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Assessment of Geographic Setting on Oil Spill Impact Severity in the United States – *Insights from Two Key Spill Events in Support of Risk Assessment for Science-Based Decision Making*

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Abstract: Two significant hydrocarbon spills have occurred in U.S. waters to date; the Exxon Valdez spill in Prince William Sound, Alaska and the Deepwater Horizon blowout in the Gulf of Mexico. A review of the lessons learned and outcomes from these two deleterious events, in markedly differing geographic settings, offer unique insights into oil spill prevention and impacts to the *in situ* natural system. The differences between the two spills highlight the important role geographic setting plays on the severity of impacts and recovery of the local and regional ecosystem and economy. The lessons learned from both of these spills also offer key information to support science-based decision-making for future spill prevention for a range of stakeholders. This paper reviews the environmental and economic impacts observed to highlight major differences between the two spills. Understanding how these trends and patterns affect impact severity as well as knowledge and technology needs for each system provides critical information for research, managers, and decision makers especially as extreme offshore drilling increases in both the ultra-deepwater Gulf of Mexico and the offshore Arctic regions of the U.S.

Keywords: Deepwater Horizon, Economic Impacts, Environmental impacts, Exxon Valdez, Oil Spill Prevention

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1 Introduction

The two largest single-source oil spills in U.S. history were from the Exxon Valdez tanker in Prince William Sound (PWS), Alaska and the failure of the Deepwater Horizon oil rig located in the Macondo prospect in the ultra-deepwater (>5,000 feet water depth) Gulf of Mexico (GOM). Both spills introduced large amounts of crude oil into the environment; the Exxon Valdez spilled 240,000 barrels of oil into PWS and the Deepwater Horizon released approximately 4.9 million barrels of oil in the GOM [1]. Over 1,300 miles of shoreline were oiled as a result of the Exxon Valdez spill and over 1,000 miles of shoreline were oiled from the Deepwater Horizon oil spill (Figure 1) [2, 3]. The effects of both oil spills resulted in a variety of human, economic and environmental impacts, with numerous impacts affecting all three simultaneously, such as with fisheries, mariculture, tourism, and energy related development [4]. Although the Deepwater Horizon oil spill (DHOS) was nearly tenfold the size of the Exxon Valdez oil spill (EVOS), its impacts on the local economy and environment appear to show a faster recovery rate in the GOM than in PWS [5]. This report examines the Exxon Valdez and the Deepwater Horizon oil spills by contrasting the response and cleanup efforts as well as the environmental and economic impacts to local wildlife and fisheries at the two spill locations. Given the increasing focus on hydrocarbon development in extreme offshore settings, such as ultra-deepwater and offshore U.S. Arctic, these two events offer insights for science-based decision making that represent two distinct geographic settings but also the rate and controls on recovery, and knowledge or technology gaps key to each location. Previously published work has focused on evaluating the cause and post-mortem on the causes of these two spill events [1, 2]. However, a comparison of the impact related to both these spills also offers key insights for future spill prevention, response, and science-based decision making for offshore operations in general. As more studies and assessments are developed that represent the various aspects of hydrocarbon extraction and production, it is imperative that researchers, managers, and policy makers, be aware of the effects that varying geographical conditions may have on oil spill risks, prevention strategies, as well as response and impact factors. A better understanding of the processes at play, along with key knowledge/technology gaps, will help drive more accurate, robust, and ultimately useful assessments, models, and technologies going forward for a range of needs.

2 Lessons Learned - Cleanup

Arguably, the most important aspect following an oil spill disaster is the cleanup and response. The differences between the climate, location, and timing of both the Exxon Valdez and the Deepwater Horizon oil spills resulted in different approaches towards their cleanup and response. Many of the regulations in place for the DHOS were the result of the EVOS, which was also the first major oil spill to occur in U.S. waters. As a result of the EVOS, the Oil Pollution Act (OPA) was

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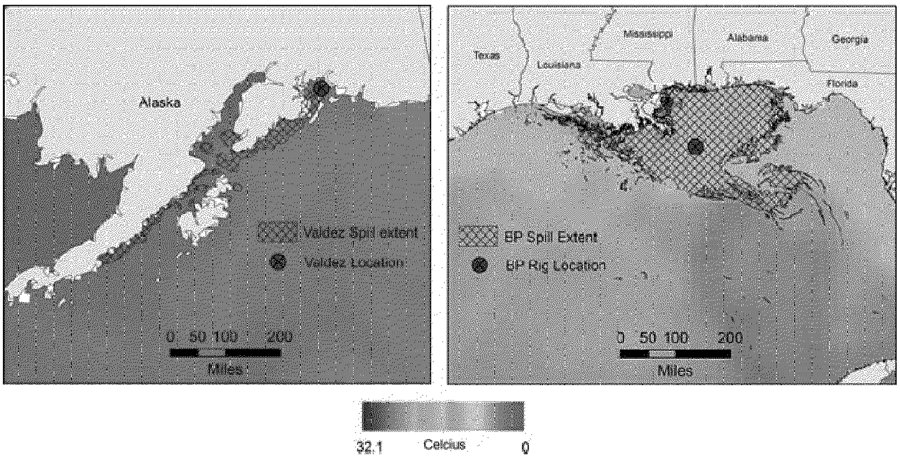

Figure 1 Location, extent, and sea surface temperature at the time of the Exxon Valdez oil spill (left) and the Deepwater Horizon oil spill (right).

signed into law, which was set in place to improve the national response to oil spill disasters, making them more timely and efficient. Moreover, the Oil Spill Liability Trust Fund was also created to help offset removal costs and damages from oil spills [6]. In addition the EVOS helped advance microbial technology and bioremediation techniques that were subsequently applied to the DHOS area [7]. As a result, when disaster struck in the Gulf, the response to the spill was much more coordinated and recovery was much more obtainable.

2.1 *Factors impeding Cleanup*

2.1.1 Weather

One of the largest difficulties in responding to the EVOS was the weather following the spill. For the first 3 days, March 24 – 27 1989, waters were calm around the spill area but early cleanup efforts were uncoordinated and moved slowly during the initial damage assessment. On the fourth day, however, 75 mile per hour wind gusts moved the oil further into protected waters and forced skimmers, booms, and other cleanup equipment to move to sheltered water for protection [8]. Many field crews were also called off cleanup due to the winter weather conditions, and as a result the spill increased in extent.

2.1.2 Temperature/Climate

PWS has lower average sea surface and atmospheric temperatures than the GOM and is relatively isolated while the GOM is open and has much warmer air and sea temperature (Figure 1). A very important factor to consider is that the cold temperatures, both atmospheric and sea surface in PWS hindered oil eating bacteria, which is what seems to be a significant contributor to the cleanup of oil in the

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GOM resulting from the DHOS [3]. Additionally, the cold conditions of the Arctic environment cause natural breakdown of oil to occur more slowly [9, 10]. In the GOM, the openness of the area, large extent, and warmer waters furthered the rapid dispersal and degradation of the oil. In addition, the spill in the GOM was at a single point location allowing crews to inject dispersant (COREXIT 9500) directly into the plume [3]. Wind and waves worked to further mix the oil and dispersants together, making the GOM significantly less difficult to clean up [9].

2.1.3 Oil Microbes and Bioremediation

Naturally occurring microbes that metabolize hydrocarbons exist in both the GOM and PWS. These microbes are sensitive to temperatures and routinely slow their metabolism in colder climates. As such, the microbes that exist in PWS occur in fewer numbers and metabolize oil more slowly. During the EVOS, no remediation techniques were applied to the affected water body (dispersants or microbes), but bioremediation techniques were applied to the oiled shoreline [3]. This was done successfully by the application of several different fertilizers containing nitrogen and phosphate in an effort to increase the onshore breakdown of oil [11]. However, the reapplication of fertilizers to the area soon exhausted its effectiveness and applications ceased after several years [12].

Alternatively, the GOM saw a great improvement in cleanup by way of bioremediation. A 2004 study involving five strains of oil eating bacteria found an optimum temperature range for oil microbes to be 20-30°C, which is right in line with the average sea surface temperature in the GOM at the time of the spill [9, 13]. This greatly decreased the residence time of the oil in the GOM and had a major impact on the degradation of oil. The GOM also contains hundreds of natural seeps which can release as much oil combined in a year as the Exxon Valdez spilled in total [14]. Thus, the baseline hydrocarbon presence in the water column of the GOM appears to have provided a staging area for oil eating microbes to grow and thrive prior to the spill [3].

The location and type of spill was an important factor for determining the techniques that could be enlisted to combat the spill. The surface spill and choppy waters during the EVOS cleanup effort made it difficult to use dispersants on the slick. The nature of the DHOS allowed response teams to pump millions of gallons of dispersants directly into the oil plume which, within four hours, had significant effects on the amount of oil rising to the surface [3].

3 Environmental and Economic Impacts

3.1 *Wildlife*

3.1.1 Overview

Any oil spill event can have devastating consequences to the wildlife. As seen with these two spills, the deleterious effects extend beyond just the commercially

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important fishery species to other species including marine mammals, sea birds and reptiles. Adverse effects to wildlife were seen at both locations.

The direct impacts to species were more easily quantifiable for terrestrial species at both locations. In comparison to the EVOS, the DHOS is still fairly recent. As of April 20, 2011 the United States Fisheries and Wildlife Department reported 4,389 visibly oiled birds, 474 visibly oiled sea turtles, and 12 visibly oiled mammals [15]; significantly less than the numbers observed in PWS for the same post spill period. Estimates in a report from the Center for Biological Diversity released one year after the DHOS used multiplicative factors to estimate the total number of potential wildlife affected. The Center estimates that 6,000 sea birds, 26,000 dolphins and whales, and up to 82,000 sea birds were likely affected [16].

The numbers are large but are still considerably less than the numbers observed in PWS over the same post spill period, which estimated that up to 30,000 sea birds had been affected within one year after the spill occurred [17]. Total numbers of injured wildlife as reported by the Exxon Valdez Oil Spill Trustee Council are: 250,000 dead seabirds, 22 killer whales, 2,800 sea otters, 200 harbor seals and countless numbers of fish eggs. In addition, there were 121 bald eagle carcasses found in the vicinity of the spill, with estimates reaching up to 250 total dead eagles [18]. Compared in the short-term, initial impacts to species observed from both spills seem to be more significant, by way of the numbers of wildlife affected by the spill, following the EVOS than the impacts following the DHOS.

3.1.2 Prince William Sound

Terrestrial wildlife in PWS was predominantly affected by the length of time the oil resided in the system. The oil on the surface of the water caused various respiratory effects along with ingestion problems, and external coating of sea otters, sea birds and other fauna.

Sea otters (*Enhydra lutris*) were one of the species that were greatly impacted by the EVOS and as a result were studied extensively. A number of oiled sea otters were collected and taken to examination centers following the spill. Tissue samples were taken and analyzed along with a visual inspection of the animals to assess the degree of harm. Tissue samples showed interstitial pulmonary emphysema, gastric erosion and hemorrhage, and centrilobular hepatic necrosis [19]. Of the approximate 6,500 sea otters in PWS, estimated mortality from the spill ranges as high as 2,650 otters [20, 21]. Immediately following the spill, sea otter acute mortality varied but was up to 40% higher than what it was pre spill. Mortality rate following the spill continued to increase over time, but eventually returned to normal levels by 1998, yet sea otters are still considered recovering in PWS [22].

Another important species affected in both the short and long term by the EVOS was the killer whale (*Orcinus orca*) population. At the time of the spill, the area had two distinct populations, the resident AB pod and transient AT1 group. From 1989-1990, fourteen whales disappeared out of the 36 that made up the AB pod,

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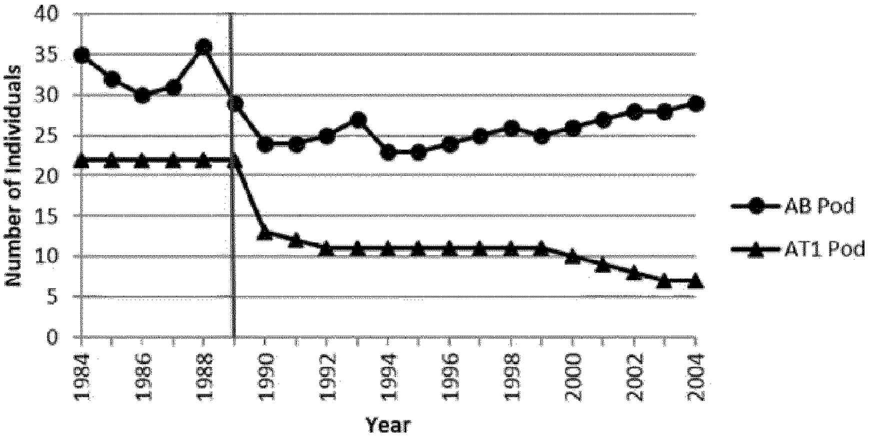

Figure 2 Population trends of the two resident killer whale groups in PWS from 1984 - 2004.

which resulted in a 40% loss of their members over the course of the spill [23]. The AT1 group saw a loss of nine whales out of the 22 in the winter following the EVOS. The loss to both pods was the highest mortality rate ever recorded and it is unlikely that natural mortality was the cause of the decline [24]. The largest effect to both whale pods was the disproportionate loss of young females and juveniles which is reported as unusual for killer whales. The AT1 pod has not seen a successful recruitment since prior to the spill. The catastrophic mortality event to the killer whale populations in the area is unprecedented with no other event similar to this ever being recorded.

3.1.3 Gulf of Mexico

In the GOM, estimates are still being made to determine the extent to which wildlife has been affected by the DHOS and will continue to be monitored for years to come. This includes marine mammals, sea birds, reptiles and others. Because of the unprecedented release of oil at great depths, concerns were centered on the depletion of oxygen in the deeper ocean on which many species depend [25, 26, 27].

Another concern was the health of benthic communities since the dispersants being applied to the plume could cause oil to to linger in the water column and buildup on the ocean floor [26]. Through multivariate methods applied to sediment samples taken from the ocean floor, research indicates a reduction in diversity extending from the DHOS well head out 3km in all directions [27]. Even more interesting is that benthic effects were correlated to total hydrocarbon concentrations in relation to the distance to the DHOS well-head, but not to natural hydrocarbon seeps. The results from the study are a good indication that the effects seen on the ocean floor are a result of the oil spill and not from natural seeps.

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3.2 Fisheries

3.2.1 Overview

The spatial extent of oil and chemical dispersants used for cleanup overlapped with the daily and seasonal movements of numerous commercially important species in both PWS and the GOM. The economic and social importance of commercial fisheries in these regions triggered concerns from fisheries managers, policymakers, scientists, stakeholders, and the general public over the range, magnitude, and duration of effects from oil and dispersant exposure on numerous species and the fisheries they support. Research has identified a range of direct and indirect effects on commercial species from oil exposure, including increased mortality, reduced growth rates, morphologic and genetic abnormalities, fouling of critical nursery and foraging grounds, alterations in food web structure, and changes in fishing pressure [2, 4, 28]. However, research has shown that the scope, magnitude, and duration of effects from oil varied greatly between commercial fisheries in PWS and the GOM.

3.2.2 Prince William Sound

Research on the impacts to commercial species from the EVOS has predominately been focused on salmon (*Oncorhynchus*) and Pacific herring (*Clupea pallasii*) fisheries in PWS. Salmon are one of the largest fisheries in the region, and during the EVOS, billions of salmon eggs failed to hatch. In addition, there was rampant premature hatching, reduced growth rates, morphological and genetic abnormalities, and increased mortality [4, 29, 30]. The combination of these factors greatly affected salmon recruitment and abundance, especially the 1989 cohort which resulted in the closure of the salmon fishery after the oil spill due to concerns over a declining population [31]. Commercial harvest of pink salmon (*Oncorhynchus gorbuscha)* prior to the EVOS ranged from a high of 23.5 million fish in 1984 to a low of 2.1 million in 1988 [18]. After the oil spill, commercial catches decreased 11% ranging from 12.5 million in 1990 to a low of 1.9 million in 1992 [18]. Since the spill, numbers have returned with natural variability and indicators such as juvenile growth and survival have remained within normal bounds. The current state of pink salmon has been listed as recovered and has been since 1999 [18].

The Pacific herring fishery in PWS has been stressed since 1993. Along with their commercial importance, herring are a staple of many marine species diets including marine mammals, birds and other fish [22]. Pacific herring were affected differently than the salmon fishery and have yet to return to commercial harvest levels observed prior to the EVOS. The annual spawning migration into the shallow intertidal and sub-tidal regions of PWS occurs between late March and early April, overlapping with the EVOS. This raised concerns over the effects of oil exposure on herring, at all life stages, to various oil contaminants which resulted in the closure of the fishery in the spring of 1989 [32].

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Initial herring observations during the spill suggested that the exposure of adult herring to oil was minimal [33]. However, recent studies using acoustics have identified certain behaviors of adult herring, including predatory avoidance and gulping air at the surface that make them more vulnerable to surface oil, particularly the exposure of their respiratory and digestive systems to oil [34, 35]. Adult herring collected from areas exposed to the EVOS also displayed signs of lesions and were void of gut parasites more frequently than adult herring not exposed to the oil spill [32].

Impacts to Pacific herring eggs and larvae were harder to discern, but research indicated that at the peak of spawning (mid-April) 34-43% of the shoreline utilized for spawning overlapped with oil, potentially impacting 41-52% of the herring eggs produced in PWS [32]. Furthermore, findings from a chemical analysis of seawater at spawn sites in PWS also showed a similar overlap with detectable levels of oil [36]. This, along with research suggesting that Pacific herring eggs that were exposed to Exxon Valdez oil produced significantly more deformed larvae than the eggs collected from non-oiled locations, strongly suggests that herring eggs were exposed to toxins from the oil spill in 1989 and could thus be a major contributor to the collapse of the fishery [36, 37].

The immediate impacts to the herring population were not obvious following the spill, however. In fact, above average harvests followed the spill from 1990 to 1992 [33]. It was not until 1993 that fishery managers began questioning the effects of the spill on the herring fishery. In 1993 the herring population in PWS completely collapsed. There was an 86% decrease in harvest from 1992 to 1993, with only 26,267 tons harvested in 1993 (Figure 3) [38]. Since 1993, the herring fishery in PWS has been closed 18 out of 24 years post spill, with estimates that

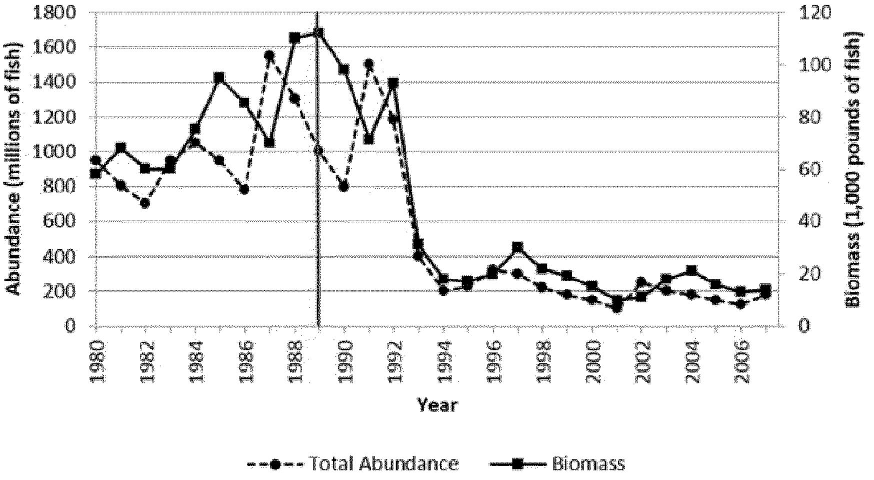

Figure 3 Abundance and biomass of the Prince William Sound Pacific herring fishery from 1980 – 2007.

the herring population is only 15% of what it was prior to the spill [31]. Decades of research have suggested many different factors that could have led to the population decline, including the EVOS, commercial fishing, disease, and changing environmental conditions [31, 33, 34, 36, 39, 40]. However, more recent studies suggest that the population decline was, to some extent, affected by the EVOS with research suggesting the impact on the 1989 cohort could have affected the decline (age-3 are when cohorts typically return to spawn and enter the fishery; the 1989 cohort would be age-3 in 1993) as well as some results showing a decline in the population biomass from the time of the spill until 1993 [34].

3.2.3 Gulf of Mexico

The duration and magnitude of the DHOS had a large impact on commercial fisheries within the GOM [28]. Consequently and in parallel to the EVOS, fish were contaminated with hydrocarbons that forced NOAA to close a large portion of fishable waters surrounding the oil slick [41]. Research on the specific impacts to species within the GOM is ongoing and will continue for years to come, but some immediate impacts can be inferred from commercial landings data following the spill.

The dominant and highest value fisheries in the GOM are the brown (*Farfantepenaeus aztecus*) and white (*Litopenaeus setiferus*) shrimp fisheries. From 2008–2009, annual landings averaged over $140 million for brown and white shrimp. Combined, the GOM shrimp fishery contributed 73% of the total U.S. shrimp landing for those years [38]. After the DHOS, the 2010 commercial brown shrimp landings decreased from the 2009 numbers by about 50 million pounds, but quickly rebounded back to 2009 levels by 2012 (Table 1) [38]. Surprisingly, the white shrimp fishery did not see any decrease in numbers and at the end of 2010 total landings had an overall increase from the 2009 harvest. Two years after the spill the shrimp fisheries were considered in good condition and expected to recover to pre-harvest levels by the end of 2012 (Table 1). The gulf menhaden (*Brevoortia patronus*) fishery, one the largest commercial finfish species in the GOM, displayed a similar trend as white shrimp. In 2008 and 2009 menhaden landings were upwards of a billion pounds. According to NOAA Commercial Fisheries Statistics, the landings for 2010 reached almost 2 billion pounds, a possible indication of the quick rebound of fisheries in the GOM (Table 1).

Despite the size, magnitude, and duration of the DHOS in the GOM, commercial landings data suggest that a majority of its fisheries were on the way to recovery just one year after the spill, if not earlier. However, these results are only based on short-term data and there is still the need to conduct additional research on the potential short and long term effects of oil and dispersants on commercial species [42]. For example, several finfish species were spawning during the time of the oil spill, suggesting that the harmful effects on eggs, larva and juveniles from the oil and dispersants used could persist for years after the spill, and that the severity of those effects might not be immediately detectable, akin to the effects observed

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Table 1 The top commercial fishing species in the Gulf of Mexico with total pounds and dollar value.

Year	Species	Total Pounds	Value ($)
2012	Brown Shrimp	104,142,699	187,280,317
2011	Brown Shrimp	117,819,078	200,426,456
2010	**Brown Shrimp**	**72,689,003**	**136,115,037**
2009	Brown Shrimp	124,209,468	144,116,709
2008	Brown Shrimp	79,066,734	141,719,646
2012	White Shrimp	104,374,206	196,999,096
2011	White Shrimp	180,056,614	417,084,816
2010	**White Shrimp**	**183,697,978**	**345,460,532**
2009	White Shrimp	116,599,055	158,510,700
2008	White Shrimp	98,294,953	199,627,196
2012	Menhaden	915,581,400	67,390,998
2011	Menhaden	2,748,576,444	207,037,746
2010	**Menhaden**	**1,934,049,520**	**132,038,736**
2009	Menhaden	1,165,948,499	69,455,569
2008	Menhaden	927,517,142	64,376,291

with the Pacific herring population in PWS. But, in a study which investigated the species-by-species catch rates as well as juvenile catch rates in 2010 following the spill, researchers concluded that catastrophic losses of 2010 cohorts were largely avoided, however they also stressed that attention should be given to the delayed and indirect effects that could still affect populations [42].

In response to the DHOS in the GOM, immediate concerns over the safety of seafood caused a large area of fishing grounds to be closed. Temporary closures in the fishing seasons and grounds had significant financial effects on local fishermen, fishing communities, and related businesses from the loss of revenue, profit, wages, and jobs [28]. Recovery times for a species, and therefore the fisheries and the other businesses they support, can vary based on the length of exposure to oil and dispersants, the mobility and movement of the species, the ontogenetic stage of the species when its exposed, its feeding and reproductive patterns, as well as the environmental conditions of the region [4].

The DHOS had direct effects to the commercial fisheries in the GOM. The largest impact came from fishing closures, which shut down a large majority of commercial fisheries in the central GOM (87,000 square miles of fishing ground). The closures impacted the total landings for four out of the five GOM states along

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with the associated revenue the landings provide [43]. Not only was the supply of seafood negatively impacted, but the demand as well. Public opinion of oiled seafood caused a drop in demand. A survey conducted by the Louisiana Office of Tourism, found that only 14% of respondents realized that oyster beds had not been contaminated with oil [5]. The perception that the fisheries were harmed was just as negatively impactful as the direct impacts to the fisheries, which in some cases was much less than the perceived impact [44].

The commercial fisheries appear to have been more resilient to the effects of the DHOS and have recovered faster than the commercial species impacted by the EVOS in PWS. The current landings numbers for commercial fisheries in the GOM have shown considerable improvement since the time of the spill. Both locations saw economic and ecologic hardship following the closures of fishable waters in the regions. The nature of the two spills also had a significant influence on the impact to the commercial fish species. In both locations, the commercial fisheries are on their way to recovery. As we reflect on the two spills, scientists must be weary of the lingering effects seen in PWS. Significant impacts were not discernible for many species until years after the initial spill. Continued monitoring must take place in the GOM to make sure commercial fisheries do not see a collapse similar to that observed with herring in PWS. Without acknowledgment of the past situations it is likely that they will be repeated with even more serious consequences.

4 Conclusion

The DHOS and the EVOS were the two most significant offshore oil spills in U.S. history to date. The fisheries at each location were affected differently by each oil spill, largely due to environmental differences between the areas. The DHOS released 205 million gallons of oil into the Gulf of Mexico, about 19 times more than the EVOS. By examining fisheries reports and using them as an indicator of oil spill affects, it seems as though the GOM is recovering much faster. This can be largely attributed to the location of the spill, the response time, and the various dispersal techniques used on the oil slicks. The warmer temperatures and open waters of the GOM allowed for natural degradation processes to take place more readily. In addition response crews accessed the Deepwater Horizon site much more efficiently and quickly. The combination of natural and anthropogenic effects on the DHOS helped clear the GOM much faster than in PWS. In turn this allowed for a faster recovery of the fisheries and economy of the GOM.

The comparison between the two spills highlights some important concepts that should be considered when looking at the presence of oil exploration in Arctic areas and the importance the spill prevention and distinctive region-specific technology needs to ensure safe operation and development in each region. First, oil degrading bacteria do not respond as well and are not as abundant in cooler conditions. Second, Arctic weather conditions have a stronger effect on response time and cleanup effort. Also, seasonal ice cover would make responses to subsurface

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ruptures much harder. Effects on the environment can translate to economic impacts, such as with fisheries, mariculture, tourism, and energy related development. While oil spills will always be a threat to the surrounding ecosystems, it appears that oil in an Arctic ecosystem would have stronger and more lasting effects than oil spills in more moderate climates. Thus, research, spill prevention technologies, and impact mitigation activities related to Arctic drilling should carefully consider the lessons offered by the two most significant oil spills in U.S. history. Ultimately, lessons learned from these two distinctive regions, paired with improved understanding of engineering requirements to ensure safe and reliable operations are vital to spill prevention and mitigation of impacts in either region.

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