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Gulf of Mexico Water Resources

Utilizing NASA Earth Observations to detect factors contributing to hypoxic events in the southern Gulf of Mexico

 **Technical Report** 

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Rebecca Chapman (Project Lead)

Irma Caraballo Álvarez

Alannah Johansen

Åse Mitchell

Bridget Smith

Mackenzie Taggart

Dr. Juan L. Torres-Pérez, Bay Area Environmental Research Institute, DEVELOP National Program

(Science Advisor)

Dr. Sherry L. Palacios, Bay Area Environmental Research Institute (Science Advisor)

Chase Mueller, Bay Area Environmental Research Institute (Science Advisor)

# I. Abstract

Monitoring and analyzing harmful algal blooms (HABs) and hypoxic events in the southern coastal areas of the Gulf of Mexico (GoM) is important for watershed management and mitigation of environmental degradation. This study uncovered trends and dynamic characteristics of chlorophyll-a (Chl) concentration, sea surface temperature (SST), colored dissolved organic matter index (CDOM), and photosynthetically available radiation (PAR), as evident in 8-day standard mapped image (SMI) products from the MODIS instrument on the Aqua platform from 2002-2015 using Clark Labs TerrSet Earth Trends Modeler (ETM). Additionally, sediment and nutrient loading values of the Grijalva-Usumacinta watershed were modeled using the ArcGIS Soil and Water Assessment Tool (SWAT). Normalized Difference Turbidity Index (NDTI) and Floating Algae Index (FAI) were generated using Landsat 8 Operational Land Imager (OLI) scenes for 2014-2015. These results indicated high levels of nutrient and sediment loading from the Grijalva-Usumacinta River Basin, correlating to high frequencies of hypoxic events and HABs in the coastal region of the southern GoM.

**Keywords**

Remote Sensing, Harmful Algal Blooms, Hypoxia, Nitrogen, Phosphorous, Sediment Loading, Grijalva-Usumacinta River Basin, Gulf of Mexico

# II. Introduction

**2.1 Background**

An exponential increase in the occurrence of coastal dead zones has been observed worldwide since the 1960s (Diaz and Rosenberg, 2008). These zones are characterized by hypoxic waters, where dissolved oxygen concentrations can no longer support marine life. Hypoxia occurs naturally and cyclically in coastal waters during upwelling events. Upwelling brings nutrients and organic sediments from the ocean floor into the photic zone. This results in a proliferation of primary producers throughout the water column, from suspended phytoplankton to coastal benthic communities of aquatic plants and macro-algae. However, the sudden increase in cell density blocks sunlight from reaching deeper waters. Therefore, the benthic communities that initially flourished during the nutrient influx start experiencing high mortality rates due to a lack of solar radiation. The consequent detritus accumulation then supports a large population of decomposers, who, in turn, deplete dissolved oxygen reserves due to high cellular respiration rates. Although this is a naturally occurring process, deforestation, fertilizer runoff, and erosion have all contributed to excess nutrient and sediment loading in coastal zones, thereby increasing the frequencies of algal blooms and hypoxic events (Rabalais et al., 2002).

Persistent seasonal hypoxia and dead zones occur frequently in the Gulf of Mexico (GoM) and are known to be influenced by runoff from the Mississippi River Basin (Diaz and Rosenberg, 2008). Unfortunately, little is known about the second largest contributor of sediment and runoff into the GoM, the Grijalva-Usumacinta River Basin. This watershed is an important source of drinking water, hydroelectric energy, fisheries, and other natural resources to the 6 million people who live within the region. Since the early 2000s, increasing frequencies of hypoxic events and algal blooms have been observed along the coastal continental shelf surrounding the river delta (Signoret *et al*., 2006). Additionally, many blooms in the southern GoM have been composed of toxin-producing algal species. These harmful algal blooms (HABs) have been implicated in eutrophication, fish kills, economic loss for fisheries, and human illness (Rabalais *et al*., 2002).

The federal government of Mexico has adopted a variety of laws aimed at the protection of surface and coastal water resources (Gutierrez, 2008). Unfortunately, many of the current water quality standards are outdated, and few are enforced (Oswald Spring, 2014). Therefore, a current assessment of the region is needed in order to create adequate environmental protection policies. Recently, a large collaborative effort between governmental and academic organizations has formed to focus resources on monitoring and controlling hypoxic events and HABs (Álvarez Torres & Gold, 2012). Combining these efforts with analyses of NASA Earth Observations will be vital in understanding the most important factors contributing to the degradation of water quality in this system due to HABs and hypoxic events.

**2.2 Objectives**

This project addressed the Water Resources Application area within NASA’s Applied Sciences Program. The main objective of this study was to use NASA Earth observations to identify indicators of hypoxic events and HABs in the southern Gulf of Mexico and connect their occurrences to nutrient and sediment loading from the Grijalva - Usumacinta River Basin.

Although there are challenges to directly measure dissolved oxygen using remote sensing techniques, several known indicators of hypoxic events and HABs can be detected or derived from Earth Observations. These indicators include chlorophyll-a (Chl), normalized difference turbidity index (NDTI), floating algal index (FAI), colored dissolved organic matter (CDOM), sea surface temperature (SST), and photosynthetically-available radiation (PAR).

Landsat 8 Operational Land Imager (OLI) remotely sensed imagery were used to perform a time series of FAI and NDTI in the southern Bay of Campeche (study area β) from 2013-14. Anomalies of Chl, SST, CDOM and PAR were determined for the entire GoM (study area γ) from 2002-14 using TerrSet Earth Trends Modeler (ETM) (Clark Labs, 2015) to determine timing and occurrences of algal blooms. These L3, 8-day SMI products were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua platform. Finally, the nutrient and sediment loading was modeled for the entire Grijalva-Usumacinta River Basin (study area α) using the ArcGIS Soil and Water Assessment Tool (SWAT) (ESRI, 2015) and compared to the timing of bloom events. Results of this study will be used to aid local environmental, fisheries, tourism, and health authorities in revising water quality standards and mitigating the impacts of future hypoxic events in the region.

**2.3 Study Areas**

Analyses were performed in three separate study areas: (α) the Usumacinta-Grijalva River Basin, (β) the coastal region along the southern end of the Bay of Campeche, and (γ) the Gulf of Mexico as a whole.

The Usumacinta-Grijalva River Basin is the second largest freshwater contributor to the Gulf of Mexico. The headwaters for both rivers are in Guatemala, however, the majority of the basin falls within the political boundaries of Mexico, with drainage from the states of Tabasco, Chiapas, and Campeche. Precipitation patterns are seasonal and determined by a tropical monsoon climate regime which results in a June to October wet season. Tropical rain forests historically dominated the basin, however, extensive deforestation has occurred in the region for the purposes of coffee plantations, cattle ranching, and slash-and-burn agriculture.

In the lowlands, the rivers extend into an expanse of marshes, swamps, bogs, and mangroves along the coast and delta. Unfortunately, both rivers have been engineered to reduce flooding, which has resulted in significant degradation of these wetlands.

The coastal waters influenced by the inflow from the Grijalva-Usumacinta River plume are located in the southern Bay of Campeche, off the coast of Tabasco. The natural resources of this coastal ecosystem support the local communities, as well as the fisheries and tourism industries.

**2.4 Project Partners**

The NASA DEVELOP Mexico Water Resources team at the Ames Research Center partnered with a variety of governmental and academic organizations for this international project. The goal of these partnerships was to add analyses from NASA Earth Observations to the recent efforts in water quality assessment and management in the region. This large collaborative effort includes the following organizations:

* Consorcio de Instituciones de Investigación Marina del Golfo de México y del Caribe (CiiMar-GoMC)
* Centro del Cambio Global y la Sustentabilidad en el Sureste (CCGSS)
* Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO)
* Centro Nacional de Datos Oceanográficos (CENDO)
* Universidad Autónoma de Baja California (UABC)
* Universidad Juárez Autónoma De Tabasco (UJAT)
* Secretaría de Marina (SEMAR)

Recently, CiiMar-GoMC, UJAT, CONABIO, UABC, and CCGSS have collaborated to focus resources on implementing *in-situ* water quality monitoring and management strategies for both hypoxia and HABs in the Bay of Campeche (Alvarez Torres and Gold, 2012). Additionally, the Federal Ministry of Health, through its directorship on Sanitary Risks Protection, is conducting surveys to identify and quantify the phytoplankton species that proliferate during HABs. Resources for *in-situ* environmental monitoring are limited, thus analyses of remotely-sensed data will be invaluable in increasing understanding of the drivers contributing to the high frequencies of hypoxic events in the southern GoM.

# III. Methodology

**3.1 Data Acquisition:**

**Aqua MODIS Standard Mapped Image (SMI) Products**

Aboard NASA’s Aqua satellite is the MODIS instrument, containing 36 spectral bands. SMI L3, 8-day composites for 2002-2014 were downloaded through the Ocean Color database. These data were produced and distributed through NASA Goddard Space Flight Center's Ocean Color Data Processing System (OCDPS) (NASA Goddard OCDPS, 2010). SMI products are byte-valued two-dimensional arrays of an equidistant cylindrical projection of the globe containing scaled real values. These products were used in creating a time series of Chl, SST, PAR, and CDOM.

**Landsat 8 Surface Reflectance (SR) Products**

Landsat 8 scenes were also acquired, processed, and analyzed for this project. SR climate data records (CDRs) were obtained and accessed through the USGS Earth Explorer database. CDR data from the OLI sensor were generated using the L8SR algorithm to atmospherically correct images online (USGS, 2015). Landsat 8 has eight 30-meter resolution spectral bands and one 15-meter resolution panchromatic band. These data were used for analyzing years 2013 - 2014 to derive FAI and NDTI in study area α. Bands 2, 3, 4, 5, and 6 were used to derive FAI and NDTI.

***In-situ* Data**

Streamflow data from the Grijalva - Usumacinta watershed were necessary for calibrating the SWAT model. These data were obtained from the Banco Nacional de Datos de Aguas Superficiales (BANDAS).

**Ancillary Data**

Ancillary data such as weather data, land cover maps, soil maps, and Digital Elevation Models (DEM’s) were required to appropriately run SWAT. SWAT is a hydrologic modeler used in this project to analyze stream, soil, slope, weather and land use data Grijalva-Usumacinta River Basin. Weather data utilized for this study were obtained from Texas A&M University. These data included temperature, precipitation, wind speed, relative humidity, and solar radiation. Land cover and soil maps were obtained from the United Nations University – Institute for Water, Environment, and Health (UNU-INWEH) database (UNU-INWEH, 2015). Two forms of Digital Elevation Models (DEM) were obtained from the USGS Earth Explorer database. ASTER GLOBAL DEMs provided 10 detailed tiles needed in study region β. These tiles were mosaicked together using ArcGIS, and merged with the larger DEM obtained from the Global 30 Arc-Second Elevation (GTOPO30) DEMs. These tiles provided the additional coverage in study area β that the GTOPO30 DEMs could not provide.

**3.2 Data Processing**

**Satellite Data**

MODIS products were processed using TerrSet’s Geospatial Monitoring and Modeling Software. TerrSet Earth Trends Modeler (ETM) was used to analyze Chl, SST, CDOM, and PAR for patterns consistent with algal blooms or hypoxic events. As determined by Stumpf *et al*. (2003), anomalies in Chl spectral signatures serve as the first indication timing and occurrence of algal blooms. Additionally, the CDOM to Chl reflectance ratio was developed by Morel and Gentili (2009) as a way of distinguishing live phytoplankton from detritus in the open ocean.

Landsat 8 scenes were processed using an ArcPy reflectance to index script in order to produce FAI and NDTI. FAI was followed from Hu (2009), who derived this index for open oceans and determined that this method is less influenced by atmospheric conditions than either Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI). NDTI was developed by Lacaux *et al*. (2006) as a method to isolate turbidity from all other spectral signatures.

Scientific advisors from the Bay Area Environmental Research Institute (BAERI) provided the script to automate FAI and NDTI. This script iterated through a chosen folder of TIFF files and applied FAI and NDTI to all images, with the resultant output being a new folder of raster files. Within the script, NDTI requires a customized setting for the minimum and maximum target pixels. There is a default setting to choose from, but for more accurate results in the study region, the invariants were chosen by hand. This was done by selecting and averaging multiple satellite image target pixel values of where the brightest and darkest land pixels were within a 3 x 3 grid. These values were set to 0.1752 maximum and .0289 minimum.

***In-Situ* Data**

To prepare *in-situ* data for SWAT analysis, the team georeferenced the acquired stream gauge data for further analysis and validation of the SWAT model. BANDAS provided a locator map of the Grijalva-Usumacinta watershed where each gauge station was located by its respective number. Georeferencing was done appropriately in ArcMap and the coordinates were exported into an MS Excel table that was used for further analysis in SWAT.

**3.3 Data Analysis**

**MODIS Earth Trends Analysis**

Short and long-term global trend analyses and temporal profiling for the GoM were performed for Chl, SST, CDOM, and PAR using TerrSet’s Earth Trends Modeler (ETM). The team explored the possibility of lagged relationships between series over time with linear modeling. This project also performed spectral decomposition using extended principal component analysis. This allows for a search for recurrent spatial and temporal patterns across each Chl, SST, CDOM, and PAR series.

**Landsat 8 FAI & NDTI Analysis**

ArcMap was used to analyze FAI and NDTI for Landsat 8 data. After the indices were applied to the raster datasets, the four tiles were mosaicked together in ArcMap and then analyzed using TerrSet’s Earth Trends Modeler (ETM). A user defined shapefile of the water in study area alpha was created to clip the index results to the final datasets, allowing for a stronger analysis.

**SWAT Analysis**

ArcMap was utilized for analyzing basin data in study area β using the SWAT tool. The SWAT application delineated a watershed area based on the DEM, which served as a model input, along with weather, soil, and hydrologic data. The river gauge data were used to calibrate the SWAT model for a more accurate look at the nutrient and sediment loading that are contributing to hypoxia in the southern GoM.

# IV. Results & Discussion

**Analysis of Results:**

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| Analysis Placeholder |

**Limitations:**

While executing this project, certain limitations arose within our methodological approach due to the nature of the models incorporated, as well as the spatial resolution of the Earth Observations utilized. *In-situ* chlorophyll-*a* and turbidity data do exist for the southern GoM, however the data collected are spatially and temporally limited. For this reason, validation of FAI and NDTI was performed using a separate Landsat 8 scene from the northern GoM where *in-situ* data are readily available. Second, the Grijalva-Usumacinta River Basin is a complex system with multiple distributaries that serve as outlets within the delta. Although the SWAT model was calibrated using gauge data from an extensive network, several of the smaller, yet influential, distributaries were not reflected in the delineated watershed. Third, the algorithm used to derive level III SMI MODIS products was designed for Class 1 open ocean waters. Therefore, additional uncertainty exists within the Class 2 waters influenced by the river basin where the study area is located (Moore et al., 2009).

**Errors & Uncertainty:**

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| Errors Placeholder |

**Future Work:**

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| Future Work Placeholder |

# V. Conclusions

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| Conclusions Placeholder |

Satellite measurements of Chl-*a* anomalies and SST can provide many important indicators of HABs. However, identifying species-specific blooms remains a challenge in remote sensing and may be mitigated with the availability of hyperspectral missions.

# VI. Acknowledgments

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# VIII. Content Innovation

**Audio Slides:** Earthzine Virtual Poster Session (VPS): Haunting the Gulf: Dead Zones Linger in Shallow Waters

**Glossary Viewer:** Creation of a glossary application of all the terms, methods, and abbreviations used in this project to allow for an effortless and enjoyable reading experience.

# IV. Appendices