/10/2010	5.3E+07	7.7E+09	7.8E+09
6/11/2010	2.7E+07	8.7E+10	8.7E+10
6/12/2010	2.1E+07	1.4E+11	1.4E+11
6/13/2010	2.7E+07	1.8E+11	1.8E+11
6/14/2010	3.4E+07	1.8E+11	1.8E+11
6/15/2010	4.0E+07	1.9E+11	1.9E+11
6/16/2010	3.5E+07	1.6E+11	1.6E+11
6/17/2010	3.0E+07	1.7E+11	1.7E+11
6/18/2010	2.3E+07	1.9E+11	1.9E+11
6/19/2010	1.6E+07	2.1E+11	2.1E+11
6/20/2010	2.7E+07	1.2E+11	1.2E+11
6/21/2010	2.1E+07	1.4E+11	1.4E+11
6/22/2010	1.5E+07	1.3E+11	1.3E+11
6/23/2010	5.3E+06	7.4E+10	7.4E+10

Date	Estuarine (m^3)	Offshore and shelf (m^3)	Total estuarine, shelf, and offshore (m^3)
6/24/2010	1.9E+07	4.5E+10	4.5E+10
6/25/2010	3.3E+07	8.9E+10	8.9E+10
6/26/2010	2.7E+07	1.6E+11	1.6E+11
6/27/2010	1.1E+08	9.9E+10	9.9E+10
6/28/2010	9.0E+07	6.8E+10	6.8E+10
6/29/2010	6.0E+07	3.8E+10	3.8E+10
6/30/2010	5.9E+07	7.4E+09	7.4E+09
7/1/2010	1.1E+08	4.3E+10	4.3E+10
7/2/2010	1.9E+08	1.2E+11	1.2E+11
7/3/2010	2.9E+07	2.4E+10	2.4E+10
7/4/2010	6.3E+07	2.1E+10	2.1E+10
7/5/2010	9.6E+07	2.2E+10	2.2E+10
7/6/2010	5.6E+07	2.1E+10	2.1E+10
7/7/2010	1.7E+07	1.8E+10	1.8E+10
7/8/2010	4.8E+07	2.7E+10	2.7E+10
7/9/2010	2.3E+08	4.6E+10	4.6E+10
7/10/2010	1.4E+07	1.9E+09	1.9E+09
7/11/2010	8.3E+06	3.0E+10	3.0E+10
7/12/2010	3.8E+06	1.7E+10	1.7E+10
7/13/2010	3.9E+06	2.8E+10	2.8E+10
7/14/2010	4.1E+06	3.8E+10	3.9E+10
7/15/2010	4.2E+06	3.1E+10	3.1E+10
7/16/2010	4.3E+06	2.4E+10	2.4E+10
7/17/2010	4.5E+06	2.7E+10	2.7E+10
7/18/2010	3.9E+06	4.3E+10	4.3E+10
7/19/2010	3.4E+06	5.2E+10	5.2E+10
7/20/2010	2.8E+06	5.8E+10	5.8E+10
7/21/2010	2.3E+06	1.4E+10	1.4E+10
7/22/2010	1.3E+05	2.7E+10	2.7E+10
7/23/2010	4.7E+06	4.0E+10	4.0E+10
7/24/2010	9.2E+06	5.3E+10	5.3E+10
7/25/2010	1.4E+07	2.1E+10	2.1E+10
7/26/2010	2.7E+07	1.0E+10	1.0E+10

Date	Estuarine (m^3)	Offshore and shelf (m^3)	Total estuarine, shelf, and offshore (m^3)
7/27/2010	2.0E+07	5.1E+09	5.1E+09
7/28/2010	5.8E+05	4.8E+09	4.8E+09
7/29/2010	4.4E+07	4.6E+09	4.6E+09
7/30/2010	3.2E+07	4.3E+09	4.3E+09
7/31/2010	2.9E+07	3.4E+09	3.5E+09
8/1/2010	2.7E+07	2.5E+09	2.6E+09
8/2/2010	1.3E+08	6.8E+08	8.1E+08
8/3/2010	6.8E+07	3.4E+08	4.1E+08
8/4/2010	5.8E+06	0.0E+00	5.8E+06
8/5/2010	2.5E+07	1.3E+08	1.6E+08
8/6/2010	7.7E+06	1.1E+08	1.1E+08
8/7/2010	4.1E+06	1.0E+08	1.1E+08
8/8/2010	1.1E+06	9.6E+07	9.8E+07
8/9/2010	1.3E+06	9.1E+07	9.3E+07
8/10/2010	1.0E+06	0.0E+00	1.0E+06
8/11/2010	7.3E+05	6.3E+06	7.0E+06
Cumulative total (m^3-days)	3.1E+09	6.3E+12	6.3E+12
Max (m^3)	3.6E+08	2.1E+11	2.1E+11
Average (m^3)	3.1E+07	5.7E+10	5.7E+10
Cumulative total (gallon-days)	8.3E+11	1.7E+15	1.7E+15
Max (gallons)	9.4E+10	5.4E+13	5.4E+13
Average (gallons)	8.2E+09	1.5E+13	1.5E+13
Note: Totals may not sum due to rounding.			