

Graphical Exploration of the Deep-Water Horizon Oil Spill

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1. Introduction

April 20th, 2010 marked the beginning of the largest and worst oil spill in the history of off-shore drilling. Following an explosion in the Deep-Water Horizon drilling rig and failure of all emergency systems, crude oil began to gush into the ocean. After an estimated 4.9 million barrels of oil spilled into the sea, the leak was finally stopped on July 15th of 2010 when the well head was capped. The completion of the relief well took until September 19, 2010. The immediate impact of the oil spill on people and wildlife alike was overwhelming and can still be felt. The oil destroyed many habitats for birds, turtles, and other marine wildlife. Waters had to be closed for fishing, affecting the livelihood of the people that depended on the fishing industry. Longterm effects are certain. It is of course impossible to do an analysis that can reflect the breadth and complexity of the effects of the oil spill. However, based on data provided by government sources we want to graphically demonstrate the impact of the spill on wildlife, measured salinity - which has a major influence in determining oceanic flow, and environmental pollution through chemicals found in oil, in particular Polycyclic Aromatic Hydrocarbons (PAHs).

1.1. Tools used

R (R Development Core Team, 2011), `ggplot2` (Wickham, 2009), `RgoogleMaps` (Loecher, 2011), link between `ggplot2` and `RgoogleMaps` provided by Kahle (2010) as part of his entry in the `ggplot2` competition.

1.2. Structure of this paper

Animal Sightings
Chemicals
Salinity

2. Graphical Exploration

2.1. Animal Sightings

One of the visually most impressive and very emotional effects of any oil spill might be the pictures of oiled beaches littered with the washed-up bodies of oil-blackened animals. Counts for animal sightings, both alive and dead, are collected by the local Departments of Natural Resources and National Agencies. For the Data Expo 2011 Challenge we had access to data from the National Marine Sanctuary, the Office of

Variable	Description
Class	type of animal found: Birds (5,552), Whales and Dolphins (98), Sea Turtles (546)
Species	species of animal
Latitude	latitude in degrees
Longitude	longitude in degrees
Alive	condition of animal: Alive (2,197), Dead (6,196)
Observation Date	date of observation 'mm-dd-yyyy'.

Table 1: Animal Sightings between April 26, 2010 and October 18, 2010, source: Avian Observations from US Fish and Wildlife (Southeast Region), Marine Mammal Observations reported by the National Marine Sanctuary, NOAA, and the Office of Protected Resources, NOAA.

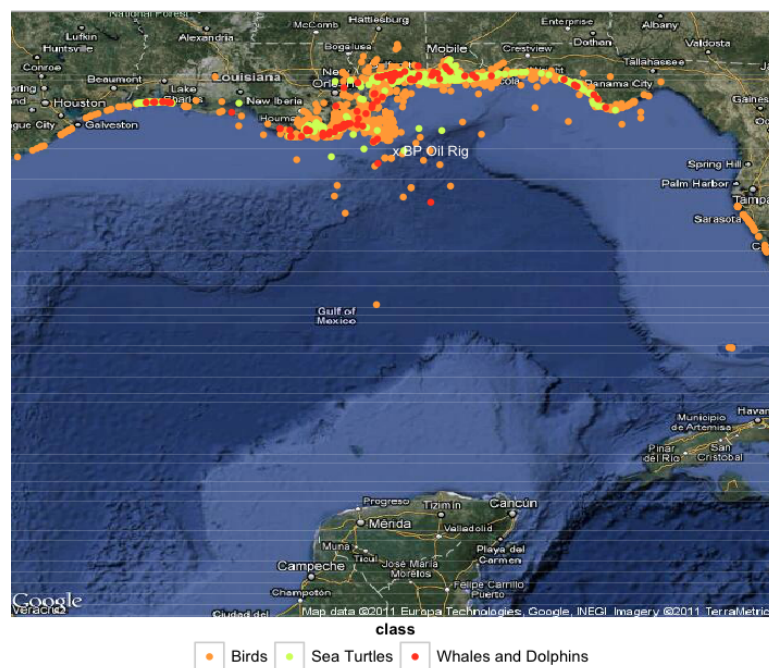


Figure 1: Affected area: the graphic shows a satellite map of some of the area directly affected by the oil spill. The dots on top show locations of dead animal sightings.

Protected Resources as well as the Bureau US Fish and Wildlife. Table?? gives an overview of the variables that we used for our graphical exploration.

Figure 1 shows a satellite map, overlaid by a scatterplot indicating locations of animal sightings. Most of the sightings follow the coastline - which is not surprising, since that is where we have the easiest access to make these kind of observations. This already points us to several problems with an interpretation of the data: firstly, the data is purely observational - records are only available since the oil spill, but not before, reducing our conclusions to a qualitative nature. An additional complication is the selection bias that we are facing, since some of the areas presumably impacted by the oil spill are less accessible to observation than others. Furthermore, locations of dead animals sightings are affected by currents. It would be very wrong to interpret beaches as particularly dangerous because of the many sightings of dead animals. Instead, we can draw comparisons on a larger scale by comparing coastal regions and use the number of dead animals as an indicator of the effect on a particular region. We have to be aware that we are also dealing with a large percentage of unknowns: an unknown number of animals will have decayed or sunk to the seabed before being washed up on the beach, thereby going unnoticed and unreported.

With those caveats in mind, we can still tell from the satellite map in figure 1 that the highest concentration of dead animals were found along the shores of Louisiana and Mississippi, closest to the oil rig. Each of the orange dots corresponds to one dead bird, yellow dots indicate dead sea turtle sightings, and red dots indicate large mammals, such as whales and dolphins. Overall a total of 6,196 animals were reported dead during a six month period.

Birds, sea turtles, and dolphins and whales had unique death patterns during the data collection period as Figure 2 illustrates. The figure at the top shows a cumulative death rate for each species over time. Birds responded later to the disaster than sea turtles, whales and dolphins. Birds had a relatively low death rate from May to July and then the rate began to increase. Sea turtles and dolphins and whales, on the other hand, had the highest death rates from May to July and from there it began to flatten out. These patterns are re-enforced in the figure at the bottom, which shows daily death counts for each class of animal. For sea turtles, dolphins, and whales, the highest death counts per day occurred mainly in the earlier weeks and then decreased over time. The majority of dead bird findings occurred later in time and their death counts per day began to climb rapidly around July. After the leak was stopped, on July 15th, the number of daily deaths shows a high variability until it begins to decrease by mid-September. For sea turtles, also, stopping the leak seems to have the most profound impact on reducing the daily death counts.

Four species of sea turtles were found and identified during the data collection period, all of which are considered to be either threatened or endangered. These species are: Kemp's ridley, Hawksbill Sea Turtle, Green Sea Turtle, and Loggerhead Sea Turtle. Figure 3 shows when and where these turtles were found and whether they were living or dead. Most dead turtles, of all species, were found along the shoreline. Most turtles that were found alive were found off the coast. There were two main areas on the coasts of Louisiana and Florida in which the bulk of live sea turtles were found. This is most evident among the Green Sea Turtle and Kemp's ridley. Very

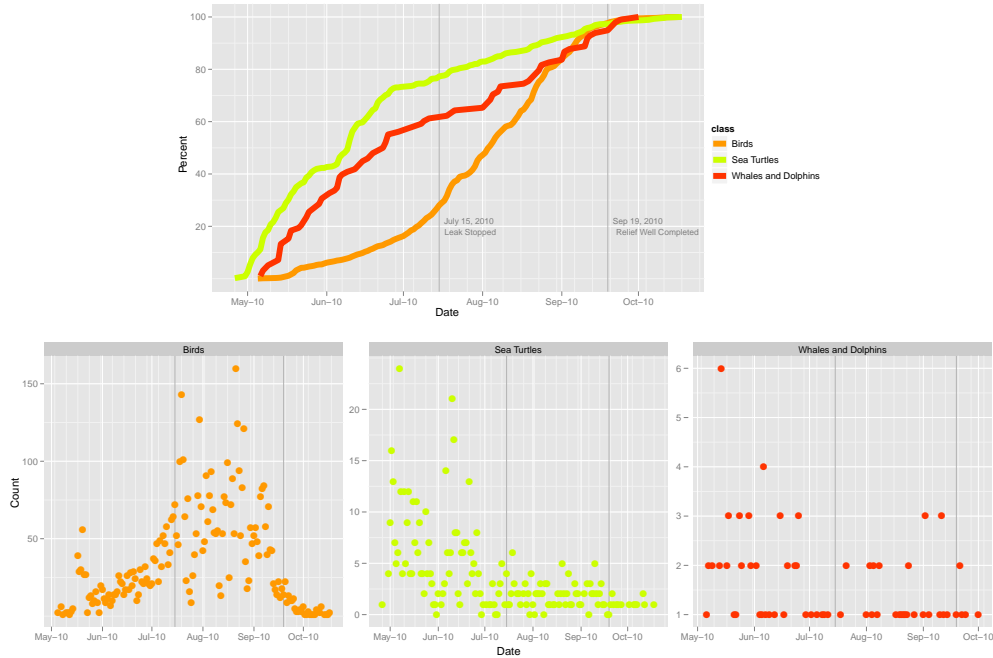


Figure 2: Cumulative animal death rates by class (top) and absolute number of dead animal sightings (bottom) between April and October 2010.

few turtles were found after September. The species with the greatest number of casualties found was Kemp’s ridley, an endangered species which lives primarily in the Gulf of Mexico. It is more common for Kemp’s ridley sea turtles to be present in the northern part of the Gulf of Mexico during June, July, and August. Female Kemp’s ridleys, like other sea turtles, nest between May and July and lay their eggs on various beaches of the Gulf of Mexico Office of Protected Resources (2011). From this information, we can understand that there were more turtles in the area during the months after the oil spill occurred, and thus more sea turtles to be found. After August, however, it would be natural for these turtles to begin to leave the area and head south.

2.2. Chemicals

Various chemicals were sampled in the Gulf of Mexico during the months following the oil spill. This analysis focuses on Polycyclic Aromatic Hydrocarbons firstly because of their direct relationship with oil and secondly because of their toxicity to wildlife. Polycyclic Aromatic Hydrocarbons, or PAHs, are semi-volatile organic substances which come mainly from oil and the burning of oil. However, they can also come exhaust and from the burning of gas, coal, garbage and other organic substances (Agency, 2010). Many of these substances are considered carcinogenic, mutagenic, and teratogenic and all are considered harmful to the health of living organisms. New information on each PAH substance was found from the EPA website (Agency, 2010) and put into the data set for this analysis. In order to do a proper analysis on the

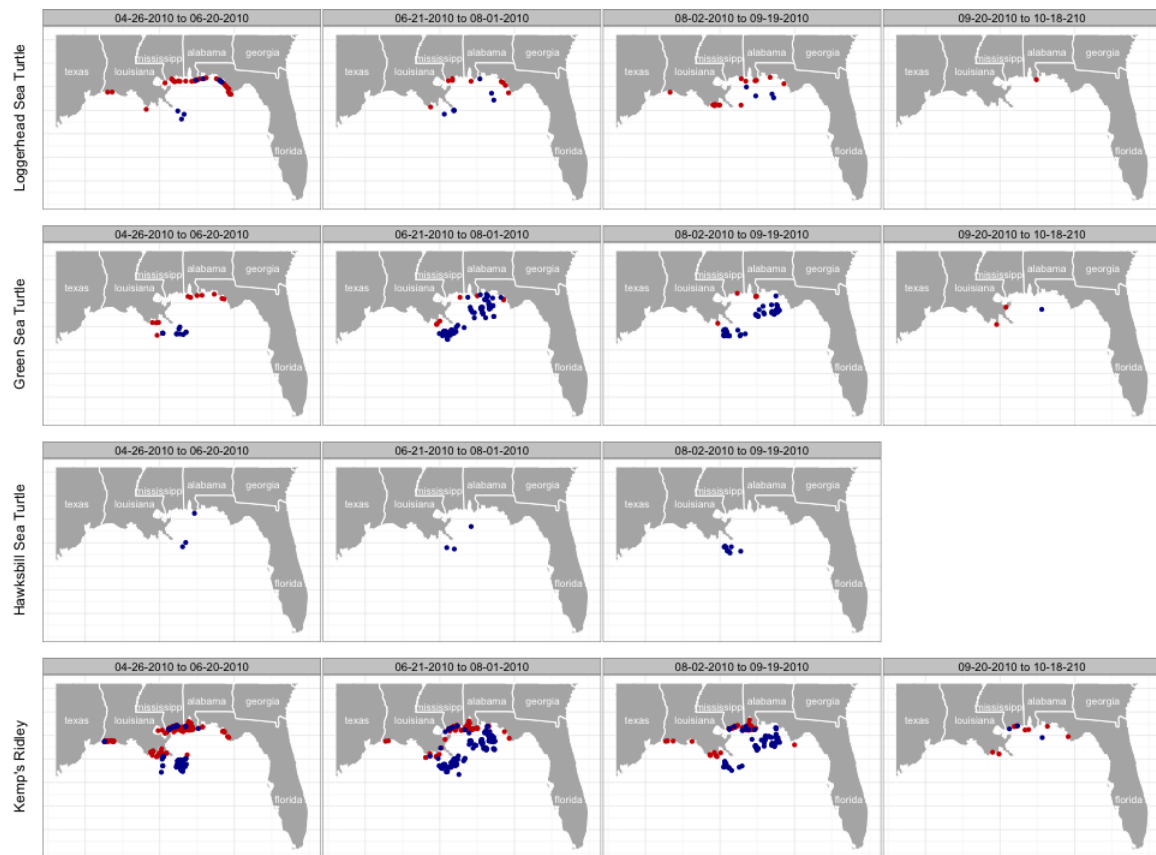


Figure 3: Four species of endangered or critically endangered sea turtles observed in the Gulf of Mexico from April 26th to October 18th 2010. Blue dots indicate turtles found alive; red dots indicate those found dead.

Variable	Description
Substance	Polycyclic Aromatic Hydrocarbon (PAH) substance
Date	date of observation.
Latitude	latitude in degrees.
Longitude	longitude in degrees.
Result	measured amount
Unit	unit of measurement: ug/L for water, ug/k for sediment.
Danger Level*	health effects: carcinogenic (23,201) or other health effects(3640).
Alkylation Multiplier**	values for calculations
Acute Potency Divisor**	values for calculations
Chronic Potency Divisor**	values for calculations

Table 2: Water and sediment chemistry data of petrochemical products, sampled near the coastline in the months after the oil spill, source: US Environmental Protection Agency.

*added to data set according to Agency

**added to data set according to Dave Mount (2010)

existence of these chemicals after the spill and how they may have effected life in the Gulf of Mexico it was necessary to put the measurements into an interpretable form. We followed the approach by Dave Mount (2010): measurements of the PAHs at unique locations will be looked at in terms of their acute and chronic potency. An area is considered at a chronic level when the amount of harmful substances is thought to bring harmful effects over a long period of time. An area is considered at an acute level when the amount of harmful substances rapidly induces a negative effect in an organism. The following describes the process in which we could analyze these PAHs in terms of their acute and chronic levels.

Each PAH substance has a unique acute and chronic potency divisor which are used to find the acute and chronic potency ratio, respectively. The potency divisors, which are used in the calculations, can be thought of as the amount of the substance that can be considered dangerous by itself. So, each measured amount of a substance is divided by the chronic and acute potency divisors so that, at each location, we have a ratio of the danger. For surface water and sediment samples alike, these ratios are additive and each substances' contribution must be summed up for each unique location in order to determine the complete effect. The following formulas show how we attained the chronic and acute benchmark values for water. After all of this was done, several areas along the beaches of the Gulf of Mexico were found to be at a chronic or acute level.

Water

$$\begin{aligned}
 \text{ChronicBenchmarkValue} &= \sum \frac{\text{AlkylationMultiplier} \times \text{MeasuredAmountof Substance(ug/L)}}{\text{ChronicPotencyDivisor}} \\
 \text{AcuteBenchmarkValue} &= \sum \frac{\text{AlkylationMultiplier} \times \text{MeasuredAmountof Substance(ug/L)}}{\text{AcutePotencyDivisor}}
 \end{aligned}$$

For substances measured in sediment, the amount of organic carbon for that area must be used to find the acute and chronic potency ratios. Taking the organic carbon into consideration is important for sediment samples because, when it is present in the sediment, the PAHs bind to it, thus making the PAHs less toxic. Organic carbon, like any other substance, was measured at each location. These concentrations of organic carbon at each unique location were put into a separate data set. Then, the organic carbon data set and the PAH sediment data set could be horizontally merged by unique combinations of Latitude and Longitude. This is done so that each measured concentration of a PAH substance has an accurate corresponding organic carbon measurement. The following formulas show how we attained the chronic and acute benchmark values for sediment.

Sediment

$$ChronicBenchmarkValue = \sum \frac{\left(\frac{MeasuredAmountofSubstance(ug/kg)}{OrganicCarbon} \right) \times AlkylationMultiplier}{ChronicPotencyDivisor}$$

$$AcuteBenchmarkValue = \sum \frac{\left(\frac{MeasuredAmountofSubstance(ug/kg)}{OrganicCarbon} \right) \times AlkylationMultiplier}{AcutePotencyDivisor}$$

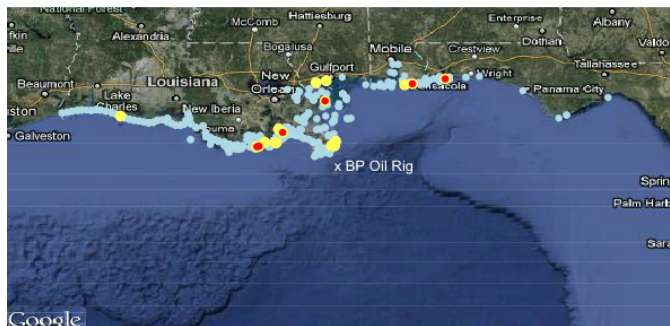


Figure 4: Map showing chronic and acute levels of Polycyclic Aromatic Hydrocarbons: Yellow dots represent those considered at a chronic level, red dots represent those considered at an acute level. Light blue dots indicate all samples. Most dangerous area seems to be around the outermost shore of Louisiana as there are many points which had PAH levels at or above chronic or acute benchmarks.

Figure 4 shows areas which meet or exceed the chronic and acute benchmarks. The yellow dots represent areas which meet or exceed the chronic benchmark and the red dots represent areas which meet or exceed the acute benchmark. The light blue dots indicate all areas which were tested. For this graphic, average values of each substance for each unique location were used. This way, there is exactly one measurement of each substance at each location. There were several areas which had dangerous levels of these PAH substances. Particularly along the outer coast of Louisiana, many of the observed PAH values exceeded the benchmarks. This is the area which may have received the most direct contact with the oil.

Figure 5 shows the log of the acute potency ratios not equal to 0 for measurements taken from May 2010 to August 2010. The log was taken so that we could more easily see the variation, as many of the samples were near 0. Some measurements of PAH substances exceeded the acute potency ratio alone, meaning that, even if there were

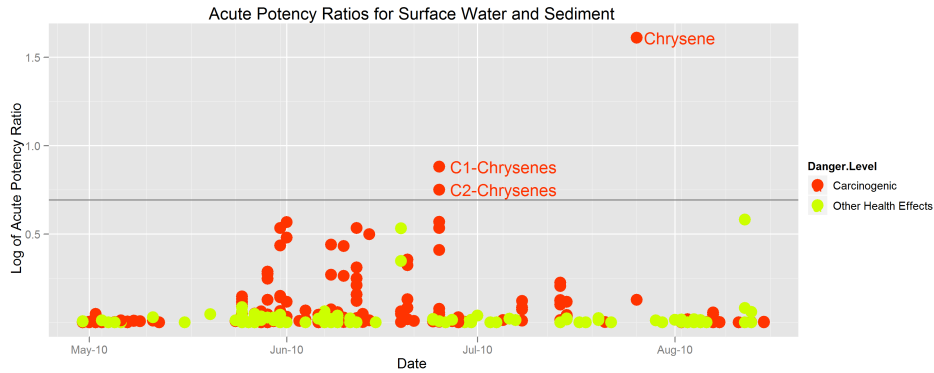


Figure 5: Timeline of logarithm of acute potency ratios. Points are colored by the substance’s effect on health. There is a period of time between June and July in which the acute value is heightened. Points which alone exceed the acute benchmark are labeled with the name of the substance.

Variable	Description
Date	date of observation.
Latitude	latitude in degrees
Longitude	longitude in degrees.
Depth	depth of measurement in feet
Salinity	amount of salinity in mg/l
Type	type of measuring device: Boat (24,381), Float (10,332), Glider (368,563)

Table 3: , source: XXX

no other PAH substances in the area, that one substance was enough to be acutely dangerous. These three acutely dangerous measurements are labeled on the timeline as C1-Chrysenes, C2-Chrysenes, and Chrysene. The Chrysene family is considered a carcinogenic substance. There seems to be a period of time between June and July in which the measurements of these PAH substance had higher values than during the rest of the time.

2.3. Salinity

Boats, floats, and gliders recorded salinity, temperature, and depth measurements at various locations in the Gulf of Mexico. The floats tended to stay in the deeper water while the boats and the gliders were free to go all around the gulf. You can see the patterns of these three measuring methods in Figure 6. Each measuring device would take measurements at the surface and then take measurements at various depths at each location.

In Figure 7 you can see all salinity measurements over the data collection period. In both the left and right graphic, the points are color coordinated by time. The right graphic shows only points where salinity levels are below 34 mg/l. The vast majority of the salinity measurements stayed within set boundaries. Other points varied from

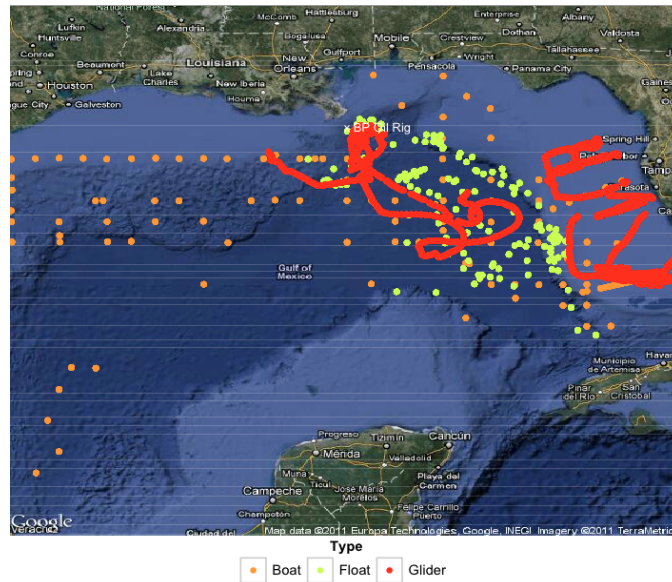


Figure 6: Paths of Boats, Floats, and Gliders.

the rest and seemed to be unusually low. In the right graphic of Figure 7 you can see when and where these unusual values occurred. The highest concentration of these points is found near the rig during June and July.

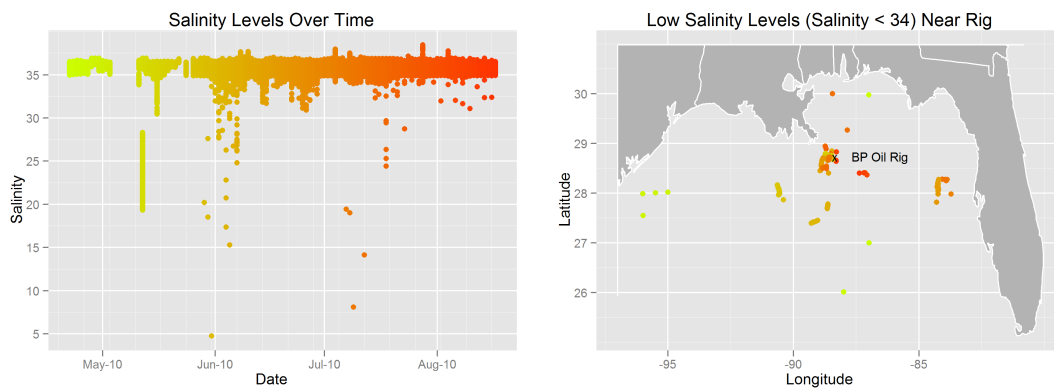


Figure 7: Salinity measurements: over time (left) and by location (right); Salinity measurements only rarely fall below 34 mg/l. In the months after the start of the oil spill salinity frequently drops below 34 mg/l. For later weeks this happens in particular in locations close to the oil rig.

Depth and salinity form a close relationship as you can see in Figure 8. Normally, salinity levels would stay between 38 and 34 mg/l. This trend was violated for many measurements taken near the surface but then resumed normal measurements at greater depths. There were also two measurements taken by a boat which do not follow the normal relationship. The surface water measurement was far below normal observations and from there salinity dropped rapidly with depth.

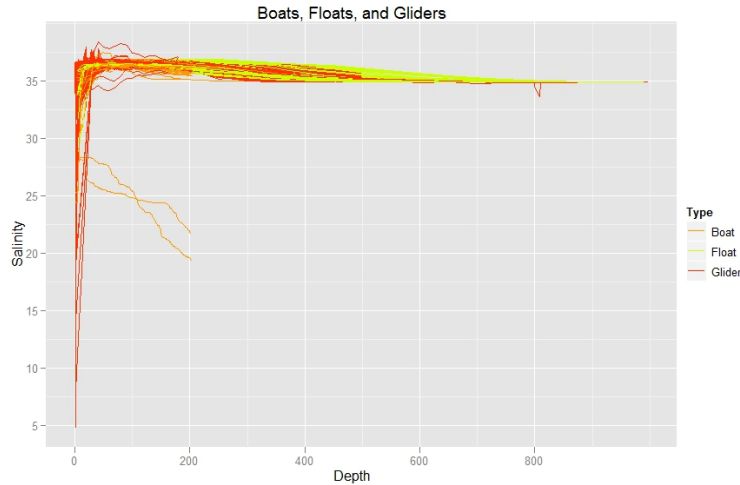


Figure 8: Relationship between depth and salinity grouped by each unique latitude and longitude combination. Depth and salinity almost always maintain a fixed relationship, as seen in most of the observations. However, some areas, mainly those at the surface of the water, experienced unusually low values of salinity. Two areas, which were measured by a boat, had a depth-salinity relationship very unlike the rest.

3. Conclusions

Although there is no doubt the oil spill caused a tremendous amount of damage, the lack of data makes it difficult to make conclusions. We have no information on the actual cause of death of the birds, sea turtles, dolphins, and whales. We also do not have past data to compare these findings with and so we can only reasonably assume that this quantity of dead birds, sea turtles, dolphins, and whales is unusual. It is also hard to make definite inferences based on the PAH measurements. While we know PAH substances were found at harmful levels along the coast, we do not have baseline data to compare these post-spill levels with. As with the animal deaths, we can only reasonably assume that the high levels of PAHs are unusual for the area. Past data was available for salinity, however, the area in which these pre-spill salinity values were measured is quite different from the area in which the post-spill salinity values were measured. Salinity measurements taken along the coastline will be quite different and therefore not comparable to those taken in the middle of the Gulf of Mexico. Better baseline data would have facilitated making conclusions about the effects of the Deep-Water Horizon oil spill on chemicals in the gulf, these chemicals' effects on wildlife, and salinity levels.

What we do know is that the environmental conditions were highly unfavorable during the months after the oil spill. Polycyclic Aromatic Hydrocarbons were found at chronic and acute levels along the shoreline of the Gulf of Mexico. These levels are high enough to cause cancer and disrupt reproduction, development, and the immune system of organisms. Effects of these PAHs are likely to be felt long after the spill. Animals which did survive the initial spill and its aftermath such as birds, sea turtles, dolphins, and whales are all at risk of having health problems for the rest

of their lives. For this reason, the numbers in Figure 1, which only cover a 5 month period after the spill, do not entirely represent the number of animals that will have ultimately died as a result of the oil spill. The Deep-Water Horizon oil spill was a disaster which affected the environment, wildlife, and society upon impact, and will continue to do so indefinitely.

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