

Integration of Spatial Data to Support Risk and Impact Assessments for Deep and Ultra-deepwater Hydrocarbon Activities in the Gulf of Mexico

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Cover Illustration: The front cover image represents a simplified diagram of the process we are using to model impacts of potential future oil spills from submerged oil wells in the Gulf of Mexico.

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Integration of Spatial Data to Support Risk and Impact Assessments for Deep and Ultra-deepwater Hydrocarbon Activities in the Gulf of Mexico

**Spatial Environmental Energy Research Laboratory:
National Energy Technology Laboratory and Oregon State University**

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Acronyms and Abbreviations

Term	Description
API	American Petroleum Institute
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
DEM	Digital Elevation Model
DOE	Department of Energy
GBIF	Global Biodiversity Information Facility
GOM	Gulf of Mexico
GSMFC	Gulf States Marine Fisheries Commission
HARN	High Accuracy Reference Network
IAM	Integrated-risk-assessment modeling
IASNFS	Intra-America Seas Nowcast/Forecast System
INSTAAR	The Institute of Arctic and Alpine Research
MMC	Multipurpose Marine Cadastre
MMS	Minerals Management Service
NCOM	Navy Coastal Ocean Model
NETL	National Energy Technology Laboratory
NGDC	National Geophysical Data Center
NGI	Northern Gulf Institute
NLCD	National Landcover Dataset
NOAA	National Oceanic and Atmospheric Administration
NWI	National Wildlife Inventory
OBIS	Ocean Biological Information System
OCS	Outer continental shelf
OSC	Oil Spill Commission
OSU	Oregon State University
PHP	PHP Hypertext Preprocessor
SEAMAP	Southeast Area Monitoring and Assessment Program
SEER	Spatial Environmental Energy Research
TWDB	Texas Water Development Board
USCG	United States Coast Guard
UTM	Universal Transverse Mercator
WGS	World Geodetic System

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- Alabama Department of Conservation and Natural Resources, Marine Resources Division
- Army Corps of Engineers
- Bureau of Safety and Environmental Enforcement (BSEE)
- Bureau of Ocean Energy Management (BOEM)
- Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute
- Gulf States Marine Fisheries Commission (GSMFC)
- National Oceanic and Atmospheric Administration (NOAA)
- National Wildlife Inventory (NWI)
- Naval Research Laboratory (NRL)
- Northern Gulf Institute (NGI)
- Texas Water Development Board (TWDB)
- Texas Parks and Wildlife Department (TPWD), Coastal Fisheries Division

1. EXECUTIVE SUMMARY

This report summarizes datasets from the Gulf of Mexico used by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL) integrated risk assessment project team to support risk assessment predictions and research for this region. The report describes data collected and/or generated to date. After the Deepwater-Horizon oil spill, the Federal Oil Spill Commission reported that our understanding of the impact of oil spills on the environment and humans was inadequate (OSC, 2011). This report summarizes the data requirements and current status of datasets identified for use in support of Gulf of Mexico integrated-risk-assessment modeling (GOM-IAM) for the subsurface, wellbore, and water column systems. Since 2011, the project team has focused on integrating and analyzing geospatial datasets, such as air emissions data, water column data, species distribution data, subsurface geology (reservoir properties, structure and lithology), industry infrastructure (wells, pipelines, etc.), oceanographic data (currents, salinities, etc.). The goal of this work is to develop geospatial relationships to support assessment of deepwater and ultra-deepwater regions using data available from public and commercial sources. Ultimately, the derivative relationships (i.e., data models) developed by this project will be made publically available, providing a unique and basin-wide resource for the Gulf of Mexico. In addition, access to publically available primary datasets will be facilitated by the Energy Data eXchange (<https://edx.netl.doe.gov/>), either by direct posting of the data or by posting information and links that direct users how to access the datasets.

2. PROJECT MOTIVATION AND OVERVIEW

Production from offshore drilling in U.S. federal waters, currently primarily limited to the Gulf of Mexico (GOM) and California, now roughly equals production from the Alaskan North Slope (EIA, 2012) and is a key component of the U.S. energy independence. Increasingly, exploration in these maturing offshore regions is moving into deep and ultra-deepwater environments (EIA, 2012). At the same time more attention is being placed on frontier areas that garner strong public and environmental concerns, such as offshore of the Alaska North Slope (Beaufort and Chukchi Seas), offshore eastern U.S., and the eastern Gulf of Mexico. The risks associated with offshore hydrocarbon development on regional infrastructure and the environment was illustrated by the disturbance caused in 2005 by hurricanes Katrina and Rita and the 2010 Deepwater Horizon disaster. These events clearly demonstrated a need for an integrated and improved evaluation of natural and engineered attributes (geologic, engineering, water column and atmospheric) associated with the entire system to allow for rapid evaluation and assessment of risks and environmental implications of development.

After the Deepwater-Horizon oil spill, the Federal Oil Spill Commission reported that our understanding of the impact of oil spills on the environment and humans was inadequate (OSC, 2011). In 2011, NETL researchers initiated a multi-faceted study focused on conducting quantitative risk assessments and research that compiles and evaluates key attributes of ultra-deepwater and frontier regions of the Gulf of Mexico to estimate potential risks related to development, and as needed to conduct rapid predictions in the case of a future unexpected loss of control event. Many of the datasets necessary for these assessments are available from existing resources (including other governmental agencies, industry, etc.). Thus, in addition to developing the necessary integrated-risk-assessment modeling (IAM) tools to simulate the subsurface, wellbore, and water column components of this engineered-natural system, it is also necessary to develop and/or assemble data characterizing the in situ system to support these models. Given the volume of pre-existing data available from disparate sources, a significant focus of the data portion of this study is focused on the integration of various data sources to support timely, rapid and quantitative assessments of safety and environmental issues. Finally, as key data gaps were identified, primary interpretations and analyses were pursued to close those gaps.

The focus of this report is to summarize the data requirements and current status of datasets identified for use in support of GOM-IAM for the subsurface, wellbore, and water column systems. Since the fall of 2011, the project team has focused on integrating and analyzing geospatial datasets, such as subsurface geology (reservoir properties, structure and lithology), water column data, oceanographic data (currents, salinities, etc.), industry infrastructure (wells, pipelines, etc.), and species distribution data to support assessment of deep/“frontier” regions using public and commercial sources. The primary data integration effort is anticipated to reach completion in the fall of 2013 when the majority of these datasets will be released collectively through EDX.

2.1 GEOGRAPHIC AND GEOLOGIC FRAMEWORK

The Gulf of Mexico is a large ocean basin bounded by five U.S. states to the north and east, and Mexico and Cuba to the south and west (Figure 1). In the Late Triassic, the basin began to form through sea-floor spreading due to the breakup of Pangea (Galloway, 2009; Salvador, 1987). The area existed as a shallow sea for millions of years as tectonic plates slowly separated, and thick layers of salt were deposited across the basin. As the American continents shifted toward their current locations and sea level rose and fell, thousands of meters of sediment filled the basin and buried the salt. Included in these sediments were the carbon-rich layers that today have become sources of hydrocarbons and the strata that now form reservoirs and traps for migrated hydrocarbons. The loading of the salt sheet prompted movement of the salt and deformation of the overlying strata, leaving older, allochthonous salt formations on top of younger sediments. Combined with passive subsidence and active tectonics, this has generated a complex system of faults and minibasins that help to trap reservoirs of hydrocarbons below the surface (Dribus et al., 2008; Galloway, 2009; Konyukhov, 2008; Salvador, 1991; Wu et al., 2009a; Wu et al., 1990b).

The formation of the Gulf of Mexico and its depositional and structural environments are discussed in detail by (Buffler and Thomas, 1994; Diegel et al., 1995; Galloway, 2009; Konyukhov, 2008; Salvador, 1987; Salvador, 1991; Sawyer et al., 1991; Wu et al., 1990a; Wu et al., 1990b) among others. In the U.S. Gulf of Mexico, formations that produce hydrocarbons are generally sands such as the Wilcox or Frio formations, which are porous and permeable enough to allow hydrocarbon storage and flow and are often capped by fine-grained, impermeable strata such as clays or carbonates. Source rocks are typically older, Jurassic and Cretaceous strata, though hydrocarbons have been discovered in rocks of these ages as well (Galloway, 2009; Lach, 2010).

The complex geology of the Gulf of Mexico, combined with water depths of up to 10,000 ft, contribute to making deep water (defined here as >500 ft water depth) and ultra-deepwater (defined here as >5000 ft water depth) drilling difficult and potentially hazardous. Blowouts, or uncontrolled releases of hydrocarbons, can result if unexpected extreme conditions are encountered during operations, discharging a liquid and gaseous mix of hydrocarbons into the water column. The characteristics of the discharge are defined and controlled by the properties of the subsurface reservoir and the well, including temperature, pressure, porosity, permeability, reservoir sizes, hydrocarbon densities, and gas to oil ratios. All of these are ultimately controlled by the lithology, depth, structure, and fluid type in the area of interest.



Figure 1: The Northern Gulf of Mexico including the major bays, sounds and lagoons.

2.2 INFRASTRUCTURE FRAMEWORK

Deepwater and ultra-deepwater Gulf of Mexico resources reside within federally regulated waters in the Gulf of Mexico. Federal waters begin 3 nautical miles away from any state's coast (9 nautical miles for Texas and the Gulf Coast of Florida) (43 USC §§ 1301-1315, 2002). Federal waters are divided into outer continental shelf (OCS) blocks and official protraction diagrams, mathematically defined in the Universal Transverse Mercator Grid System (Thormahlen, 1999), which are further subdivided into generally 3 mi² blocks that are leased to companies interested in drilling (BOEM, 2012). Within the Gulf of Mexico there are 29,175 available lease blocks and of those, more than 5,000 have been leased and are considered active as of August 2012 (BOEM and NOAA, 2012). These federal blocks and leases are commonly used to reference the location of key infrastructure associated with offshore operations.

Drilling platforms and pipelines form the supporting infrastructure as boreholes are drilled for exploration and production. There are over 7000 active platforms drilling in the Gulf of Mexico. Many occur in shallow waters (<500 ft water depth) due to their ease of accessibility, but as these wells become exhausted the quest for oil continues to expand to deeper waters.

For every drilling platform in the Gulf an associated oil line must be put in place to transport the oil to shore. From there the oil is connected to additional oil lines and distributed to the greater United States for refinement and use. Many of the oil lines go through sensitive environmental areas including coral reef, marshes, marine and terrestrial sanctuaries, which are put at greater risk of being exposed to crude oil (Johnston et al., 2009).

2.3 WATER COLUMN FRAMEWORK

The Gulf of Mexico is a large marine ecosystem supporting a complex and diverse range of habitats, species, and human activities. The Gulf of Mexico's ecosystems are heavily influenced by its unique physiographic and hydrodynamic characteristics. Characterized by complex shoreline comprising of rivers, channels, and estuaries, twice-daily, low amplitude tides, and

numerous, interconnected surface currents, including the highly variable Loop Current which bring warm tropical waters into the Gulf. Interactions between these warm surface currents, the shallow continental shelf, and numerous, nutrient freshwater inputs from major rivers like the Mississippi River, result in high levels of productivity that help support the diversity and abundance of species within the Gulf of Mexico (Wilkinson et al., 2009). The diverse marine habitats within the Gulf are influenced by the physiographic characteristics, such as longshore sediment transport which developed the extensive chain of barrier islands that form shallow lagoons and sheltered areas for species; and the variety of bottom types, including mud, sand, silt, and shell that provide a range of substrates ideal for seagrasses, coral reefs, oyster reefs, and tidal marshes (Wilkinson et al., 2009). The unique characteristics that make the Gulf of Mexico a diverse and rich ecosystem also allow it to support a broad range of human activities including, hydrocarbon development, shipping and transportation, tourism, and commercial and recreational fishing.

This complexity and diversity results in a broad range of potential impacts that could result from a natural hydrocarbon seep, oil spill, or a blowout. The fate of released hydrocarbons through the water column is influenced by its momentum, buoyancy, and the entrainment of water, currents, and winds (Lee and Cheung, 1991). Released hydrocarbons can wash ashore on beaches, reefs, estuaries, and marshes, or they may undergo density and buoyancy changes that cause them to sink where they may remain for some time on the ocean floor, endangering benthic habitats (Korotenko et al., 2002). Modeling the potential distribution of oil requires accurate estimates concerning the physiology and composition of oil and gas reservoirs, the location and depth of current and potential drilling sites, and the hydrodynamic properties of water in the open ocean and estuaries. Currents and tides change continuously, especially in the Gulf of Mexico's Loop Current, so hydrodynamic data must be available for the entire Gulf of Mexico on a temporal resolution of at least several hours.

A natural hydrocarbon seep or uncontrolled release event can also have diverse effects on coastal communities and coastal and marine ecosystems. Coastal communities are frequently affected by the loss of critical ecosystem services that often benefit humans, such as the availability of healthy seafood, clean beaches, and unpredictable changes in tourism, jobs, and local economies (Jernelöv, 2010; Levy and Gopalakrishnan, 2010; Lubechenco and Sutley, 2010). Effects on coastal and marine ecosystems can include impacts to habitats such as wetlands, reefs, mangroves, and seagrasses; economically important species such as shrimp, shellfish, and finfish; and endangered or threatened species including birds, turtles, and marine mammals (Bjorndal et al., 2011; Campagna et al., 2011; Jernelöv, 2010; Levy and Gopalakrishnan, 2010).

2.4 DATA OVERVIEW

For the subsurface, this project includes development of a database of subsurface geologic, physical, and pore-filling media attributes for the deepwater (>500 m water depth) Gulf of Mexico. This database of subsurface attributes is anticipated to be released via EDX in the fall of 2013. Ultimately, the database will include a number of key parameters that will be compiled and interpolated for the region: depth to the tops of formations, mean formation thickness, mean porosity, permeability (where available), temperature gradient, pressure gradient, structural components, likely pore-filling media composition, etc. This effort will continue to utilize resources such as, existing subsurface interpretations, in conjunction with interpretation of

wireline logs, core, seismic, and other physical datasets, particularly for the deep and ultra-deepwater regions where recent drilling activities are not well represented by existing datasets.

In addition, this project is developing a database of water column attributes and geospatial layers to characterize the physical and biologic components of the Gulf of Mexico. Key parameters such as, bathymetry, currents, species distributions, temperature profiles, pressure profiles, salinity profiles, seafloor sediment composition, water chemistry composition, anthropogenic features such as pipelines, wells, platforms, shipping lanes, etc. are being compiled and interpolated for the region. This effort has utilized resources such as, existing interpretations and datasets from a variety of sources, including National Oceanic and Atmospheric Administration (NOAA), Bureau of Safety and Environmental Enforcement (BSEE), U.S. Coast Guard (USCG), etc. These data can be used to provide relevant, spatially distributed inputs for the risk models.

3. APPROACH

Since the Gulf of Mexico is a large and complex region, we began by evaluating each dataset and then selecting the most appropriate data to be processed into a standard comprehensive dataset. While there are a large number of datasets available for the Gulf of Mexico, there are challenges with assembling a uniform dataset for the entire Gulf. These challenges included defining a spatial reference system for all of the data, standardizing resolution for raster datasets, ensuring the data are properly registered on the earth's surface, checking the data for accuracy, processing the data into uniform datasets, and then disseminating the data through appropriate websites.

3.1 SPATIAL REFERENCE SYSTEM

Our area of interest in the Gulf of Mexico is approximately 1500 km from east to west and 2000 km from north to south. The existing spatial data for the Gulf is available in a variety of spatial reference systems (projection and datum) and units. While much of the information on the infrastructure is in the North American Datum from 1927, which is the standard used by industry and government in the Gulf of Mexico (Thormahlen, 1999), the bulk of other spatial information uses the World Geodetic System from 1984 (WGS 84), which is compatible for our purposes with the High Accuracy Reference Network (HARN). Similarly, some of the spatial data was available in feet, but the bulk of other information is in the International System of Units, or SI Units (i.e. the metric system). To ensure compatibility across the datasets, and in working with other researchers, all data was converted to WGS 84 in meters. Using geographic projection for this large of an area would result in distortion causing large errors in analysis. Using the Universal Transverse Mercator (UTM) system would require dividing the Gulf of Mexico into several strips making modeling more complex. Because of this, we decided to create a new spatial reference system just for the Gulf of Mexico, referred to as "GOMAlbers".

The main goal of selecting an appropriate spatial reference should be to minimize distortion within the area of interest. Every projection method introduces some distortion, and different classes of projections control certain types of distortion (distance, area, shape) at the expense of others. A standard approach to selecting a projection class is described in (Maling, 1992), which states that areas lying in temperate latitudes are best mapped using a conical projection. Following that suggestion, we selected an Albers Equal-Area projection, and adjusted the projection parameters to distribute the errors so that they were reasonable throughout the Gulf. We placed the central meridian at 88°W, and two standard parallels at 25°N and 28°N, and then calculated the maximum percent scale errors over the entire area using a projection distortion tool in ArcGIS (Brayman, 2009).

Results of these calculations are shown in Figure 2. The errors introduced by the projection are less than 0.1 percent through most of the Gulf, with maximum errors of less than 0.3 percent in the northern Gulf and less than 0.7 percent over the entire Gulf. The complete set of parameters for the GOMAlbers spatial reference system is given in Table 1.

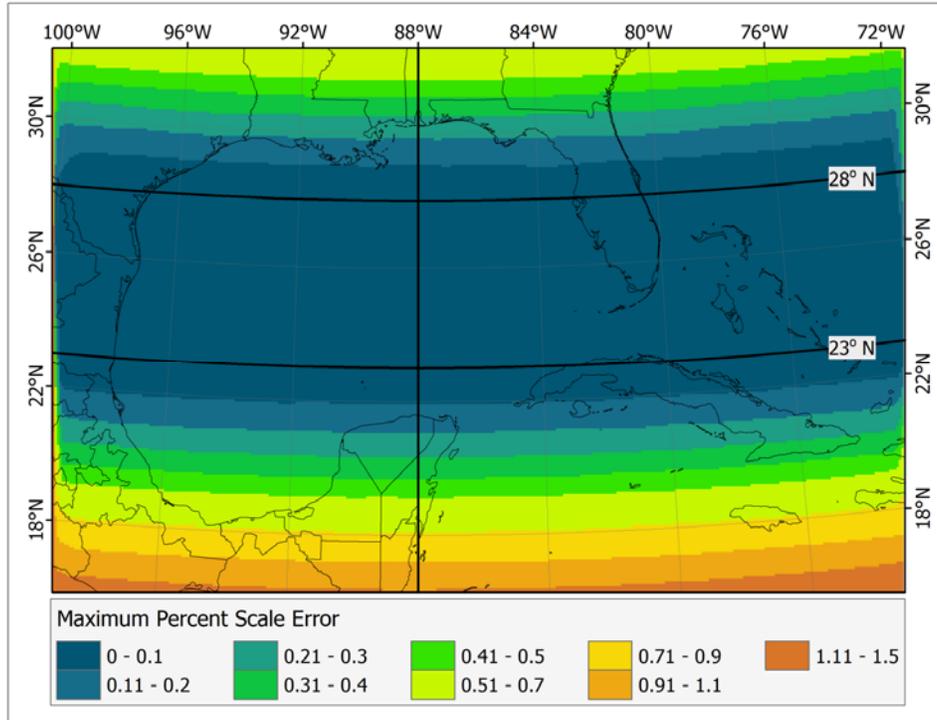


Figure 2: Distortion in the GOMAlbers spatial reference.

Table 1: GOMAlbers spatial reference

Parameter	Value
Projection	Albers Equal-Area
False Easting	1,200,000
False Northing	0
Central meridian	88 degrees west
1st Standard Parallel	23 degrees north
2nd Standard Parallel	28 degrees north
Latitude of Origin	16 degrees north
Datum	World Geodetic System 1984 (WGS84)
Units	Meters

3.2 RESOLUTION

Subsurface data

Subsurface data in the Gulf of Mexico are primarily from drilled wells and geophysical surveys. Geophysical surveys are relatively extensive, but are not widely accessible. Borehole data available are irregularly spaced in both location (Figure 3) and depth, particularly in deep and ultra-deepwater. To estimate values in regions where data are sparse, a variably-sized grid

system will be used, averaging the known values where data exist and interpolating between existing values where necessary. This will require interpolation in three dimensions.

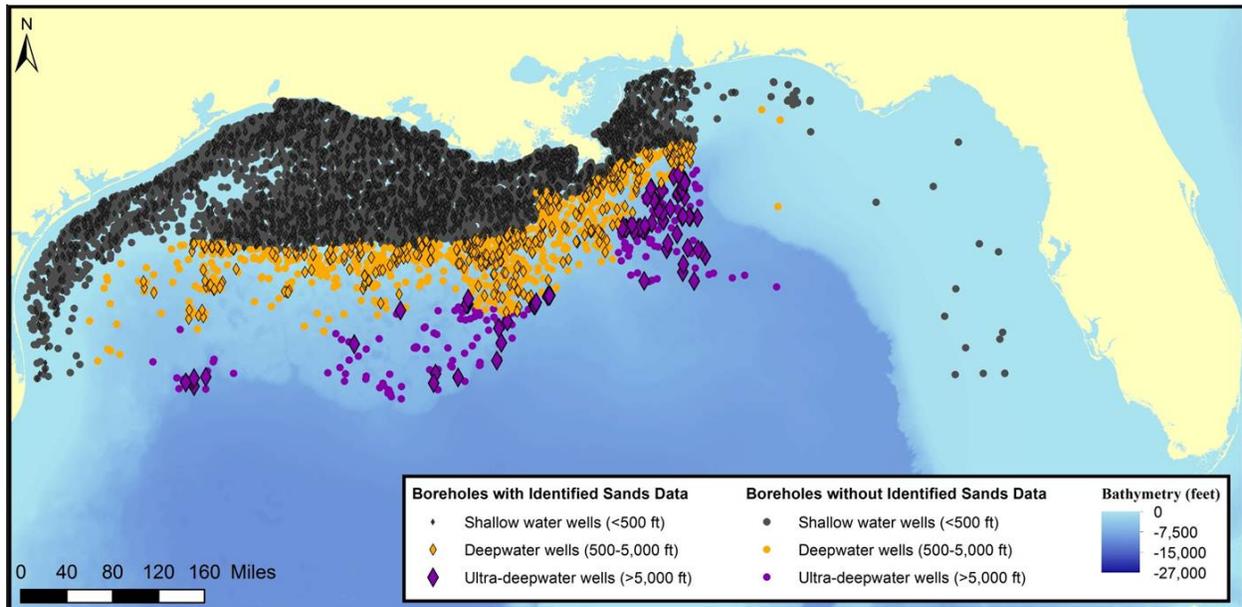


Figure 3: Top - Gulf of Mexico boreholes with identified sands data (diamonds) and without identified sands data (circles). Classified based on water depth; less than 500 ft in black, between 500–5,000 ft in orange, and greater than 5,000 ft in purple. Point data from BSEE "2008 Sands" Atlas of Gulf of Mexico Gas & Oil Sands Data and July 2012 borehole data.

Water column and surface data

To provide a balance between data size and resolution, the raster data for the northern Gulf of Mexico was created in two different resolutions, 30 m and 90 m. Modeling with raster data along the intricate coastal regions of the Gulf requires raster data that can represent at least the major channels where water flows in and out of the estuaries. Some of these are just over 30 m in width requiring the use of raster data that is 30 m or better in resolution. However, the northern half of the Gulf of Mexico is approximately 1500 by 1000 km. At 30 m a raster image of this area would be about 1.5 Gigapixels (approximately 1.5 billion pixels). At the same time the complexity and available data for the open ocean portion of the Gulf is much lower. This means we can use lower resolution data for the open waters than in the coastal areas. There is also data available at 90 m for the entire Gulf reducing the overall raster size to 180 megapixels (or 180 million pixels), which will provide faster access times.

The approach chosen is to represent the coastal areas at 30 m with a series of rectangular areas and then represent the open Gulf at 90 m (Figure 4). The areas along the coast were selected to ensure that entire coastal water systems are contained within a single area. These rasters overlap by at least 30 km to allow modeling software to first update the position of model elements, such as oil spills and animals, and then check to see if the elements need to be moved into another area. The raster data used with modeling such as tides, currents, temperature, and salinity will then be rendered within each of the areas at the specified resolution.



Figure 4: Selected resolution areas for the Northern Gulf of Mexico. Raster data for coastal areas will be at 30 m, while data for the open water will be at 90 m.

3.3 REGISTRATION

Subsurface data

Subsurface data must be registered not only to the proper location on the earth's surface but to the correct depth as well. Gulf of Mexico boreholes with sand data or well logs have been located on the surface by correlating the unique identifier of the well to the same identifier on a list of borehole information available from the BSEE. The locations are checked based on the given offshore area and lease block for the wells of interest. Listed subsurface depths are either referenced to sea level (subsea depth) or the level of the kelly bushing, which is given with the data. Geospatial software allows all depths to be referenced to sea level. Well logs are obtained as TIFF images showing the depth scale generated during logging, which is manually entered into IHS's Petra software to be comparable to other data.

Because wells are often not drilled vertically, actual locations of the data within a well, such as the location of a sand formation, may vary laterally between the surface and bottom location of the well. Both surface and bottom-hole locations for Gulf of Mexico boreholes are available from BSEE. Directional surveys can be used to correct for this, but are currently inaccessible.

Water column and surface data

It is critical that all datasets are properly registered to the earth's surface (i.e. align with one another spatially). We used the National Oceanographic and Atmospheric Administration's (NOAA) nautical charts (Appendix B) to provide a check on the registration and completeness of other datasets. These charts are available in vector and raster versions from the NOAA website. Because we were only using them for registration, we downloaded the raster charts that were of intermediate resolution for the entire U.S. Gulf coast (Appendix A). All datasets were then checked against these charts and were rejected if there were errors of more than 15 meters or one-half our highest target resolution.

3.4 PROCESSING

Subsurface data

Where available subsurface data do not have associated spatial information, they have been correlated to a list of well information from the BSEE (downloaded 7/10/2012, updated periodically) using the unique American Petroleum Institute (API) identifying number assigned to each well. Data are visualized and analyzed using both ArcGIS and IHS's Petra version 3.8.1. Well logs are imported as raster images into Petra, which is used as a database and for visualization and correlation of subsurface data. Raster images are depth-registered then correlated to their nearest spatial neighbors using the log patterns.

Water column and surface data

A variety of GIS-based tools were used to complete the processing. ArcGIS for Desktop version 10.0 was used for most of the visualization, projection, and sub-sampling tasks. When problems with ArcGIS occurred, we also used ArcGIS version 9 and BlueSpray from SchoonerTurtles, Inc. BlueSpray was also used to visualize large datasets. The Python scripting language was used with the Wingware development environment to write scripts for batch processing large numbers of files. The software package "R" was used for statistical analysis (<http://www.r-project.org/>).

A Structured Query Language (SQL) database design was created to allow integration and querying of the survey data. The database was created in PostgreSQL with the PostGIS extension. The PHP Hypertext Preprocessor (PHP) language was used to process and insert data into the database. PHP was also used to provide access to the database through the website.

3.5 DISSEMINATION

All of the data mentioned here is publically available through the Energy Data Exchange (EDX) at <https://edx.netl.doe.gov/>. EDX will serve as the primary resource for IAM datasets from NETL but also serves as a coordination and collaboration tool to help drive other users/consumers of these data to those resources.

In addition, working datasets are coordinated for the project team, but are also available to the public, on the Spatial Environmental Energy Research (SEER) website at <http://seer.science.oregonstate.edu>. This includes the file-based data and access to the database of survey data. Additional datasets and model results will be made available through the same websites as they become available.

4. RESULTS

4.1 SUBSURFACE

Interpretation of geologic units below the surface relies on information from published literature and the use of borehole and geophysical information. When available and appropriate, this includes borehole wireline logs, borehole-specific tests, cores, cuttings, and 2D/3D geophysical surveys. Generally, wireline logs are the most available dataset at present. 2D/3D geophysical surveys have been acquired by commercial and public institutions, but access to them is generally restricted to industry or sponsors. Resources for data currently utilized by this project for interpretation and analyses are summarized in Table 2 below.

BSEE makes well logs and historical documents from the original production companies available for purchase through their online ordering system. A link to BSEE’s resources is also provided through EDX. Also available from the BSEE data center, along with information regarding Gulf of Mexico drilling infrastructure, production, and well data, is a data set describing 13,625 reservoir sands below the U.S. federal waters. Data include well, depth, sand name, age, thickness, porosity, water saturation, permeability, temperature, and pressure, among others, and hydrocarbon production statistics, including the estimated amount and type of resource available. As of December 2012, the most recent data available are from June 2011 and contain data through 2008 (BSEE). Both data sets contain information submitted to BSEE, or its predecessor the Minerals Management Service (MMS), by oil companies, other government agencies, and the public. To spatially reference these data sets, they are used in conjunction with a list of information about more than 50,000 wells, which is updated regularly by BSEE, by correlating the API identifiers.

Eventually, other information from published sources, in conjunction with the well logs, will be used to correlate geologic units across the entire deep water Gulf of Mexico. For example, wireline log correlations and interpretation of geologic strata and subsurface properties will augment available point data. Previous subsurface interpretations in the Gulf of Mexico have been limited to smaller, more specific areas of interest, as evident in the literature (Bernman and Rosenfield, 2007; Mancini et al., 2008; Prather et al., 1998). Our focus is on closing the data gaps across the Gulf and providing an overall geologic framework estimating subsurface properties, such as porosity, temperature, and pressure, in areas of interest, for use in modeling hydrocarbon reservoirs.

Table 2: Sources of subsurface data

Name	Used For	Area Covered
Bureau of Safety & Environmental Enforcement (BSEE) Well Information	Location information for well logs, sands table API numbers	Coastal areas to open water
Bureau of Safety & Environmental Enforcement (BSEE) Atlas of Gulf of Mexico Gas & Oil Sands Data	Proxy for geologic units when correlating logs; contains subsurface properties for reservoir	Coastal areas to open water

4.2 BATHYMETRY

Bathymetry datasets for the Gulf of Mexico are available from numerous sources, collected using a variety of methods and encompassing various spatio-temporal extents at different spatial resolutions. Using the main authoritative source for bathymetry in U.S. waters, NOAA, bathymetric data were downloaded from the National Geophysical Data Center (NGDC) at 90 x 90 m resolution for the open waters of the Gulf of Mexico and at 30 x 30 m for the Gulf’s surrounding estuaries. Data gaps in the higher resolution bathymetry datasets for the estuaries were rectified using either a re-sampled 1/3 arc-second Digital Elevation Models (DEM) rasters from NOAA or by interpolating hydrographic survey point data into a new bathymetry raster layer (data from various sources, see Table 3).

A bathymetry raster for the entire Gulf of Mexico extent was created using ArcGIS by mosaicking the 30 x 30 m estuary bathymetry datasets with the 90 x 90 m bathymetry layer. Before processing the high resolution areas the 90 x 90 m bathymetry layer was re-sampled to make the coastal areas a uniform 30 x 30 m cell size. The mosaic tool and the pre-defined study extents for the Gulf (Figure 4) were then used to create 30 x 30 m bathymetry layers for the estuaries and coasts and a 90 x 90 m bathymetry layer for the open waters of the Gulf. These data will then be leveraged for modeling subsurface characteristics, the movement and behavior of hydrocarbon plumes, and species, to assist with the evaluation and assessment of risks and potential impacts from hydrocarbon development in the Gulf of Mexico.

Table 3: Sources of bathymetry data

Name	Data Type	Area Covered
NOAA coastal inundation data set Coastal DEM	Raster, 90 m	South Padre Island Panama City Mobile Bay
TWDB Hydrographic Surveys	Points	Sabine Lake
NOAA Hydrographic Survey Data	Raster, 30 m	Aransas Bay Atchafalaya Bay Baffin Bay Barataria Bay Corpus Christi Bay Galveston Bay Matagorda Bay Mississippi Sound Mobile Bay San Antonio Bay Terrebonne Bay Calcasieu Lake

One caveat identified by utilizing this method of combining different spatial resolution bathymetry rasters was a loss of bathymetry data detail for ship channels between the estuaries

and open waters of the Gulf (Figure 5). This problem was noticed in the 90 x 90 m bathymetry layer for the Matagorda Ship Channel in Matagorda Bay, Texas (Figure 5). For our modeling purposes, this data discrepancy would prevent the appropriate movement of hydrocarbons and organisms into and out of the bays. The problem was fixed by creating a new shapefile in ArcGIS with a set depth attribute of -15 m to represent the continuation of the shipping channel into the open water. Once the shapefile was created, it was then converted into a raster using the depth attribute as the value field and then the new shipping lane raster was mosaicked into the associated 90 x 90 m bathymetry resolution area.

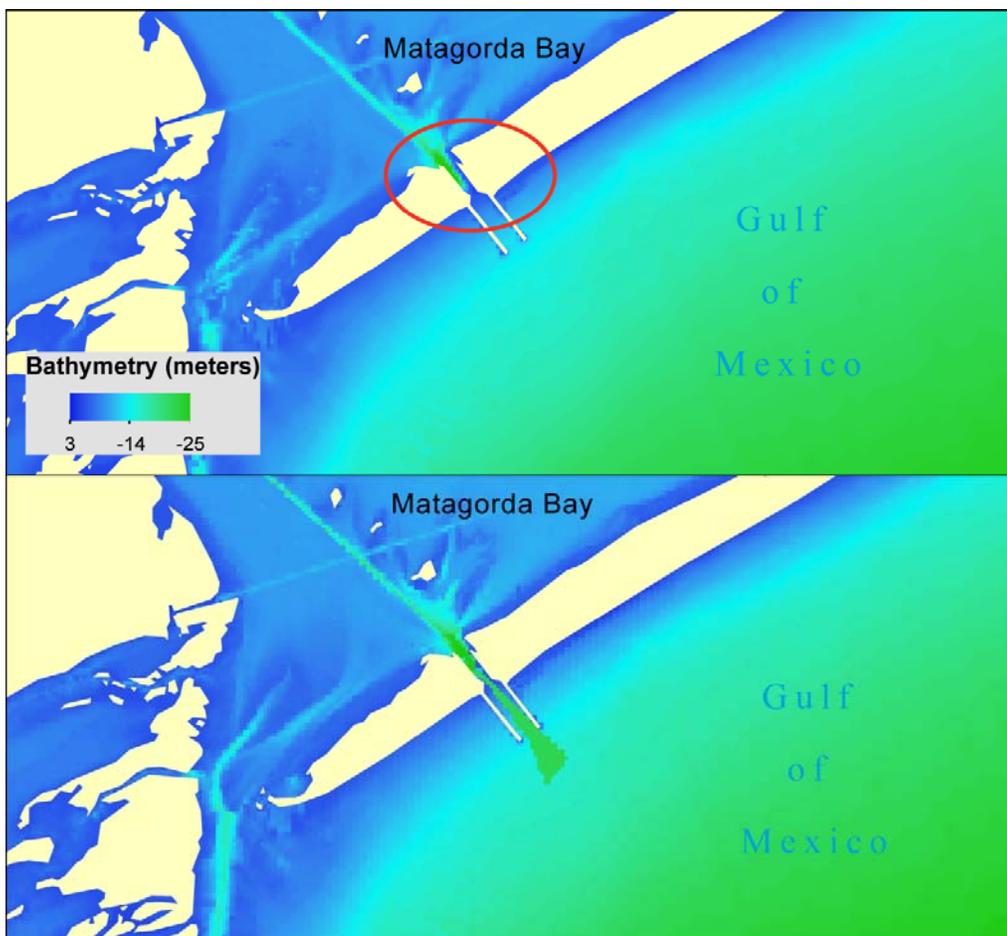


Figure 5: Edits made to the bathymetry layer to extend the Matagorda Bay shipping channel into open water.

4.3 BOTTOM TYPE

Understanding correlations between bottom type and species distributes can help predict species locations and be used to assess potential impacts on a species from a natural hydrocarbon seep or uncontrolled loss. The bottom type for our analysis was derived from over 230,000 point locations within Gulf of Mexico, provided by The Institute of Arctic and Alpine Research (INSTAAR), that contained categories for the proportion of mud, clay, silt, and sand for each point on the seabed (Jenkins, 2010). These data were parsed and each bottom type category was separated for processing focusing on quantifying the amount of mud or sand throughout the Gulf

since bottom dwelling organisms target habitats with a certain mud or sand composition (Cook and Lidner, 1970; Springer and Bullis, 1954). Once each bottom type category was separate, the points were smoothed based on their percent composition for each bottom type to create a continuous surface of bottom types for our study areas (Figure 6).

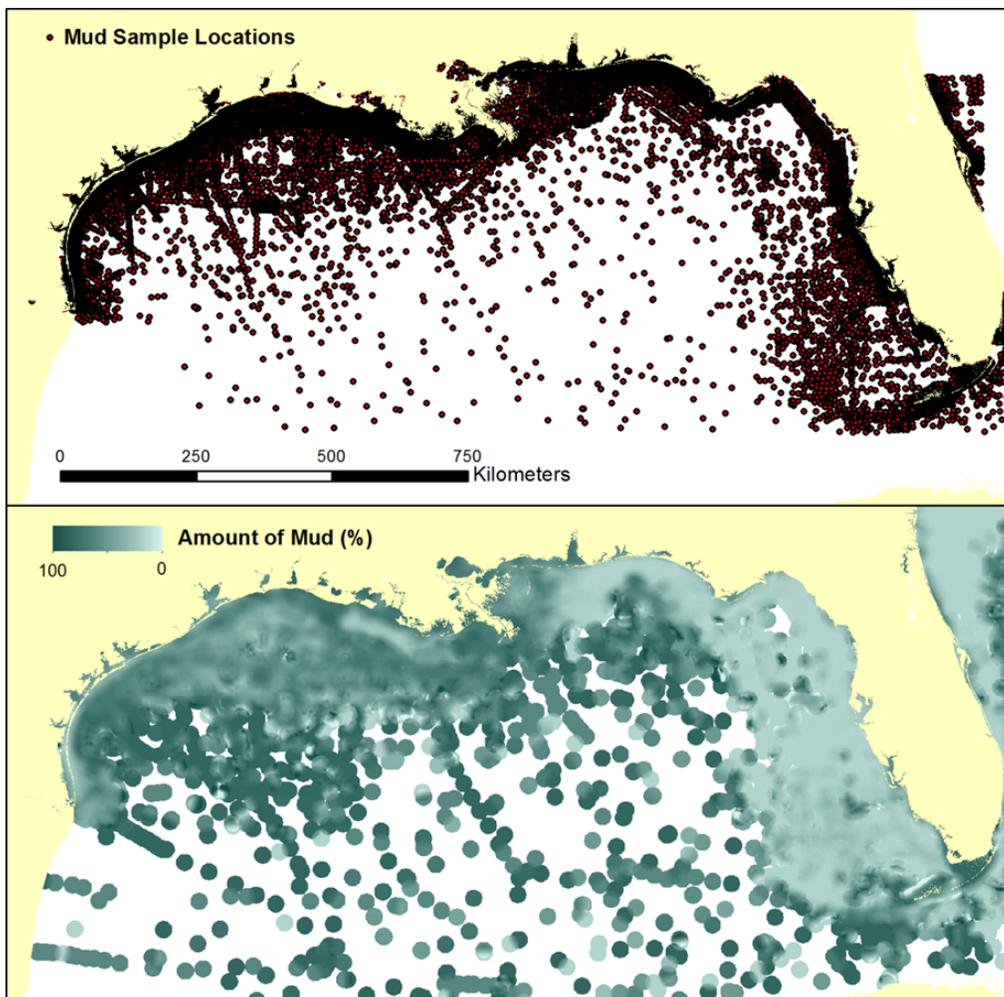


Figure 6: Top - Point locations for bottom sediment samples taken from the Gulf of Mexico. Bottom - Continuous surface derived from the bottom sample point locations. Continuous surface created by kernel smoothing.

4.4 INFRASTRUCTURE AND BOUNDARIES

Information about the infrastructure supporting hydrocarbon development within the Gulf of Mexico, including drilling platforms, wells, pipelines, and lease blocks, (Figure 7) are maintained by BOEM and BSEE and made available through the Multipurpose Marine Cadastre (MMC) website. The information available for download includes 7,020 platform structures, 43,941 exploratory wells, and over 15,900 pipelines available to transport hydrocarbons out of the Gulf of Mexico. Once the required infrastructure datasets were downloaded (Table 4) some of the datasets needed to be converted from an Arc Interchange format (.e00 file extension) into a shapefile with the appropriate spatial reference system using ArcGIS. These infrastructure

datasets will be used to better understand the connections between deep water hydrocarbon development and land, helping to identify potential development sites and identify potential infrastructures that might be impacted by a spill or blowout.

Table 4: Sources of infrastructure and boundary data

Name	Data Type	Area Covered
MMC Drilling Platforms	Points	Open Water
MMC Oil and Natural Gas Wells	Points	Open Water
MMC Selected Pipelines	Points, polylines	Open Water
MMC Active Oil and Gas Leases	Polygons	Open Water
MMC Outer Continental Shelf Lease Blocks	Polygons	Open Water
MMC Outer Continental Shelf Protraction Diagrams	Polygons	Open Water

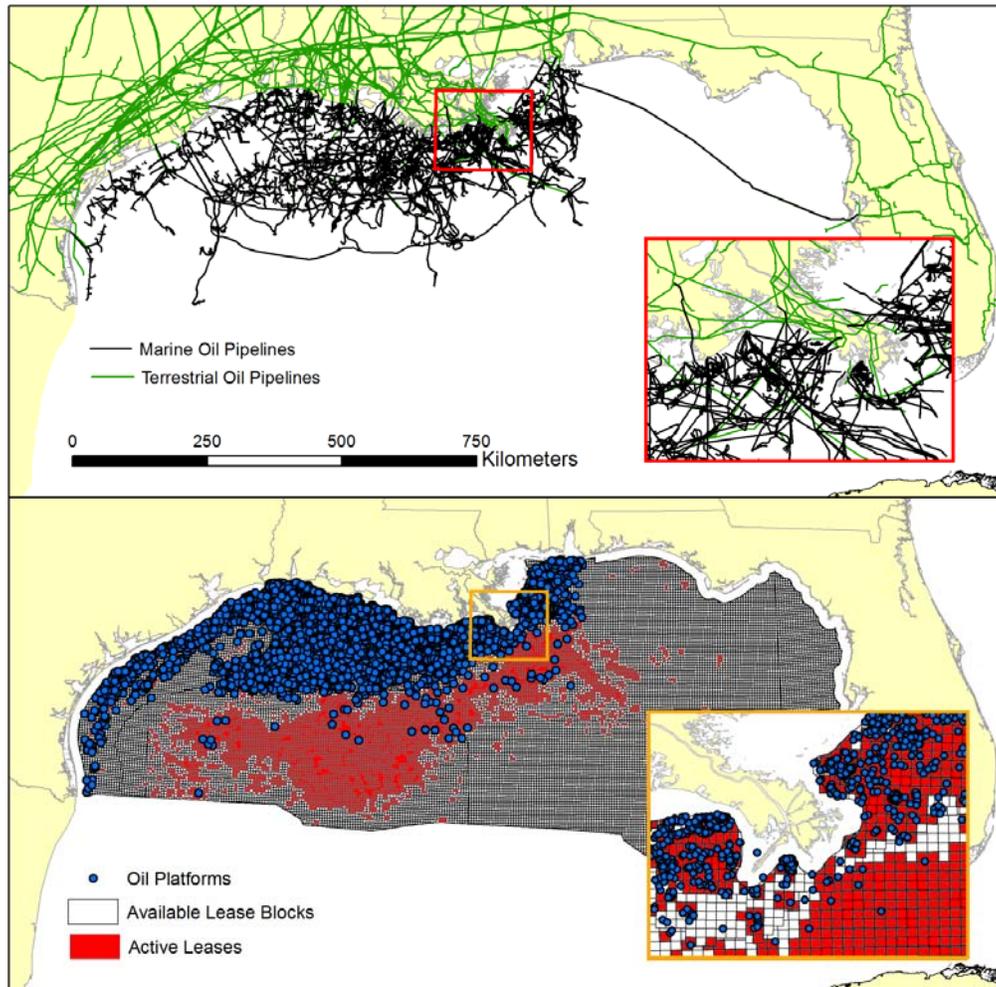


Figure 7: Top - Pipelines connecting marine oil wells to terrestrial oil refineries. Bottom - Point locations for Oil platforms in the Gulf of Mexico with available and active lease blocks.

4.5 PHYSICAL OCEANOGRAPHIC DATA

Current and tide data within the Gulf and surrounding estuaries are collected by a number of buoys, tidal stations and stream gauges (NOAA, 2012), which are used to build models at different spatio-temporal resolutions. Hydrodynamic properties for the open ocean are provided from the Intra-Americas Seas Nowcast/Forecast System (IASNFS) model and the AmSeas (America Seas) model (Table 5). Both models are based off the Naval Research Laboratory's Navy Coastal Ocean Model (NCOM) and provide predicted currents, salinity (Figure 8), sea surface height, sea surface temperature, mixed layer depth, and maximum gradient density. IASNFS data, provided by the Northern Gulf Institute (NGI), has a 3.7 km spatial and 6 hr temporal resolution for predicted values prior to 2011, after which the AmSeas model will be used, since it provides an improved 3 km spatial and 3 hr temporal resolution. For the estuaries surrounding the Gulf, current and tide data from models created by the Texas Water Development Board (TWDB) and NOAA (Table 5) were utilized since they provided a higher spatial resolution for tide and current predictions within the estuaries, thus providing the necessary spatial resolution required for our modeling tasks. The hydrologic and hydrodynamic predictions will feed into our models to better predict hydrocarbon movements and behaviors after a natural seep or uncontrolled loss event, and the movements and behaviors of species within the Gulf.

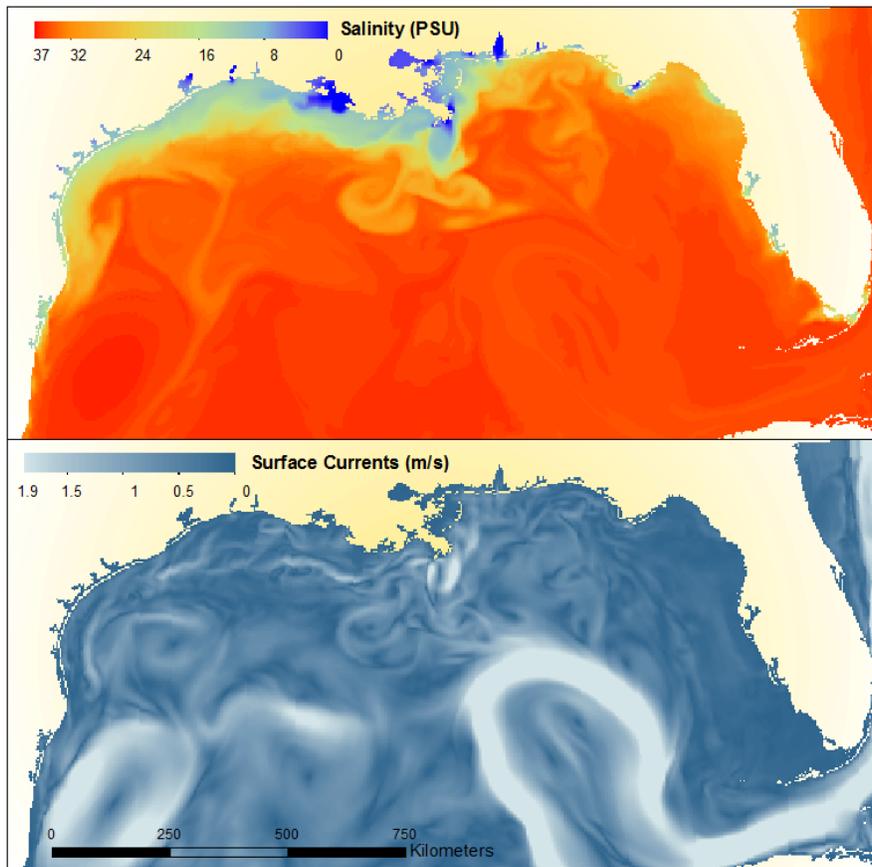


Figure 8: IASNFS nowcast of sea-surface salinity and currents for April 20, 2010 (12:00 GMT).

Table 5: Sources of data on water movement

Name	Data Type	Area Covered
Navy Coastal Ocean Model (NCOM) including IASNFS and AmSeas models	Point	Open Ocean
Northern Gulf of Mexico Operational Forecast System (NGOFS)	Point	Louisiana coastal oceans and estuaries
Tampa Bay Operational Forecast System (TBOFS)	Point	Tampa Bay
TWDBs TxBLEND	Point	All Texas estuaries

4.6 ESTUARINE HABITATS

The importance of estuarine habitats to various species throughout their life, including threatened, endangered, and commercially-important species, required the assimilation habitat data Gulf-wide. Although numerous sources classify estuarine habitats surrounding the Gulf (Table 6), the National Wetlands Inventory (NWI) was utilized due to its spatial coverage and high spatio-temporal resolution. NWI, provided by the U.S. Fish and Wildlife Service, is a hierarchical system that classifies wetlands by system (marine, estuarine, riverine, etc.), water regime (subtidal, intertidal, non-tidal, etc.), and bottom type (mud, sand, gravel) and vegetation characteristics (emergent, shrub-scrub, submerged, etc.).

Table 6: Data sources evaluated for use in assembling estuarine habitat layer

Name	Data Type	Area Covered
National Wetlands Inventory	Polygon	United States
Submerged Aquatic Vegetation	Polygon	Texas and Alabama
Environmental Sensitivity Index	Polygon	All gulf coast states
NOAA Seagrass	Polygon	Gulf of Mexico
National Landcover Dataset (NLCD)	Raster, 30m	United States

The NWIs data were downloaded for each of the five Gulf States and merged/clipped in ArcGIS to our predetermined resolution area boundaries (Figure 4). For each resolution area we extracted NWI polygons coded as intertidal emergent wetland or aquatic bed (excluding algal and floating vascular types), and these were coded to indicate high-value habitat for estuarine-dependent species. All other subtidal polygons were extracted and coded to indicate secondary habitat or travel corridors for migrating species. Finally, the resulting vector layers were converted to 30 x 30 m rasters (Figure 9), which are incorporated into our model to predict the patterns and movements of species and help estimate potential impacts to estuarine habitats and the species found within them.

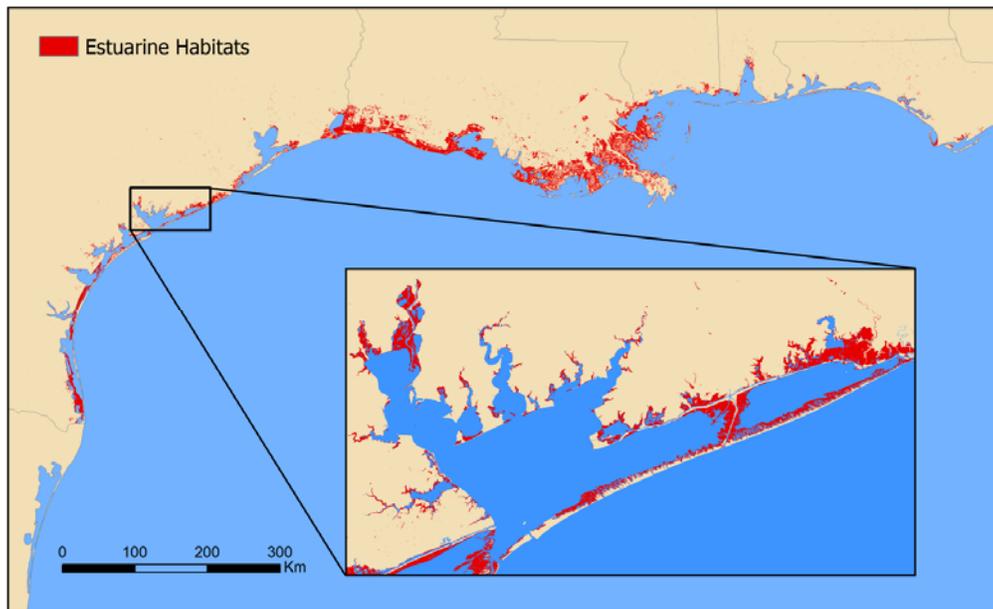


Figure 9: Intertidal emergent wetlands and submerged aquatic vegetation comprise the estuarine habitats layer.

4.7 SPECIES OCCURRENCES

A wide range of species occurrence data are collected in the open waters and surrounding estuaries of the Gulf of Mexico by various state and federal agencies, universities, and non-governmental organizations. Species occurrence data were obtained from fisheries-independent sampling efforts performed by federal and state agencies throughout the surrounding estuaries and open waters of the Gulf of Mexico (Table 7). Sampling methods used by the agencies varied, including the fishing gear used, collection and/or methods used to assess hydrologic and physical attributes, and how species were counted, measured, and weighed. Specific information about the sampling procedure can be obtained directly from each agency listed below. Despite different sampling methods, each sample included information about its location (latitude and longitude), species observed, species abundance and a subsample of individual species length. Some agencies also included information about species weight (individual and species), sex, maturity stage, and information about the bottom type from where the sample was collected, and certain hydrologic characteristics, including salinity, temperature, and depth. Since the species occurrence datasets obtained varied in both their data collection and processing methods by source, it resulted in datasets with different spatial and temporal resolutions (Table 7).

Table 7: Current list of species occurrence data sources and the difference between the datasets

Survey	Data Source	Types of Data	Species Information Obtained	Spatial Extent	Maximum Temporal Resolution
Southeast Area Monitoring and Assessment Program (SEAMAP)	Gulf States Marine Fisheries Commission (GSMFC)	Species occurrence, hydrologic data, bottom type	All species observed	Estuaries and open waters throughout the Gulf	02/1982-11/2011
Texas Fisheries-Independent Monitoring Program	Texas Parks and Wildlife Department - Coastal Fisheries Division	Species occurrence, hydrologic data	Brown and White Shrimp	Texas estuaries	01/1982-12/2011
Florida Fisheries-Independent Monitoring Program	Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute	Species occurrence	All species observed	Florida estuaries	03/1989-04/2012
Alabama Fisheries Assessment and Monitoring Program	Alabama Department of Conservation and Natural Resources-Marine Resources Division	Species occurrence, hydrologic data	All species observed	Alabama estuaries and some open water	01/2002-12/2011

To utilize the datasets for this study, a PostgreSQL database was designed to compile the species occurrence data into a common, unified data format (Figure 10). To compile the species occurrence data, each data source was converted from its original data format into tab-delimited text files, which were then parsed using a PHP script to write the information into the correct PostgreSQL database table (Figure 10). Once species occurrence datasets are loaded into the database, they can be queried and extracted into ArcGIS and used to create a layer for species abundance and distribution. The resulting spatial layers can then be used to validate species ranges for desired species of interest and the results of our models.

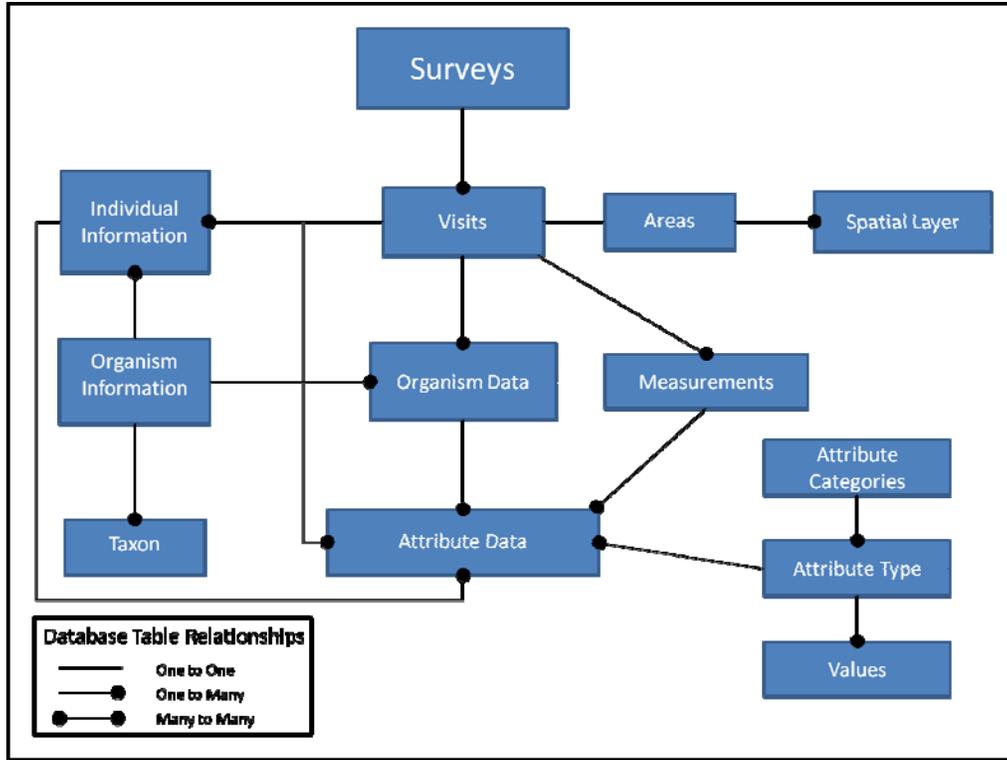


Figure 10: Structure and relationships in PostgreSQL database for combined species occurrence data.

To develop and test our model, our primary focus was on obtaining species occurrence datasets for commercially-important species of shrimp and finfish. We are also investigating data sources for non-commercial species, including protected, threatened, and endangered species, such as birds, sea turtles, and marine mammals from sources including the Ocean Biological Information System (OBIS), the Global Biodiversity Information Facility (GBIF), and the eBird dataset from Cornell University. Once the model has been developed, the goal is to model the potential impacts natural seeps and uncontrolled loss events could have on a variety of species within the Gulf of Mexico.

5. SUMMARY

The process of obtaining datasets, verifying their quality, and processing the data to suite our needs required different levels of effort. Although many datasets are readily available online for the Gulf of Mexico, other datasets required contacting sources to obtain the data or to clarify how the data collected, processed, and analyzed. In some cases, we are still negotiating with various agencies for datasets that would provide us with more information or fill in spatial and temporal data gaps. The amount of data available also varied greatly by source. For example, data available for commercial species far outweighed the data available for non-commercial species, including threatened and endangered species. Information on the uncertainty of most of the data was also difficult to obtain. In some cases we could not find detailed protocol definitions for how the data were collected so uncertainty was largely unknown. Therefore, it would be beneficial if the quality of the data were checked and documented with more uniform methods and made readily available with the datasets. We would also recommend that datasets be provided in standard file formats such as Shapefiles and TIFF files, and that proprietary formats such as Geodatabases are avoided.

The amount of data already available for the Gulf is impressive and will facilitate research and management activities for years to come. However, we are still working on collecting additional datasets to fill in gaps in our models, and identify additional datasets to help evaluate the economic impacts of potential hydrocarbon events. By the end of this project, we hope to make a large number of data sets relative to the Gulf of Mexico available in one location, in a common spatial reference, and in standard, open file formats so that other users who can utilize and leverage these datasets for their research can access the data quickly without having to replicating our efforts.

6. REFERENCES

- Annual Energy Outlook 2012 with Projections to 2035*; DOE/EIA-0383(2012); U.S. Department of Energy, Energy Information Administration, 2012.
- Berman, A. E.; Rosenfield, J. H. A new depositional model for the deepwater Wilcox-equivalent Whopper Sand - Changing the Paradigm. *World Oil Online* [Internet]. **2007**, 228.
- Bjorndal, K. A.; Bowen, B. W.; Chaloupka, M.; Crowder, L. B.; Heppell, S. S.; Jones, C. M.; Lutcavage, M. E.; Policansky, D.; Solow, A. R.; Witherington, B. E. Better science needed for restoration in the Gulf of Mexico. *Science* **2011**, 331, 537–538.
- Bureau of Ocean Energy Management (BOEM). Regional Leasing [Internet]. Available from: <http://www.boem.gov/Oil-and-Gas-Energy-Program/Leasing/Regional-Leasing/Index.aspx>
- Bureau of Ocean Energy Management (BOEM) and National Oceanic and Atmospheric Administration (NOAA). Multipurpose Marine Cadastre [Internet]. NOAA Coastal Services Center. Available from: <http://www.marinecadastre.gov>
- Boesch, D. F.; Turner, R. E. Dependence of Fishery Species on Salt Marshes—The Role of Food and Refuge. *Estuaries* **1984**, 7, 460–468.
- Brayman, M. Projection Analysis Distortion Tool [Internet]. ArcGIS Resource Center: ESRI Available from: <http://resources.arcgis.com/gallery/file/Geoprocessing-Model-and-Script-Tool-Gallery/details?entryID=6329253E-1422-2418-A0E5-8830C780E9D4>
- Buffler, R. T.; Thomas, W. A. Crustal structure and evolution of the southeastern margin of North America and the Gulf of Mexico basin. In *Phanerozoic Evolution of North American Continent-Ocean Transitions*; Speed, R. C. Ed. Geological Society of America: Boulder, CO, 1994.
- Campagna, C.; Short, F. T.; Polidoro, B. A.; McManus, R.; Collette, B. B.; Pilcher, N. J.; Mitcheson, Y. S.; Stuart, S. N.; Carpenter, K. E. Gulf of Mexico oil blowout increases risks to globally threatened species. *BioScience* **2011**, 61, 393–397.
- Cook, H. L.; Lindner, M. J. *Synopsis of biological data on the brown shrimp Penaeus aztecus aztecus Ives, 1981*; FAO Fisheries Report 57; Food and Agricultural Organization Fisheries, 1970; 1471–1497.
- Cowardin, L. M.; Carter, V.; Golet, F. C.; LaRoe, E. T. *Classification of Wetlands and Deepwater Habitats of the United States*. FWS/OBS-79/31; U.S. Department of the Interior, 1979. Available from: <http://www.fws.gov/wetlands/Documents/Classification-of-Wetlands-and-Deepwater-Habitats-of-the-United-States.pdf>
- Diegel, F. A.; Karlo, J. F.; Schuster, D. C.; Shoup, R. C.; Tauvers, P. R. Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin. *Salt Tectonics: A Global Perspective* **1995**, 65, 109–151.
- Dribus, J. R.; Jackson, M. P. A.; Kapoor, J.; Smith, M. F. The Prize Beneath the Salt. *Oilfield Review* [Internet] 2008, 20, 5–17. Available from: http://www.slb.com/resources/publications/industry_articles/oilfield_review/2008/or2008aut01_prizebeneath.aspx

- ESRI. *ArcGIS 10.0*. Environmental Systems Research Institute: Redlands, CA, 2012.
- Galloway, W. E. Depositional evolution of the Gulf of Mexico sedimentary basin. In *The Sedimentary Basins of the United States and Canada*, Miall, A. D. Ed. Elsevier, 2009; 505–549.
- Gulfsource.org. *The Gulf Ecosystem* [Internet]. Available from:
<http://gulfsource.org/ecosystem.html>
- Jenkins, C. J. *Seafloor Substrates*. INSTAAR, University of Colorado: Boulder, CO, 2010.
- Jernelöv, A. The Threats from Oil Spills: Now, Then, and in the Future. *Ambio* **2010**, *39*, 353–366.
- Johnston, J.; Cahoon, D.; La Peyre, M. Outer Continental Shelf (OCS)–Related Pipelines and Navigation Canals in the Western and Central Gulf of Mexico: Relative Impacts on Wetland Habitats and Effectiveness of Mitigation. OCS Study MMS 2009-048; 2009, 200.
- Konyukhov, A. I. Geological structure, evolution stages, and petroliferous complexes of the Gulf of Mexico basin. *Lithology and Mineral Resources* **2008**, *43*, 380–393.
- Korotenko, K. A.; Mamedov, R. M.; Mooers, C. N. K. Prediction of the Transport and Dispersal of Oil in the South Caspian Sea Resulting from Blowouts. *Environmental Fluid Mechanics* **2002**, *1*, 383–414.
- Lach, J. *IOR For Deepwater Gulf of Mexico 07121-1701*, Final; RPSEA, 2010.
- Lee, J. H. W.; Cheung, V. Generalized Lagrangian Model for Buoyant Jets in Currents. *Journal of Environmental Engineering* **1991**, *166*, 1085–1106.
- Levy, J. K.; Gopalakrishnan, C. Promoting ecological sustainability and community resilience in the US Gulf Coast after the 2010 Deepwater Horizon oil spill. *Journal of Natural Resources Policy Research* **2010**, *2*, 297–315.
- Lubchenco, J.; Sutley, N. Proposed US policy for ocean, coast, and Great Lakes stewardship. *Science* **2010**, *328*, 1485–1486.
- Maling, D. H. *Coordinate systems and map projections*; Pergamon Press: Oxford, New York, 1992.
- Mancini, E. A.; Obid, J.; Badali, M.; Liu, K.; Parcell, W. C. Sequence-stratigraphic analysis of Jurassic and Cretaceous strata and petroleum exploration in the central and eastern Gulf coastal plain, United States. *Aapg Bulletin* **2008**, *92*, 1655–1686.
- National Oceanic and Atmospheric Administration (NOAA). Center for Operational Oceanographic Products and Services [Internet]. Available from:
<http://tidesandcurrents.noaa.gov/>
- Oil Spill Commission (OSC). Final Report of the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling [Internet], 2011. Available from:
www.oilspillcommission.gov

- Prather, B. E.; Booth, J. R.; Steffens, G. S.; Craig, P. A. Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico. *Aapg Bulletin-American Association of Petroleum Geologists* **1998**, *82*, 701–728.
- Salvador, A. Late Triassic-Jurassic Paleogeography And Origin Of Gulf Of Mexico Basin. *Aapg Bulletin-American Association of Petroleum Geologists* **1987**, *71*, 419–451.
- Salvador, A. Origin and development of the Gulf of Mexico basin. In *The Gulf of Mexico Basin*, Salvador, A., Ed. Geological Society of America: Boulder, Colorado, 1991.
- Sawyer, D. S.; Buffler, R. T.; Pilger, R. H. The crust under the Gulf of Mexico basin. In *The Gulf of Mexico Basin*, Salvador, A. Ed. Geological Society of America: Boulder, Colorado, 1991.
- Springer, S.; Bullis, H. R. J. Exploratory shrimp fishing in the Gulf of Mexico, summary report for 1952–1954. *Commercial Fisheries Review* **1954**, *16*, 1–16.
- Submerged Lands Act. *U.S. Code*, Title 43. Public Lands, Chapter 29. Submerged Lands General Provisions, 43 USC §§ 1301-1315, 2002.
- Thormahlen, L. F. *Boundary Development on the Outer Continental Shelf*; U.S. Department of the Interior, Minerals Management Service: Lakewood, CO, 1999.
- Wilkinson, T.; Wiken, E.; Bezaury-Creel, J.; Hourigan, T.; Agardy, T.; Herrmann, H.; Janishevski, L.; Madden, C.; Morgan, L.; Padilla, M. *Marine Ecoregions of North America*; Commission for Environmental Cooperation: Montreal, Canada, 2009.
- Wu, S. G.; Bally, A. W.; Cramez, C. Allochthonous salt, structure and stratigraphy of the north-eastern Gulf Of Mexico Part II. Structure. *Marine and Petroleum Geology* **1990a**, *7*, 334–340.
- Wu, S. G.; Vail, P. R.; Cramez, C. Allochthonous salt, structure and stratigraphy of the north-eastern Gulf Of Mexico. Part I. Stratigraphy. *Marine and Petroleum Geology* **1990b**, *7*, 318–324.
- Yapa, P. D.; Zheng, L.; Nakata, K. Modeling Underwater Oil/Gas Jets and Plumes. *Journal of Hydraulic Engineering* **1999**, *125*, 481–491.

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APPENDIX A – DATA SOURCES AND WEBSITES

Website	Dataset	URL
Gulf States Marine Fisheries Commission	SeaMap	http://www.gsmfc.org
Bureau of Safety and Environmental Enforcement	Well Data Atlas of Gulf of Mexico Gas and Oil Sands Wireline logs	http://data.bsee.gov
Multipurpose Marine Cadastre	Active Leases OCS Blocks OCS Block Leases Pipelines Oil and Gas Platforms Oil and Gas Wells	http://www.marinecadastre.gov/Data/default.aspx
NOAA Gulf of Mexico Data Atlas	Bottom Sediments	http://www.ncddc.noaa.gov/website/DataAtlas/atlas.htm
Texas Water Development Board	Estuary hydrodynamic model outputs for Texas	http://www.twdb.state.tx.us/surfacewater_n/bays/oilspill/
Northern Gulf Institute - Ecosystem Data Assembly Center	AmSeas and IASNFS hydrodynamic model outputs	http://www.northerngulfinstitute.org/edac/
NOAA National Operational Coastal Modeling Program	Nearshore hydrodynamic outputs for Eastern LATEX shelf	http://tidesandcurrents.noaa.gov/models.html
U.S. Fish and Wildlife Service National Wetlands Inventory	National Wetlands Inventory	http://www.fws.gov/wetlands/
NOAA Digital Coast; USGS Gulf of Mexico Integrated Science	Submerged Aquatic Vegetation	http://csc.noaa.gov/digitalcoast/data/benthiccover http://gulfsoci.usgs.gov/
NOAA Office of Response and Restoration	Environmental Sensitivity Index	http://response.restoration.noaa.gov/esi
NOAA Coastal Ecosystem Maps	NOAA Seagrass	http://www.ncddc.noaa.gov/website/CHP/viewer.htm
Multi-Resolution Land Characteristics Consortium	National Landcover Dataset (NLCD)	http://www.mrlc.gov/

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APPENDIX B – NOAA NAVIGATIONAL CHARTS

Below is a list of the NOAA navigational charts that were used to verify spatial registration and completeness of datasets.

13001 - Lower Laguna Madre
13004 - Upper Laguna Madre
13007 - Corpus Christi
11313 - Espiritu Santo Bay
11316 - Matagorda Bay
11321 - Freeport
11323 - Entry to Galveston Bay
11326 - Galveston Bay
11332 - Entry to Sabine Lake
11341 - Sabine Lake
11345 - Vermillion Bay
11352 - Timalier Bay
11358 - Barataria Bay
11361 - Mississippi passes into the gulf
11363 - Chandeleur Islands
11364 - Mississippi River outlet
11371 - Lake Borgne
11373 - Pascagoula
11376 - Mobile Bay
11382 - Pensacola Bay
11388 - Chctawhatchee Bay
11389 - St Andrew Bay
11401 - Apalachicola Bay
11405 - Apalachee Bay
11407 - Deadman Bay
11408 - Waccassa Bay
11409 - Bayport
11412 - Tampa Bay
11424 - Venice

11426 - San Carlos Bay

11429 - Cape Romano

11431 - Cape Sable

11442 - Key West

11452 - Florida Bay



The National Energy Technology Laboratory (NETL) conducts cutting-edge energy research and technology development and analyzes energy systems and international energy issues for the U.S. Department of Energy. The NETL-Regional University Alliance (NETL-RUA) is an applied research collaboration that combines NETL's energy research expertise with the broad capabilities of five nationally recognized, regional universities: Carnegie Mellon University (CMU), The Pennsylvania State University (PSU), the University of Pittsburgh (Pitt), Virginia Tech (VT), and West Virginia University (WVU), and the engineering and construction expertise of an industry partner (URS). The NETL-RUA leverages its expertise with current fossil energy sources to discover and develop sustainable energy systems of the future, introduce new technology, and boost economic development and national security.



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