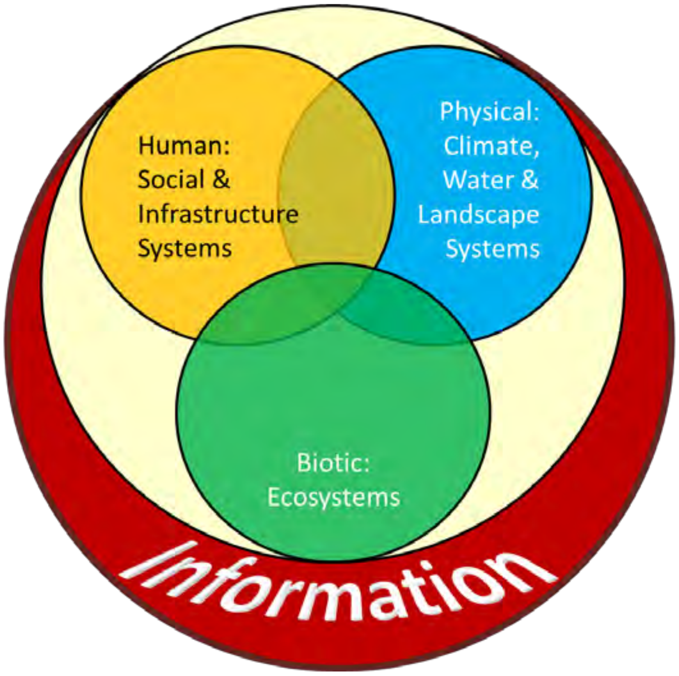
Ecosystem Approach to Management for the Northern Gulf of Mexico

By The Northern Gulf Institute Ecosystem Team



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Executive Summary

This report documents efforts toward implementing an Integrated Ecosystem Assessment (IEA) of selected Gulf of Mexico ecosystems as part of an overall Ecosystem Approach to Management (EAM) effort by the National Oceanic and Atmospheric Administration.

The work described here had the following objectives:

a. Develop indicators that will define ecosystem "States" for previously initiated Integrated Ecosystem Assessments (IEA) of Perdido Bay, Florida; Mississippi Sound, Mississippi; Barataria Basin, Louisiana; and Galveston Bay, Texas;
b. Produce a model framework to link State indicators to Drivers and Pressures; and
c. Create a prototype system for the northern Gulf that incorporates findings of these IEA.

The systems approach to resource management is defined here as: Managing resources holistically -- with the knowledge that the human ecosystem includes a variety of components that interact with each other individually and globally through processes, behaviors, and feedback mechanisms which must be elucidated in order to describe the effects of external forces and internal actions. Integrated Ecosystem Assessment (IEA) is "syntheses and quantitative analysis of information on relevant physical, chemical, ecological, and human processes in relation to specified ecosystem management objectives" and begins with the identification of a critical management or policy question which helps shape and inform ecosystem management.

IEA employs a Drivers-Pressures-States-Impacts-Responses (DPSIR) framework for scoping the ecosystem assessment process and setting management goals. However, the word "Impacts" has negative connotations that may inhibit its applications to some ecosystem effects. For that reason, some practitioners replace "Impacts" in the DPSIR framework with "Ecosystem Services", producing the acronym DPSER.

The work presented here employs conceptual and numerical models of physical and ecosystem processes and establishes a risk framework of interpreting findings. Ecosystem Risk is defined as a measure of the probability and the magnitude of ecosystem effects. The effects can be ecosystem services preserved, gained, or lost. It also employs Sulis, a natural resource assessment system, as an architecture and a software framework. Development of an ecosystem model with food web and fisheries components was begun.

Four systems are examined here – Galveston Bay, Texas; Barataria Basin, Louisiana; Mississippi Sound in Louisiana, Mississippi, and Alabama, and Perdido Bay, Florida. They represent a variety of northern Gulf of Mexico estuarine ecosystems over a rather narrow range of latitude, thus offering ample opportunities for contrast and comparison.

Three Driver categories – Hydrologic Modification, Climate, and Human-Related Processes – and 13 Pressures have been identified that are pertinent to at least one of the four systems. Salient commonalities are that (1) Human-Related Processes dominate Drivers for the region, with Local Population Size and Tourism/Recreation cited for all systems and (2) five Pressures

manifest those drivers: increased fishing effort, increased urban/coastal development, increased boat traffic, increased nutrients, and increased pollution.

Nearly equal distributions of Pressures were identified at different scales, ranging from individual lagoons to entire estuaries, but substantial dissimilarities in at least some physical processes suggests that while management measures may be similar at multiple scales, evaluation of the system's behavior in response to those measures may not be. For example, total dissolved nitrogen (TDN) concentrations were always higher within each of the individual Perdido Bay lagoons than in the surrounding Bay. These results suggest that the assessment step should include both the smaller scale features and the overall system.

Human-Related Processes is the most prevalent IEA Driver category, affecting all four systems. Five related Pressures – *Increased Fishing Effort, Urban/Coastal Development, Boat Traffic, Nutrients,* and *Pollution* are common to all four systems. Human-related pressures are *fishing effort, urban and coastal development, boat traffic, eutrophication* and *chemical pollution.*

Habitat modification or loss is the most common Impact associated with the four-system Drivers-Pressures-States, followed by *Lack of support for responses* and *Change/loss of native species*. Other impacts, such as *Increased storm surge* and *Eutrophication*, tended to be applicable to one or two systems instead of all four.

Primary Ecosystem Services affected by the impacts, in decreasing order of occurrence, for the four systems are *Habitat Formation, Food,* and *Educational*.

As the size of coastal systems increase (for instance when we move from small lagoons to large estuaries), or as we move from the coastal environment to offshore pelagic environments, the relative importance of human-generated stressors is reduced, with natural stressors (climate processes) becoming more important.

The work described here demonstrates that:

- The IEA/EAM framework based on the DPSIR/DPSER process is a valid approach to identify, prioritize and manage natural and human-induced stressors in Gulf of Mexico systems. Application of this approach to four systems in the Gulf of Mexico that range widely in environmental, societal and economic characteristics shows that this approach is comprehensive and adaptable to the whole suite of natural-human systems in the Gulf of Mexico.
- The Sulis Community Ecosystem Models and Informatics Services can be used for performing Integrated Ecosystem Assessments, including the framework for evaluation of management responses including risk assessment. Uncertainty and risk can be successfully addressed by extending well-established practices from the physical sciences to ecosystem sciences and modeling.
- The TroSim ecosystem model will provide a management assessment tool for Mississippi Sound.

- The Gulf of Mexico offers an excellent domain in which to develop, evaluate and validate strategies for environmentally and economically-sustainable development and exploitation. These resource management strategies can then be applied to allow for a vibrant economy combined with sustained environmental health. Completing the IEA/EAM framework in the Gulf of Mexico will allow this management strategy development to be accomplished.

Preface

This work was performed with funding from the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration to the Northern Gulf Institute.

The work was accomplished by a multi-institution, interdisciplinary team consisting of:

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Sulis is a product of the Northern Gulf Institute (NGI) developed with funding from NGI, NOAA, Corps of Engineers, and NSF. Much of the ecosystem modeling work was supported by the Northern Gulf Institute with funds provided by the Gulf Research Institute from BP oil spill research funding.

Dr. Robert Moorhead is Director of the NGI, Dr. Steven Ashby is Co-Director, and Dr. John Harding is Chief Scientific Officer. The NGI web site is at http://www.northerngulfinstitute.org

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1. Introduction

This report documents efforts toward implementing an Integrated Ecosystem Assessment (IEA) of selected Gulf of Mexico ecosystems as part of an overall Ecosystem Approach to Management (EAM) effort by the National Oceanic and Atmospheric Administration.

1.1. Objectives

The work described here had the following objectives:

a. Develop indicators that will define ecosystem "States" for previously initiated Integrated Ecosystem Assessments (IEA) of Perdido Bay, Florida; Mississippi Sound, Mississippi; Barataria Basin, Louisiana; and Galveston, Texas;
b. Produce a model framework to link State indicators to Drivers and Pressures; and
c. Create a prototype system for the northern Gulf that incorporates findings of these IEA.

This report describes the process and results of achieving these objectives.

1.2. Background

The overall goal of this effort is to contribute toward the NOAA goal of an Ecosystem Approach to Management (EAM) and bringing Coastal and Marine Spatial Planning (CMSP) concepts to systems and regions throughout the northern Gulf of Mexico. Previous work on three of the estuarine systems examined IEA Pressures and Drivers and recommended steps to complete and extend those efforts. (NGI 2010)

The work fits within the Northern Gulf Institute's themes, specifically: Ecosystem-based management; Geospatial data/information and visualization in environmental science; and Climate change and climate variability effects on regional ecosystems. (NGI 2012)

1.3. Approach

The work has been accomplished by an interdisciplinary team drawn from NGI partner institutions and Memoranda of Agreement (MOA) signatories Harte Research Institute and Environmental Protection Agency Gulf Sciences Division through the following Tasks:

a. Apply the Drivers and Pressures analysis to the entire Perdido Bay and to sub-estuaries in Mississippi Sound and Barataria Basin, in order to separate the effects of scale from the effects of geographical location.
b. Use the stakeholder groups already assembled plus upstream (watershed) groups to validate the work reported earlier and to continue the IEA definition of States, Impacts, and Responses for these three systems.
c. Continue development of the Sulis toolkit (NGI 2010), with an emphasis on tools supporting incorporating EAM into Coastal and Marine Spatial Planning and involving Gulf of Mexico Alliance stakeholders.
d. Select one new system. Galveston Bay, Texas (with low freshwater flows) was selected and an initial assessment made of Drivers and Pressures.

e. Prepare site-specific reports.
f. Identify a suitable model and risk analysis framework
g. Generate roll-up report on all work to date.

1.4. Scope

This document is the roll-up report of Task (g) in the above approach. For that reason it repeats some material from the first report (NGI 2010) in order to provide a stand-alone description of the results.

Section 2 is a summary of the Ecosystem Approach to Management and how Integrated Ecosystem Assessments and the Drivers-Pressures-States-Impacts-Responses (DPSIR) fit into EAM. It elaborates on the use of models' risk assessment on EAM, since these tools are often misunderstood.

Section 3 describes the philosophy and design of the Sulis natural resources assessment system, including its Conceptual Earth Ecosystem Model, the models and methods implemented in support of that conceptual model, and the informatics services component that makes resource information accessible and understandable to those with management responsibilities.

Sections 3 and 4 describe the four estuarine ecosystems examined and summarize the DPSIR results, with details provided in the appendices. Section 5 provides an assessment of the systems, examines the effects of scale on DPSIR assessments, and presents the pilot Sulis application for Perdido Bay.

Section 6 summarizes the findings to date and recommends future work.

2. Ecosystem Approach to Management

2.1. NOAA Goals

NOAA's Vision Statement is:

> *An informed society that uses a comprehensive understanding of the role of the oceans, coasts, and atmosphere in the global ecosystem to make the best social and economic decisions.*

NOAA's strategic objectives of Healthy Oceans ("Marine fisheries, habitats, and biodiversity are sustained within healthy and productive ecosystems") and Resilient Coastal Communities and Economies ("Coastal and Great Lakes communities are environmentally and economically sustainable") are supported through an Ecosystem Approach to Management (EAM). (NOAA 2008)

2.2. Systems Approaches to Resources Management

Ecosystem management is similar to management of other natural resources – using a systems approach is advocated across a spectrum of resource types – air, land, water, and biota – and across the globe. Unfortunately, it has nearly as many definitions as applications. For our purposes, a systems approach to resources management is defined as:

> Managing resources holistically -- with the knowledge that the human ecosystem includes a variety of components that interact with each other individually and globally through processes, behaviors, and feedback mechanisms which must be elucidated in order to describe the effects of external forces and internal actions.

The word holistic has often been misused, but is so uniquely descriptive of what this work strives for that we are compelled to use it. Derived from the Greek *holos*, meaning "altogether" or "entire", which was defined by Aristotle (350 BCE) as, "the whole is greater than the sum of the parts". Jan Smuts[1] (1926) is credited with coining the English term holism, which he described as "the tendency in nature to form wholes that are greater than the sum of the parts through creative evolution." The definition has been refined and applied in diverse fields, most vividly by Douglas Adams (1987) as the "fundamental interconnectedness of all things". Adams' definition helps to remind us first, that economic development and a healthy ecosystem are fundamentally connected as interacting contributions to the quality of life, and second, that what happens in one part of a system affects other, often unseen aspects and areas of the system.

[1] Smuts was a military leader, statesman (the only person to sign the charters of both the League of Nations and United Nations), and scholar (Albert Einstein said that Smuts was one of only 11 people in the world who understood the Theory of Relativity).

Smuts' concept of holism was much more than interconnectedness. He saw it as an active force in the universe, responsible for organizing "wholes". He defined wholes as "… composites which have an internal structure, function, or character which clearly differentiates them from mere mechanical additions or constructions …". He described a water molecule (more than a simple mixture of hydrogen and oxygen atoms), cells (more than a collection of water, minerals, and organic molecules), an organism (more than a collection of cells), and the universe as wholes. We might add ecosystems, societies, and watersheds to his list. Smuts also presented holism as the "… ultimate synthesizing, ordering, organizing, regulating activity in the universe …".

Examples of the interconnectedness of Smuts' "wholes" abound. For example:

- Paine (1966) reported on a set of coastal ecosystems in which 15 large species existed in relative equilibrium. Removing the starfish from some of the systems resulted in a crash so severe that one year later only 8 species dominated, while the control systems remained in balance.
- Savory (1999) describes a lush, wildlife-rich Luangwa Valley in Zambia that was converted to a national park and game preserve by relocating local hunting and farming villages. Within a few decades the landscape became denuded of vegetation, serious riverbank erosion occurred, and game species all but disappeared because villagers were replaced by park employees and tourists.

While it may be clear that ecosystems should be treated as holistic systems, doing so presents difficulties. Ecosystems are Complex Adaptive Systems, which implies much more than simply saying they are complicated. Complex Adaptive Systems experience emergent behaviors, or state changes ostensibly unpredictable from current or past states; alternate stable states; and trajectories rather than stable states, making reductionist analyses very difficult (Harris 2007).

2.3. Ecosystem Approach to Management

The Interagency Ecosystem Management Task Force (CEQ 1995) offered the following:

> *The ecosystem approach is a method for sustaining or restoring natural systems and their functions and values. It is goal driven, and it is based on a collaboratively developed vision of desired future conditions that integrates ecological, economic, and social factors. It is applied within a geographic framework defined primarily by ecological boundaries.*

The Ecosystem Approach to Management (EAM) as used here is synonymous with Ecosystem-Based Management (EBM). Rosenberg and McLeod (2005) define EBM as "… taking a place-based, ecosystem approach to management, with the goal of sustaining the long-term capacity of the system to deliver ecosystem services." EBM is sometimes referred to as Ecosystem Approach to Management (EAM) and implemented through a process called Integrated Ecosystem Assessment (IEA) (Levin et al. 2008; Levin et al. 2009). EAM has a conceptual analog in Integrated Watershed Management (e.g., Miller and Reidlinger 2010) and Regional

Sediment Management (USACE 2004) in that the system is considered as a whole with many interdependent components.

Lubchenco and Petes (2010) distinguish EBM from past management practices by noting that EBM provides a mechanism for making decisions about sectors (e.g., fisheries, oil & gas development, land development, navigation projects) based not on single sector results but based on a goal of healthy, productive, and resilient ecosystems. Ecosystem in this context indicates a geographically determined system of organisms (including humans), and the biological, chemical, physical, and social conditions that surround them. A flow chart depicting the generic EBM/EAM process is shown in Figure 2.1.

EBM also underpins the practice of Coastal and Marine Spatial Planning (CMSP), which is employed worldwide to coordinate development and conservation activities (e.g., Ehler & Douvere 2009).

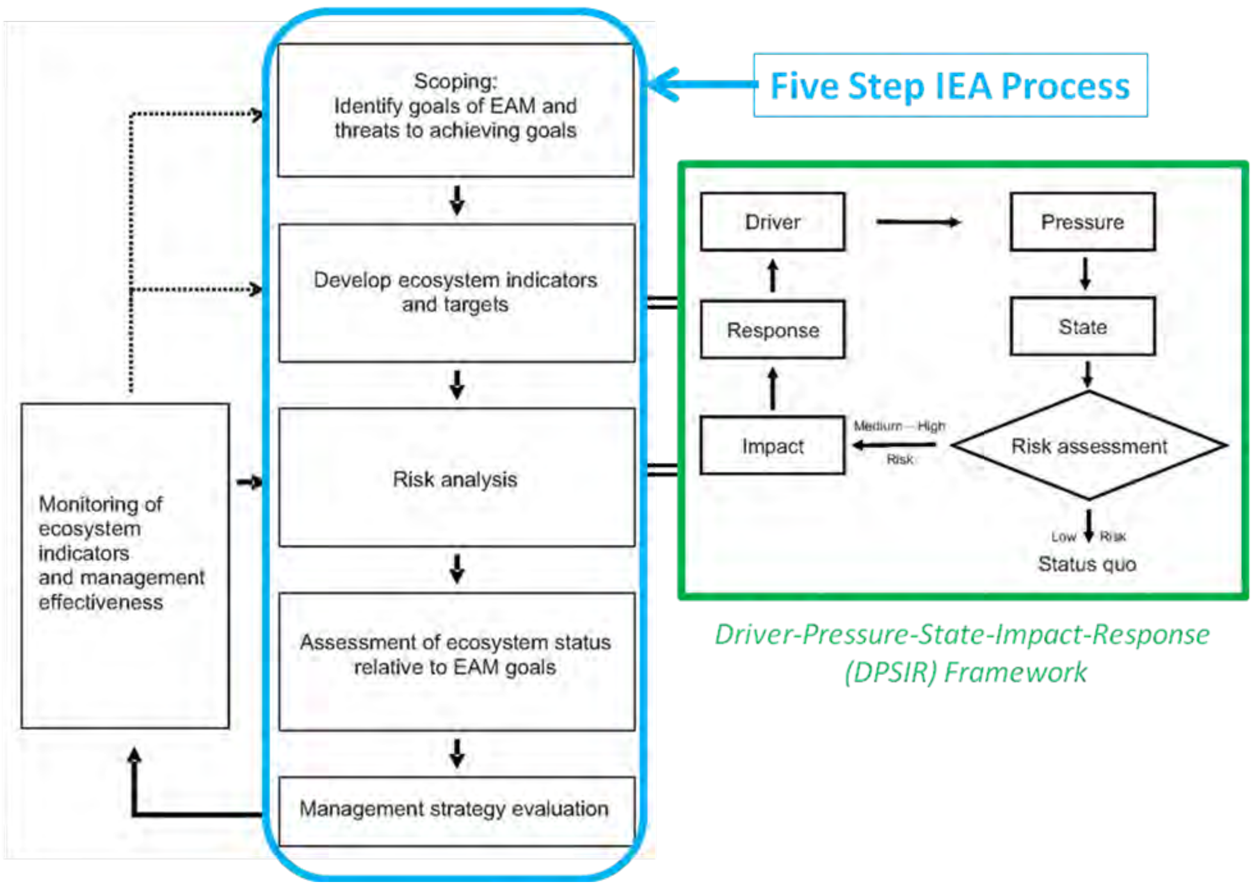

Figure 2.1. Ecosystem Approach to Management Schematic (Adapted from Levin et al. 2009). The DPSIR (or DPSER as discussed in Section 2.5) approach is shown in the inset.

2.4. Integrated Ecosystem Assessment

Integrated Ecosystem Assessment (IEA) is "a syntheses and quantitative analysis of information on relevant physical, chemical, ecological, and human processes in relation to specified ecosystem management objectives" (NOAA 2011a) and begins with the identification of a critical management or policy question which helps shape and inform ecosystem management. IEAs provide a process where scientists can work closely with stakeholders and managers to identify management issues and to provide robust decision support information. IEAs integrate diverse ecosystem data to analyze ecosystem and community status relative to a defined issue and then predict a future status based upon forecasts of natural ecosystem variability together with the evaluation of alternative management strategies. Through the process of Integrated Ecosystem Assessment, the benefits and risks of the alternative management actions are evaluated and defined in order to inform stakeholders and managers of the decisions. After a decision is made, there is a continuous evaluation of the alternative management action which then informs the IEA process to allow for adaptive management.

An IEA consists of identifying key issues that need to be addressed through policy and management; assessing the status, indicators, and trends of the current ecosystem in relation to the management targets; assessing the environmental, economic, and social causes and ramifications of the ecosystem trends; forecasting ecosystem conditions under different scopes of policy and/or management actions; periodic re-evaluation of the effectiveness of the management process chosen relative to emerging ecosystem issues; and identifying crucial knowledge and data gaps that will help guide future research and data acquisition efforts (Levin et al. 2008).

The overarching goal of the IEA process is to create well-defined ecosystem objectives based on science, as well as to integrate diverse coastal, marine, and Great Lakes data together and think about the way decisions affect the ecosystem and services the ecosystem provides in order to promote ecosystem sustainability under the increasing demands placed on these environments. IEAs also involve and inform stakeholders and governmental agencies and integrate data collected by federal agencies, states, non-governmental organizations, regional entities, and academic institutions.

An IEA "uses approaches that determine the probability that ecological or socioeconomic properties of systems will move beyond or return to within acceptable limits as defined by management objectives" (Levin, et al. 2008). IEAs also provide a way to evaluate trade-offs in management strategies among competing ecosystem-use sectors. In order to achieve the goals NOAA has set forth for IEAs and to evaluate management strategies, five steps were identified that now form the IEA process (Levin, et al. 2008). NOAA's IEA framework details the IEA scope, indicator development, risk analysis, assessment of ecosystem status, management strategy evaluation, and monitoring and evaluation (NOAA 2011b).

***Scoping**:* This step begins with a review of existing documents and information and ends with stakeholder, resource manager, and policy maker involvement to identify the management objectives, define the ecosystem to be assessed, identify ecosystem attributes of concern, and identify stressors relevant to the ecosystem being examined. Scoping is where broad goals are reduced to specific ecosystem objectives that managers and policy makers need to consider. The scoping process includes working closely with stakeholders and managers to detail priority management issues that need to be addressed through the IEA process where the issues are clearly identified and defined. This step enables the iteration of the IEA process. The scale and scope of the identified issues drive the assessment process. Engagement with stakeholders and mangers begins with the scoping step but continues through the entire process.

***Indicator Development*:** After the issues and goals are identified, the indicator development step comes in where the goals and indicators are tested and prioritized in order to measure the ecosystem status. The indicator development stage is where researchers develop and test indicators that reflect the ecosystem attributes and stressors identified in the scoping process. Specific indicators are dictated by the identified problems and are linked with decision criteria. In some cases, this means following a species or numerous species. In other cases, the indicator may be a substitute for an ecosystem attribute indicated in the scoping process (e.g. resiliency to perturbation may be an attribute and species diversity may be an indicator of resiliency) (Levin, et al. 2008). For most problems, numerous indicators are needed. The indicator development step allows the identification of indicators that need to be monitored. The management scenarios are evaluated as are the tradeoffs, the socio-economic implications, and management performances. The key interactions among ecosystem components are considered. The data gaps are identified as are the risks and uncertainties associated with the alternative management scenarios.

***Risk Analysis*:** After the indicators are identified, a risk analysis is performed. This analysis evaluates the risk human activities and natural processes pose to the indicators. NOAA has set the risk analysis to follow a hierarchical approach that moves from a comprehensive, qualitative analysis to a more focused, semi-qualitative approach, and finally ends with a highly focused, fully quantitative approach. Initially, this step helps filter out potential risks so that more in-depth and quantitative analyses are limited to selected ecosystem indicators and threats to those indicators. The goal of this step is to fully explore the susceptibility of an indicator to threats and to the resiliency of the indicator. Another goal of the risk analyses is to explain if new indicator values are due to natural variability or not. This step identifies the relationship between each IEA indicator and the potential threats in order to assess the current state of each risk and the probability that an indicator will reach an identified undesired state. The ecological, economic, and social processes that drive the current system are considered so that it can be seen how they might change in the future and change the ecological, economic, and social processes.

***Overall Ecosystem Assessment*:** After a risk analysis is run for each ecosystem indicator, the results are then integrated in the overall ecosystem assessment phase. This assessment quantifies the status of the ecosystem relative to historical status and identified targets. The risk analysis quantifies the status of each ecosystem indicator and the overall ecosystem assessment considers the status of all the ecosystem indicators simultaneously. The interaction between the broad ecosystem components are considered as they were in the risk analysis step. The management strategy evaluation builds on the previous steps to allow for the evaluation of management actions in terms of effectiveness and performance. Assessment of the management action in relation to the targeted elements in the system occurs. Management strategy evaluation also facilitates the analysis for the trade-offs in the plans and provides managers and stakeholders with informed management options. The quantification of the trade-offs among ecosystem services is very important as it can describe the potential trade-offs resulting from current and future management decisions.

***Evaluation*:** The final step in the IEA framework is monitoring and evaluation using developed ecosystem modeling frameworks to evaluate to what potential different management strategies influence the state of natural and human indicators. In order to accomplish this, a Management Strategy Evaluation (MSE) is implemented. "In MSEs, a simulation model is used to generate true ecosystem dynamics. Data are sampled from the model to simulate research surveys, these data are then passed to risk analysis and assessment models. Theses assessment models estimate the predicted status of individual indicators and the ecosystem as a whole. Based on this assessment of the simulated ecosystem, a management decision is simulated. Human response to this simulated decision is modeled and potentially influences the simulated ecosystem state. By repeating this cycle, the full management cycle can be simulated. This allows the testing of the utility of modifying indicators and threshold levels, assessments, monitoring plans, management strategies, and decision rules," (Levin, et al. 2007). As such, MSEs can filter which policies and methods meet acknowledged management objectives in IEA. After the managers or stakeholders chose a management option they feel is the best approach to the problem, this step allows for the monitoring of the defined indicators to assess the effectiveness of the adaptive management. This step also allows for external peer review and routine updates of the assessments.

The IEA approach has roots in decision theory and systems analysis and IEA implementation forces decision makers, managers, and scientists to confront multiple issues at the same time. For example, IEA allows for a quantitative evaluation of goals identified in the indicator development step. It also allows for the identification and evaluation of trade-offs among diverse objectives, a key benefit of systems analysis.

In order to follow the IEA framework to inform decision makers, managers, and scientists, the United States has been divided into eight areas based upon physical location. These eight regional ecosystems are the Great Lakes Regional Ecosystem, the Gulf of Mexico Regional

Ecosystem, the Puerto Rico/Caribbean Regional Ecosystem, the Southeast Regional Ecosystem, the Northeast Regional Ecosystem, the West Regional Ecosystem, the Alaska Complex Regional Ecosystem, and the Pacific Islands Regional Ecosystem. IEA may be able to address problems only on a regional scale, but on a local scale is significantly more easily comprehended.

Issues associated with marine and coastal ecosystems include things as diverse as navigation, tourism, ecosystem conservation, energy, and fisheries management. However, despite complex issues in coastal and marine areas, parts of the IEA framework have been successfully implemented to develop management plans for marine areas. An example of this IEA framework implementation is in Puget Sound (Levin et al. 2009). In Puget Sound a comprehensive scoping process (step 1) lead to the identification of ecosystem indicators (step 2) and perform risk assessment (step 3) and MSEs (step 5) (McClure and Ruckelshaus 2007).

In summary, integrated ecosystem assessment is a framework that can be used to organize science, which influences decisions in marine and coastal environments. IEAs can be implemented on multiple scales and across different sectors. The goal of the IEA framework is to help guide the process of synthesizing and analyzing scientific information supporting ecosystems. IEAs inform managers, policy makers, and scientists of the management decisions that can be implemented across diverse and usually conflicting sector uses.

2.5. DPSIR Process

Steps 1 and 2 of the IEA process employ the Driver-Pressure-State-Impact-Response (DPSIR) framework, with the framework terms described by Levin et al. (2009) (see Figure 2.2) as:

> ***Drivers*** *are factors that result in pressures that in turn cause changes in the system. For the purposes of an IEA, both natural and anthropogenic forcing factors are considered; an example of the former is climate variability while the latter include factors such as human population size in the coastal zone and associated coastal development, demand for seafood, etc. In principle, human driving forces can be assessed and controlled. Natural environmental changes cannot be controlled but must be accounted for in management.*
>
> ***Pressures*** *include factors such as coastal pollution, habitat loss and degradation, and fishing effort that can be mapped to specific drivers. For example, coastal development results in increased coastal armoring and the loss of associated intertidal habitat.*
>
> ***State variables*** *are indicators of the condition of the ecosystem (including physical, chemical, and biotic factors). Impacts comprise measures of the effect of change in these state variables such as loss of biodiversity, declines in productivity and yield, etc.*
>
> ***Impacts*** *are measured with respect to management objectives and the risks associated with exceeding or returning to below these targets and limits.*
>
> ***Responses*** *are the actions (regulatory and otherwise) that are taken in response to predicted impacts. Forcing factors under human control trigger management responses when target values are not met as indicated by risk assessments. Natural drivers may*

require adaptational response to minimize risk. For example, changes in climate conditions that in turn affect the basic productivity characteristics of a system may require changes in ecosystem reference points that reflect the shifting environmental states.

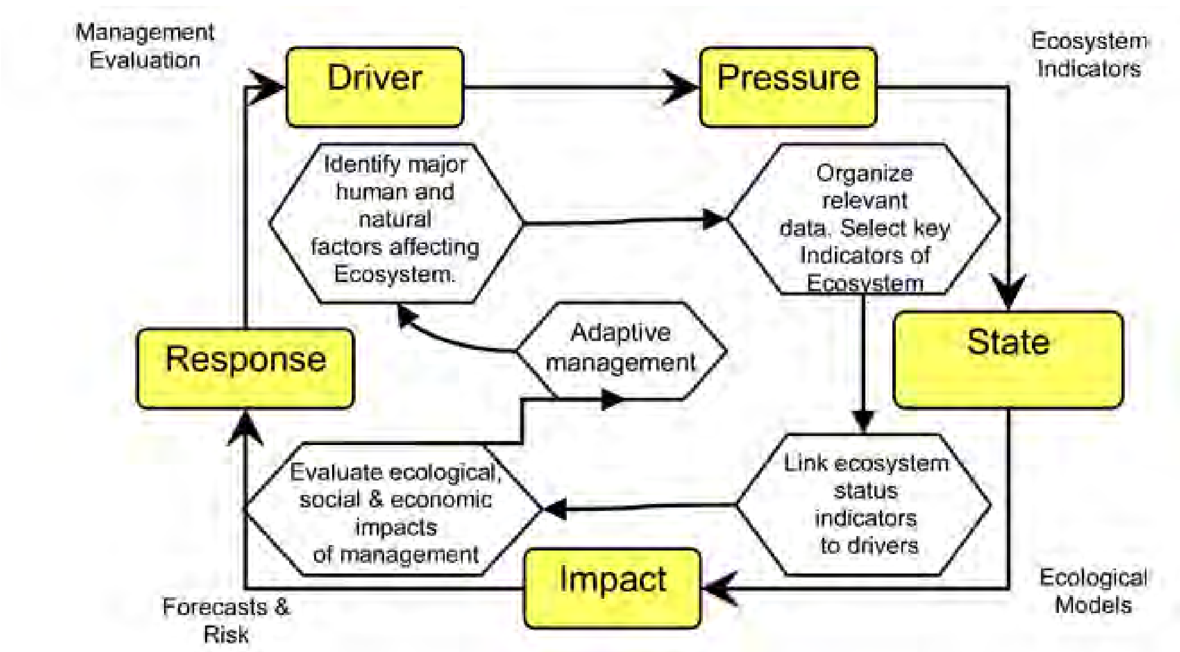

Figure 2.2. DPSIR Framework (Source: NOAA 2009)

It should be noted that many practitioners experience difficulty distinguishing Drivers from Pressures. Our effort has tended to place into the Drivers category those factors that cannot be readily managed and restrict Pressures to those manifestations that are potentially manageable. However, the distinction need not be rigid for practical application of the DPSIR process. As long as the Drivers and Pressures are reliably identified, classifying them as one or the other may not be essential.

The word “Impacts” has negative connotations that may inhibit its applications to some ecosystem effects. For example, enrichment by nutrients may be either beneficial or detrimental to a system, depending on its state and uses. For that reason, some practitioners replace “Impacts” in the DPSIR framework with “Ecosystem Services”, producing the acronym DPSER (e.g., Nuttle et al. 2010).

2.6. Models and Modeling

Models are an integral part of many ecosystem assessments and computational biology models are becoming a valuable tool across the research spectrum (e.g., see the 13 April 2012 issue of *Science* magazine for a broad view). The work described here is employing several kinds and levels of modeling, so a brief discussion of models and modeling is included.

We use the word “model” to label a variety of different things. We use it to describe the occupation of a person who wears designer clothing on a fashion runway, an ideal such as “model parent”, or a small imitation of the real thing such as a model airplane. One of us was once complimented by a student calling him a model professor, only to hear the student confide to classmates that she meant the latter definition.

Sir Peter Medawar said that the business of science is telling stories which are scrupulously tested to see if they are stories about real life.[2] We can use his insight to define a model as being a story that describes real life, or, more formally as a representation of a process or thing which can be used to predict some aspect of the process or thing’s behavior. Neither definition requires that a model be true in the sense that is accurate in every respect. A model is successful if it describes, to an acceptable level of accuracy, those aspects of real life that we are interested in. A plastic toy airplane can tell us a lot about what a particular type of plane looks like, but nothing about how well it flies. A fashion model may tell us how skinny people look in jeans, but not how we look in those same jeans.

We can refine these definitions by qualifying them, as in:

- Conceptual Model – uses logical or relational statements to represent a process (examples: water runs downhill, oysters thrive in salty water)
- Mathematical Model – uses mathematical expressions to represent a process (examples: Newton’s Second Law, Conservation of Mass)
- Numerical Model – uses numerical techniques such as approximation and iteration to obtain approximate solutions to mathematical models (examples: EFDC, Atlantis)

Conceptual models can be quantified if needed. In studies of Mississippi River Diversions to increase oyster production in Louisiana and Mississippi, the models for beneficial impacts to oyster production have sometimes consisted of the “Ford Line” which represented a target zone for the 15 ppt salinity contour and in other cases the “Soileau Line” which is an annual cycle of salinities along a target zone. (Chatry and Chew 1985, McAnally and Berger 1997) In both cases fisheries biologists noted the limitations of such simple quantifications but used them to identify quantitative distinctions among multiple diversion plans.

Some mathematical models, such as Newton’s Second Law, do such a good job of prediction that they earn the appellation of “law”, even though they are still approximations within specific limits, as demonstrated by Albert Einstein in his Theory of Relativity. Simple mathematical models, such as Manning’s Equation for open channel flow, can be solved by algebraic methods. More complex models, such as the Navier-Stokes equations for flow, must be solved by numerical methods.

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2. Paraphrased from several publications, including “Two Conceptions about Science,” in a collection of Medawar’s essays titled, The Strange Case of the Spotted Mice, Oxford University Press, 1996. Sir Peter won the 1960 Noble prize for his work in immune effects in skin grafts.

Numerical models offer multiple benefits to the understanding and management of ecosystem effects. Three example applications illustrate the benefits – (1) integrating knowledge into a testable, holistic framework, (2) Conducting controlled (numerical) experiments, and (3) predicting future ecosystem effects. As an example of the second application, field observations of ecosystem perturbation can be confounded by other contributing driver processes, such as weather variability and fishing pressures. When those observations are used to create and validate models the effects of single causative factors be separated out and understood through model sensitivity experiments. Since there is no one-size-fits-all model, a variety of models must be used in dozens to thousands of simulations in order to properly identify the separate effects of all significant drivers and processes.

2.7. Risk Assessments

In the vernacular, risk is given definitions such as, the chance of losing money in an investment. Such definitions are correct to a point; however, to manage risk requires more rigor, including a precise definition and expressing risk quantitatively.

Risk for assessment and management has at least two components – the probability of an event and the consequences of that event. For purposes of this report, Ecosystem Risk is defined as:

Ecosystem Risk – a measure of the probability and the magnitude of ecosystem effects.

The effects can be ecosystem services preserved, gained, or lost. Some form of this definition is widely used in the context of decision-making, e.g., by ISO (2009) and NRC (2007).

This two component effect can be visualized by means of Figure 2.3. The vertical axis represents the probability of an event, ranging from very low, such as in a 500-year return period storm, to a rather high probability, such as an annual hypoxic event. The horizontal axis represents the consequences of the event – low consequences might include small economic damages, whereas high consequences might include loss of human life. Another display of risk is shown in Figure 2.4, in which the 3 categories of Figure 2.3 have been expanded to 5 by the introduction of "very" modifiers in tabular form. Tabular form discourages attempts to interpolate readings that appear more precise than justified by the available information.

The above discussion frames risk in terms of losses, but it can also be expressed in terms of benefits if needed to support decision-making. Also note that the probabilities and consequences were quantified only in an approximate sense, with three categories. Even three to five categories can provide useful information, but increasing precision (with comparable accuracy) provides increasingly detailed decision support.

Distinctions among High to Low risk categories can be arbitrary, since the goal is usually to rank events or actions, not assign an absolute value; however, absolute values can be used, with separation into categories based on specific risk management objectives, such as limiting the number of sea turtles killed or achieving ecosystem services that exceed the cost of managing non-point sources of nutrients.

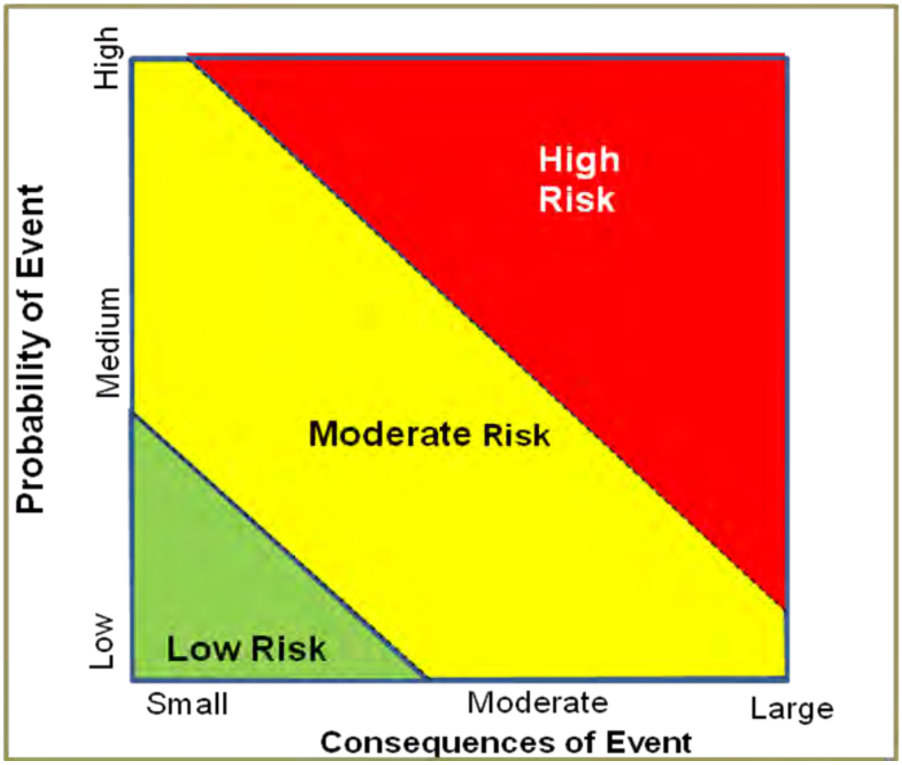

Figure 2.3. Illustration of the interplay of probability and consequences of an event in defining risk.

Probability of Event	Consequences of Event		
	Small	Moderate	Large
High	Moderate Risk	High Risk	Very High Risk
Medium	Low Risk	Moderate Risk	High Risk
Low	Very Low Risk	Low Risk	Moderate Risk

Figure 2.4 Risk displayed in tabular form.

Risk and uncertainty are inextricably linked and often expressed as the single phrase in books, papers, and at least one scholarly journal. Uncertainty is used here to denote the property of indefiniteness, or the lack of precise and accurate knowledge of something. The "something" may be a quantity (e.g., mass of dissolved oxygen), a future event (e.g., hypoxic episode), or a state (e.g., hypoxia). Uncertainty may be expressed:

- Qualitatively (e.g., acceptable, tolerable, etc.)
- Semi-quantitatively (e.g., large, medium, or small)
- Quantitatively as a qualified value or as a probabilistic distribution
- Quantitatively as a deterministic range.

Proper consideration of uncertainty is a key aspect of risk assessment, since both axes of Figure 2.3 – "Probability of an Event" and "Consequences of an Event" must be scaled, or at least rank-ordered, to place an event in a risk category and uncertainty is essential to proper scaling of both.

The National Research Council identified four key components in managing risk and resources: public participation, risk assessment, risk management, and public policy decision-making (NRC 1994). EPA (1998) defines Ecological Risk Assessment as: "a process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors." The NRC defines risk management as "the process of weighing policy alternatives and selecting the most appropriate regulatory action, integrating the results of risk assessment with engineering data and with social, economic and political concerns to reach a decision" (NRC 1994).

Assessment must begin before Management, but the process is iterative. Both EPA and the NOAA National Marine Fisheries Service (Nash et al. 2005) use the World Health Organization's framework for ecological risk assessment and management, shown in Figure 2.5. It consists of three iterative Risk Assessment steps – Problem Formulation, Problem Analysis, and Risk Characterization, followed by the Risk Management step.

Nash et al. (2005) assessed risks of aquaculture pens having a physical impact on marine habitat. by the following steps, keyed to Figure 2.5:

a. State the hypothesis as a perceived risk

b. Provide background information on typical designs

c. Build a conceptual model of how damage may occur

d. Analyze the effects on biological end points of diversity, habitat, and abundance

e. Render an opinion on the hypothesis

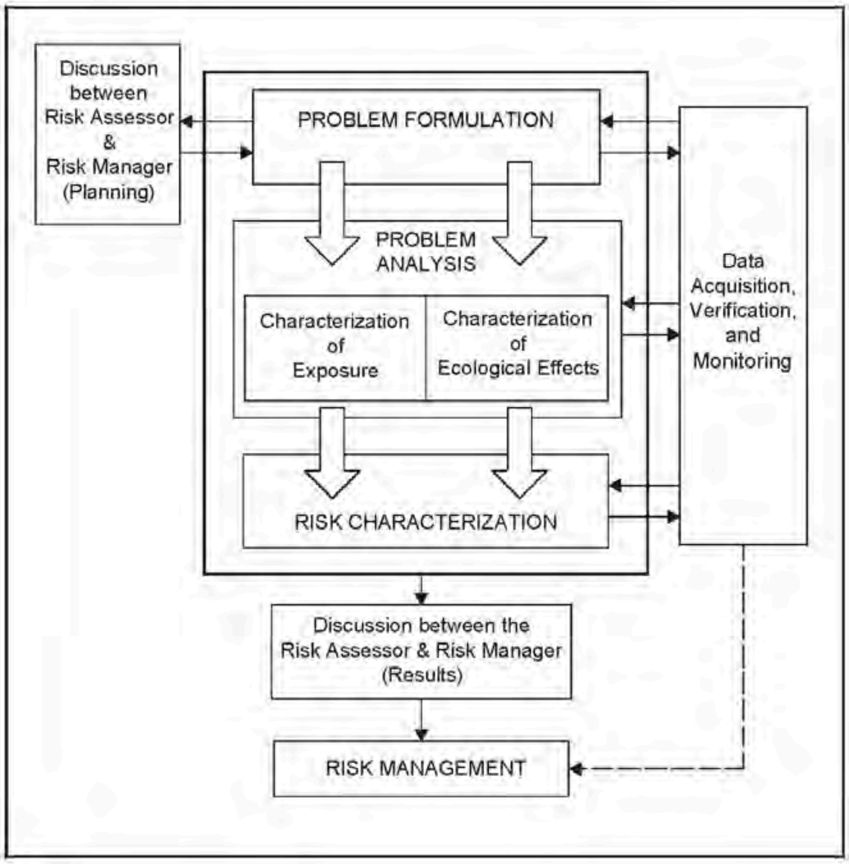

Figure 2.5. The World Health Organization Framework (Source: Nash et al. 2005)

Bayesian Belief networks offer an approach to risk assessment when relationships are understood qualitatively, but not quantitatively. In a typical application, experts are polled to elicit educated opinions on whether certain circumstances will have positive, negative, or neutral effects. A statistical summary of those opinions is used to construct a tabular set of probable outcomes. McNay et al. (2006) used that approach to assess caribou habitat in British Columbia, where woodland caribou are listed as a threatened species. With management solutions ranging from forest harvesting procedures to hunting regulation under consideration, experts assessed the influence of several input conditions (e.g., topography, weather, predation, and hunting regulations) on habitat attributes (e.g., lichen abundance and forest stand characteristics) and ultimately caribou populations over multiple decades. An example network from that work is shown in Figure 2.6. It is one of multiple networks used to calculate habitat value, then caribou populations under various scenarios. The work found that predation by wolves was the most important driver in determining population size and that forest stand age as mediated by harvesting was the most important management input, followed by road construction and hunting regulations.

This example contains many of the elements of a risk analysis – including statistical descriptions of environmental conditions, predictions of future changes, and Bayesian treatment of cause-and-effect relationships to arrive at a probabilistic estimate of the caribou ecosystem consequences. While the authors explicitly limited their conclusions to a research orientation, they also included a sensitivity analysis of management action effectiveness which could ultimately become an operational system for management decisions.

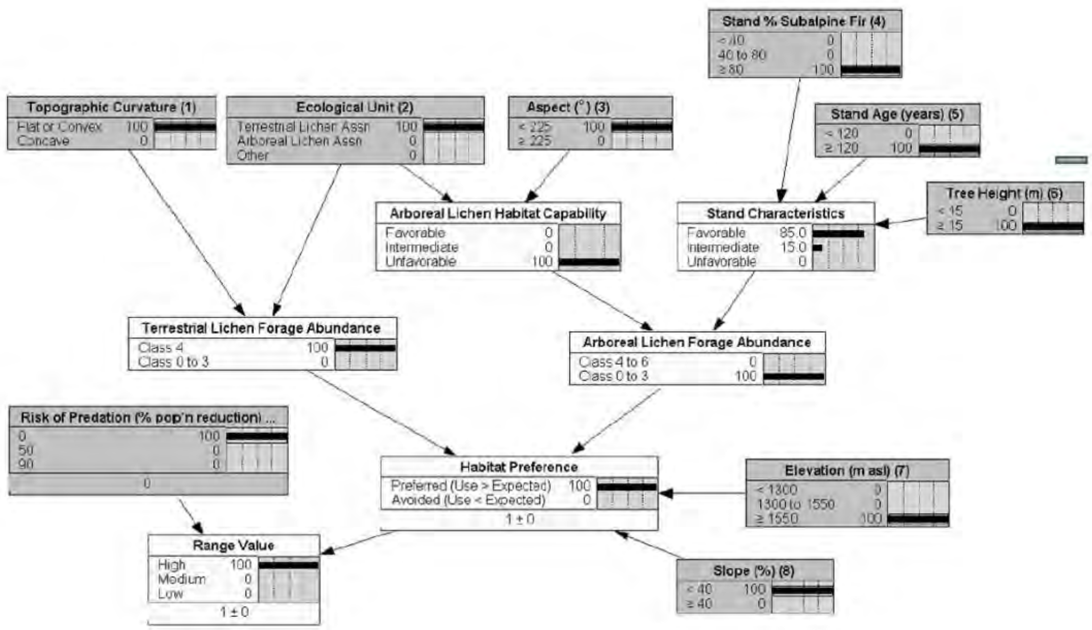

Figure 2.6. Example BBN for Caribou Habitat (Source: McNay et al. 2006)

3. Sulis for Ecosystem Assessment

3.1. Introduction

Integrated Ecosystem Assessment can be performed in an ad hoc approach in which each step is performed independently using various tools and approaches. A more organized approach is to use semi-standard protocols with variation as needed to best fit the location environment. Sulis[3], a natural resource assessment system, provides an architecture and a software framework that is well-suited to IEA.

Healthy Watersheds – Healthy Oceans – Healthy Ecosystems is the underlying goal of Sulis. It provides users ready access to natural resources information in a useful form to better understand aquascapes and their processes, to evaluate the probable consequences of management decisions and natural change, and to make informed assessments with a holistic perspective. The key words in this description include:

- Ecosystem indicates a geographically determined system of organisms (including humans), and the biological, chemical, physical, and social conditions that surround them.
- Users are those who manage water, land, and ecosystem resources at the federal, state, and local level; stakeholders who want to understand the effects of natural and anthropogenic changes and be able to influence policy and implementation; and those who advise both groups.
- Ready access implies that a variety of users from technophiles to the technologically limited can operate the system without becoming a computer specialist.
- Natural resources information includes a variety of information types (e.g., water quantity and quality, land use, biotic health) and formats (model results, spreadsheets, gis shape files, etc.)
- Aquascape is used to indicate that the perspective is that of the complete hydrologic footprint (figure 3.1), including that of a watershed – an area of the earth's surface from which water flows downhill to a single outflow point – plus the water-spread – the coastal and ocean area which receives the watershed's flow and in turn feeds back to coastal and upstream climate, hydrology, and ecosystems.
- Holistic is used to denote the fundamental interconnectedness of all parts of the ecosystem and the generative powers of ecosystems.

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[3] Sulis is the Celtic mythological goddess of wisdom, usually associated with the hot springs at Bath, England.

Sulis provides a systematic approach to holistic water, land, and ecosystem resources assessment through two major components (see Figure 3.2):

- Sulis Community Ecosystem Models – Numerical models of the physical environment, biota, and human activities.
- Sulis Informatics Services - Tools for data assimilation and manipulation, modeling, analysis, synthesis, visualization, and decision support.

Sulis Community Ecosystem Models (Sulis CEM) are designed to provide quantitative and qualitative information about the physical, biotic, and human systems environment and the interactions among them, as shown in the Conceptual Earth Ecosystem Model of Figures 3.2 and 3.3. They presently include models for the complete hydrologic cycle (weather, runoff, flow to and in the ocean, and evapotranspiration) and transport processes (sediment, nutrients, etc.). Work is ongoing to complete the biotic models and human systems models that will make up the complete suite (see Figure 3.3).

Sulis Informatics Services (Sulis IS) provides user access to the model results and to observed data from multiple databases and provides multiple tools to view and analyze the results. Those tools include Geographic Information System (GIS) mapping and layering, standard model data formats, and advanced visualization tools (all presently active) and analysis toolkits that provide enhanced results and decision support (inference engine, Composite Risk calculator, and others in development.)

Together Sulis CEM and Sulis IS enable informed decision-making with a holistic perspective. Among the management functions that can be facilitated with Sulis are: Regional Sediment Management, Ecosystem Approach to Management (EAM), and Coastal and Marine Spatial Planning.

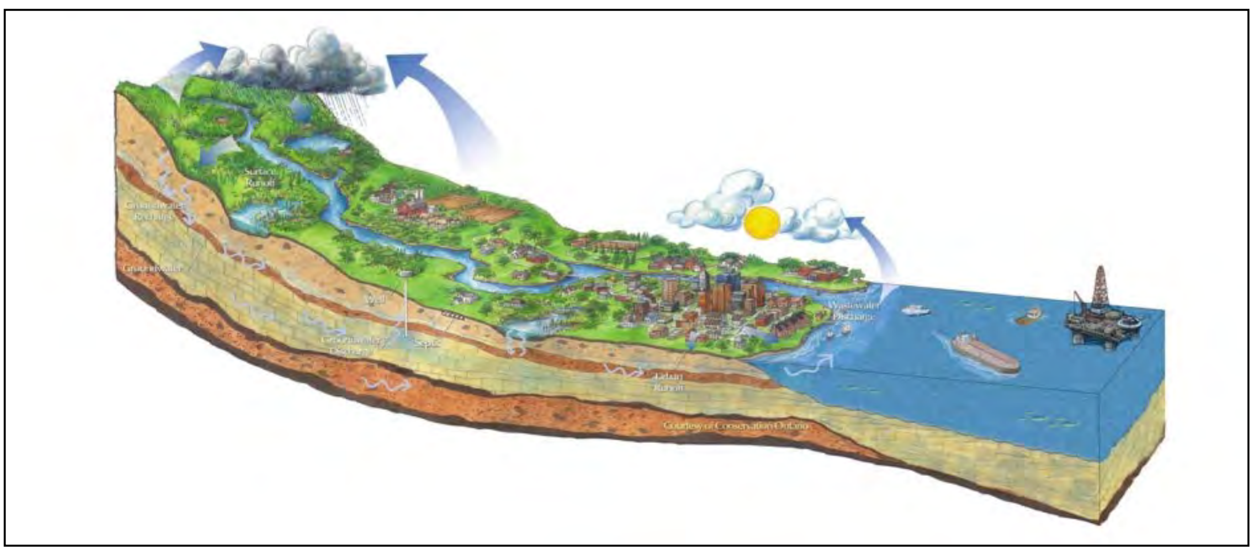

Figure 3.1. Schematic of the aquascape. (Source: Conservation Ontario. Used with permission.)

3.2. Conceptual Ecosystem Model

The NGI Conceptual Earth Ecosystem Model (CEEM) integrates the complex human, biotic, chemical, and physical interactions of the ecosystem that result from human and natural system perturbations and represents them in a manner that enables subsequent quantification. Sulis CEM is based on this conceptual model.

The CEEM is based on the model shown in Figures 3.2 and 3.3. Figure 3.2 illustrates how physical processes, biotic processes, and human activities overlap and interact. Figure 3.3 provides additional detail about these components, breaking the systems down into sub-systems with some of the information, energy, and matter flows depicted in a second level view. Colors indicate which of the three primary components are represented.

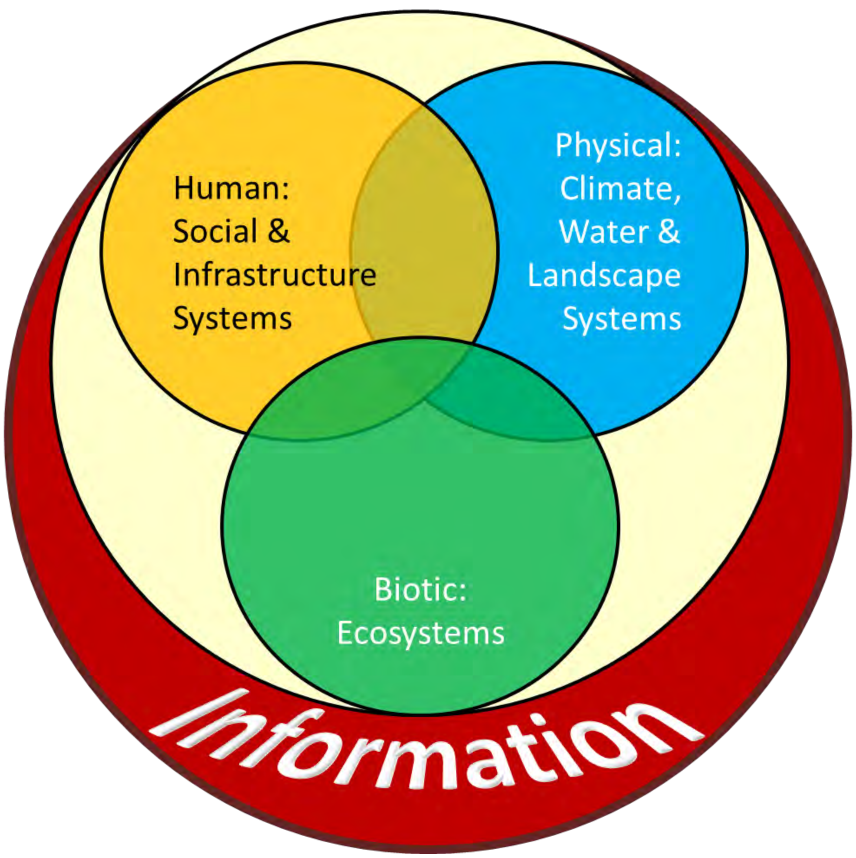

Figure 3.2. Conceptual Earth Ecosystem Model Level 1

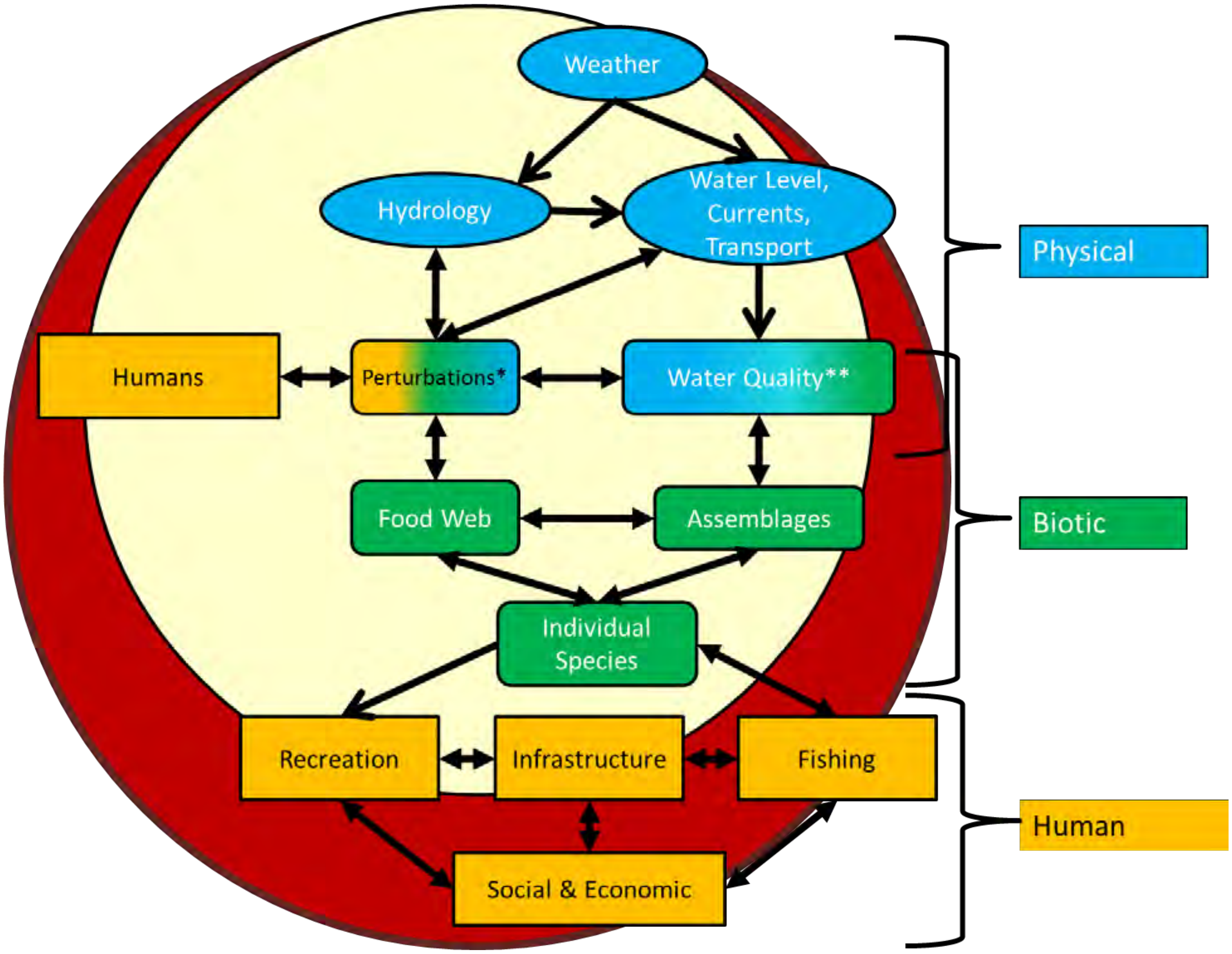

Figure 3.3. Conceptual Earth Ecosystem Model Level 2.

(Perturbations include hazards and management activities.)

A third level of detail (not presented here) increases the granularity of the conceptual model and identifies model components that transform the qualitative conceptual model to a suite of quantitative models that compute wind, precipitation, water levels and velocities, transport of sediment, nutrients, and pollutants, dissolved oxygen, food web flows, species populations, fisheries yield, and economic and social effects. Human effects are exerted through infrastructure, land and water uses, and fishing. CEEM expressed quantitatively, as models in the Sulis CEM, provides a key element of ecosystem-based management. The collection of Sulis CEM community models integrate with Sulis Informatics Services to provide Ecosystem-Based Management decision support.

3.3. Sulis CEM: Models and Model Systems

The Sulis CEM framework knits together useful numerical models for the hydrologic cycle and for tracking the transport and fate of dissolved and suspended materials (including contaminants) and their subsequent effects on the ecosystem, with consistent input and output data standards, plus common verification/validation standards. The models are designed to conserve solutions across multiple models domains with varying temporal and spatial scales and provide consistent expectations for model ability and limitations.

Individual models for each of the significant processes (atmospherics, hydrology/hydraulics, transport, water quality, biogeochemistry, and ecosystem impacts) either already exist (e.g., NCOM model of the Gulf, EFDC for Mississippi Sound and Mobile Bay), or will be created from other NGI projects (e.g., an Ecosystem Model of the northern Gulf).

Modeling experts have often struggled with the challenges involved in passing information from one kind of model to another. Having a set of community models with an encompassing architecture makes those handoffs virtually seamless and rapid.

3.4. Informatics Services

Informatics combines information science, computer science, and information systems engineering to store, access, analyze, and communicate data in order to make it useful. It employs cyberinfrastructure, described by the National Science Foundation as:

> *… tools and related services such as supercomputers, high-capacity mass-storage systems, system software suites and programming environments, scalable interactive visualization tools, productivity software libraries and tools, large-scale data repositories and digitized scientific data management systems, networks of various reach and granularity and an array of software tools and services that hide the complexities and heterogeneity of contemporary cyberinfrastructure while seeking to provide ubiquitous access and enhanced usability*. (NSF 2012)

Sulis Informatics Services (SIS) employs cyberinfrastructure to produce and share useful data, tools, and model results that enable informed decisions, scientific discovery, and integrated research and education for the benefit of technical specialists, resource managers, and, to a lesser extent, the general population. It consists of five major components:

- User interface – a graphical, three-layer set of screen displays to enable user input and to display results. (Figure 3.4)
- Observed data – field observations from institutional databases[4] such as NOAA's NESDIS and EDAC, the Corps' eCoastal and CorpsMap, USGS real-time and historical gauge data, EPA's BASINS and Storet, and locally compiled and quality assured data.

[4] Institutional databases may be accessed through hyperlinks and downloads, not by recreating those databases, unless the user has a specific need to store data locally.

- Tools – Tools for predicting impacts of decisions and projects. Simple tools are built in. More complex numerical models reside in Sulis Earth Ecosystem Community Models.
- Model Results Database – a local repository of geography-specific model predictions which can be extracted and displayed and/or analyzed by the Inference Engine.
- Inference Engine – a program that evaluates user requests, fetches data, performs analyses, and generates customized results for the user.

The logical layout of these services is shown in Figure 3.4.

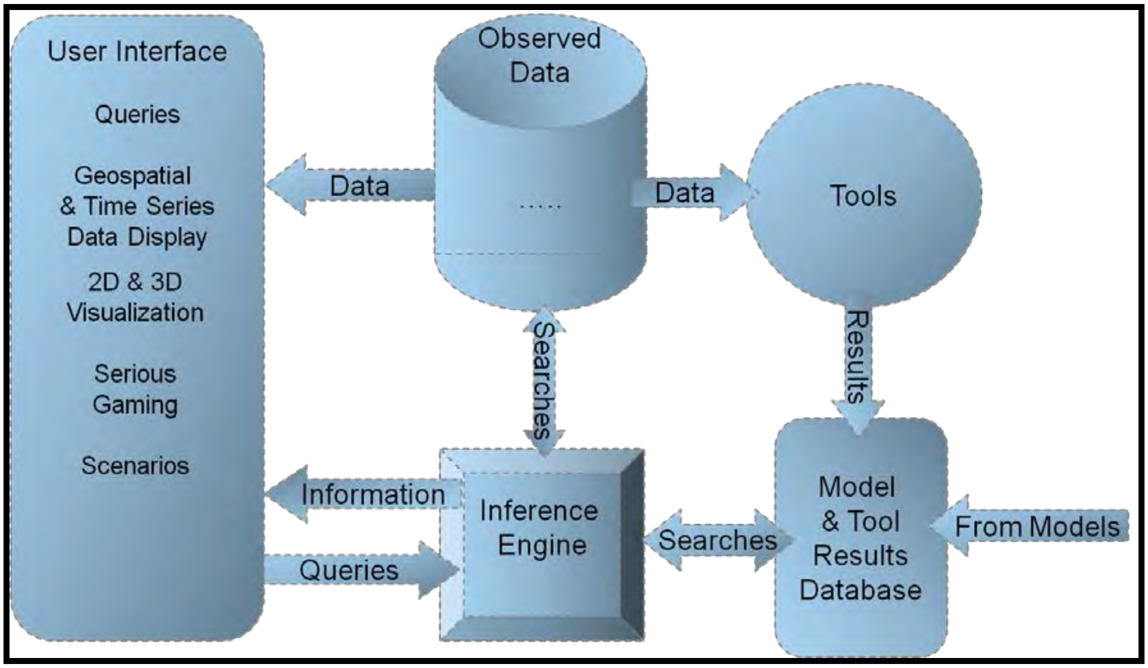

Figure 3.4. Sulis Information Services Architecture

SIS includes standard software components, used in every application, and custom components, specific to the aquascape of interest. The user interface and inference engine have a standard design. Models and data from models and observations are custom components for a specific aquascape. For example, Sulis for Regional Sediment Management in the Mobile Basin and Coastal and Marine Spatial Planning (CMSP) for the Gulf of Mexico would share the same basic toolset in the user interface and inference engine, but each would have its own models and databases unique to their application.

3.5. Ecosystem Model

The Mississippi Sound/Bight region was selected in order to explore the parameterization and execution of coupled hydrodynamic/ecosystem-function models to: 1) incorporate ground truth data into the coupled models of the system (i.e. data infusion); 2) capture historical dynamics to test the fidelity of hindcast models (i.e. model validatiom); 3) provide predictive analyses of ecosystem response to modeled perturbations and ameliorative management efforts (i.e. model forecasting); and later, 4) develop management strategies for appropriate response(s) based on predicted effects and risk assessment (i.e. the Ecosystem Approach to Management, or EAM). Such an ambitious analysis requires large and diverse data sets and close coordination among multidisciplinary approaches and perspectives.

The ecosystem-integrated approach is ideally suited for the assessment of the environmental impacts of hazards, such as the Deepwater Horizon spill. The broad goal is to use the IEA framework to build an ecosystem modeling tool specifically designed to make use of ongoing research and monitoring planned or ongoing in the Gulf).

Development of an ecosystem model is a by nature a collaborative activity that capitalizes on multiple sets of expertise, as well as multiple sets of perspectives about model input data and model output. Model development is a cyclical process involving numerous opportunities for external review and comment separated by model refinement and data analysis. Currently, the emphasis of the NGI Ecosystem Group is on understanding impacts at the ecosystem level which requires that group members both integrate ongoing research into the model, as well as look at synergistic effects that extend across individual impacts in the MS Sound/Bight region. This effort is nearly complete and has focused on a workshop approach that was centered on a core team for model development. More specifically, model development was structured around three workshops from 2011-2012. These model workshops were intended to bring together a wider group of researchers with modeling expertise to obtain input on model development and to peer-review the results in real-time.

The workshop process produced a data inventory, model inventory, and a model selection (see Appendix C for details). After careful review of the available hydrodynamic models available for the MS Sound/Bight region-of-interest, FVCOM was selected as the physical processes model to which the ecosystem model will be coupled. Based on power, scalability, and ease-of-use, the Fulford et al. (2010) Trophic Simulation Model (TroSiM) was selected as the ecological model.

The modeling approach involved three main components:

1) Food web component – the existing TroSiM model would be optimized to contain only those functional groups germane to the initial simulation and calibration steps, offering dynamical food web interactions within MS Sound/Bight habitats, focusing primarily on the oyster reef habitat as the initial test case.
2) Hydrodynamic/water quality component – the existing FVCOM model grid, boundary conditions, and hydrodynamical code for the MS Sound/Bight region would be utilized to produce estimated flowfields (and other pertinent physical forcings), all of which shall be coupled to the ecological model.
3) Fisheries component – an addendum to the food web component, to allow for commercial fishing pools as a mortality source for fishable functional groups. Ultimately, this component will be driven by social-economic factors and shall therefore provide the linkage point to larger Earth Systems Models (in the future).

Within the model architecture of TroSiM, a wide variety of competition parameters and diet matrices require definition and quantification for each functional group selected within the model simulation. Parameterization of the following functional groups, selected for customization within TroSiM, has been completed:

- Phytoplankton (3 exemplars)
- Periphyton (1 exemplar)
- Submerged Aquatic Vegetation (1 exemplar)
- Emergent Plants (1 exemplar)
- Zooplankton (3 exemplars)
- Zoobenthos (Eastern Oyster + 2 additional exemplars)
- Pelagic Omnivorous Fish (3 exemplars)
- Pelagic Piscivorous Fish (1 exemplar)
- Benthic Omnivorous Fish (2 exemplars)
- Heterotrophic Bacteria (1 exemplar)

4. Ecosystems Examined

Four ecosystems are examined here – Galveston Bay, Texas; Barataria Basin, Louisiana; Mississippi Sound in Louisiana, Mississippi, and Alabama, and Perdido Bay, Florida. They represent a variety of northern Gulf of Mexico estuarine ecosystems but over a rather narrow range of latitude, thus offering ample opportunities for contrast and comparison. Figure 4.1 shows the estuaries and their drainage basins.

Figure 4.1. The Four Estuarine Ecosystems Selected for Analysis

4.1. Galveston Bay, Texas

Galveston Bay (Figure 4.2) is the largest estuary in Texas and is comprised of four major sub-bays: Galveston, Trinity, East, and West Bays. It is a very shallow system (average of about 2 m) that covers about 1600 km^2). However, the watershed is much bigger and covers an area of 62,000 km^2. The quality and quantity of water draining from this large area affects the physical, chemical, and biological characteristics of the estuary.

Several habitats can be found in the Galveston Bay estuary: wetlands (salt, brackish, and fresh marsh), oyster reefs, seagrass meadows, mud flats, and open water.

Figure 4.2. Galveston Bay

4.2. Barataria Basin, Louisiana

The Barataria Basin(Figure 4.3) is an irregularly shaped bar-built estuary, approximately 120 km in length, located west of the Mississippi River in southeastern Louisiana. The basin spans approximately 6,300 km^2, including portions of nine governmental parishes. It is bounded on the north and east by the Mississippi River, on the west by Bayou Lafourche, a former distributary channel of the Mississippi River, and on the south by a barrier island chain and the Gulf of Mexico. The basin consists of a foundation of pro-delta clay deposits overlain by a mixture of swamp forest, fresh, intermediate, brackish, and saline marshes, barrier islands, natural levees, and former distributary channels of the Mississippi River (Coleman et al. 1998). The basin is divided into 5 major habitats based on vegetation type (wetland size data from US Army Corps of Engineers 2004):

- Freshwater swamp forest (~955 km^2)
- Fresh marsh (~653 km^2)
- Intermediate marsh (~311 km^2)
- Brackish marsh (~257 km^2)
- Salt marsh (~499 km^2)

Figure 4.3. Barataria Basin

4.3. Mississippi Sound: Mississippi, Alabama, and Louisiana

Mississippi Sound (Figure 4.4) is a shallow, partially stratified estuary that is variably influenced by the Gulf of Mexico, principally through the barrier islands passes, and the coastal watershed, mainly through the six major rivers that connect to the Sound, as well as the Mississippi river via Lake Pontchartrain in Louisiana when the Bonnet Carre spillway or other diversions are operated. The Mississippi Sound ecosystem is comprised of the Sound and the connected coastal watersheds that feed into it from three principal embayments (St Louis Bay, Biloxi Bay, and the Pascagoula River distributary). The natural coastal boundaries of sinuous bayous fringed with emergent marsh vegetation and sandy barrier islands have been substantially altered by human activities such as shoreline hardening and dredging, as well as natural climatic events such as hurricanes. The Mississippi Sound contains approximately 2023 km^2 of open water and 283 km^2 of emergent marsh.

The relative importance of marine and freshwater influence to the Sound changes seasonally, as well as daily in response to climatic variability and freshwater diversion; and affects species distributions, species production and spawning success, aquatic nutrient concentrations, water clarity, and even human health.

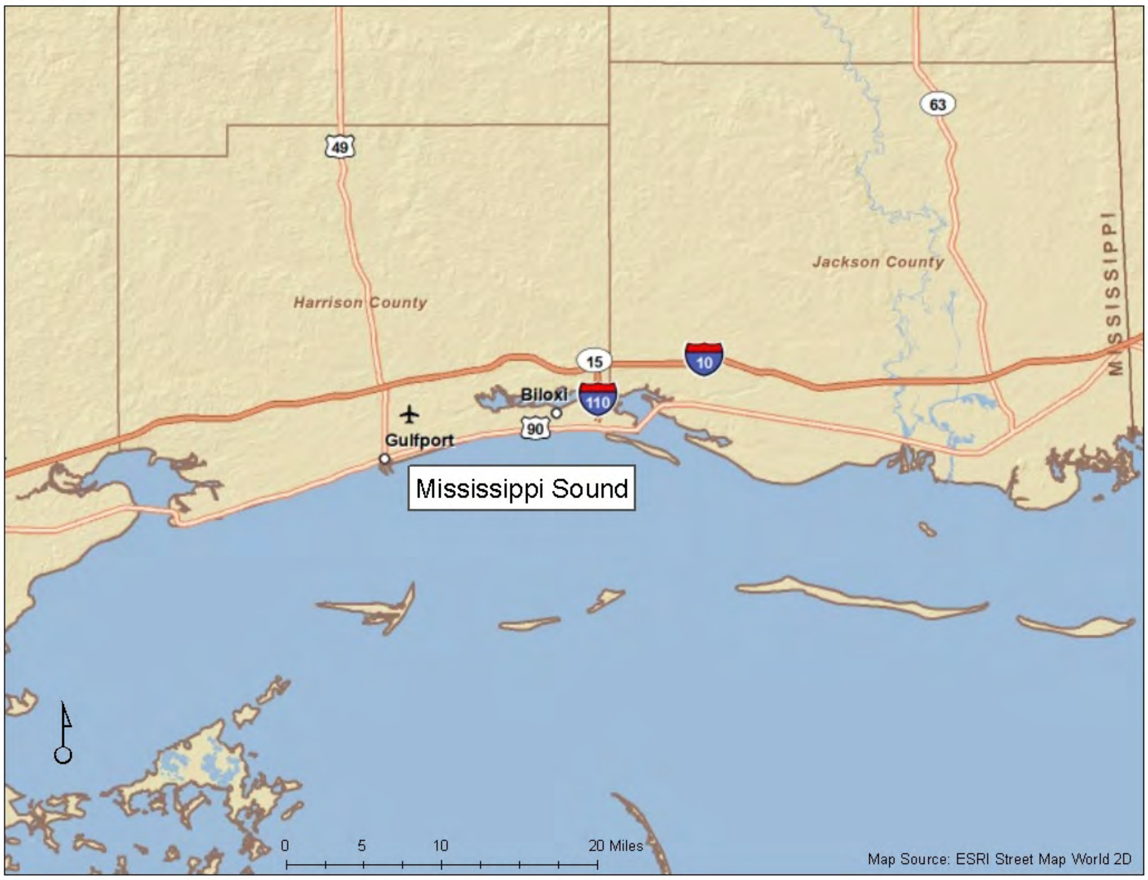

Figure 4.4. Mississippi Sound

4.4. Perdido Bay, Florida

Perdido Bay (Figure 4.5) is a shallow estuary that lies on the border between Florida and Alabama. On the southern edge, Perdido Bay is connected to the Gulf of Mexico through Perdido Pass and the Intracoastal Water Way, which links Lower Perdido Bay with Big Lagoon and Mobile Bay. On the northern edge the bay is fed by the Perdido River, which drains an area of 3000 km^2. Perdido Bay is approximately 50 km long, has an average width of 4 km and is on average 2 m deep. Perdido Bay is impacted by several anthropogenic stressors, including increased shoreline and watershed development, storm water run-off, septic tanks, effluent from waste water treatment, industrial discharges, agriculture, and silviculture.

Figure 4.5. Perdido Bay and Sites

Despite its relatively modest size (approximately 130 km^2), Perdido Bay encompasses a wide range of habitats, each of which is impacted differently by anthropogenic stressors. The bay can be divided into 3 distinct geographic regions: Upper Perdido Bay (north of the bridge of route 98), Middle Perdido Bay (between the bridge and Inerarity Point) and Lower Perdido Bay, which includes the areas around Ono Island and Perdido Pass. These regions are fringed by a series of bayous and lagoons, each with varying degrees of anthropogenic disturbance. Lower Perdido Bay is highly developed and receives significant amounts of stormwater run-off. It is also the part of the bay with the highest salinity, as it is closest to the Gulf of Mexico. Perdido Pass has a relatively good water quality compared to the rest of Perdido Bay. This allows for the presence of patchy seagrass beds in the shallow areas near Ono Island and Big Lagoon. Middle Perdido Bay includes the deepest parts of the estuary. This area is often strongly stratified, especially during periods of increased precipitation, when the lighter fresh water from run-off and river discharge overlays the heavier, more saline water from the Gulf. The deeper parts of Middle Perdido Bay can become hypoxic when stratification is strong and water temperatures are high. The upper parts of Perdido Bay are less developed, but receive significant amounts of run-off from agricultural activities in nearby Baldwin County (AL). Upper Perdido Bay receives nutrients from a couple of point sources, including a paper mill which discharges into the bay through Elevenmile Creek and a sewage treatment plant which discharges through Bayou

Marcus Creek. This area is more susceptible to phytoplankton blooms than the other parts of the bay.

The small bayous and lagoons surrounding Perdido Bay are very different in their physiochemical characteristics and size. Some of these systems, such as Tarkiln Bayou and State Park lagoon, are relatively pristine. They contain submerged aquatic vegetation and are surrounded by significant amounts of maritime forest and/or salt marsh. Others, such as Kees Bayou and Ingram Bayou are moderately impacted by either stormwater run-off or fertilizer. They still retain many characteristics from the healthy sites, such as fragmented seagrass beds or fringing marsh vegetation. Some bayous and lagoons are severely impacted by stormwater run-off, shoreline modification and fertilizer from golf courses or agriculture. Examples of these heavily impacted sites are Gongora, Weekly Bayou and Bayou Garcon.

5. System Assessments

5.1. Statistical Measures

Physical characteristics of the four sites are shown in Table 5.1. The systems range in surface area from 130 km^2 for Perdido to 6,300 km^2 for Barataria and in ratio of drainage area to surface area from 3.3 for Barataria Bay (the open water portion of the Basin) to 46 for Galveston. A simplified version of the Simmons Number (ratio of volume of freshwater inflow in one tidal cycle to product of tide range and surface area) is less than one in all four sites, indicating that tides will dominate over freshwater flow for average conditions. Low Simmons Numbers usually indicate well-mixed estuarine systems; however, any one of the estuaries may become locally and temporarily stratified by freshwater flow pulses, solar heating, and/or evaporation from the surface. Mean salinities are similar across the four, but salinities can range from zero to 30 ppt depending on location and freshwater pulses. Morphologies, depths, and bed composition are similar and typical of U.S. Gulf coast estuaries, with the Barataria Bay and Basin representing something of a divergence, since it is cut off from its original freshwater source, the Mississippi River, by levees.

The last column of Table 5.1 shows the average values for the 31 Gulf estuaries (except Mississippi River) according to EPA (1999). The Mississippi River is excluded from the averages because its unique size makes it unrepresentative and it skews the results.

Table 5.2 compares some environmental quality measures as reported by EPA (1999). Perdido Bay stands out with the largest relative areas of hypoxia and low DO, but Barataria has the largest relative area of anoxic conditions. Perdido is listed with a surprising 100 percent of its area showing benthos degradation and Barataria with none. None of the four sites showed significant fish pathologies. Otherwise the four sites can be considered as representing the range of Gulf-wide averages, again shown on the left.

Galveston Bay, Barataria Basin and Mississippi Sound are large areas with a multitude of stakeholders. Perdido Bay is somewhat smaller, but the selected lagoons are smaller still, illustrating some of the differences of scale. Barataria Basin is a complex of islands, marshes, shallow bays and interconnected channels; whereas Galveston Bay, Mississippi Sound, and Perdido Bay are open waters surrounded by both fringe marshes and sandy shores.

Each of the systems exhibits the small, mostly diurnal tidal range of the northern Gulf, generally less than about half a meter (Table 5.1). Surges associated with tropical and extra-tropical storms are aperiodic occurrences and can be as much as 10 m in extreme events. Freshwater inflows range from the relatively small but mostly unregulated flow of the Perdido Basin, to significant Mississippi Sound inflows of the partly regulated primary tributaries plus the large flows of the Pearl, and Mobile Rivers at the lateral boundaries, to highly regulated flows of the Barataria Basin diversions. Massive Mississippi River discharges may affect the offshore salinities of either Barataria, Mississippi Sound, and even Galveston Bay, depending on Gulf circulation patterns.

Table 5.1. Physical Attributes of Systems

Attribute	Perdido Bay	Mississippi Sound	Barataria Bay	Galveston Bay	Gulf Average[3]
Surface Area[1], S (km^2)	130	4,800	1,700	1,400	1,010
Drainage Area[1], D (km^2)	3,100	70,000	5,700	64,000	40,000
Ratio D/S	24	15	3.3	46	40
Mean Freshwater Inflow, Q (cms) [1]	62	1,240	156	430	200
Precipitation-Evaporation[4] (mm/mo)	+10	--	-7	-26	--
Mean Tidal Range[1], TR (m)	0.25	0.75	0.1	0.6	--
Simmons No.	0.17	0.03	0.02	0.05	--
Mean Salinity[1] (ppt)	15	24	13	11	21
Morphology	Coastal plain/bar-built lagoon	Bar-built	Bar-built/deltaic	Coastal plain/bar-built	--
Mean Depth [1] (m)	3	4	2	2	3
Bed composition sand/silt-clay[2] (%)	22/78	40/60	33/67	39/61	48/52
Coastal wetlands[2] (1000 m^2)	690	4,300	6.300	1,600	1600
Submerged aquatic vegetation (1000 m^2)[2]	0	120	--	73	120

Sources: * Gulfbase 2012; [2] EPA 1999, [3] Calculated from EPA 1999. Mississippi River excluded. [4] Calculated from NCDC (2012)

Table 5.2 Environmental Quality Measures (source: EPA 1999)

Attribute	Perdido Bay	Mississippi Sound	Barataria Bay	Galveston Bay	Gulf Average*
Area with hypoxia (%)	48	19	22	21	25
Area with anoxia (%)	1	<1	14	<1	8
Area with low DO (%)	100	19	11	<1	15
Area with high sediment contaminants (%)	92	6	0	17	19
Low Water Clarity (% of area)	8	5	23	39	21
Area with degraded benthos (%)	100	18	0	45	36
Fish with pathology (%)	0	<0.01	0.05	0.06	3
Area of harvest limited shellfish beds (%)	100	63	41	61	66
High TDN (%)	0	<1	100	<1	14
High Chl (%)	0	<1	100	0	21

Definitions
Low Water Clarity = < 10% Transmission of ambient light to 1 m depth
High TDN = Total dissolved nitrogen >= 1 mg/L
High Chlorophyll = Chlorophyll *a* > 20 ug/L
Hypoxia = at least 1 event of DO >0, <= 2 mg/L
Anoxia = at least 1 event of DO =0 mg/L
Low DO = Minimum bottom dissolved oxygen conc. over 12 hours is < 2 mg/L
High Sediment Contaminants = more than 5 analytes had concentrations > ER-L (Long et al. 1995)
Coastal Wetlands includes Salt/Fresh Marsh, Forested Scrub/Shrub, Tidal Flats
SAV = Submerged Aquatic Vegetation
Degraded Benthos = Benthic index < criteria for a province
% Fish with Pathology = Number of fish with observed pathology / number of fish sampled
Harvest Limited Shellfish Beds include beds conditionally approved, restricted, & prohibited for harvest
* Calculated. Mississippi River excluded

The Barataria Basin has a relatively low population density but relatively high industrial activity, with the latter driven mainly by the petroleum and fishing industries. Mississippi Sound is bordered by the heavily populated Mississippi, Louisiana, and Alabama coastlines, with a mix of tourism and industry. Perdido Bay has significant residential population, tourism, and fishing, but little industry, and the three lagoons examined in detail range from highly populated to pristine.

5.2. Drivers and Pressures

Table 5.3 lists the Drivers and Pressures for Perdido Bay, Mississippi Sound, Barataria Basin, and Galveston Bay as updated for this report. Figure 5.1 illustrates the same information graphically. Drivers are grouped into three major categories and 10 subcategories as shown in the Table column headings and Figure 5.1 horizontal axis.

- Hydrologic Modifications
    - Exploration and Navigation Canals
    - Flood Levee and Dam Construction
    - Freshwater Diversion
- Climate
    - Sea Level Rise/Subsidence
    - Extreme Weather Events
    - Climate Variability
- Human-Related Processes
    - Local Population Size
    - Trade/Industry
    - Socio-Political-Educational Perceptions
    - Tourism/Recreation

While Hydrologic Modifications are a Human-Related Process, they are separated here for two reasons – first, Hydrologic Modifications have such a large effect in some areas (such as Barataria) that they dwarf other human influences, and second, they are purposeful, i.e., they are intended to directly modify the physical environment, unlike other Human-Related Processes that indirectly serve as Drivers.

Corresponding to these Drivers, thirteen Pressures have been identified that are pertinent to at least one of the four systems, and they are shown as rows in Table 5.3. The intersections of applicable Pressures and Drivers are denoted by a G, B, M, or P in the table cell for Galveston, Barataria, Mississippi Sound, or Perdido, respectively. For example, the Driver “flood levee and dam construction” is manifested as the Pressure “altered river input” in two of the systems, Barataria and Mississippi Sound. Drivers and pressures for Galveston Bay were identified by the authors by reviewing a report by the Galveston Bay National Estuary Program (GNEP 1993) and translating that information into the DPSIR form.

Salient commonalities are that (1) Human-Related Processes dominate Drivers for the region, with Local Population Size and Tourism/Recreation cited for all systems and (2) five Pressures manifest those drivers:

- Increased Fishing Effort
- Increased Urban/Coastal Development
- Increased Boat Traffic
- Increased Nutrients
- Increased Pollution

A marked difference is seen between Drivers and Pressures at the Perdido Bay sites and the other systems, with Perdido experiencing only one significant Driver – Extreme Weather Events – outside the major category of Human-Related Processes; whereas Galveston Bay, Barataria Basin and Mississippi Sound experience the entire range of Drivers. This difference may be due to the scale of the analyses (three lagoons within Perdido Bay vs. large basins for the others) and/or to the difference in physical environments. Some of the Drivers and Pressures are shared by all three systems but differ in scale and type. For example:

Dredging of exploration and navigation canals in Barataria Basin alters internal wetland connectivity by direct wetland removal, redirecting water flows from overland to more of a channelized pattern, providing a more direct conduit for salt water intrusion, and by isolating areas of wetlands via dredged material banks (impoundments). These channels also increase boat traffic damage (wake, grounding, and anchor-related). In Mississippi Sound these channels are mostly in shallow but open coastal waters and may impact barrier islands, but few wetlands. In Perdido Bay dredged channels are small and used by recreational and fishing craft.

Flood levees and dam construction alter riverine (Mississippi River and Bayou Lafourche) input by cutting off freshwater, sediment and nutrient input that is needed to sustain the Barataria wetlands. They alter internal wetland connectivity by isolating some wetland areas. Flood levees have also increased coastal development pressures, by reducing flood frequency and impacts, and thus making these areas more appealing to developers. In Mississippi Sound and Perdido Bay levees do not play a role, but upstream impoundments capture sediment and attenuate flood flows to some degree, but much less than the near total control of the Barataria Basin.

Freshwater diversions have been initiated as a management tool in Barataria to ameliorate the effects caused by leveeing the Mississippi River. They reconnect the riverine resources to the wetlands in a small-scale and controlled manner. They are vehicles for introducing freshwater, nutrients, and pollutants. While they have not previously played a substantial role in the other two systems, proposals to use the Leaf or Pascagoula Rivers in Mississippi to carve oil storage caverns in salt domes would raise enormous issues for ecosystem management in Mississippi Sound.

Extreme weather events such as river floods, increase riverine input to the basins. Hurricanes and severe tropical storms alter internal wetland connectivity and decrease land elevation through direct marsh destruction and/or redistribution. These events also redistribute sediments from the marsh and barrier island systems, which can either be deposited within or removed from the system. Severe droughts can result in wetland vegetation death and resulting decrease in land elevation. Annual climatic ***variability*** alters local riverine input through the annual spring discharge of the rivers and local bayous. Winds associated with winter cold fronts cause a 'set up' and 'set down,' in which coastal waters flush into and out of the system. This often results in redistribution of basin salinity and sediment. While these effects are experienced by all three systems, Barataria and coastal Mississippi are more strongly threatened because of subsidence and bathymetry, respectively.

Local population size results in increased urban and coastal development, impacts wetland biodiversity, and generally results in degraded wetlands. As population increases, fishing demand increases and there is increased boat traffic damage (wake, grounding, and anchor-related). Humans also introduce non-indigenous plant and animal species. In addition, increased urban and coastal development leads to increased point and non-point sources of nutrients and pollutants; however, in Perdido Bay increased nutrients and pollutants come primarily from coastal watersheds; in Mississippi Sound they drain from almost the entire state of Mississippi; and in Barataria they come from a huge swath of middle America. These differences in scale make analyses of the issues and planning of solutions significantly different enterprises.

Trade and industry in Barataria Basin and Mississippi Sound primarily include oil and gas exploration and production, navigation, ship building, and commercial fisheries. Industrial activities can lead to increased point and non-point sources of nutrients and pollutants. Increased boat traffic damage (wake, grounding, and anchor-related) is associated with a number of trade industries, and non-indigenous plant and animal species can be introduced through ship ballasts and other activities (aquaculture - tilapia, fur trade - nutria, etc.). There is a large commercial fishing (fin fish, crab, shrimp, oysters) industry, which leads to increased fishing pressures. Cypress mulch has also become an increasing trade activity, leading to increased logging pressure in upper Barataria Basin. Perdido Bay has much less industrial activity, with trade dominated by tourism, residential communities, and fishing.

Socio-political-educational perceptions in all three systems are such that there is a disconnect between policy and public education and perception of the issues, such as point and non-point sources of nutrients and pollutants (e.g., dumping of vessel waste, littering, sewage treatment in coastal camps), introduction of non-indigenous species (e.g., landscaping, exotic pets), logging (e.g., demand for cypress mulch), and development in sensitive coastal areas. In addition, the regulatory frameworks can be unclear and often unevenly enforced in different management areas. For example, the current knowledge on maintaining sustainable cypress forests is not consistently applied (USACE 2005) and many laws and regulations are enforced by different state agencies with varying emphases. Such disconnects frustrate stakeholders and ultimately undermine restoration efforts.

Table 5.3. Common Drivers (Columns) and Pressures (Rows) for Barataria Basin (B), Mississippi Sound (M), Perdido Bay (P), and Galveston Bay* (G). (Absence of a letter code indicates that either the Driver-Pressure combination does not apply to that system.)

PRESSURES	DRIVERS									
	Hydrologic Modifications			Climate			Human-Related Processes			
	Exploration & navigation canals	*Flood levee & dam construction*	*Freshwater diversion*	*Sea Level Rise/ Subsidence*	*Extreme Weather Events*	*Variability*	*Local Population Size*	*Trade/ Industry*	*Socio-Political-Educational Perceptions*	*Tourism/ Recreation*
Altered riverine input		B M G	B M P G		B G	B M G	M		M	
Altered internal wetland connectivity	B	B		B M G	B M G		M G	B M	M	
Increased nutrients (point and non-point)			B			M G	B P M G	B P M G	P M G	B M G
Increased pollution (point and non-point)	G		B G				B P M G	B P M	B M	B P M
Increased dredging	B G	M	M				P M	B M	M	B M
Increased fishing effort			M G			M	B M G	B M G	M	B P M G
Increased boat traffic	B G						B M	B M	M	B P

PRESSURES	DRIVERS									
	Hydrologic Modifications			Climate			Human-Related Processes			
	Exploration & navigation canals	*Flood levee & dam construction*	*Freshwater diversion*	*Sea Level Rise/ Subsidence*	*Extreme Weather Events*	*Variability*	*Local Population Size*	*Trade/ Industry*	*Socio-Political-Educational Perceptions*	*Tourism/ Recreation*
(wakes, grounding, and anchoring)										M G
Introduction of non-indigenous species			M		M	M G	B M	B M	B M G	B M
Increased urban/coastal development	M	B	M				B P M G	B M G	B P M G	B P M G
Increased resource extraction								B G	B G	
Redistribution of marsh & barrier island sediment	M G		M G	G	B M G	B M G	M	M	M	M
Decreased land elevation				B G	B M					
Critical habitat degradation	M	M	M G	M G	P M	M G	M G	M G	M	M G

* Note: Galveston Bay Drivers and Pressure were determined by a different process than the other systems, as noted in Appendix A.

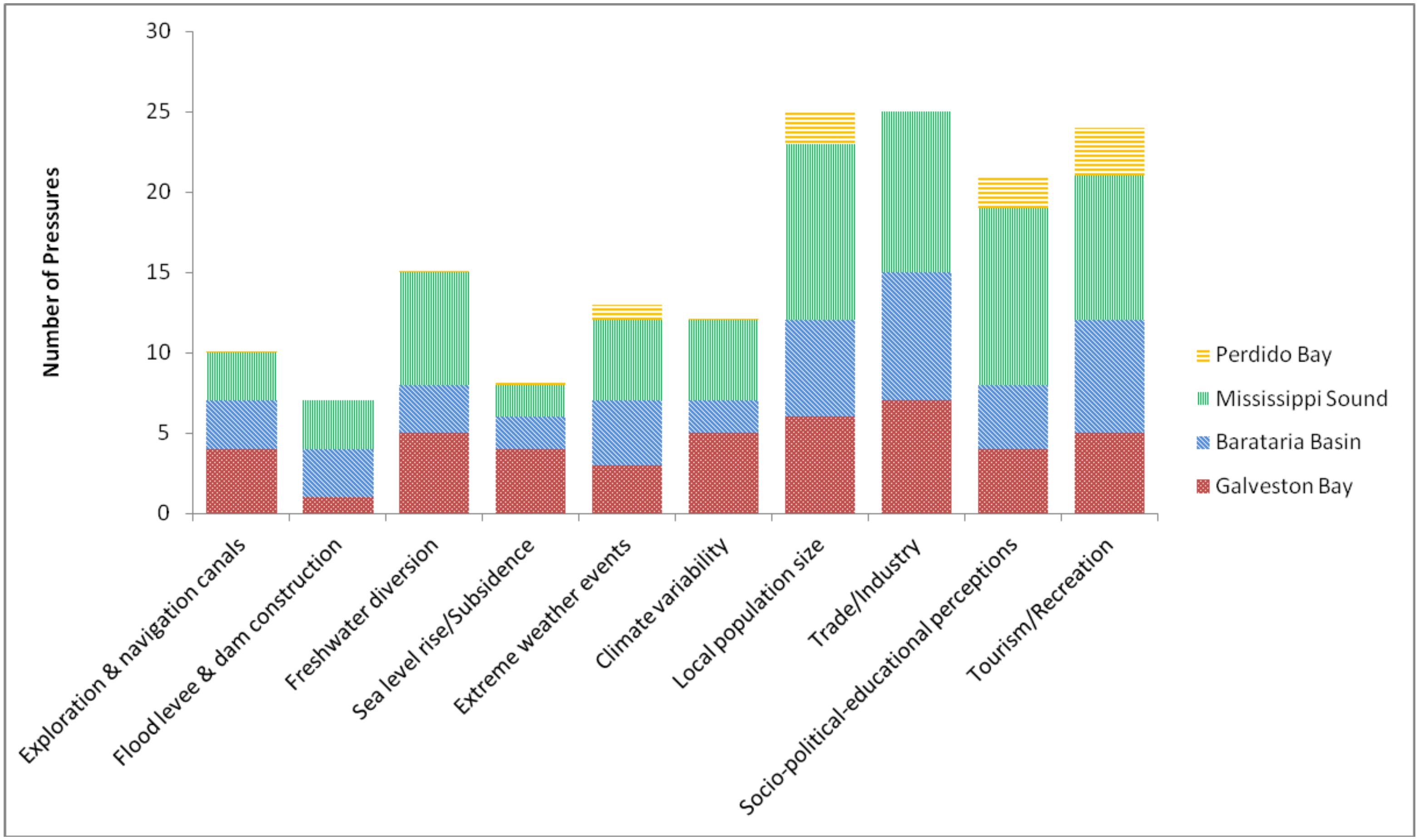

Figure 5.1 Numbers of Drivers-Pressures Experienced by Location

Tourism and recreation can lead to increased urban and coastal development, such as coastal camps and marinas, producing increased point and non-point sources of nutrients and pollutants. The Gulf is a popular fishing destination, for both fresh and salt water fishing, and increased fishing demand is linked to these activities. Increased recreational boating increases boat traffic damage and dredging for marinas and boat slips. Some tourist and recreation activities can also introduce non-indigenous plant and animal species, by transporting plant (e.g., hydrilla) and animal (e.g., live bait) species.

5.3. States, Ecosystem Services, and Responses

Table 5.2 lists some characteristic statistical states of the four sites. Table 5.4 lists the recommended 18 State variables and 8 general Impacts in the DPSIR construct) for the 13 Pressures listed in Table 5.3. The states and ecosystem services are generic and non-quantified. For discussions of the specifics for each site, see the appendices.

Responses, or management measures, tend to be unique to each site, pressure and sometimes state. Table 5.5 lists the Pressures and States common to all four sites, with a corresponding list of possible Responses, or management measures intended to improve the system State by relieving or ameliorating the corresponding Pressure. Selection of a Response will depend on modeling the state variables to evaluate possible outcomes, the uncertainty associated with events and outcomes, and finally, risk assessment.

Habitat modification or loss is the most common Impact associated with the four-system Drivers-Pressures-States, followed by *Lack of support for responses* and *Change/loss of native species*. Other impacts , such as *increased storm surge* and *Eutrophication*, tended to be applicable to a single system.

Ecosystem Services (using the Millennium Assessment (2005) categories) affected by the impacts, in decreasing order of occurrence, for the four systems are:

- Habitat Formation
- Food
- Educational
- Biological Regulation
- Aesthetics
- Recreational
- Nutrient Cycling
- Freshwater
- Ornamental

Table 5.4. States and Ecosystem Services for Identified Pressures (page 1 of 2)

Pressure(s)	**State Variable(s)**	**Impacts**	**Ecosystem Services Affected***
Altered riverine input	River water flux into wetland	Modification or loss of habitat	Habitat formation
Altered internal wetland connectivity	Wetland water levels, Wetland material and organism exchange	Change in material and/or organism exchange	Habitat formation Biological regulation Food
		Modification or loss of habitat	Habitat formation
Increased nutrients	Nutrient concentrations	Eutrophication of coastal water bodies	Nutrient cycling Aesthetics Recreational
		Increased vegetation stress	Aesthetics Disturbance regulation
		Modification or loss of habitat	Habitat formation
	Public understanding of nutrient levels	Lack of support for responses to address the issue	Educational
Increased pollutants	Target pollutant (i.e. mercury) concentrations	Increased stress on habitats and/or organisms	Food Fresh water
		Commercial and/or recreational organisms no longer safe for consumption	Food Recreational
	Public understanding of Target pollutants (i.e. mercury)	Lack of support for responses to address the issue	Educational
Increased dredging	Area of wetland habitat	Modification or loss of habitat	Habitat formation
Increased fishing effort	Fisheries catch	Decrease in or loss of fishery	Food

Pressure(s)	**State Variable(s)**	**Impacts**	**Ecosystem Services Affected***
Increased boat traffic	Area of bottom damage, linear measure of bank erosion	Modification or loss of habitat	Habitat formation
Non-indigenous species introduction	Public understanding of non-indigenous species issues	Lack of support for responses to address the issue	Educational
	Species type and abundance	Change/loss of native species	Food Aesthetics Ornamental resources Biological regulation
Increased Urban/coast development	Population in the coastal zone, acres of developed land in the coastal zone	Modification or loss of habitat	Habitat formation
	Public understanding of coastal development issues	Lack of support for responses to address the issue	Educational
Increased resource extraction	Areal extent or number of resource extraction operations	Modification or loss of habitat	Habitat formation
Redistribution of marsh and/or barrier island sediments	Habitat area	Modification or loss of habitat	Habitat formation
Decreased land elevation	Habitat area and elevation	Modification or loss of habitat Increased storm surge	Habitat formation Flood regulation
Critical Habitat degradation	Habitat area	Modification or loss of habitat	Habitat formation Food
	Species type and abundance	Change/loss of native species	Food Biological regulation

* Ecosystem services as identified by Millennium Ecosystem Assessment (2005)

Table 5.5 General Responses to Pressures and Ecosystem Services (page 1 of 3)

Pressure(s)	**Impacts**	**Responses**
Altered riverine input	Modification or loss of habitat	Regulation of upstream storage and diversions to accommodate environmental flow requirements
		Water control structures and procedures
		Morphological modification
Altered internal wetland connectivity	Change in material and/or organism exchange	Morphological modification
	Modification or loss of habitat	Zoning
		Creation of new or enhanced habitat
		Public outreach and education
		Morphological modification
		Water and sediment controls
Increased nutrients	Eutrophication of coastal water bodies	Public outreach and education
		Wastewater treatment
		Best Management Practices for Nonpoint Sources
		Regulation of upstream storage and diversions to accommodate environmental flow requirements.
		Water control structures and procedures
		Morphological modification
	Increased vegetation stress	Same as above
	Modification or loss of habitat	Same as above
	Lack of support for responses to address the issue	Public outreach and education

Pressure(s)	Impacts	Responses
Increased pollutants	Increased stress on habitats and/or organisms	Public outreach and education
		Wastewater treatment
		Best Management Practices for Nonpoint Sources
		Water control structures and procedures
	Commercial and/or recreational organisms no longer safe for consumption	Public outreach and education
		Remediation of point sources
		Regulation of incidental sources
	Lack of support for responses to address the issue	Public outreach and education
Increased dredging	Modification or loss of habitat	Regulation of dredging activities
		Decommissioning/re-purposing of channels
		Adoption of improved dredging and beneficial uses
		Adoption of non-dredging sediment management methods
		Creation of new or improved habitat
Increased fishing effort	Decrease in or loss of fishery	Size, catch, season limits
Increased boat traffic	Modification or loss of habitat	Vessel, speed, and traffic restrictions
		Bank protection
		Boater education
		Creation of new or improved habitat

Pressure(s)	**Impacts**	**Responses**
Non-indigenous species introduction	Lack of support for responses to address the issue	Public outreach and education
	Change/loss of native species	Creation of new or improved habitat
		Eradication
Increased Urban/coast development	Modification or loss of habitat	Zoning
		Creation of new or enhanced habitat
		Morphological modification
		Water and sediment controls
	Lack of support for responses to address the issue	Public outreach and education
Increased resource extraction	Modification or loss of habitat	Public outreach and education
		Regulation of extraction
		Creation of new or enhanced habitat
		Morphological modification
		Water and sediment controls
Redistribution of marsh of barrier island sediment	Modification or loss of habitat	Same as above
Decreased land elevation	Modification or loss of habitat	Same as above
Critical habitat degreation	Modification or loss of habitat	Same as above
	Change/loss of native species	Creation of new or enhanced habitat
		Stocking/restocking species

From Table 5.5 it can be seen that the most frequent management responses, in decreasing number of occurrences, are:

- Public outreach and education
- Creation of new or improved habitat
- Morphological modification
- Water and sediment controls
- Best Management Practices for Nonpoint Sources
- Regulation of extraction
- Wastewater treatment
- Water control structures and procedures
- Regulation of upstream storage and diversions to accommodate environmental flow requirements.
- Adoption of improved dredging and beneficial uses

5.4. Effects of Scale

Examples from Barataria Basin and Perdido bay illustrate the effect of scaling issues in IEA. The Barataria Basin consists of sub-basins made up of open water and a gradient of marshes from saline to fresh. Figure 5.2 shows the variation in two simple physical properties – tide range and salinity – across those sub-basin categories. The Basin average tide range of 0.1 m is one-third of the maximum tide range and 10 times the minimum range. While all are micro-tidal, the difference in flushing and circulation between a 0.3 m tide range and one of 0.01 m is substantial. Salinity exhibits a similar pattern, varying from less than 1 ppt to about 16 ppt, or fresh to brackish.

This level of difference in physical processes is not unique to the Barataria Basin. Each of the four estuaries exhibits similar patterns of large variation in tide range, salinity, depth, and other features across the estuary. Most often the variation is longitudinal, from the river to the sea, but lateral differences are also present.

Table 5.6 shows a Drivers and Pressures summary for Barataria Basin. The number of Pressures for each Sub-Driver are fairly consistent across the sub-basins, with only one sub-driver – freshwater diversion – not exerting nearly equal pressures across all sub-basins.

This dichotomy of nearly equal distributions of Pressures but substantial dissimilarities in at least some physical processes suggests that while management measures may be similar at multiple scales, evaluation of the system's behavior in response to those measures may not be. The assessment step should include both the smaller scale features and the overall system in order to resolve the question.

The Perdido Bay assessment provides another picture of scale effects. Figure 5.3 shows a state variable, total dissolved nitrogen, variability for three small lagoons and for the larger bay across several periods. Total dissolved nitrogen (TDN) concentrations were always higher within each of the lagoons than in the surrounding bay. The magnitude of this difference varies over time, but differences seem highest in Kees Bayou during summer. These results suggest that nutrients are rapidly assimilated and end up in local populations of primary producers.

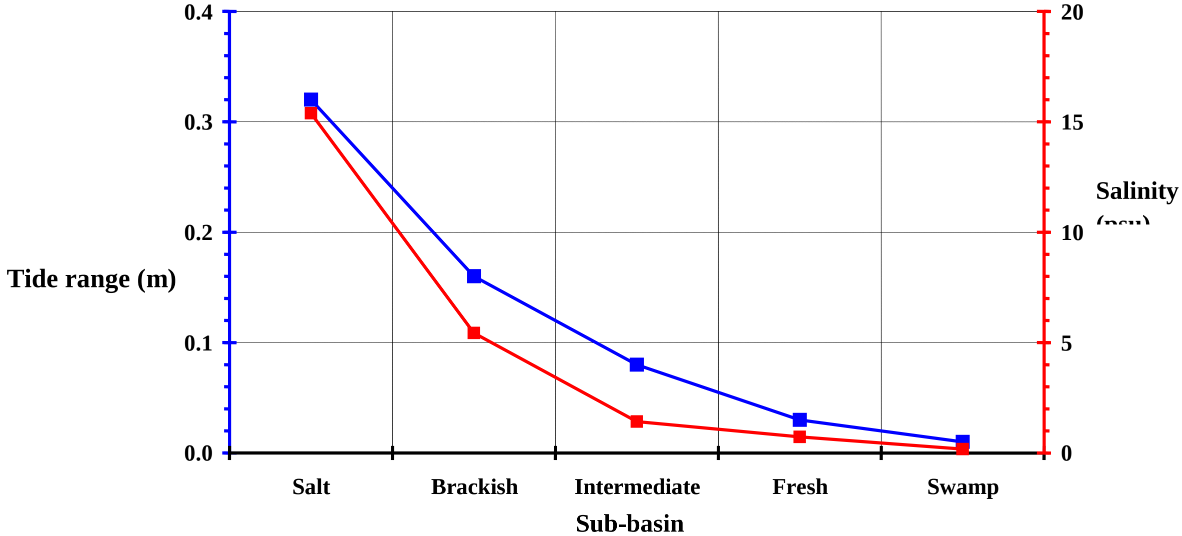

Figure 5.2 Tide and Salinity variation across the Barataria Sub-basins

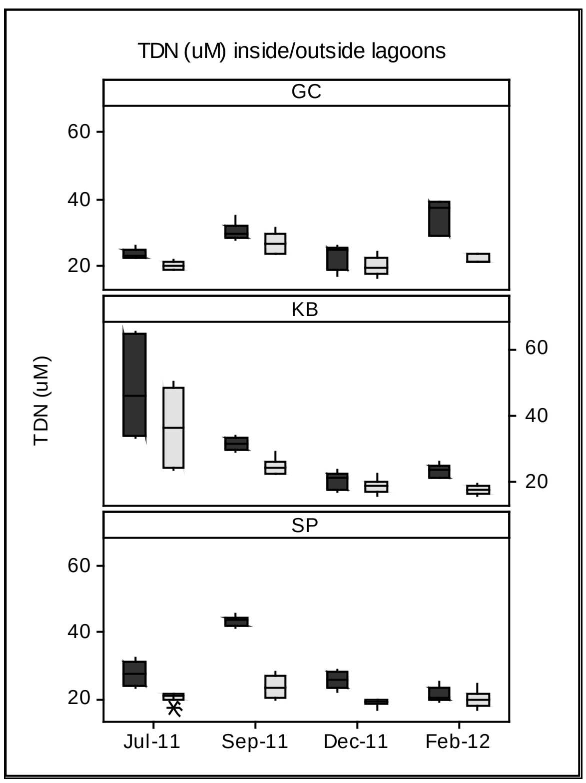

Figure 5.3. Total dissolved nitrogen inside (dark grey) and outside (light grey) the three lagoons in Lower Perdido Bay.

Table 5.6 Numbers of Pressures Experienced by Sub-Basins in Barataria

Sub-Driver	Sub-Basin					
	Swamp forest	Fresh marsh	Intermediate marsh	Brackish marsh	Salt marsh	Basin total
Exploration & navigation canals	2	2	4	5	5	18
Flood levee & dam construction	3	2	3	3	3	14
Freshwater diversion	0	4	4	4	1	13
Sea level rise / subsidence	2	2	2	2	2	10
Extreme weather events	1	1	2	4	4	12
Variability	1	1	1	2	2	7
Local population size	7	6	6	7	7	33
Trade / industry	8	6	6	8	8	36
Socio-political-educational perceptions	5	4	4	4	4	21
Tourism / recreation	6	6	6	6	6	30
Total	35	34	38	45	42	194

5.5. Sulis Implementation

The front page of the Sulis Informatics Services Northern Gulf EAM website (http://www.ngi.msstate.edu/sulis/applications/EAM) is shown in Figure 5.4. The inset map displays the Gulf of Mexico with the four selected aquascapes highlighted. On the left side are five buttons representing the presently functional services – Data Discovery, Basin Maps, DPSER results, Risk Assessment, and Community Models. The Basin Map drop-down menu on the upper right enables the user to change background for the map. Also shown in this image are some critical habitats for illustrative purposes, but those data layers are explored elsewhere.

Figure 5.4. Sulis Informatics Services EAM Front Page

Clicking the Data Discovery Button brings up Figure 5.5, which is a generic geoportal for data, not limited to EAM. It features options to share data, log in as registered user, and on the left, search for data. Entering the search term “Mobile Bay”, for example, yields Figure 5.6A, which shows the area of coverage for Mobile Bay data and, on the right, a list of the data sources for Mobile Bay that are presently identified within Sulis.

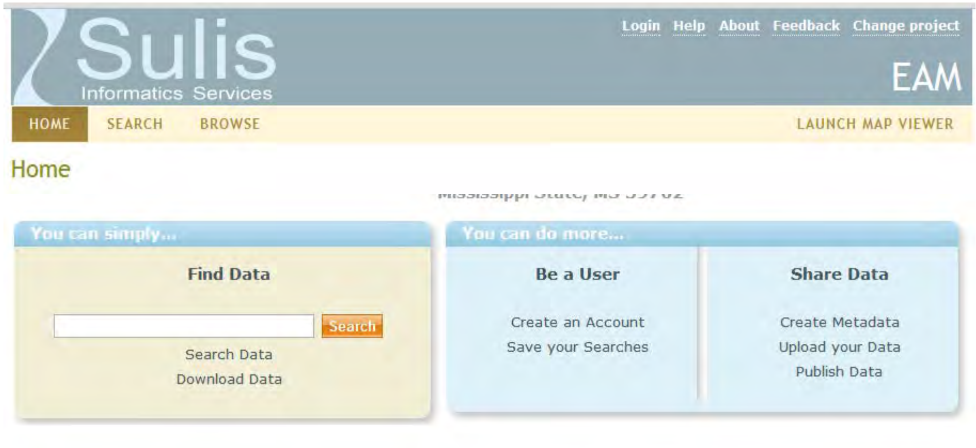

Figure 5.5 Data Discovery Option

For each data source various access options are given as available, including metadata display, hosting web site, and mapping options. The first item in Figure 5.6A has been expanded, showing additional detail and a number of options, and that is magnified for legibility in Figure 5.6B. It describes the data as coastal relief information from the NCDDC and provides options to examine the metadata and to map the data in several formats, such as KML and GIS. The geoportal functionality has been customized for specific datasets that are beyond standard geospatial data types and products. Specifically the geoportal has been customized to visualize complex model data with server-side technology that uses EnVis, a custom visualization tool developed by Mississippi State University. These options are available in the Details section of the selected data by selecting the Explore option. Figure 5.7 displays a visualization of ADCIRC model data of sea surface height for hurricane Ivan provide by LSU for the Northern Gulf Coast Hazards Collaboratory (NGCHC).

The geoportal data discovery engine is flexible and powerful and is not restricted to EAM project information. It is scalable in design so that more experienced users able to take advantage of its full power and functionality. Clicking the “EAM Basin Map” in Figure 5.4 is the usual way to access information for this project, and it leads to resources shared through the ArcGIS Portal shown in Figure 5.8. This allows for users to incorporate other data and resources shared within this portal and external data sources.

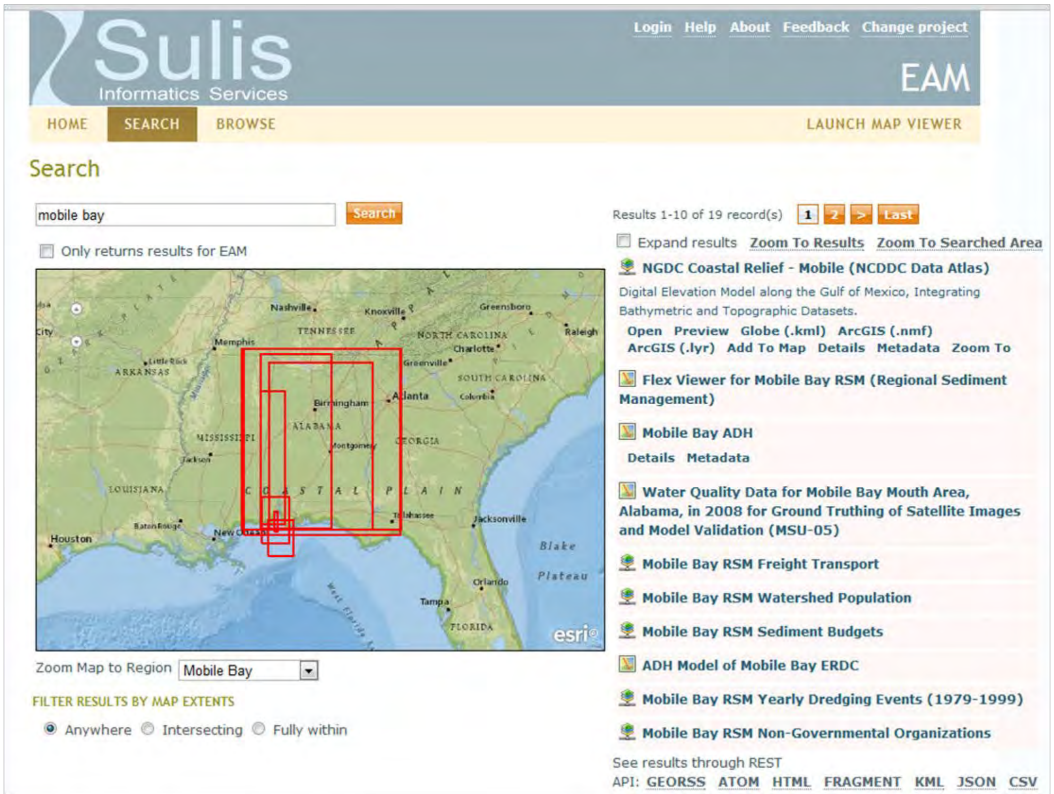

Figure 5.6A Results of Data Discovery on the Search Term "Mobile Bay".

Figure 5.6B. Enlarged view of data details from top item in Figure 5.6A

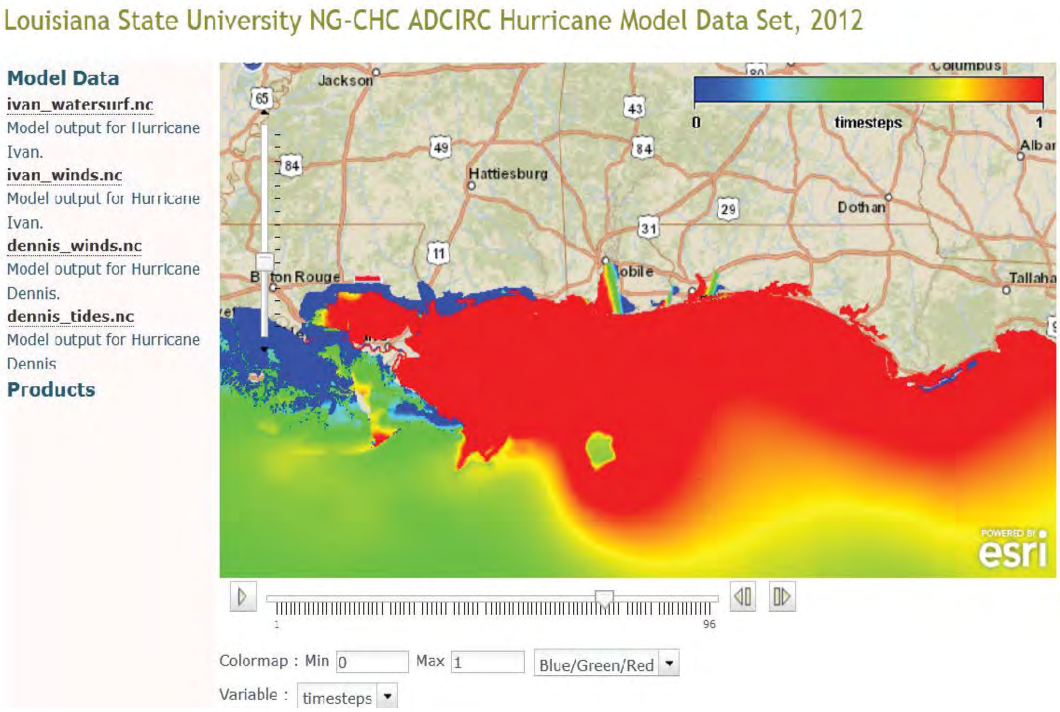

Figure 5.7 Custom Sulis geoportal model visualization of LSU NGCHC data for hurricane Ivan.

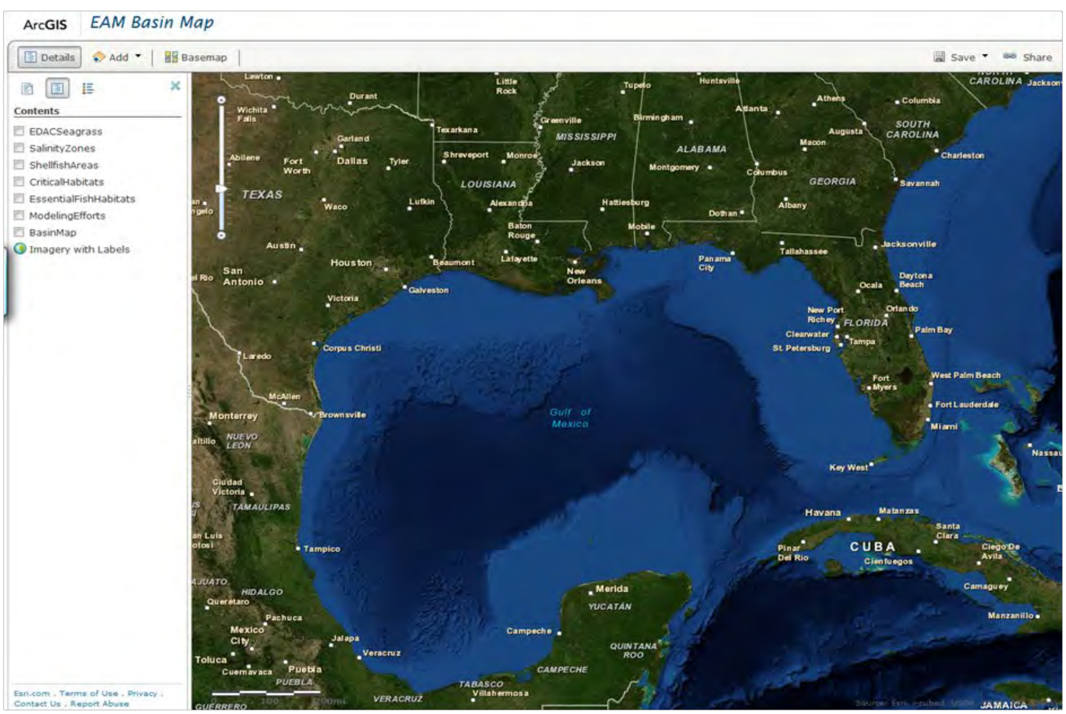

Figure 5.8. Basin Map Screen for Sulis Gulf EAM Project

Several different base maps are available by clicking that button on the top of the screen. Here the base map of satellite imagery with place name labels has been selected. The left side of Figure 5.7 shows the data layers available for this project at the time of this report:

- EDAC Sea Grass
- Salinity Zones
- Shellfish Areas
- Critical Habitats
- Essential Fish Habitats
- Modeling Efforts
- Basin Map

Any or all of the above list can be activated by the user and displayed on the map. Select layers offer information with a mouse click and more advanced users can customize the information returned by enabling and configuring the pop-up for any of the layers within the data groups. Checking only the box next to Essential Fish Habitat and the "Legend" option produces the screen shown in Figure 5.9. The data are from the NOAA-NGI Environmental Data Assembly Center (EDAC) database and reside on the NCDDC server, from which Sulis reads and displays them. Other data displayed as options in Figure 5.8 can be explored via the Sulis web site.

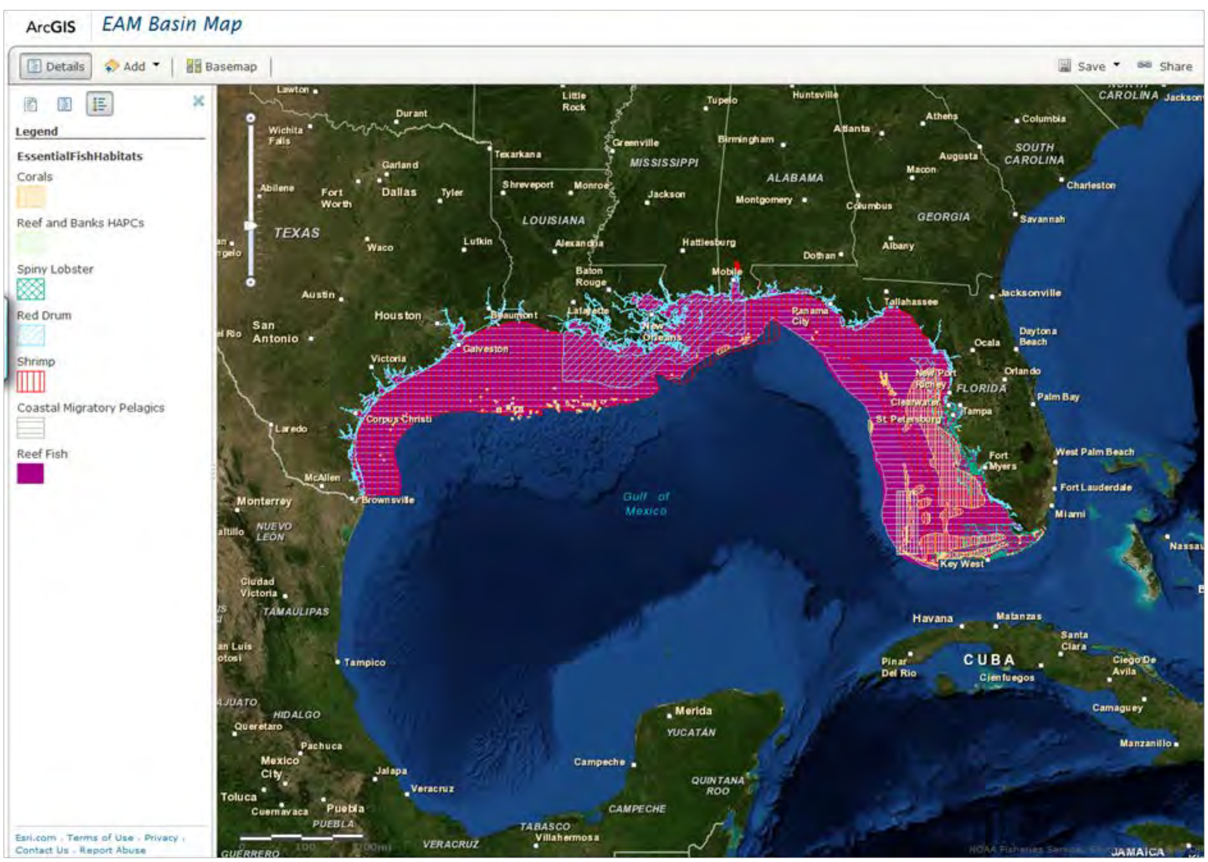

Figure 5.9 Essential Fish Habitat Display in Sulis Gulf EAM

The DPSIR/DPSER and Risk Assessment pages are in preparation at the time of this report and will be described in subsequent work.

Selecting the Community Models button on Figure 5.4 offers two options 1) Map View and 2) Tabular View. The Map View option produces the screen capture in Figure 5.9, which shows all the models in the Sulis inventory, denoted by shapes showing the model boundary outlines. At the bottom of the screen is a scrollable list providing a description of the models by name, level number (corresponding to levels in the CEEM described in Section 3.2) and area of coverage.

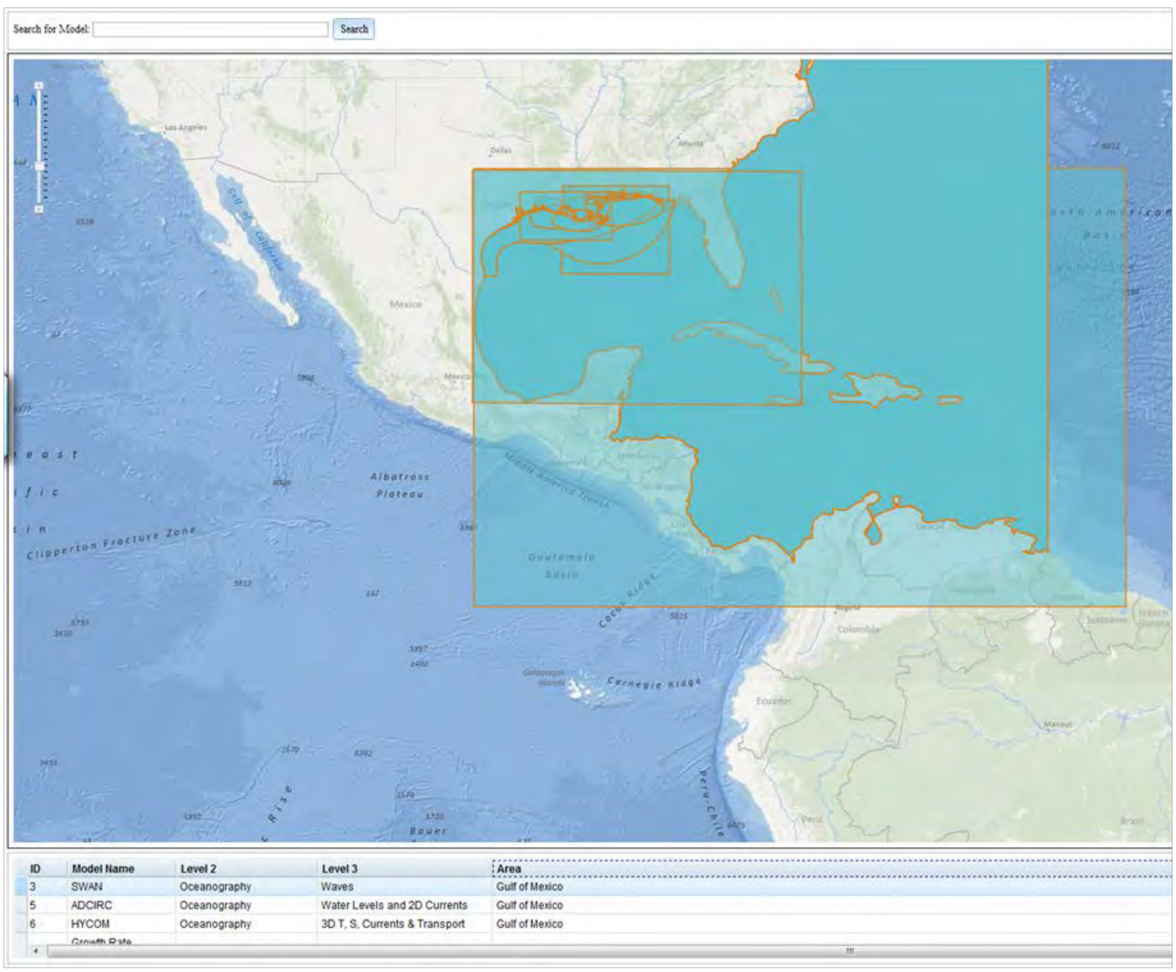

Figure 5.10 Sulis Community Models Inventory Screen.

Entering “Perdido” in the search box at the upper left corner of Figure 5.10 produces Figure 5.11, a map of models for the Perdido Basin. Three models are listed in the list at the bottom – two HSPF hydrologic models and one EFDC hydrodynamic, salinity, and sediment model. The

Tabular View option generates search results in a tabular list of the models with additional information on processes, points of contact, etc. as shown in Figure 5.12.

Work is ongoing to add features and data to the Sulis Informatics Services.

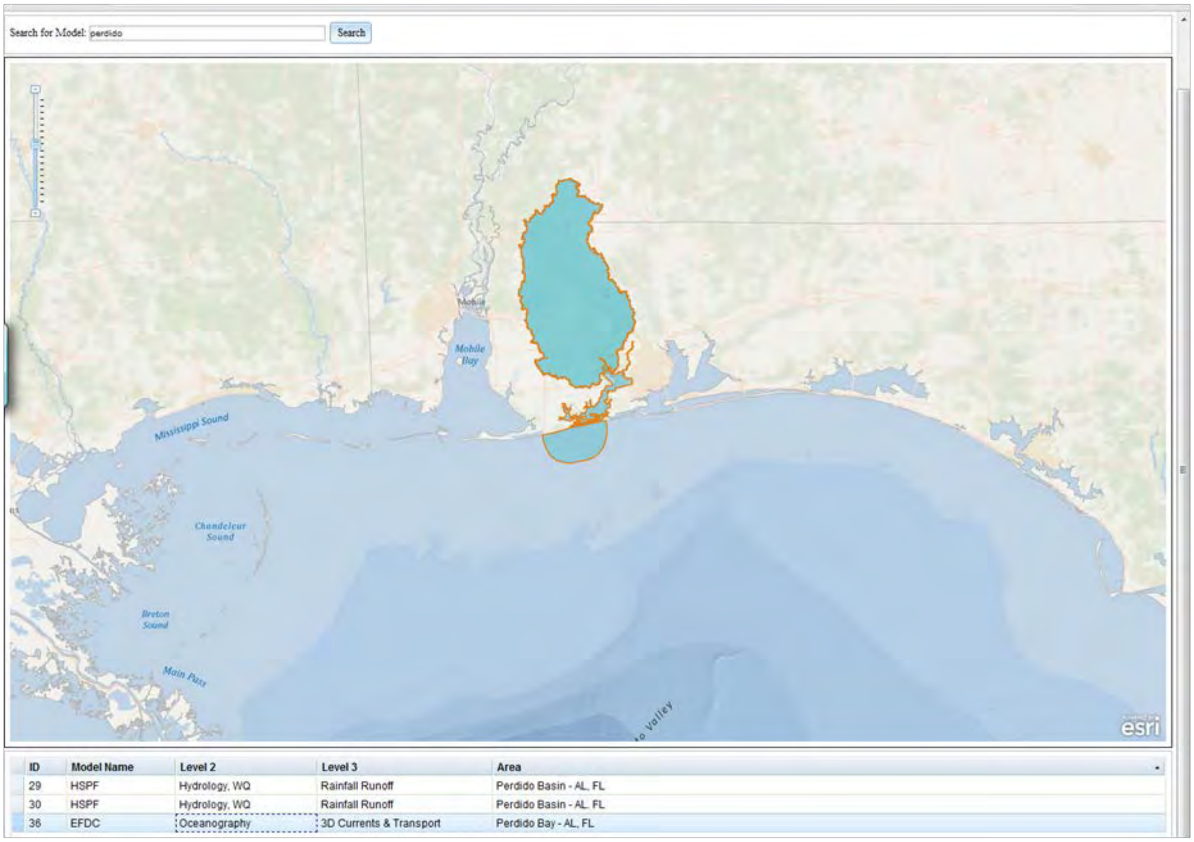

Figure 5.11. Display of Perdido Basin models from the Inventory.

Sulis
Informatics Services & Ecosystem Assessment

Search for Models: perdido Search

Model ID	Model Name	Level 1	Level 2	Level 3	Area	Purpose	Point of Contact
29	HSPF	Physical	Hydrology, WQ	Rainfall Runoff	Perdido Basin - AL, FL	Predicting FW flow to estuary for DWH Spill study	J. Diaz, MSU
30	HSPF	Physical	Hydrology, WQ	Rainfall Runoff	Perdido Basin - AL, FL	Predicting FW flow to estuary for DWH Spill study	J. Diaz, MSU
36	EFDC	Physical	Oceanography	3D Currents & Transport	Perdido Bay - AL, FL	Predicting currents and transport for salinity study	V. Alarcon, MSU

Figure 5.12. Tabular Display of Perdido Basin Models.

6. Risk Assessment Framework

The Sulis Risk assessment framework is based on the principles and practices described in Section 2.7. It assumes that risk will be based on analytic tools, or models, as described in Section 3.2 and depicted in Figure 3.3.

Figure 6.1 expresses the Conceptual Earth Ecosystem Model of Figure 3.3 in terms of the Sulis Community Ecosystem Models in which computational tools represent each of The CEEM processes. Beginning (arbitrarily) with tools and models for Weather (labeled “1” in the Figure), which provide input to Landscape models (2), Hydrologic models (3), Economic and Social models (7), and so on to all the other model types (not all arrows are shown so as to reduce clutter). Landscape models provide input to Hydrologic models, Water Quality models (5) and so on. Some commonly used numerical models are listed in the circles as examples.

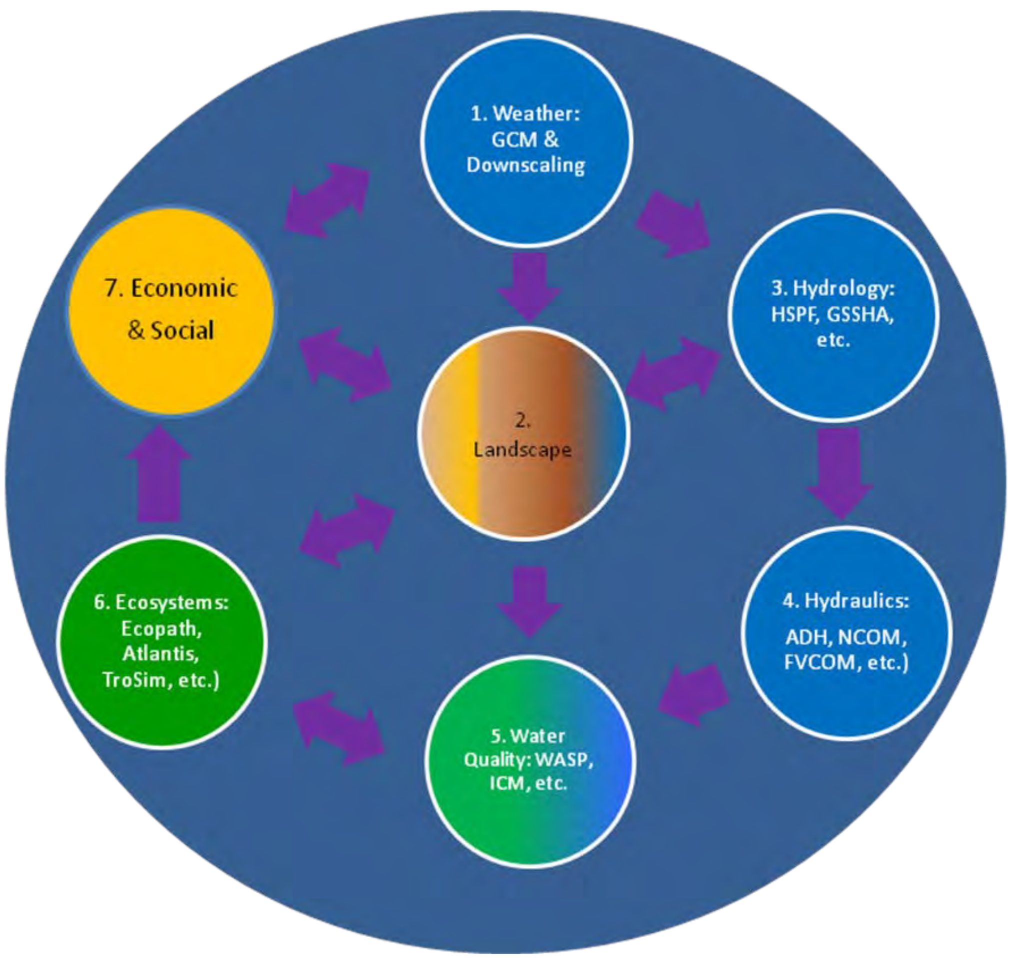

Figure 6.1 Sulis Community Ecosystem Model Schematic

All of the arrows, both explicit and implied, in Figure 6.1 show information output from one tool serving as input to another tool. That information consists of three basic types:

- Observed Data
- Model parameter values
- Model outputs

Each of these information types exhibit uncertainty. Observed data contain uncertainty in the form of measurement error, temporal and spatial gaps, finite coverage, and interpretation/analysis error. For example, surveyed land surface elevations contain error from inaccurate instruments, reading error, imprecise locations, inadequate spatial resolution and coverage, and datum plane adjustments ranging from subsiding benchmarks to inaccurate geoid models. Numerical model parameter values such as boundary roughness, constituent decay rates, and predation rates typically suffer from a lack of data against which to calibrate them and/or no practical method to measure them directly. Model outputs include the propagated uncertainty of inputs from observed data and parameter values plus error introduced by model structural error (inadequate or incomplete equations) and numerical error (e.g., truncation, averaging, approximating, etc.)

Compounding these uncertainties is natural variability. From weather-altering sun spot cycles to genetic expressions in biota to human responses, nature is decidedly non-deterministic. Natural processes can be either random, which are successfully described in probabilistic terms, such as maximum likelihood estimates and probability distribution functions (PDF), or chaotic, in which the underlying process is so complicated that it appears to be random. Turbulence in fluids is an example of the latter. Random variables that vary in time can be described by similar statistical methods, known as stochastic analyses. (For various perspectives on uncertainty, see Lehrter and Cebrian (2010), NRC (1994), Morgan and Henrion (1990), and USACE (1996).)

This litany of uncertainty might seem to render impossible the task of assessing outcomes with any degree of confidence; however, mathematical science, systems engineering, and risk procedures provide tools which, properly used, quantify and manage all these uncertainties so that they can be harnessed for sound decision-making. For example, it isn't presently possible to predict the exact air temperature in New Orleans at 1 PM on May 1st one year in the future; however, a maximum likelihood estimate can be made along with variances that will bracket the exact temperature to any specified degree of certainty (variance).

Figure 6.2 illustrates a systems view of any one of the model/computational tools in Figure 6.1. The model uses three types of input to make computations and produce outputs that provide inputs to the next model. Each of the inputs – observed data (O), prior model outputs (MI), and parameter values (P) – exhibits uncertainty, each characterized by a unique PDF, illustrated by the schematic curves in the bubbles. Those uncertainty distributions are propagated through the model computations and produce outputs with a different PDF (MO) that flow into the next model. Systems analysis and statistical procedures can be used to capture and compute the resulting outputs' probability distributions.

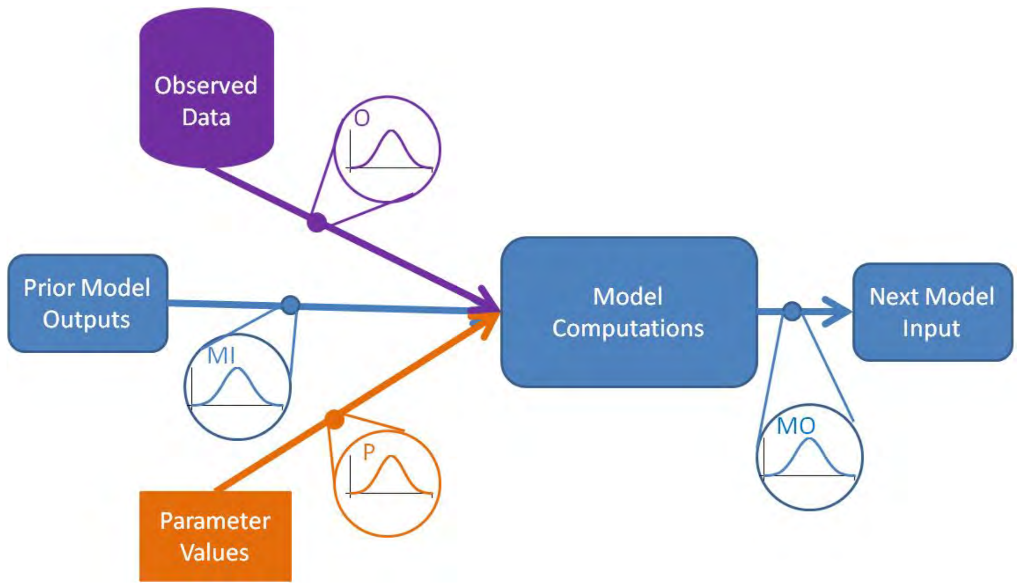

Figure 6.2. Systems view of uncertainty propagating as probability distribution functions from information sources through models.

Good modeling practice employs a standard validation process whenever possible and practicable. That validation process addresses many uncertainty issues and provides statistically sound estimates of system behavior when properly applied. The validation process models periods for which observed data are available and can be compared with model outputs. Modeling multiple observed data sets representing a variety of events (e.g., high, medium and low river discharge; storm and non-storm periods; hypoxic and oxic conditions; etc.) produces model output versus observation data sets which can be analyzed statistically to generate expected error distributions for the model outputs.

For conditions different than those of validation periods sensitivity simulation results can be used in two ways – the largest bounds from sensitivity runs indicate a range of potential uncertainty from parameter uncertainty or the statistical combination of the bounds from more than one source – with the former preferred. The larger of these versus the validation uncertainty can be used for base to plan comparisons[5]. Those would be combined with the natural variability estimates for other parameters such as discharge to get the uncertainty bounds for absolute predictions (not base to plan change) in cases different than the validation conditions.

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[5] Base to plan comparisons, in which the model simulations are exactly the same between the base model output and the plan model output <u>except</u> for introduction of a management plan, such as freshwater diversion, catch limits, etc. are considered ideal use of a model in that changes can be expressed in terms of trends and rates, not absolute values.

Traditional methods for calculating uncertainty propagation by sensitivity analysis employ hundreds to thousands of simulations in a Monte Carlo analysis to arrive at outputs' PDF. Those methods are impractical for the sophisticated models used in IEA, including hydrodynamics and transport process models because each simulation can require multiple days of computing time. To overcome this obstacle, point-estimate approaches (e.g., Diaz et al. 2008) and stochastic uncertainty estimates (e.g., Savant 2008) can provide statistically sound estimates of uncertainty propagation using a small number of model simulations. Similarly, some types of uncertainty are difficult to quantify and require specialized approaches such as fuzzy logic and Bayesian Belief Networks. Both traditional and non-traditional approaches will be employed in the Sulis risk assessment engine as appropriate.

Table 6.1. Data Inputs for Hydrologic Models

VARIABLE	**VARIATION IN:**		**SOURCE**
	SPACE	**TIME**	
Landscape			
Forest cover fraction	X		USGS or state land cover map
Impervious land	X		USGS or state land cover map
Land elevation and slope	X		USGS or state digital elevation model
Pervious land	X		USGS or state Land cover map
Shaded area	X	X	Vegetative input file and time series
Soil characteristics	X		USDA soil map
Stream geometry	X		Field data, maps and empirical relationships
Landscape discretization	X		Prepared from above data
Weather			
Air Temperature	X	X	NOAA NWS stations
Cloud cover	X	X	NOAA NWS stations
Wind velocity	X	X	NOAA NWS stations
Dew point	X	X	NOAA NWS stations
Cloud cover light extinction parameters	X	X	Modeled by (1)
Degree-days	X	X	Modeled by (1)
Evapotranspiration parameters	X	X	Modeled by (2)
Groundwater temperature	X	X	Modeled by (3)
Precipitation	X	X	NOAA stations
Snow cover	X	IC	Modeled by (1)
Snow parameters	X	X	Literature
Soil temperature parameters	X	X	Literature
Solar radiation	X	X	NOAA NWS stations

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Hydrology			
Distance of overland flow	X		Digital elevation model
Groundwater elevation	X	X	Modeled by (3)
Groundwater recovery rate parameters	X		Literature
Inflows	BC	X	USGS gage data
Outflows	BC	IC	USGS gage data or modeled by (3)
Soil infiltration rate parameters	X		USDA soil data or literature
Soil Moisture	X	IC	Modeled by (2)
Soil moisture transport parameters	X		Literature
Soil temperature	X	IC	Modeled by (2)
Subsurface flow parameters	X	X	Literature
Surface flow parameters	X	X	Literature
Surface water temperature	X	IC	Modeled by (2)
Water interception zone storage parameters	X	X	Literature
Water volumes	X	IC	USGS data
Water withdrawals	X	X	State and local permit files
Agriculture			
Crop and growth parameters	X	X	Field data and literature
Irrigation parameters	X	X	Field data
Nutrient applications	X	X	Field data
Pesticide applications	X	X	Field data
Constituents			
Atmospheric deposition rates	X	X	
Constituent concentrations	X	IC	Modeled by (5)
Constituent kinetics parameters	X	X	Literature
Groundwater DO &CO2 parameters	X	X	Literature
Inflow concentrations at boundaries	BC	X	USGS or EPA data or modeled by (5)
Outflows concentrations at boundaries	BC	IC	USGS or EPA data or modeled by (5)
Sediment characteristics	X	IC	Field survey
Sediment inflows by class	BC	X	Field survey
Sediment outflows by class	X	IC	Field survey
Sediment transport & deposition/erosion parameters	X	X	Literature or flume experiment
Solution phase parameters	X		Literature

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Suspended sediment concentration	X	IC	USGS or EPA data or modeled by (5)
Biological Processes			
Benthic concentrations	X	IC	Modeled by (5)
Benthic kinetics parameters	X	X	Literature
Biomass concentration	X	X	Field survey or modeled by (5)
Plankton Concentration by type	X	X	Field survey or modeled by (5)
Plankton kinetics parameters	X	X	Literature

Notes: X = Data coverage needed. BC = At boundary locations only. IC – Initial conditions only. Numbers in parentheses indicate which model group from Figure 6.1 is used.

Table 6.2. Data Inputs for Hydrodynamic Models

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Waterscape			
Shoreline and bathymetry	X	IC	NOAA /USACE Charts, field surveys
Bed composition	X		Literature and field surveys
Submerged vegetation	X	X	Literature and field surveys
Discretization	X		Prepared from above data
Weather			
Air Temperature	X	X	NOAA NWS stations
Wind velocity	X	X	NOAA NWS stations
Evapotranspiration parameters	X	X	Modeled by (2)
Precipitation	X	X	NOAA NWS stations
Hydrology			
Groundwater inflows	X	X	Literature or modeled by (3)
Inflows and outflows	BC	X	USGS gage data or modeled by (3)
Boundary water levels	BC	IC	USGS gage data or modeled by (3)
Water temperature	X	IC	Modeled by (3)
Water withdrawals	X	X	State and local permit files
Hydraulics			
Boundary roughness	X	X	Literature
Diffusion parameters	X		Literature
Wind wave parameters	X		Literature
Wind-current coupling parameters	X		Literature
Incident waves	X	X	NOAA/USACE wave data

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Water density	X		Computed from temperature and dissolved and suspended solids
Water viscosity	X		Computed from temperature and dissolved and suspended solids
Salinity	BC	IC	Literature and field surveys
Sediment loads by class	BC	IC	Literature and field surveys
Heat transfer parameters	X		Literature

Notes:

X = Data coverage needed

BC = At boundary locations only

IC – Initial conditions only

Numbers in parentheses indicate which model group from Figure 6.1 is used.

Table 6.3. Data Inputs for Water Quality Models

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Waterscape			
Shoreline and bathymetry	X	IC	NOAA /USACE Charts, field surveys
Discretization	X		Prepared from above data or duplicated from (4)
Weather			
Air Temperature	X	X	NOAA NWS stations
Wind velocity	X	X	NOAA NWS stations
Evapotranspiration parameters	X	X	Modeled by (4)
Precipitation	X	X	NOAA NWS stations
Hydrology			
Groundwater inflows	X	X	Literature or modeled by (3)
Inflows and outflows	x	X	USGS gage data
Water temperature	X	IC	Modeled by (2)
Hydraulics			
Water levels and velocities	X	x	Modeled by (4)
Salinity	x	x	Modeled by (4)
Sediment loads by class	x	x	Modeled by (4)
Wave height and period	X	x	Modeled by (4)
Constituents			
Constituent concentrations	x	IC	Field survey
Inflow loads			
Atmospheric	X	X	Literature or field survey

VARIABLE	VARIATION IN:		SOURCE
	SPACE	TIME	
Groundwater	X	X	Literature or field survey
Point discharges	X	X	Discharge permits
Watershed runoff	x	x	Modeled by (3)
Mass diffusion parameters	x		Literature
Constituent kinetics parameters	x		Literature

Notes:

X = Data coverage needed

BC = At boundary locations only

IC – Initial conditions only

Numbers in parentheses indicate which model group from Figure 6.1 is used.

7. Summary and Conclusions

Four ecosystems in the northern Gulf of Mexico – Galveston Bay, Barataria Basin, Mississippi Sound, and Perdido Bay have been assessed using the Drivers-Pressures-States-Impacts-Responses framework employed in Integrated Ecosystem Assessments. These systems offer a range of geographic, hydrologic, and population characteristics that is typical of much of the region from the Northern Texas Gulf coast through the Florida Panhandle.

Human-Related Processes are the most prevalent of IEA Driver categories, affecting all four systems. Five related Pressures -- *Increased Fishing Effort, Urban/Coastal Development, Boat Traffic, Nutrients,* and *Pollution* are common to all four systems. Human-related pressures are *fishing effort, urban and coastal development, boat traffic, eutrophication* and *chemical pollution.*

Habitat modification or loss is the most common Impact associated with the four-system Drivers-Pressures-States, followed by *Lack of support for responses* and *Change/loss of native species*. Other impacts , such as *Increased storm surge* and *Eutrophication*, tended to be applicable to one or two systems instead of all four.

Primary Ecosystem Services affected by the impacts, in decreasing order of occurrence for the four systems, are *Habitat Formation, Food,* and *Educational*.

As the size of coastal systems increase (for instance, moving from small lagoons to large estuaries), or moving from the coastal environment to offshore pelagic environments, the relative importance of human-generated stressors is reduced, with natural stressors (climate processes) becoming more important.

The work described here demonstrates that:

- The IEA/EAM framework based on the DPSIR/DPSER process is a valid approach to identify, prioritize and manage natural and human-induced stressors in Gulf of Mexico systems. Application of this approach to four systems in the Gulf of Mexico that range widely in environmental, societal and economic characteristics shows that this approach is comprehensive and adaptable to the whole suite of natural-human systems in the Gulf of Mexico.
- The Sulis Community Ecosystem Models and Informatics Services can be used for performing Integrated Ecosystem Assessments, including providing the framework for evaluation of management responses with risk assessment. Uncertainty and risk can be successfully addressed by extending well-established practices from the physical sciences to ecosystem sciences and modeling.
- The TroSim ecosystem model will provide a management assessment tool for Mississippi Sound.

- The Gulf of Mexico offers an excellent domain in which to develop, evaluate and validate strategies for environmentally and economically-sustainable development and exploitation. These resource management strategies can then be applied to allow for a vibrant economy combined with sustained environmental health. Completing the IEA/EAM framework in the Gulf of Mexico will help accomplish this management strategy.

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Appendices

Appendix A: Galveston Bay

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According to the Galveston Bay National Estuary Program, Galveston Bay is the longest estuary in Texas and is comprised of four major sub-bays: Galveston, Trinity, East, and West Bays. It is a very shallow system (average of about 7 feet) that covers about 384,000 acres (600 square miles). However, the watershed is much bigger and covers an area of 24,000 square miles. The quality and quantity of water draining from this large area affects the physical, chemical, and biological characteristics of the estuary.

Several habitats can be found in the Galveston Bay estuary: wetlands (salt, brackish, and fresh marsh), oyster reefs, seagrass meadows, mud flats, and open water.

GALVESTON BAY MODELS

The Harte Research Institute recently completed a project titled "Assessment of Changing Ecosystem Services Provided by Marsh Habitat in the Galveston Bay Region". Goals of this project were (1) to assess the change in the marsh structure and link that to the quality and capacity of particular ecosystem services provided and (2) assess the change in the value of ecosystem services as a result of relative sea level rise. This was done by utilizing the results of the Sea Level Affecting Marshes Model (SLAMM) 6 application to Galveston Bay. SLAMM simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise. Map distributions of wetlands are predicted under conditions of accelerated sea level rise, and results are summarized in tabular and graphical form. Additional information on this model can be found at http://warrenpinnacle.com/prof/SLAMM/SLAMM_Model_Overview.html

"A conceptual model of the Galveston Bay Ecosystem" has been developed by the Galveston Bay National Estuary Program in 1993. The goal of this project was development of a set of habitat-based, problem oriented, nested, hierarchical, box-and-arrow conceptual models tiered to three levels of complexity. (1) Simple, nontechnical models that facilitate understanding of important issues by the public focus on the landscape approach and provide an overview of the ecosystem. (2) Complex detailed models that reflect scientific consensus describe the structure, function and connectivity of the habitat components of the ecosystem and it s connections to adjacent habitats. (3) Simple technical models useful to decision-makers, resource managers and bay users describe the interconnectedness of the ecosystem (http://gbic.tamug.edu/gbeppubs/42/GBNEP42_cover-contents.pdf).

On June 30, 2004, ship traffic in Galveston Bay, Texas, gained a new tool to assist in safe navigation. The Galveston Bay Operational Forecast System (GBOFS), created by NOAA's National Ocean Service, provides mariners, port managers and emergency response teams with present and future conditions of water levels, currents, temperature and salinity.

GBOFS "nowcast" (for present conditions) and "forecast" (for future conditions) products are generated by a three-dimensional hydrodynamic model that uses real-time and forecast data to predict this information at thousands of locations throughout Galveston Bay. The information GBOFS provides assists port managers and shippers in making decisions regarding maximum tonnage and passage times without compromising safety (http://tidesandcurrents.noaa.gov/ofs/gbofs/gbofs.html).

Currents are computed with a model called TxBLEND. The model was developed at Notre Dame University and was subsequently adopted, modified, and applied by the Texas Water Development Board's Environmental Section to Texas' bays and estuaries. TxBLEND is a two-dimensional (vertically-averaged) finite element model which solves the continuity equation, momentum equations, and the advection-diffusion equation for conservation of salt. The numerical grid for Galveston Bay consists of 2113 nodes, Matagorda Bay has 2927, Corpus Christi Bay has 4218, and Sabine Lake has 2341 nodes. The computational time step for the Matagorda Bay model is 150 seconds, and for the other bays and Sabine Lake, it is 300 seconds. Water velocities and depths are calculated by TxBLEND at each of these nodes for each time step, but results are displayed only every three hours within the three-day window described above, and only for the few nodal locations shown (http://midgewater.twdb.state.tx.us/bays_estuaries/bhydpage.html#TxBlend_desc).

The purpose of this research is to more tightly integrated GIS and water quality modeling through use of Schematic Network Processing. Two methods for modeling the transport of pollutants through a river system are presented. The basic premise of these methods is the same. Both start with the a geodatabase representation of the basin and a schematic network abstraction of hydrologic transport. The two methods differ in how SchemaLink and SchemaNode features process passed and received loads. The bacteria study uses runoff and expected mean concentration (EMC) grids to estimate the load from a watershed that reaches the river. This load is then decayed as it travels through the river using a decay coefficient documented in literature. The nitrogen study uses statistical regression to optimize parameters describing the proportion of watershed load that is delivered to the river and the portion that is decayed as the load travels downstream. This approach, first introduced in SPARROW (SPAtially Referenced Regressions On Watershed attributes), involves statistically relating observed water-quality data to spatially reference basin characteristics (Smith et al 1997). The purpose of this case study was to estimate the transport of bacteria from non-point sources to the Galveston Bay from a GIS environment with ArcToolbox 9.0 technology ((http://www.crwr.utexas.edu/gis/gishydro03/WaterQuality/WaterQuality.htm) and (http://www.google.com.mx/url?sa=t&rct=j&q=galveston%20bay%20water%20quality%20model&source=web&cd=2&ved=0CCgQFjAB&url=http%3A%2F%2Fwww.crwr.utexas.edu%2Fgis%2Fgishydro03%2FWaterQuality%2FWQModelingBacteria.doc&ei=Lw3NTvetCYWHtwfUxOGeAQ&usg=AFQjCNG6m2-rKq_Bq45SX9KPj61MxfDgWQ&cad=rja))

Appendix 1 to Appendix A is a summary of modeling efforts by Dr. Thomas Minello of the NOAA Southeast Fishery Science Center.

The Galveston Bay National Estuary Program's report "***A Conceptual Model of the Galveston Bay Ecosystem***" published in 1993 does not use the same terminology as the current NGI's "Integrated Ecosystem Assessment Initiative for Selected Systems in the Northern Gulf of Mexico". However, the NEP report clearly identifies and describes the components of the estuarine ecosystem (from open Bay water to benthic habitats such as seagrass and marsh) and investigates existing connections among components. This makes up the bulk of the report.

Of interest to the IEA project is the section on "perturbations", which are defined as "disturbances of equilibrium". Specifically, the reports states that: "Ward and others (1982) defined perturbation as any activity that represents a departure from the normal state and can potentially result in effects upon the fish and wildlife resources of [Galveston Bay], either directly upon the organisms involved, or indirectly through alterations in the bay environment." They note that a key element of the definition of "perturbation" is what is regarded as the "normal" state. Dependent upon the temporal scale invoked, climatic extremes, such as floods, hurricanes and droughts, can be regarded as variations in the "normal" state rather than perturbations, although such events are certainly disruptive of the ecosystem." Therefore, the perturbations identified for the Galveston Bay ecosystem may be somewhat comparable to the "pressures" identified in the NIG IEA report.

Perturbations:

- Fresh water inflow modification
- Subsidence
- Shoreline development
- Dredge and fill
- Point source pollution
- Non-point source pollution
- Commercial fishing
- Recreational fishing
- Boating and marinas
- Petroleum activity
- Oil/chemical spills
- Circulation
- Shoreline erosion
- Exotic species
- Storms and hurricanes

The NEP report does not discuss the sources of perturbations, which may be comparable to what we define as "drivers". However, limiting factors have been identified where possible. A list of limiting factors is provided below for each ecosystem component.

Open Bay Water limiting factors:

Light
Inorganic nutrients
Temperature

Open Bay Bottom limiting factors:

Turbidity
Sediment resuspension
Detritus input
Salinity
Temperature
Predation

Oyster Reefs limiting factors:

Extremes in salinity
High turbidity
Weak current
Substrate availability
Phytoplankton
Predators, parasites, pathogens
Extremes in temperatures
Suspended particulates

Seagrass Meadows limiting factors:

Water transparency
Salinity
Temperature
Substrate
Bottom topography
Depth
Nutrients

Peripheral Marsh limiting factors:

Nutrients
Tidal exchange
Soil and water salinity

Intertidal Mud Flat limiting factors:

Water transparency
Temperature
Tidal range
Nutrients

Peripheral Marsh Embayment limiting factors: unknown

Attachment 1 to Appendix A

NOAA Southeast Fishery Science Center
Fishery Ecology Branch of the Galveston Laboratory

The mission of the Fishery Ecology Branch is to identify and describe relationships between fishery production and the coastal environment.

Modeling linkages between estuarine habitats and fishery production

The Fishery Ecology Branch (FEB) conducts research to support fisheries in many coastal ecosystems and habitats of the Gulf of Mexico including coastal marsh, seagrass and submerged aquatic vegetation beds, shallow unvegetated bay bottom, oyster reefs, mangroves, macroalgae beds, and coral reefs. We are working to develop ecological models that link habitats, estuarine ecosystems, and fishery production. An important objective of this work is to describe how ecological interactions affect fishery species and incorporate habitat science and ecology into stock assessments. FEB publications cited below are available from our web site at http://galveston.ssp.nmfs.gov/research/fisheryecology/publications/index.asp

Individual Based Models of shrimp production – This modeling effort was initiated following field and laboratory research showing that juvenile brown shrimp and white shrimp in Gulf estuaries were concentrated in high densities at the marsh edge (Minello 1999, Minello and Rozas 2002, Minello et al. 2008) and often received benefits of increased growth and reduced predation-related mortality in the marsh (Minello et al. 2003, Zimmerman et al. 2000). The IBMs on shrimp production were developed in cooperation with Kenny Rose from LSU and his students and post docs. The first IBM was published by Haas et al. (2004) and described this spatially explicit, individual based simulation model used to explore the role of marsh vegetation and edge habitat in brown shrimp survival. The model simulated shrimp movement, mortality, and growth of individuals from arrival as postlarvae in an estuary to 70-mm body length, when they emigrate offshore. When the model was run on habitat maps with different amounts of marsh edge, maps with the most edge resulted in the highest shrimp production. The second iteration of the model was published by Roth et al. (2008). With this version, we examined the relative effects of marsh elevation and flooding compared with spatial configuration of vegetation. Dr. Roth is currently at Michigan State University, but he is continuing to work on the model, and manuscripts are planned describing modeling runs comparing natural and created salt marsh complexes (after Rozas and Minello 2005) and comparing shrimp production from marshes in different estuaries with different flooding regimes (after Minello et al. 2012).

Estimating nekton populations and production using spatial density models, GIS, and an Equilibrium Yield approach – Estimating population size of juvenile shrimps and crabs in coastal wetlands is difficult because vegetative structure interferes with efficient sampling, nekton are not evenly distributed across wetland landscapes, spatial distributions change with tidal inundation, and landscape topography and land-water patterns in these marshes can be highly complex. We developed nonlinear models of the relationships between nekton density and distance from the marsh edge for brown shrimp, white shrimp, and blue crabs in lower Galveston Bay, TX. These models show that densities of all three species peak at flood tide within a few meters of marsh vegetation. We combined these density models with a GIS analysis of land-water patterns in marshes of lower Galveston Bay to estimate average population sizes (Minello et al. 2008). We used information on size frequencies, size–weight relationships, and growth rates, to estimate biomass and production from salt marshes and open-water habitats. This modeling approach also has been used in Galveston Bay to estimate shrimp production exported from nine created salt marshes, monetize this ecosystem service from created wetlands, and compare the value of this production with the cost of constructing the marshes (Minello et al. in press).

Bioenergetics modeling of brown shrimp production – This modeling effort was designed to examine the effects of diverting Mississippi River water into shallow estuarine nursery habitats of Louisiana. Field studies of distribution and growth indicated that brown shrimp abundance and growth was relatively low in low salinity areas of Barataria Bay (Rozas and Minello 2010, 2011). Adamack et al. (2012) describe a bioenergetic model developed to examine potential effects of changing estuarine salinity and temperature through river diversions. Model simulations were designed to predict effects on shrimp production and provide guidance for managing such diversions.

Modeling in progress

Simulation modeling of brown shrimp production from estuaries for stock assessments - In response to the NMFS Habitat Assessment Improvement Plan that focuses on the role of habitat science in stock assessments, we are converting the IBM on brown shrimp to a STELLA simulation model (isee systems, inc., Lebanon, NH). Our goal is to make the model code more accessible and explore relationships between temperature, salinity, and wetland flooding and our long-term estimates of brown shrimp standing crop from estuarine trawl surveys. Jennifer Leo is doing this work through Texas A&M University for her Ph.D. in cooperation with Dr. William Grant, and initial model runs are planned for Galveston Bay and Barataria Bay, LA. This project was funded by NOAA's NMFS Office of Science and Technology, and one of the goals is to introduce environmental and habitat-related variability into the brown shrimp stock assessment for the Gulf. Until recently, stock assessments for shrimp in the GoM have used a Virtual Population Analysis, but assessments are now being converted to Stock Synthesis 3 (SS-3), a widely used and peer reviewed assessment model (Methot 2009, Schirripa et al. 2009). SS-3 has a broad capability to incorporate habitat and environmental information, and this modeling change provides an opportunity to improve shrimp stock assessments.

Matrix modeling of white shrimp productivity – This modeling effort on white shrimp population dynamics was inspired by a model designed to identify Essential Fish Habitat in Galveston Bay based on a population analysis of red drum (Levin and Stunz 2005). We measured variability in vital rates of white shrimp in Galveston Bay (Baker and Minello 2010) and constructed a life table for this species. A population model is being developed with Masami Fujiwara (Texas A&M University), Phil Levin (NOAA NEFSC), and Ronnie Baker (James Cook University) to examine population effects of variability in mortality rates during the estuarine phase of the white shrimp life cycle.

Watershed modeling in Galveston Bay – This multidisciplinary CAMEO project titled "Developing linked watershed-marine ecosystem service models to evaluate coastal management strategies" is centered in Puget Sound, WA, but the models developed for that system are being tested in Chesapeake Bay and Galveston Bay. The objective of the project is to assess the importance of including watershed-based activities in the management of coastal and marine ecosystem services. Mary Ruckelshaus is leading a team of Stanford ecologists and fishery biologists from NOAA's NWFSC, Chesapeake Bay Office, and the SEFSC in developing a general set of linked watershed-marine models with ecosystem services as outputs and applying the models in these three diverse sites. We are comparing how management-induced changes in ecosystem structure and processes affect the provisioning of different ecosystem services within and between sites, and asking how incorporating the effects of watershed-based activities into management decisions changes marine system response. Because these watershed models are only designed to examine effects on a few fishery species, a Loop analysis also is being conducted in the three systems to describe interactions and linkages in food webs and provide a tool to assess hypotheses about food web responses (Dambacher et al. 2002, Ortiz and Wolff 2002).

Ecopath model for Galveston Bay – Our attempt to develop a Loop analysis for Galveston Bay emphasized the need for a trophic model in this system. Sutton and Guillen (2009) developed a preliminary Ecopath model for Galveston Bay, and we are currently re-parameterizing the model to incorporate recently-developed information on population size and production of shrimps and crabs (Minello et al. 2008). A workshop was held in Galveston on May 8, 2012 to discuss the revised model and explore sources of new data on trophic groups.

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Appendix B. Barataria Basin

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INTRODUCTION

In a previous report (Northern Gulf Institute Team, 2010) the NOAA Integrated Ecosystem Assessment process which follows the Driver-Pressure-State-Impact-Response (DPSIR) framework was used to develop the Drivers and Pressures for the entire Barataria Bay Basin. This report describes the drivers and pressures for sub-basins of the Barataria Basin, The report also completes the entire NOAA Driver-Pressure-State-Impact-Response (DPSIR) framework, by defining the state variables, impacts and regulatory responses for the drivers and pressures.

BARATARIA BASIN

The Barataria Basin (Figure B1) is an irregularly shaped bar-built estuary, approximately 120 km in length, located west of the Mississippi River in southeastern Louisiana. The basin spans approximately 6,300 km^2, including portions of nine governmental parishes (Ascension, Assumption, Jefferson, Lafourche, Orleans, Plaquemines, St. Charles, St. James, St. John the Baptist). It is bounded on the north and east by the Mississippi River, on the west by Bayou Lafourche, a former distributary channel of the Mississippi River, and on the south by a barrier island chain and the Gulf of Mexico. The basin consists of a foundation of pro-delta clay deposits overlain by a mixture of swamp forest, fresh, intermediate, brackish, and saline marshes, barrier islands, natural levees, and former distributary channels of the Mississippi River (Coleman et al., 1998). The basin is divided into 5 major habitats (Figure B2) based on vegetation type (wetland size data from US Army Corps of Engineers, 2004):

- Freshwater swamp forest (~955 km^2)
- Fresh marsh (~653 km^2)
- Intermediate marsh (~311 km^2)
- Brackish marsh (~257 km^2)
- Salt marsh (~499 km^2).

These habitats were used as the sub-basins in the Integrated Ecosystem Assessment using the NOAA Integrated Driver-Pressure-State-Impact-Response (DPSIR) Framework. The five sub-basins were characterized using data from the following sources (Figure B2):

1. Tidal amplitude analysis from Wiseman and Swenson (1989).

2. Water quality data from the United States Army Corps of Engineers (USACOE).

3. Water quality data from R. E. Turner at Louisiana State University (LSU).

4. Water level and salinity data from continuous stations maintained by the Louisiana Department of Wildlife and Fisheries (LDWF) and the Louisiana Department of Natural Resources (LA-DNR).

The salinity ranges from less than 1 psu in the upper reaches to 15 psu in mid-basin and to 15-20 psu at the coast. Astronomical tides in the system range from approximately 0.30 meters at the coast to about 0.03 meters in the fresh marsh (Figure B3).

Average annual precipitation for the southeastern Louisiana coastal area is approximately 175 cm (Swenson et al., 2004). Sklar (1983) estimated that approximately 40 percent of the precipitation becomes available for runoff, with most of the surplus occurring in winter, and deficits most likely to occur during the summer. Swenson and Swarzwzenski (1995) estimated the precipitation derived input to the basin is ~200 $m^3 s^{-1}$. Lower Barataria Basin also receives water from the Mississippi River from the southern end, resulting in an inverse relationship between river discharge and salinity. This inverse relationship between Mississippi river discharge and Louisiana coastal salinities was first mentioned by Geyer (1950). Barrett (1971) and Gagliano et al. (1973) further described this inverse relationship using linear statistics. Wiseman et al. (1990) used Auto-Regressive Moving Average (ARMA) models to analyze the relationship between weekly discharge of the Mississippi River and Louisiana coastal salinities. The river discharge portion of the models accounted for 30 to 50% of the variance of the observed salinity data. The results were consistent with a conceptual model in which Mississippi River discharge alters coastal salinities, which in turn propagates up-estuary and westward along the coast (Wiseman et al., 1990). Swenson and Turner (1998) developed empirical statistical models to explain the seasonal isohalines in the Barataria estuary using coastal water levels, Mississippi River discharge, and local (New Orleans) precipitation from 1980 through 1995. The models were able to explain ~50% of the variance of the observed data, and indicated that a change from low rainfall to high rainfall can shift isohalines by 10-20 km. This makes the Barataria System unique since it has a freshwater input at both ends of the estuary and is strongly influenced by the Mississippi River in the southern portions. The relationship of annual mean river discharge and precipitation to salinity is summarized in Figure B4.

A small amount of riverine input, designed to mimic a natural crevasse, was recently introduced into the basin's lower wetlands through siphons at Naomi and West Pointe à la Hache in 1992. These siphons have been working at a maximum pumping rate of 60 $m^3 s^{-1}$ of freshwater into the basin at each site. In the 1920s construction on the Gulf Intracoastal Waterway began, crossing Barataria Basin from east to west, separating the upper (fresh) wetlands from the lower (saline) wetlands. The Gulf Intracoastal Waterway (GIWW) can also serve as a conduit to deliver freshwater from the Atchafalaya River to the Barataria estuary. Swarzenski (2003) indicated that the GIWW has an average flow of about 60 $m^3 s^{-1}$. A larger diversion site, Davis Pond, was opened in 2002 with a maximum design-pumping rate of 300 $m^3 s^{-1}$ of freshwater. An analysis of operation data from 2002 through 2005 indicated a base flow of ~10 m^3s^{-1} with occasional higher discharge events of ~50 m^3s^{-1} (Swenson et al., 2006).

Averages of basic water quality parameters (based on USACOE monthly monitoring from February 19977 through March 2006) for the sub-basins are summarized in Figure B5. The general pattern is an increase in Chlorophyll, TOC, PO_4, SiO_2, TN, TP and a decrease in TSS from the Salt Marsh inland to the Swamp Forest. The constituent NO_2+NO_3 has a peak in the Intermediate Marsh.

Hydrologic modification in coastal Louisiana has significantly altered Barataria Basin. Since the flood of 1927, the increasing containment levees of the Lower Mississippi River have essentially eliminated the overbank contribution of freshwater and sediment that occurred when the river overflowed its banks seasonally, flooding the surrounding wetlands (Kesel, 1989; Snedden et al., 2007). Man-made waterways also disrupt natural water flow patterns. The Barataria Waterway navigation channel cuts north-south through the Basin, providing a more direct connection between the upper and lower wetlands. Hydrodynamic model results presented by Inoue et al. (2009) indicate that the Barataria Waterway serves as a primary conduit in bringing freshwater from the Davis Pond diversion to the lower basin. Many smaller navigation channels, canals, and natural waterways crisscross the basin, further complicating water flow patterns (Figure B6). At the northern end of the basin, Highway 90 and freight railroad beds cut off historical drainage patterns from the upper to middle basin. To the west, Bayou Lafourche, a former distributary of the Mississippi River was dammed in 1905, decreasing its freshwater and sediment input to Barataria wetlands. In addition, there are 11 failed agricultural impoundments within the basin, which are currently large open water areas (Turner and Streever, 2002).

Fresh and salt water fishing, crabbing, shrimping, and hunting are all important recreational and commercial activities supported by the habitats within the sub-basins of the Barataria Basin. Approximately 735 species of birds, finfish, shellfish, reptiles, amphibians, and mammals spend all or part of their life cycle in the basin (BTNEP, 1992). Tourism is also important to Louisiana, drawing nearly 20 million visitors a year; a high proportion of travelers in Louisiana are either in-state residents or from nearby southern states (TNS Report, 2008).

Oil and gas is a major industry in Louisiana. Louisiana currently ranks fourth in the nation in the production of crude oil and Southern Louisiana (including Barataria Basin) accounts for the majority of that total (Mckenzie et al., 1995; (www.eia.gov/state/state-energy-profiles.cfm?sid=LA)). The Caminada-Moreau Headland along the Barataria shoreline protects the highest concentration of near-gulf oil and gas infrastructure in the Louisiana coastal area (US ACE, 2004) Louisiana. Established in 1960 near the terminus of Bayou Lafourche, Port Fourchon has become one of the largest ports in the U.S. servicing the oil and gas industry. Annually, 675 million barrels of oil are transported via pipeline through the port, furnishing the nation with 15-18% of its oil supply (http://www.portfourchon.com/site100-01/1001757/docs/annual_report-_pdf_copy.pdf). The Louisiana Offshore Oil Port (LOOP) facilities are located in and offshore of the Barataria Basin system. The complex consists of an offshore (~30 km) marine terminal and an underground storage facility in the Clovelly salt dome, near Galliano and a large diameter pipeline system, including a booster pump near Fourchon, to deliver oil to the storage facility (Sasser and Visser, 1998).

Between the 2000 census and 2008 almost half of the parishes decreased in population size (Assumption, Jefferson, Orleans, and Plaquemines) and the other five parishes had small relative increase in population size (http://louisiana.hometownlocator.com/census/index.cfm). Orleans, Jefferson, and Plaquemines Parishes were severely affected by hurricanes in 2005 and 2008.

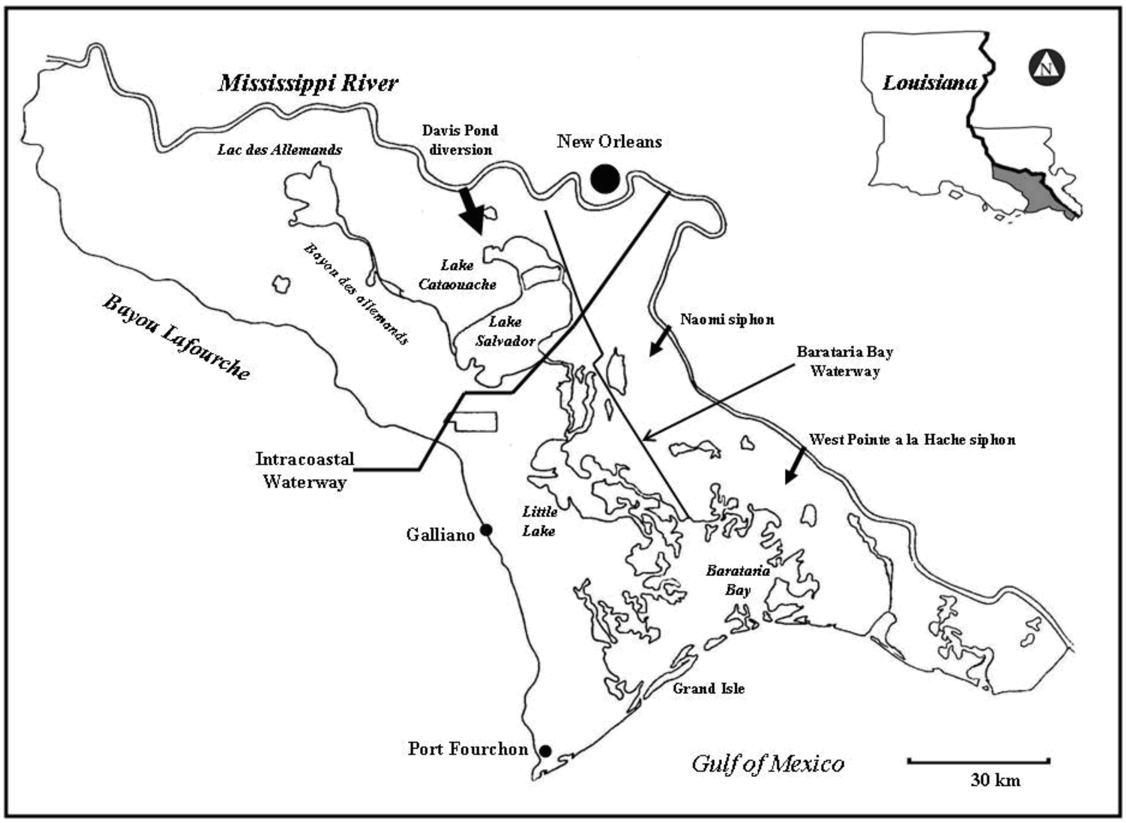

Figure B1. Map of Barataria Basin, Louisiana showing the major waterways and freshwater diverson sites.

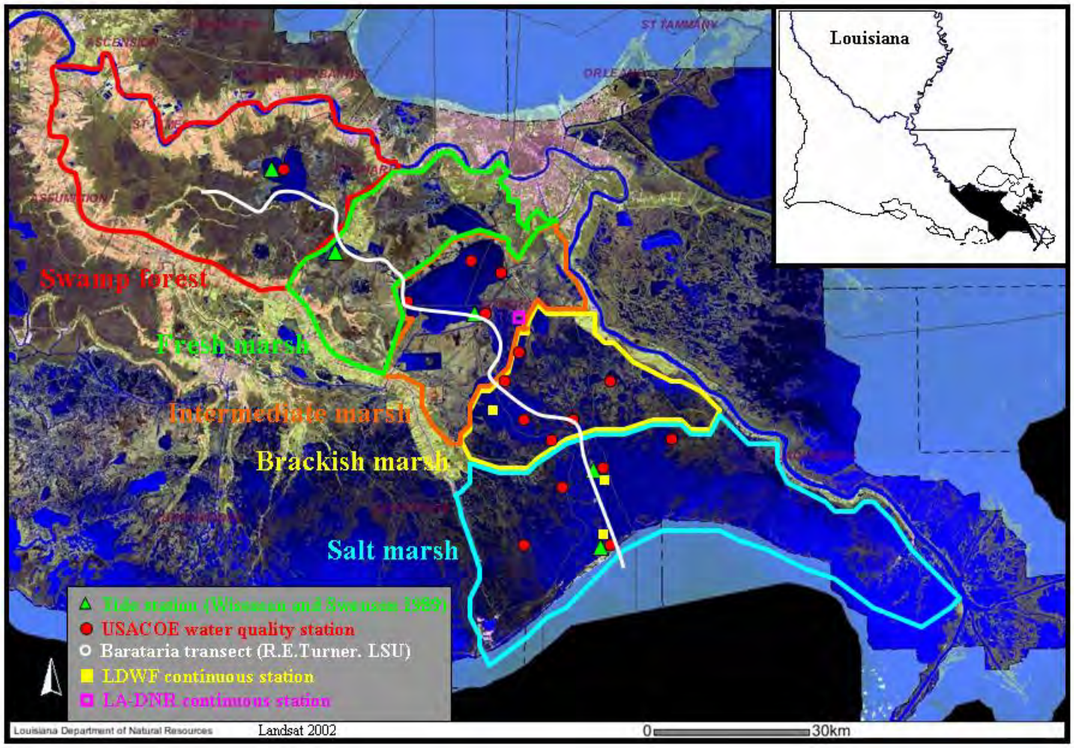

Figure B2. Map of Barataria Basin, Louisiana showing the five sub-basin defined by vegetation type and the data stations used to characterize each basin.

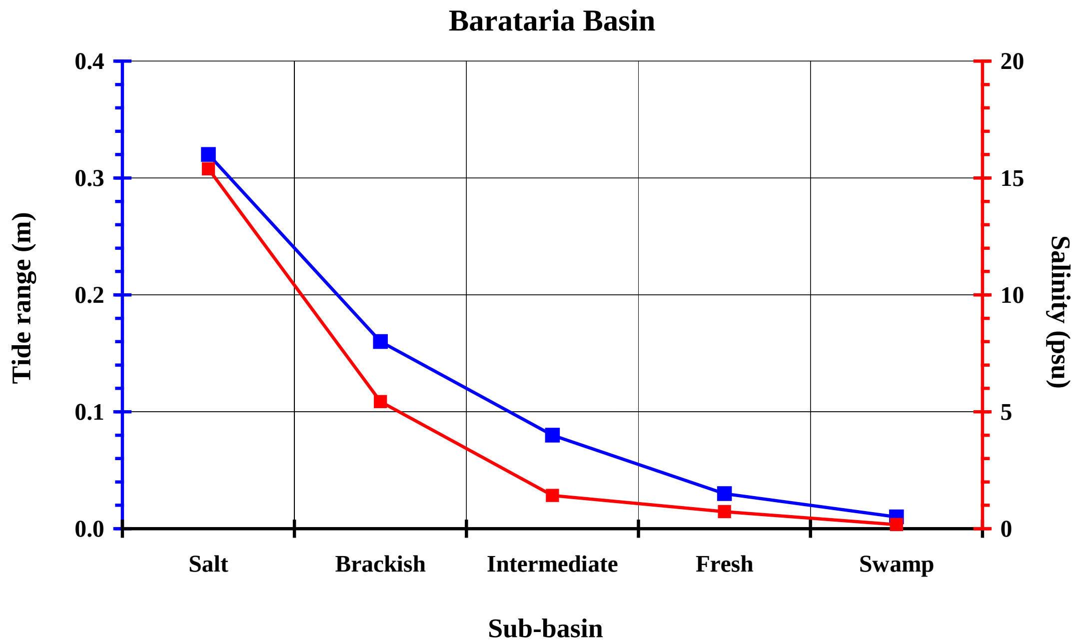

Figure B3. Tidal amplitude (blue line) and average salinity (red line) for the five sub-basins of the Barataria Basin.

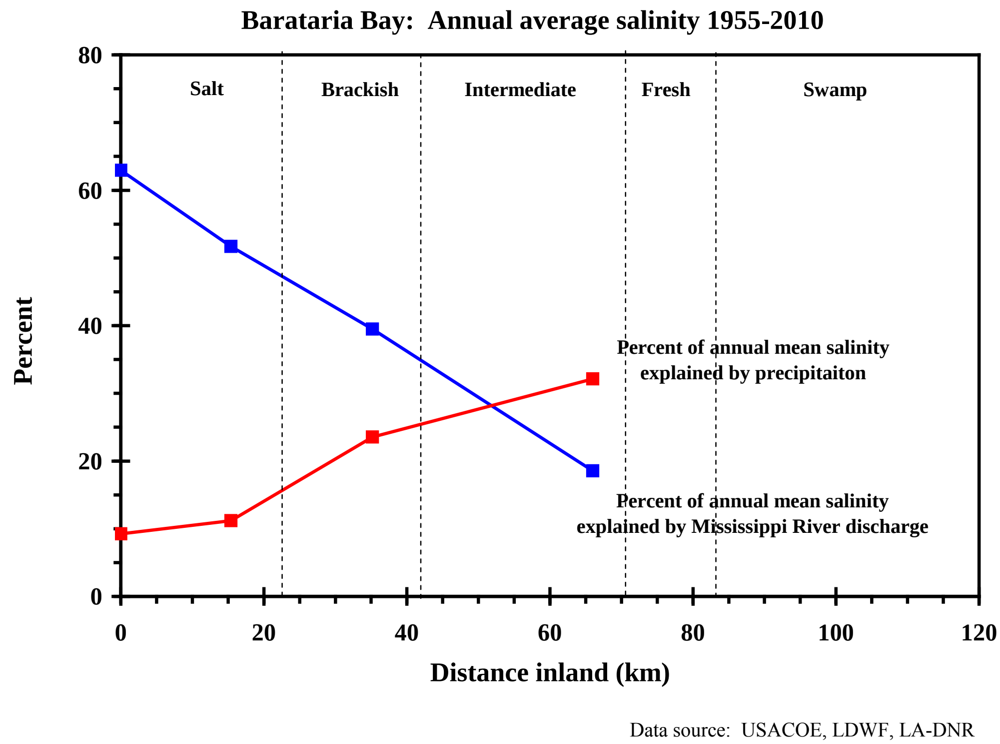

Figure B4. Percentage of the annual mean salinity explained by Mississippi River discharge (blue line) precipitaiton (red line) for the five sub-basins of the Barataria Basin.

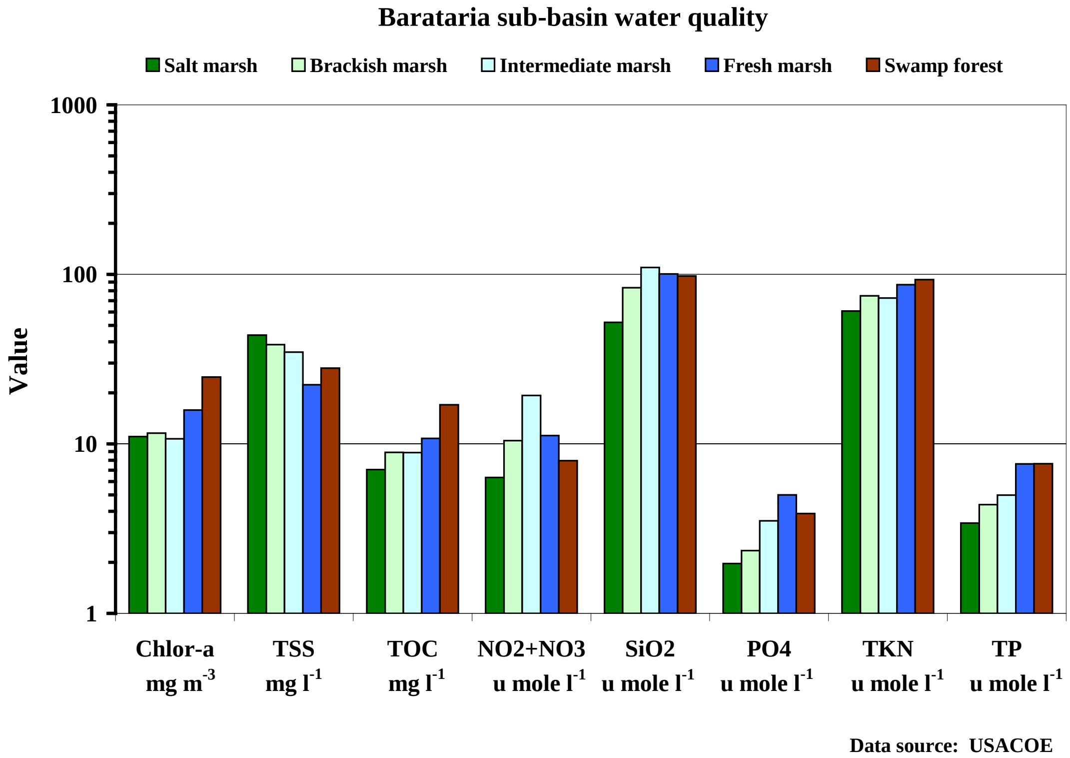

Figure B5. Summary of USACOE monthly water quality data from February, 1997 through March 2006, for the five sub-basins of the Barataria Basin.

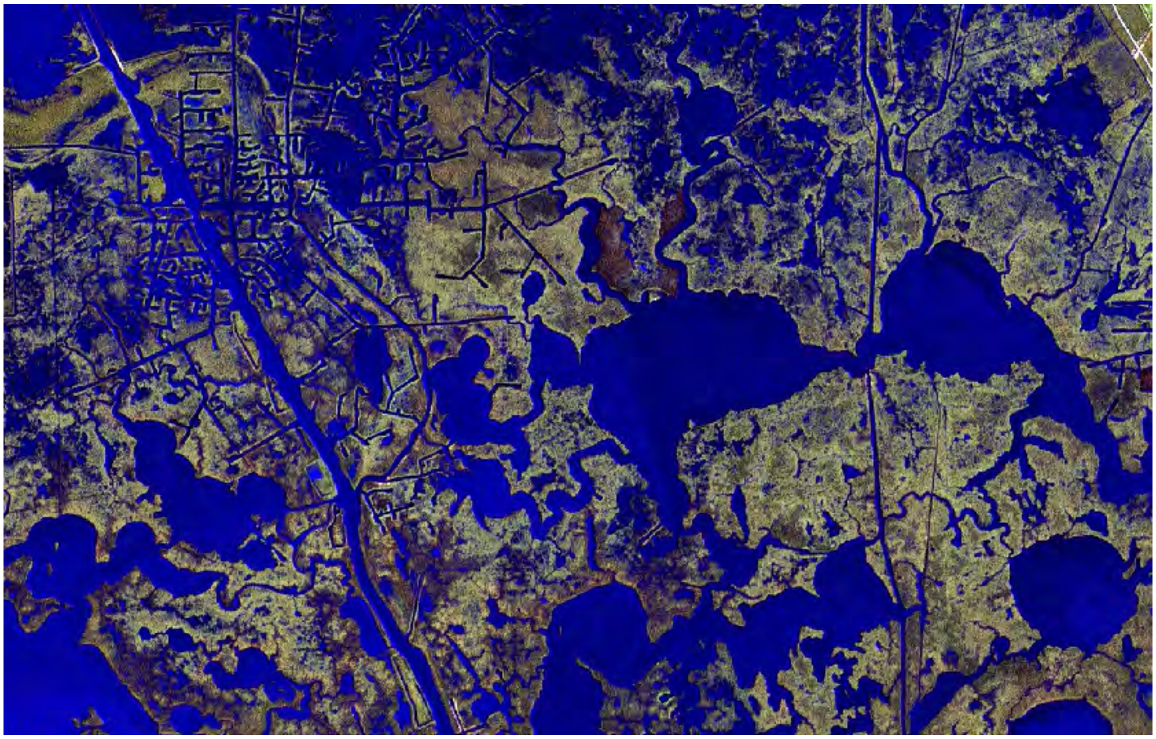

Figure B6. A portion of Barataria Basin showing a number of hydrologic modifications, including oil and gas canals, navigation channels, and impounded wetland areas.

DRIVERS AND PRESSURES

The entire NOAA Integrated Ecosystem Assessment process follows the Driver-Pressure-State-Impact-Response (DPSIR) framework. This section of the report describes the drivers and pressures in the sub-basins of the Barataria Basin. The categories were made broad so they can apply not only to the Barataria system, but also to our joint systems (Perdido Bay, Florida and Mississippi Sound, Mississippi). We used broad, big picture, terms for the drivers and pressures, so that each group could address the specifics of their particular system (Northern Gulf Institute Team, 2010). The three primary drivers are **hydrologic modification**, **climate**, and **human-related processes**, and there are a number of 'sub-drivers' under each.

Hydrologic Modification

Dredging of ***exploration and navigation canals*** alters internal wetland connectivity by direct wetland removal, redirecting water flows from overland to more of a channelized pattern, providing a more direct conduit for salt water intrusion, and by isolating areas of wetlands via dredged material banks (impoundments). These channels also increase boat traffic damage (wake, grounding, and anchor-related).

Flood levees and dam construction alter riverine (Mississippi River and Bayou Lafourche) input by cutting off freshwater, sediment and nutrient input that is needed to sustain the Barataria wetlands. They alter internal wetland connectivity by isolating some wetland areas. Flood levees have also increased coastal development pressures, by reducing flood frequency and impacts, and thus making these areas more appealing to developers.

Freshwater diversions have been initiated as a management tool to ameliorate the effects caused by leveeing the Mississippi River. They reconnect the riverine resources to the wetlands in a small-scale and controlled manner. They are vehicles for introducing freshwater, nutrients, and pollutants.

Climate

Sea level rise and subsidence act together to decrease land elevation which alters internal wetland connectivity and increases connectivity to the Gulf of Mexico.

Extreme weather events, such as river floods, increase riverine input to the basin. Hurricanes and severe tropical storms alter internal wetland connectivity and decrease land elevation through direct marsh destruction and/or redistribution. These events also redistribute sediments from the marsh and barrier island systems, which can either be deposited within or removed from the Barataria system. Severe droughts can result in wetland vegetation death and resulting decrease in land elevation.

Annual climatic ***variability*** alters local riverine input through the annual spring discharge of the Mississippi River and local bayous. Winds associated with winter cold fronts cause a ‘set up’ and ‘set down,’ in which coastal waters flush into and out of the system. This often results in redistribution of basin salinity and sediment.

Human-Related Processes

Local population size results in increased urban and coastal development, impacts wetland biodiversity, and generally results in degraded wetlands. In addition, increased urban and coastal development leads to increased point and non-point sources of nutrients and pollutants. As population increases, fishing demand increases and there is increased boat traffic damage (wake, grounding, and anchor-related). Humans also introduce non-indigenous plant and animal species.

Primary ***trade and industry*** in Barataria Basin include oil and gas exploration and production, navigation, ship building, and commercial fisheries. Dredging of exploration and navigation canals alters internal wetland connectivity and wetland biodiversity. Industrial activities can lead to increased point and non-point sources of nutrients and pollutants. Increased boat traffic damage (wake, grounding, and anchor-related) is associated with a number of trade industries in Barataria, and non-indigenous plant and animal species can be introduced through ship ballasts and other activities (aquaculture - tilapia, fur trade - nutria, etc.). There is a large commercial fishing (fin fish, crab, shrimp, oysters) industry, which leads to increased fishing pressures. Cypress mulch has also become an increasing trade activity, leading to increased logging pressure in upper Barataria Basin.

The ***socio-political-educational perceptions*** in the Barataria Basin are such that there is a disconnect between policy and public education and perception of the issues, such as point and non-point sources of nutrients and pollutants (dumping overboard vessels, littering, sewage treatment in coastal camps), introduction of non-indigenous species (landscaping, exotic pets, etc. – see Attachment B1), logging (demand for cypress mulch), and development in sensitive coastal areas. In addition, the regulatory frameworks can be unclear and often unevenly enforced in different management areas. For example, the current knowledge on maintaining sustainable cypress forests is not consistently applied (USACE, 2005). This frustrates stakeholders and ultimately undermines restoration efforts.

Some ***tourism and recreation*** leads to increased urban and coastal development, such as coastal camps, marinas, etc. These activities can result in increased point and non-point sources of nutrients and pollutants. Barataria Basin is a popular fishing destination, for both fresh and salt water fishing, and therefore increased fishing demand is linked to these activities. Increased recreational boating increases boat traffic damage (wake, grounding, and anchor-related) and dredging for marinas, boat slips, etc. Some tourist and recreation activities can also introduce non-indigenous plant and animal species, by transporting plant (e.g., hydrilla) and animal (e.g., live bait) species.

The drivers (and sub-drivers) and pressures were determined for each of the sub-basins in the Barataria basin. Table B1 presents the results for the Hydrologic Modification drivers, Table B2 presents the results for the Climate drivers, and Table B3. presents the results for the Human related drivers. A total of 194 pressures will identified for the entire Barataria Basin (Table B4) with the lowest (34) occurring in the Fresh Marsh and the highest (45) occurring in the Brackish Marsh. The Human Related drivers resulted in 120 (61.9 %) pressures, the Hydrologic Modification drivers resulted in 45 (23.2%) pressures, and the Climate Drivers resulted in 29 (14.9%) pressures.

STATE VARIABLES, INDICATORS AND RESPONSE

The impact, state variable, and response were developed for each of the drivers and resulting pressures for each sub-basin. For example, the ***driver*** 'local population size' can lead to the ***pressure*** 'Increased nutrients (point and non-point).' 'Eutrophication' is a potential ***impact*** from this system pressure (increase of nutrients is a pressure on a system but does not necessarily lead to eutrophication). The ***state variable*** that could be measured to monitor eutrophication is chlorophyll. To learn more about the dynamics of the eutrophic condition, other state variables would include nutrients, total organic carbon, algal community composition, dissolved oxygen, salinity, and temperature. A potential regulatory ***response*** would be to reduce nutrient input to the system, through a combination of policy, implementation (set TMDLs) and enforcement, and community education and outreach (e.g., "no dumping in storm drains").

The primary management concerns for Barataria Basin are wetland loss and habitat degradation. Physical factors such as subsidence and the loss of river sediments into the Barataria estuary, as well as the multiple changes to the basin's natural hydrology have contributed to wetland loss, increased flooding, and associated socio-economic losses (such as farming, fisheries resources, hunting activities, nature tourism). Hydrologic modifications have also led to a loss of habitat for fish, wildlife and other biota, a decrease in water quality needed to sustain a variety of terrestrial and aquatic systems, the introduction of toxic substances into waterways, and stressed swamp forests (cypress-tupelo). Historic wetland loss in the Barataria Basin from 1956 – 2006 is 806 km^2 (Barras et al., 2008).

A breakdown of land loss and loss rates follows:

- **1956-1978** = -442.9 km^2 or -20.1 km^2/yr
- **1978-1990** = -220.2 km^2 or -18.2 km_2/yr
- **1990-2001** = -108.8 km^2or -9.9 km^2/yr
- **2001-2004** = -15.5 km^2 or -5.1 km^2/yr
- **2004-2006** = -18.1 km^2 or -9.2 km^2/yr

Table B1. Summary of the Hydrologic Modification Drivers for the sub-basins of the Barataria Basin and their associated pressures. The major drivers and pressure for a given sub-basin are indicated by check marks.

		Drivers: Hydrologic Modifications														
		Exploration & navigation canals					Flood levee & dam construction					Freshwater diversion				
		Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt
Pressures	Altered riverine input						√	√	√	√	√		√	√	√	√
	Altered internal wetland connectivity	√	√	√	√	√	√	√	√	√	√		√	√	√	
	Increased point and non-point nutrients												√	√	√	
	Increased point and non-point pollutants												√	√	√	
	Increased dredging	√	√	√	√	√										
	Increased fishing effort															
	Increased boat traffic (wakes, grounding, anchoring)				√	√										
	Non-indigenous species introduction															
	Altered coastal biodiversity															
	Increased urban/coast development						√		√	√	√					
	Increased logging															
	Redistribution of marsh & barrier island sediment			√	√	√										
	Decreased land elevation			√	√	√										

Table B2. Summary of the Climate Drivers for the sub-basins of the Barataria Basin and their associated pressures. The major drivers and pressure for a given sub-basin are indicated by check marks.

		Drivers: Climate														
		Sea level rise / subsidence					Extreme weather events					Variability				
		Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt
Pressures	Altered riverine input						√	√	√	√	√	√	√	√	√	√
	Altered internal wetland connectivity	√	√	√	√	√			√	√	√					
	Increased point and non-point nutrients															
	Increased point and non-point pollutants															
	Increased dredging															
	Increased fishing effort															
	Increased boat traffic (wakes, grounding, anchoring)															
	Non-indigenous species introduction															
	Altered coastal biodiversity															
	Increased urban/coast development															
	Increased logging															
	Redistribution of marsh & barrier island sediment									√	√				√	√
	Decreased land elevation	√	√	√	√	√				√	√					

Table B3. Summary of the Human Related processes Drivers for the sub-basins of the Barataria Basin and their associated pressures. The major drivers and pressure for a given sub-basin are indicated by check marks.

Drivers: Human-Related Processes

Pressures	Local population size					Trade / industry					Socio-political-educational perception					Tourism / recreation				
	Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt	Swamp	Fresh	Intermediate	Brackish	Salt
Altered riverine input																				
Altered internal wetland connectivity																				
Increased point and non-point nutrients	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Increased point and non-point pollutants	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Increased dredging						√	√	√	√	√										
Increased fishing effort	√	√	√	√	√				√	√						√	√	√	√	√
Increased boat traffic (wakes, grounding, anchoring)	√	√	√	√	√	√	√	√	√	√						√	√	√	√	√
Non-indigenous species introduction	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Altered coastal biodiversity	√			√	√	√			√	√										
Increased urban/coast development	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Increased logging						√					√									
Redistribution of marsh & barrier island sediment																				
Decreased land elevation																				

Table B4. Summary of the number of Drives and their associated pressures for the sub-basins of the Barataria Basin.

Driver		Sub-driver	Number of pressure in Sub-basin: Swamp forest	Fresh marsh	Intermediate marsh	Brackish marsh	Salt marsh	Driver total	Basin total
Driver	Hydrologic modification	Exploration & navigation canals	2	2	4	5	5		18
		Flood levee & dam construction	3	2	3	3	3		14
		Freshwater diversion	0	4	4	4	1	45	13
	Climate	Sea level rise / subsidence	2	2	2	2	2		10
		Extreme weather events	1	1	2	4	4		12
		Variability	1	1	1	2	2	29	7
	Human related	Local population size	7	6	6	7	7		33
		Trade / industry	8	6	6	8	8		36
		Socio-political-educational perceptions	5	4	4	4	4		21
		Tourism / recreation	6	6	6	6	6	120	30
		Total	35	34	38	45	42	194	194

The Master Plan for the restoration on the Louisiana coast (Coastal Protection and Restoration Authority of Louisiana, 2012) outlined a series of project types to be employed in restoring the coastal area. These project types were used as large scale guidelines in developing the **state variable**s, **indicators**, and **response** under the NOAA DPSIR framework. The master plan includes the following project types:

- Protective levees
- Bank stabilization
- Barrier Island restoration
- Channel realignment
- Hydrologic restoration
- Marsh creation
- Oyster barrier reefs
- Ridge restoration
- Sediment diversion
- Shoreline protection

In 1991, the Barataria-Terrebonne National Estuary Program (BTNEP) was established, with the goal of developing management and policy goals for the restoration and preservation of the Barataria and Terrebonne Estuaries. The ecological management action plans developed by BTNEP directly address priority problems identified for the Barataria estuary. Constructed as a "Comprehensive Conservation Management Plan" as a compact between the public and the Estuary Program, the action plans are listed below under four sub-headings, Habitat Management, Water Quality, Living Resources, and Accessible and Compatible Data Sets.

Habitat Management - actions which address the issues of water and sediment flows, habitat loss, and marsh protection

Action Plan EM-1: Hydrologic Restoration

Action Plan EM-2: Freshwater and Sediment Diversions

Action Plan EM-3: Evaluate the Effectiveness of Reactivating Bayou Lafourche as a Distributary Channel of the Mississippi River

Action Plan EM-4: Beneficial Use of Dredged and Non-Indigenous Material

Action Plan EM-5: Preservation and Restoration of Barrier Islands

Action Plan EM-6: Shoreline Stabilization and Induced Sediment Deposition

Action Plan EM-7: Marsh Management

Water Quality - actions which identify water quality problems and protect water resources

Action Plan EM-8: Nutrient, Bacteria and Toxic Contaminant

Action Plan EM-9: Oil and Produced Water Spill Prevention and Early Detection

Action Plan EM-10: Reduction of Sewage Pollution

Action Plan EM-11: Reduction of Agricultural Pollution

Action Plan EM-12: Storm Water Management

Action Plan EM-13: Contaminated Sediment Data Base

Action Plan EM-14: Assessment of Toxic and Noxious Phytoplankton Blooms

Living Resources - actions which address problems associated with the plant and animal life of the estuary

Action Plan EM-15: Protection of Habitat for Migratory and Resident Birds

Action Plan EM-16: Reduction of Impacts from Exotic Vegetation

Action Plan EM-17: Zebra Mussel Monitoring and Control

Accessible and Compatible Data Sets - actions which address the need for a centralized accessible body of scientific information about the estuary and its problems

Action Plan EM-18: Centralized Data Sets

The Governors' Action Plan for Healthy and Resilient Coasts (Gulf of Mexico Alliance, 2006), for the time period 2006 through 2009, outlined 11 actions under five priority issues, some of which are directly related to Barataria Bay:

Water Quality

WQ-1: Improve harmful algal bloom detection and forecasting

WQ-2: Improve beach water quality management

WQ-3: Improve government efficiency in water quality monitoring

Wetland Restoration

R-1: Streamline coastal restoration and conservation efforts

R-2: Increase community safety by better understanding the risks of sea level rise, storm surge, and subsidence.

Environmental Education

ED-1: Galvanize local communities to protect the Gulf of Mexico through targeted education

ED-2: Conduct a public awareness campaign for the Gulf of Mexico

Characterization of Gulf Habitats

ID-1: Create and provide access to interactive habitat maps for priority Gulf of Mexico habitats.

Reduction of Nutrient Inputs

N-1: Increase regional coordination in the development of nutrient criteria

N-2: Implement nutrient reduction activities during Gulf recovery and rebuilding

N-3: Assert an aligned five Gulf State position on the need to address Gulf of Mexico hypoxia

The Governors' Action Plan II for Healthy and Resilient Coasts (Gulf of Mexico Alliance, 2009), for the time period 2009 through 2014, set a course for action designed to improve the ecosystems and economies of the Gulf. The major components are outlined below:

- Water Quality for Healthy Beaches and Seafood
- Pathogens
- Harmful Algal Blooms
- Mercury in seafood
- Monitoring
- Habitat Conservation and Restoration
- Expanded Partnerships
- Policy changes
- Technology Development
- Gulf Regional Sediment Management Master Plan
- Reversing the Downward Trend in Habitat and Ecosystem Services
- Ecosystem Integration and Assessment
- Gulf of Mexico Master Mapping Plan (GMMMP)
- Data Access and Acquisition'
- Living Marine Resources
- Emergent Wetland Status and Trends Report
- Ecological Services Valuation
- Nutrients and Nutrient Impacts
- Nutrient Characterization
- Nutrient Criteria Development
- Hypoxia
- Nutrient Reduction Strategies
- Coastal Community Resilience
- Risk and Resilience Assessment
- Risk and Resilience Management Toolbox
- Risk and Resilience Communication
- Environmental Education

- Community Education and Outreach
- Public Awareness
- K through 20 Environmental Literacy
- Economic Value Communication

The actions from the BTNEP Compact and the Governors Action Plan were used in refining the **state variables**, **indicators**, and **response** for each of the sub-basins. The entire DPSIR framework is summarized in Table B5 (Hydrologic Drivers), Table B6 (Climate Drivers) and Table B7 (Human Related Drivers).

Table B5. DPSIR framework for the sub-basins of the Barataria basin for the Hydrologic Modification drivers.

Driver	Pressure(s)	State Variable(s)	Impact	Response	Swamp	Fresh	Intermediate	Brackish	Salt
Hydrologic modification: Exploration and navigation canals	**Altered internal wetland connectivity or impoundment**	**Wetland water levels, Wetland material and organism exchange (on ground measurements)**	**Decreased material and/or organism exchange. Increased hydroperiod leading to increased plant stress to habitat change or loss.**	**Hydrologic restoration, Install water control structures, remove or gap spoil banks.**	√	√	√	√	√
Hydrologic modification: Exploration and navigation canals	**Increased dredging: direct loss of habitat**	**Area of wetland habitat (on ground measurement and/or remote sensing)**	**Loss of wetland habitat and associated ecological services**	**Regulation of dredging activity, mitigation by creation of new habitat**	√	√	√	√	√
Hydrologic modification: Exploration and navigation canals	**Increased boat traffic: wakes, grounding, anchor scars**	**Bottom damage survey, bank erosion and/or channel widening survey (on ground or possibly through remote sensing)**	**Loss and/or damage of wetland habitat (channel edge, channel or bay bottom) and associated ecological services**	**Vessel speed limits (no wake zones), Boater education, Bank line protection, mitigation by creation of new habitat**				√	√
Hydrologic modification: Exploration and navigation canals	**Redistribution of marsh and/or barrier island sediments**	**Habitat area (on ground surveys or possibly through remote sensing)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Regulation of dredging activity, mitigation by creation of new habitat**			√	√	√
Hydrologic modification: Exploration and navigation canals	**Decreased land elevation**	**Habitat area and elevation (on ground or possibly through remote sensing, surveys)**	**Loss of wetland habitat and associated ecological services.**	**Regulation of dredging activity, mitigation by creation of new habitat**			√	√	√
Hydrologic modification: Flood levee and dam construction	**Altered riverine input**	**River water flux into wetland. (on ground measurement)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Levee and/or channel realignment, hydrologic restoration, water control structures**	√	√	√	√	√
Hydrologic modification: Flood levee and dam construction	**Altered wetland connectivity or impoundment**	**Wetland water levels, Wetland material and organism exchange (on ground measurements)**	**Decreased material and/or organism exchange. Increased hydroperiod leading to increased plant stress to habitat change or loss.**	**Levee realignment, hydrologic restoration, water control structures**	√	√	√	√	√
Hydrologic modification: Flood levee and dam construction	**Increased Urban/coast development**	**Population in the coastal zone, (from census data base) acres of developed land in the coastal zone (maps from permits, remote sensing)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Zoning to limit development in coastal zone, public outreach and education, mitigation by creation of new habitat**	√		√	√	√
Hydrologic modification: Freshwater diversion	**Altered riverine input**	**River water flux into wetland. (on ground measurement)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Channel realignment, hydrologic restoration, water control structures**		√	√	√	√
Hydrologic modification: Freshwater diversion	**Altered wetland connectivity**	**Wetland water levels, Wetland material and organism exchange (on ground measurements)**	**Decreased material and/or organism exchange. Increased hydroperiod leading to increased plant stress to habitat change or loss.**	**Hydrologic restoration, water control structures**		√	√	√	
Hydrologic modification: Freshwater diversion	**Increased point an non-point nutrients**	**Nutrient concentrations (on ground sample collection)**	**Eutrophication of coastal water bodies, increased vegetation stress, change in habitat type**	**Change volume diverted and/or operation schedule for diversion, eliminate diversion**		√	√	√	
Hydrologic modification: Freshwater diversion	**Increased point an non-point pollutants**	**Target pollutant (i.e. mercury) concentrations (on ground sample collection)**	**Increased stress on habitats and/or organisms, commercial and/or recreational organisms no longer safe for consumption**	**Change volume diverted and/or operation schedule for diversion, public outreach and education, set safe pollutant limits for organisms used for consumption, eliminate diversion**		√	√	√	

Table B6. DPSIR framework for the sub-basins of the Barataria basin for the Climate drivers.

Driver	Pressure(s)	State Variable(s)	Impact	Response	Swamp	Fresh	Intermediate	Brackish	Salt
Climate: Seal level rise / subsidence	**Altered internal wetland connectivity**	**Wetland water levels, (on ground measurements)**	**Increased hydroperiod leading to increased plant stress to habitat change or loss.**	**Hydrologic restoration, water control structures**	√	√	√	√	√
Climate: Seal level rise / subsidence	**Decreased land elevation**	**Habitat area and elevation (on ground or possibly through remote sensing, surveys)**	**Loss of wetland habitat and associated ecological services.**	**Marsh creation, sediment diversions or sediment delivery**	√	√	√	√	√
Climate: Extreme weather events	**Altered riverine input**	**River water flux into wetland. (on ground measurement)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Hydrologic restoration, water control structures**	√	√	√	√	√
Climate: Extreme weather events	**Altered internal wetland connectivity**	**Wetland water levels, Wetland material and organism exchange (on ground measurements)**	**Increase in material and/or organism exchange, direct loss of habitat and associated ecological**	**Hydrologic restoration, water control structures**			√	√	√
Climate: Extreme weather events	**Redistribution of marsh and/or barrier island sediments**	**Habitat area (on ground surveys or possibly through remote sensing)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Marsh/ barrier island creation and/or restoration**				√	√
Climate: Extreme weather events	**Decreased land elevation**	**Habitat area and elevation (on ground or possibly through remote sensing, surveys)**	**Loss of wetland habitat and associated ecological services.**	**Marsh creation, sediment diversions or sediment delivery**				√	√
Climate: Variability	**Altered riverine input**	**River water flux into wetland. (on ground measurement)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Hydrologic restoration, water control structures**	√	√	√	√	√
Climate: Variability	**Redistribution of marsh and/or barrier island sediments**	**Habitat area (on ground surveys or possibly through remote sensing)**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Marsh/ barrier island creation and/or restoration**				√	√

Table B7. DPSIR framework for the sub-basins of the Barataria basin for the Human related drivers.

Driver	Pressure(s)	State Variable(s)	Impact	Response	Swamp	Fresh	Intermediate	Brackish	Salt
Human related: Local population size	Increased point an non-point nutrients	Nutrient concentrations (on ground sample collection)	Eutrophication of coastal water bodies, increased vegetation stress, change in habitat type	Wastewater treatment, outreach and education regarding proper disposal	√	√	√	√	√
Human related: Local population size	Increased point an non-point pollutants	Target pollutant (i.e. mercury) concentrations (on ground sample collection)	Increased stress on habitats and/or organisms, commercial and/or recreational organisms no longer safe for consumption	Wastewater treatment, outreach and education regarding proper disposal	√	√	√	√	√
Human related: Local population size	Increased fishing effort	Fisheries Catch data (on ground sample collection)	Decrease in or loss of fishery.	Size and/or catch limits, set harvest seasons.	√	√	√	√	√
Human related: Local population size	Increased boat traffic: wakes, grounding, anchor scars	Bottom damage survey, bank erosion and/or channel widening survey (on ground or possibly through remote sensing)	Loss and/or damage of wetland habitat (channel edge, channel or bay bottom) and associated ecological services	Vessel speed limits (no wake zones), Boater education, Bank line protection, mitigation by creation of new habitat	√	√	√	√	√
Human related: Local population size	Non-indigenous species introduction	Species inventory (on ground samples)	Change/loss of native species and associated ecological services	Outreach and education regarding transport of non-indigenous species, eradication programs	√	√	√	√	√
Human related: Local population size	Altered coastal biodiversity	Habitat area (remote sensing) Species type and abundance (on ground surveys)	Change/loss of habitat and native species with loss of associated ecological services	Habitat creation and restoration (marsh, oyster reefs, coastal ridges, barrier islands)	√			√	√
Human related: Local population size	Increased Urban/coast development	Population in the coastal zone, (from census data base) acres of developed land in the coastal zone (maps from permits,	Modification (possibly loss) of wetland habitat and associated ecological services.	Zoning to limit development in coastal zone, public outreach and education, mitigation by creation of new habitat	√	√	√	√	√
Human related: Trade / industry	Increased point an non-point nutrients	Nutrient concentrations (on ground sample collection)	Eutrophication of coastal water bodies, increased vegetation stress, change in habitat type	Regulation of overboard or industrial dumping, outreach and education	√	√	√	√	√
Human related: Trade / industry	Increased point an non-point pollutants	Target pollutant (i.e. mercury) concentrations (on ground sample collection)	Increased stress on habitats and/or organisms, commercial and/or recreational organisms no longer safe for	Regulation of overboard or industrial dumping, outreach and education	√	√	√	√	√
Human related: Trade / industry	Increased dredging: direct loss of habitat	Area of wetland habitat (on ground measurement and/or remote sensing)	Loss of wetland habitat and associated ecological services	Regulation of dredging activity, mitigation by creation of new habitat			√	√	√
Human related: Trade / industry	Increased fishing effort	Fisheries Catch data (on ground sample collection)	Decrease in or loss of fishery.	Size and/or catch limits, set harvest seasons.	√	√	√	√	√
Human related: Trade / industry	Increased boat traffic: wakes, grounding, anchor scars	Bottom damage survey, bank erosion and/or channel widening survey (on ground or possibly through remote sensing)	Loss and/or damage of wetland habitat (channel edge, channel or bay bottom) and associated ecological services	Vessel speed limits (no wake zones), Boater education, Bank line protection, mitigation by creation of new habitat	√	√	√	√	√
Human related: Trade / industry	Non-indigenous species introduction	Species inventory (on ground samples)	Change/loss of native species and associated ecological services	Outreach and education regarding transport of non-indigenous species, eradication programs	√	√	√	√	√
Human related: Trade / industry	Altered coastal biodiversity	Habitat area (remote sensing) Species type and abundance (on ground surveys)	Change/loss of habitat and native species with loss of associated ecological services	Habitat creation and restoration (marsh, oyster reefs, coastal ridges, barrier islands)	√			√	√

Table B7. (continued)

Driver	Pressure(s)	State Variable(s)	Impact	Response	Swamp	Fresh	Intermediate	Brackish	Salt
Human related: Trade / industry	**Increased Urban/coast development**	**Population in the coastal zone, (from census data base) acres of developed land in the coastal zone (maps from permits,**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Zoning to limit development in coastal zone, public outreach and education, mitigation by creation of new habitat**	√	√	√	√	√
Human related: Trade / industry	**Increased logging**	**Area of timber logged (on ground surveys of remote sensing)**	**Habitat type change, loss of habitat and associated ecological services**	**Improved logging practices, use different materials, limit logging, set aside natural areas, public outreach and education**	√				
Human related: Socio-political-educational perceptions	**Increased point an non-point nutrients**	**Public understanding of nutrient levels (Public opinion surveys)**	**Lack of support for responses to address the issue**	**Outreach and education regarding environmental safe methods of disposal**	√	√	√	√	√
Human related: Socio-political-educational perceptions	**Increased point an non-point pollutants**	**Public understanding of Target pollutants (i.e. mercury) (Public opinion surveys)**	**Lack of support for responses to address the issue**	**Outreach and education regarding environmental safe methods of disposal**	√	√	√	√	√
Human related: Socio-political-educational perceptions	**Non-indigenous species introduction**	**Public understanding of non-indigenous species issues (Public opinion surveys)**	**Lack of support for responses to address the issue**	**Outreach and education regarding transport of non-indigenous species, eradication programs**	√	√	√	√	√
Human related: Socio-political-educational perceptions	**Increased Urban/coast development**	**Public understanding of coastal development issues (Public opinion surveys)**	**Lack of support for responses to address the issue**	**Outreach and education regarding environmental pressures resulting from coastal development**	√	√	√	√	√
Human related: Socio-political-educational perceptions	**Increased logging**	**Public understanding of logging issues (Public opinion surveys)**	**Lack of support for responses to address the issue**	**Outreach and education regarding potential environmental damage from logging and possible mitigation (i.e. don't use Cypress mulch)**	√				
Human related: Tourism / recreation	**Increased point an non-point nutrients**	**Nutrient concentrations (on ground sample collection)**	**Eutrophication of coastal water bodies, increased vegetation stress, change in habitat type**	**Outreach and education regarding environmental safe methods of disposal**	√	√	√	√	√
Human related: Tourism / recreation	**Increased point an non-point pollutants**	**Target pollutant (i.e. mercury) concentrations (on ground sample collection)**	**Increased stress on habitats and/or organisms, commercial and/or recreational organisms no longer safe for consumption**	**Outreach and education regarding environmental safe methods of disposal**	√	√	√	√	√
Human related: Tourism / recreation	**Increased fishing effort**	**Fisheries Catch data (on ground sample collection)**	**Decrease in or loss of fishery.**	**Size and/or catch limits, set harvest seasons.**	√	√	√	√	√
Human related: Tourism / recreation	**Increased boat traffic: wakes, grounding, anchor scars**	**Bottom damage survey, bank erosion and/or channel widening survey (on ground or possibly through remote sensing)**	**Loss and/or damage of wetland habitat (channel edge, channel or bay bottom) and associated ecological services**	**Vessel speed limits (no wake zones), Boater education, Bank line protection, mitigation by creation of new habitat**	√	√	√	√	√
Human related: Tourism / recreation	**Non-indigenous species introduction**	**Species inventory (on ground samples)**	**Change/loss of native species and associated ecological services**	**Outreach and education regarding transport t of non-indigenous species, eradication programs**	√	√	√	√	√
Human related: Tourism / recreation	**Increased Urban/coast development**	**Population in the coastal zone, (from census data base) acres of developed land in the coastal zone (maps from permits,**	**Modification (possibly loss) of wetland habitat and associated ecological services.**	**Zoning to limit development in coastal zone, public outreach and education, mitigation by creation of new habitat**	√	√	√	√	√

CONCLUSION / NEXT STEPS

A total of 194 pressures were identified for the Barataria basin as a whole, distributed across five sub-basins:

- Swamp forest: 35 pressures
- Fresh marsh: 34 pressures
- Intermediate marsh: 38 pressures
- Brackish marsh: 45 pressures
- Salt marsh: 42 pressures.

Climate drivers resulted in ~15% of the pressures with the remainder (~85%) attributed to human activities.

Indicator variables included on the ground sampling (i.e. nutrients, species), remote sensing, and public opinion surveys. Many of the indicators are already being monitored under existing programs. A logical "next step" would be an accurate inventory of existing monitoring programs (local, state, and federal) to identify data gaps.

The responses identified range from Public Outreach and Education to larger scale construction type projects. The CWPPRA program has already implemented many marsh restoration projects that address some of the pressures we have identified. A "next step" is to look at the projects within the Barataria Basin to identify the success of implementation in reducing or eliminating a pressure.

One other "next step" would be to further refine the pressures in each of the sub-basins in order to rank them in to "high", "medium", and "low" classes. The responses need to be further refined to account for costs as well as risk/uncertainty. This would allow for the development of a priority matrix to guide response implementation. It would be desirable to implement a response to address a pressure which is having a large impact on the system as opposed to a pressure with a smaller impact on the system assuming that the cost and risk/uncertainty is reasonable. The Master plan for the Louisiana Coast (Coastal Protection and Restoration Authority of Louisiana, 2012) lists several criteria that could be considered when refining the responses:

- Support of Cultural Heritage
- Distribution of Flood Risk reduction across Socioeconomic Groups
- Flood Protection of Historic Properties
- Flood Protection of Strategic Assets
- Support of Navigation
- Support of Oil and Gas
- Sustainability
- Use of Natural Processes
- Operations and Maintenance (higher cost)

Attachment 1 To Appendix B.

Non-native species in the Barataria Basin

A non-native (non-indigenous or exotic) species is a plant animal or other biota that is living outside its original geographic boundary. These species may have been intentional introduced for agriculture, fish and wildlife management, recreational uses, or accidentally introduced from ship ballast water, "hitchhikers" hidden within other methods of transportation or materials, or through irresponsible pet owners.

Some non-native species co-exist harmoniously in their new environments but more often introduced species have negative impacts on existing native population and ecosystems. Non-native examples in Louisiana include the aquatic plant hydrilla and the zebra mussel; both have negatively affected the local environment and surface water uses. Below is a list of non-native species in the Barataria Basin (from http://www.btnep.org).

Terrestrial plants - Chinese Tallow , Purple Loosestrife, Cogon Grass

Aquatic plants - Hydrilla, Water Hyacinth, Alligator Weed, Eurasian Watermilfoil, Water Spangle, Giant Salvinia, Brazilian Waterweed, Common Salvinia, Parrot Feather, Water Lettuce, Wild Taro

Aquatic animals - Nutria, Australian Spotted Jellyfish, Apple Snails, Brown Mussel, Asian Clam, Zebra Mussels, Tilapia, Carp (spp.), Rio Grande Cichlid

Insects - Africanized Honeybee, Asian Tiger Mosquito , Formosan Termite, Mexican Boll Weevil, Red Imported Fire Ant

Mammals - Norway Rat, Feral Hogs

Birds - Monk Parakeet, European Starling, Cattle Egret

Reptiles - Brown Anole

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Appendix C: Mississippi Sound/Bight

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BACKGROUND

The Mississippi Sound is a shallow (4 m), partially-stratified estuary (McAnally et al. 2010) which occupies nearly 4,800 km^2 from Lake Borgne, Louisiana to Mobile Bay, Alabama (Moretzsohn et al. 2012) and extends seaward from the coastline to the MS/AL barrier islands (Figure C-1). The hydrography of the MS Sound is primarily influenced by marine waters entering the system from the Gulf of Mexico through the barrier island passes (McAnally et al. 2010) and almost 107 million m^3 day^{-1} of freshwater inflow from a 69,700 km^2 drainage basin (Moretzsohn et al. 2012); hence, salinities in the MS Sound more closely resemble estuarine environs (~24‰).

The coastal watershed is drained by six major rivers that connect to the Sound, as well as the Mississippi River via Lake Pontchartrain and Lake Borgne in Louisiana. The MS Sound ecosystem is comprised of the Sound and the connected coastal watersheds that feed into it from three principal embayments: St. Louis Bay, Biloxi Bay, and the Pascagoula River distributary (McAnally et al. 2010).

The natural coastal boundaries of sinuous bayous fringed with emergent marsh vegetation and sandy barrier islands have been substantially altered by human activities such as shoreline hardening and dredging, as well as natural climatic events such as hurricanes (McAnally et al. 2010). The MS Sound includes 4,326 km^2 of coastal wetlands, but only 121 km^2 of submerged aquatic vegetation, due to the significant suspended sediment load in nearshore waters (Moretzsohn et al. 2012). The MS Sound also contains approximately 2023 km^2 of open water over mostly sand/mud bottom, although there are 283 km^2 of emergent marsh along the MS coast (McAnally et al. 2010) and some 31.2 km^2 of oyster reef habitat (MDMR 2010) located almost exclusively in the shallow, nearshore waters near the mouth of St. Louis Bay (Figure C-2).

The MS Bight largely consists of open water habitats over sand/mud bottom and is loosely defined as the area extending seaward from the MS Sound to the 200m isobath, extending to the easternmost longitudinal limit of Mobile Bay, AL (-87.75° W) and constrained on the west by the Chandeleur island chain, Breton Sound, and the Louisiana bird's foot delta (Moretzsohn et al. 2012). Both the MS Sound and Bight are heavily influenced by MS River effluent.

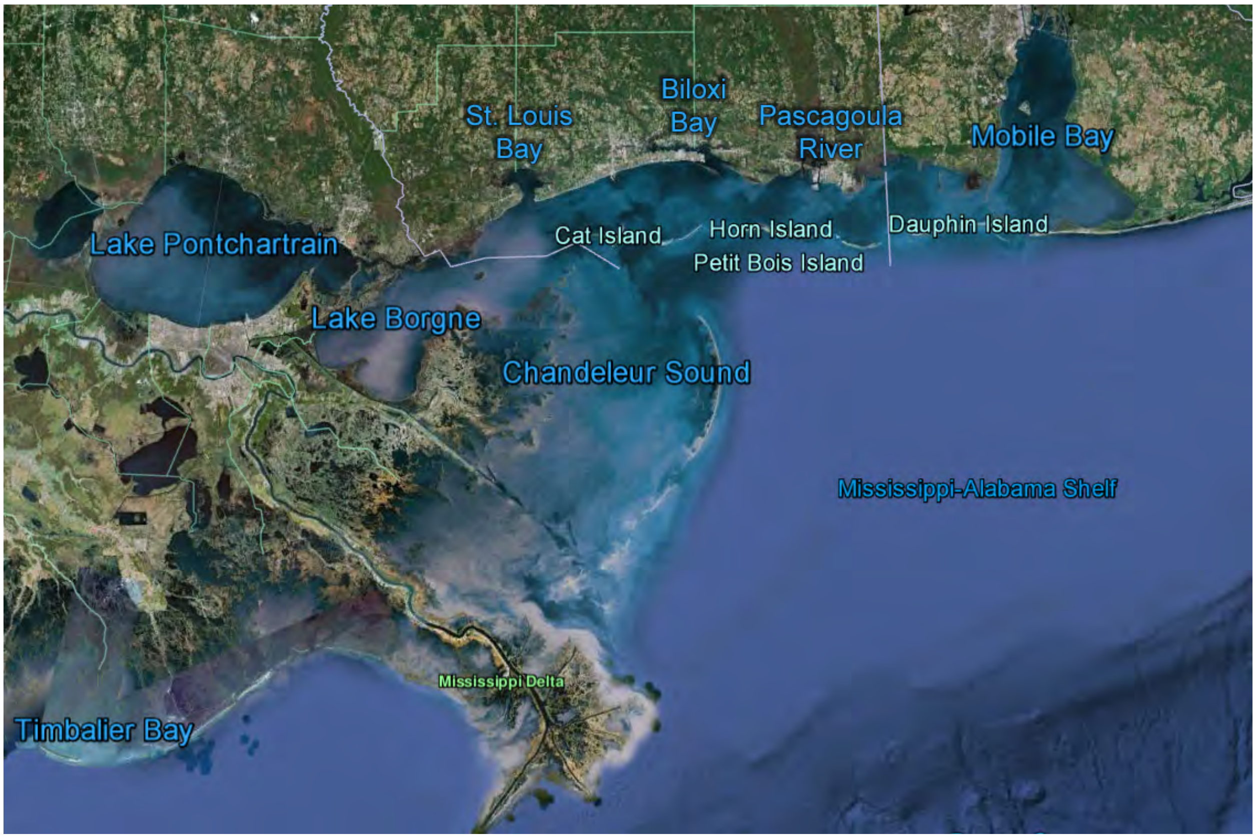

Figure C-1. Map of the Mississippi Sound and Bight, stretching from Lake Borgne, LA to the west, Mobile Bay, AL to the east, and the Mississippi River Delta, LA to the south. The MS Sound is defined as the region extending from the MS coastline seaward to the barrier island chain (Cat Island, MS to Dauphin Island, AL). The MS Bight is defined as the region extending seaward of the MS Sound, out to the 200 m isobath.

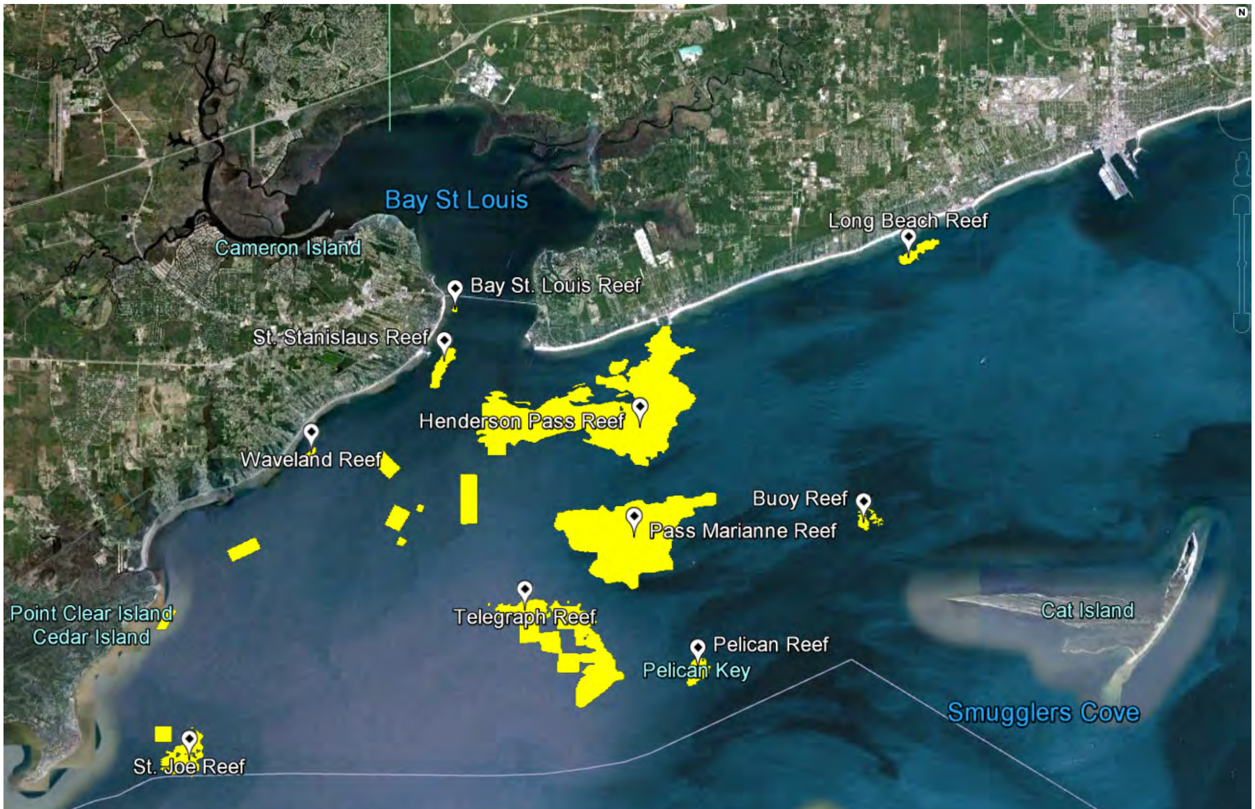

Figure C-2. Map of historic (27.8 km^2) and restorative cultch reef areas (3.4 km^2) serving as oyster reef habitat within the Mississippi Sound.

The environmental conditions within the MS Sound/Bight which are most heavily influenced by Mississippi River effluent are largely centered on the suspended sediment load (*e.g.* impacts to water quality with respect to optical clarity and sedimentation/burial rates), freshwater dilution effects (*e.g.* the diminution of *in situ* salinities and the imposition of significant stratification effects), and nutrient input (*e.g.* eutrophication). The relative importance of marine and freshwater influence to the Sound changes seasonally, as well as daily in response to climatic variability and freshwater diversion; and affects species distributions, species production and spawning success, aquatic nutrient concentrations, water clarity, and even human health (Fulford et al. 2009).

From 1981 to 2005, the average annual flux of total nitrogen and total phosphorus delivered from the Mississippi River watershed to the Gulf of Mexico was 1.47 and 0.14 million metric tons, respectively (Aulenbach et al., 2007; CENR, 2010). During that same period, the total sediment load in the lower Mississippi River ranged from 70 – 230 million tons yr^{-1}, averaging of 150 million tons yr^{-1} (Thorne et al. 2008). As a combined result of eutrophication and water-column stratification in the region, the development of hypoxia (<2.0 mg O_2 L^{-1}) in the waters east of the Mississippi River (in the Mississippi Sound & Bight) has been documented by a number of researchers (Rabalais, 1992; Rabalais and Turner, 2001; Brunner et al., 2006). More recent studies conducted off of the Mississippi coast indicate frequent and expansive regions of summer hypoxia east of the Mississippi River delta in the Mississippi Sound and Bight (Milroy and Moshogianis, 2010; Howden, pers. comm.).

INTEGRATED ECOSYSTEM ASSESSMENT (IEA) – MS SOUND/BIGHT

The IEA process is rooted in NOAA's objective to "Protect, Restore, and Manage the use of Coastal, Ocean, and Great Lakes resources through an Ecosystem Approach to Management (EAM)." (NOAA 2009). Inherent to the IEA process, the DPSIR framework is employed in order to define the salient ***Drivers*** of change within an ecosystem, which introduce specific ***Pressures*** on the ecosystem. As the ecosystem responds to these pressures, these changes can be quantified by monitoring the appropriate ***State Variables*** which themselves serve as indicators of ecosystem dynamism. The ***Impacts*** of these changes can also be quantified and are then considered within the context of resource management and the risks associated with ameliorative action. Such actions are of course a part of the management ***Response*** and are designed to change the fundamental Drivers and/or Pressures affecting the system and therefore affect positive change within the managed system; that is, an ecosystem approach to management (EAM).

DRIVERS & PRESSURES

Within the DPSIR framework, drivers represent those forces at work within the ecosystem which are measurable but largely unmanageable. Previous IEA/EAM-related assessments (Fulford et al. 2009) within the MS Sound/Bight indicate that the most important drivers at work within this system include: 1) *Hydrologic Modifications*; 2) *Climate*; and 3) *Anthropogenic Processes*.

Driver – Hydrologic Modifications: While *Hydrologic Modifications* could also be considered an *Anthropogenic Process*, they are separated here for two reasons. First, *Hydrologic Modifications* have such a large effect in some ecosystems that they dwarf the effects of other *Anthropogenic Processes*. Second, they are purposeful in that they are intended to directly modify the physical environment, unlike other *Anthropogenic Processes* that serve as Drivers.

Among the pressures which specifically arise from modifications of MS Sound/Bight hydrology, *Freshwater Diversions* are the most important, particularly with respect to the Bonnet Carre Spillway (BCS) which is capable of diverting floodwaters of the Mississippi River (MSR) into the Mississippi Sound/Bight through Lake Pontchartrain. Modifications wrought from *Exploration/Navigation Canals* (e.g. ship channel dredging) and *Levee/Dam Construction* also induce pressure on the MS Sound/Bight ecosystems.

Driver – Climate: Within the panoply of climate-related pressures, the most important of these is *Climate Variability*, primarily as a consequence of seasonal climate variation. The periodicity and intensity of *Extreme Weather Events* (*e.g.* Hurricanes) is also important to ecosystem function within the MS Sound/Bight, as these sporadic events can have a disproportionately large effect on ecosystem function and recovery. Climate-induced *Sea Level Rise/Subsidence* is particularly significant with regard to coastal wetland, emergent marsh, submerged aquatic vegetation (SAV), and oyster reef habitats.

Driver – Anthropogenic Processes: Within the broad range of human-related pressures on MS Sound/Bight ecosystems, *Local Population Size* is perhaps the most important, as the intensity of **all** anthropogenic effects will be proportional to population size. Pressures arising from *Trade/Industry* are quite significant, as these are defined by shipping activity and commercial fishing. In turn, these pressures are related to Hydrologic Drivers (e.g. increased development of exploration and navigation canals and freshwater diversions) and Anthropogenic Drivers (e.g. flourishing trade/industry leads to an increase in the local population size and other human-related processes). While *Tourism/Recreation* is indeed an important component to the Anthropogenic Driver, they are quite often eclipsed by the pressures from *Trade/Industry* (particularly with respect to the exploitation of commercial fisheries). *Perceptions* of human-related pressures are a relatively minor contributor to Anthropogenic Processes, but they are not insignificant.

STATES & STATE VARIABLES

The hierarchical relationship between the variable **Pressures** (⊳) induced by each of the three main **Drivers** (•) at work within MS Sound/Bight ecosystems can be summarized as:

- • Hydrologic Modifications
    - ⊳ Exploration and Navigation Canals
    - ⊳ Flood Levee and Dam Construction
    - ⊳ Freshwater Diversions

- • Climate
    - ⊳ Sea Level Rise/Subsidence
    - ⊳ Extreme Weather Events
    - ⊳ Climate Variability

- • Anthropogenic Processes
    - ⊳ Local Population Size
    - ⊳ Trade/Industry
    - ⊳ Socio-Political-Educational Perceptions
    - ⊳ Tourism/Recreation

Unique combinations of these drivers and pressures give rise to a multitude of "states" within MS Sound/Bight ecosystems, which can be quantified by choosing the correct **State Variables** to serve as an appropriate metric (or "indicator") of measureable changes within the affected ecosystem(s).

Specific to the *Hydrologic Modifications* driver (Table C-1), there are a total of 13 measurable "States of the Environment" (SoE) which can be directly or indirectly related to the pressures wrought therefrom. While there are another 13 similar SoE associated with the pressures induced by *Climate* (Table C-2), pressures from *Anthropogenic Processes* give rise to 41 SoE (Table C-3).

The following excerpt from the Integrated Ecosystem Assessment Initiative for Selected Systems in the Northern Gulf of Mexico Report (McAnally et al. 2010) summarizes the connectivity between the multiple drivers, pressures, and states within the MS Sound/Bight ecosystem (MSE), specifically as they relate to the SoE information presented in Tables C-1-3:

"The broad opinion… was that coastal land use is the most important factor influencing the MSE. Land use was partitioned into two pressures broadly defined as Urban/Coastal Development and Critical Habitat Degradation. These two pressures were related to several key drivers: Local Population Size, Trade/Industry (e.g., fishery, tourism, manufacturing), Socio-Political-Educational Perceptions, and Climatic Variability. In particular, the effects of climatic variability in the form of severe storm events was highlighted as an important driver of coastal land use with the most significant influence occurring in the period after a severe storm when large scale remediation efforts (e.g., shoreline repair/protection, debris removal) will occur, as well as a significant reshuffling of land use distributions as user groups enter or leave the impacted area (e.g., new development, changes in flood maps).

The second most important factor… was variability in freshwater flow and its consummate influence on sediment delivery and redistribution within the MSE. Freshwater flow is primarily controlled by the hydrologic drivers of Freshwater Diversion, Flood Levee & Dam Construction, and the dredging of Exploration and Navigation Canals, but is also influenced by Climatic Variability. These in turn result in several pressures: Altered Riverine Input, Altered Internal Wetland Connectivity, and Increased Fishing Effort as most commercially viable species are influenced by spatial distribution of optimal salinity. Freshwater pressures are also influenced by Human Related Processes such as Local Population Size, Socio-Political-Educational Perceptions of coastal residents, economic drivers such as Trade/Industry and Tourism/Recreation development.

The most important Industrial factors were shipping activity and commercial fishing. These factors include pressures for Increased Boat Traffic due to commercial navigation and ship building, as well as Increased Fishing Effort. In turn, these pressures are related to hydrologic drivers: development of Exploration and Navigation Canals and Freshwater Diversion; and human-related drivers: Local Population Size, and Trade/Industry. Climatic Drivers were not… as important in this case but may still have an effect through influences on accessibility of Sea Level Rise/Subsidence and/or Extreme Weather Events.

The most important biological factor was biodiversity, which is related to the hydrologic driver of Freshwater Diversion, the climatic driver of [Climate] Variability, and the human-related driver of Local Population Size. This factor is largely related back to land-use pressures already mentioned and … [is] included based on the point that biodiversity influences habitat quality for natural resources and thus is not simply an effect of other things already mentioned.

The final broad factors… were pollutants and toxicants, which… represent a pressure on the ecosystem related to human-related drivers: Local Population Size, Trade/Industry, and Tourism/Recreation. External pollutant sources represent a driver on the ecosystem as they are delivered into the system via the airshed or watershed…

The workshop group also examined priorities for the development of Indicators of Impact and State as defined under the DPSIR framework. The consensus view of the working group was that data regarding land use/land cover particularly temporal/spatial patterns in coastal land use is the biggest priority for an assessment of ecosystem state. Several small studies have been completed in MSE that measured current amounts of hard shoreline (Peterson et al. 2000; Partyka and Peterson 2008), as well as studies that have predicted the impact of changes in the amount of living shorelines on fish production (Jordan et al. 2009). However, a comprehensive study involving remotely sensed data closely coordinated with quantitative modeling efforts is warranted."

Altered Riverine Input (D1:P2-3; D2:P3; D3:P1,3): Describes time-dependent alterations to the quantity (and quality) of freshwater input to the watershed, at all geographical scales. Alterations within the limnological realm affect freshwater rivers, streams, lakes, and natural reservoirs. However, as these alterations propagate downstream, their effects are incident upon coastal marine and estuarine systems.

Suggested State Variable(s): Discharge Rate ($m^3\ s^{-1}$)
Nutrient Load (μmol L^{-1})
Sediment Load (mg L^{-1})
Salinity (PSU or ‰)

Altered Wetland Connectivity (D2:P1-2; D3:P1-3): Describes the ecological importance of spatially-connected terrestrial, estuarine, and marine habitats, particularly as they relate to the usage of these habitats as nursery/breeding grounds for commercially- and ecologically-important species.

Suggested State Variable(s): Number of MSE Estuaries (unitless)
Length of MSE Coastline (km)
Length of MSE River/Distributary (km)
Wetland Area (km^2 or ha)
Wetland Patch Density ($km^2\ km^{-2}$ or %)
Mean Distance between Wetland Areas (m or km)

Increased Nutrients (D2:P3; D3:P1-4): Describes the time-dependent, *in situ* concentration and molecular form of the most ecologically-important dissolved inorganic nutrients. Depending upon the complexity of the hydrologic paradigm, nutrient concentrations should be determined for each inter-connected aquatic system.

Suggested State Variable(s): Ammonium (μM)
Nitrate (μM)
Nitrite (μM)
Phosphate (μM)
Silicate (μM)

Table C-1. Variable "States of the Environment" (SoE) associated with those pressures induced by *Hydrologic Modifications*. Note that there is significant overlap between SoE indicated by *Climate* (Table C-2) and *Anthropogenic Processes* (Table C-3).

DRIVER	**1: Hydrologic Modifications**		
PRESSURE	**(1) Exploration/ Navigation Canals**	**(2) Levee/Dam Construction**	**(3) Freshwater Diversions**
STATE		Altered Riverine Input	Altered Riverine Input
		Increased Dredging	Increased Dredging
			Increased Fishing Effort
			Introduction of Non-native Species
	Increased Development		Increased Development
	Redistribution of Sediment		Redistribution of Sediment
	Degradation of Critical Habitat	Degradation of Critical Habitat	Degradation of Critical Habitat

Table C-2. Variable "States of the Environment" (SoE) associated with those pressures induced by *Climate*. Note that there is significant overlap between SoE indicated by *Hydrologic Modifications* (Table C-1) and *Anthropogenic Processes* (Table C-3).

DRIVER	**2: Climate**		
PRESSURE	**(1) Sea Level Rise/ Subsidence**	**(2) Extreme Weather Events**	**(3) Climate Variability**
STATE			Altered Riverine Input
	Altered Wetland Connectivity	Altered Wetland Connectivity	
			Increased Nutrients
			Increased Fishing Effort
		Introduction of Non-native Species	Introduction of Non-native Species
		Redistribution of Sediment	Redistribution of Sediment
		Decreased Land Elevation	
	Degradation of Critical Habitat	Degradation of Critical Habitat	Degradation of Critical Habitat

Table C-3. Variable "States of the Environment" (SoE) associated with those pressures induced by *Anthropogenic Processes*. Note that there is significant overlap between SoE indicated by *Hydrologic Modifications* (Table C-1) and *Climate* (Table C-2).

DRIVER	**3: Anthropogenic Processes**			
PRESSURE	**(1) Local Population Size**	**(2) Trade/ Industry**	**(3) Societal Perceptions**	**(4) Tourism/ Recreation**
STATE	Altered Riverine Input		Altered Riverine Input	
	Altered Wetland Connectivity	Altered Wetland Connectivity	Altered Wetland Connectivity	
	Increased Nutrients	Increased Nutrients	Increased Nutrients	Increased Nutrients
	Increased Pollution	Increased Pollution	Increased Pollution	Increased Pollution
	Increased Dredging	Increased Dredging	Increased Dredging	Increased Dredging
	Increased Fishing Effort	Increased Fishing Effort	Increased Fishing Effort	Increased Fishing Effort
	Increased Boat Traffic	Increased Boat Traffic	Increased Boat Traffic	Increased Boat Traffic
	Introduction of Non-native Species	Introduction of Non-native Species	Introduction of Non-native Species	Introduction of Non-native Species
	Increased Development	Increased Development	Increased Development	Increased Development
	Redistribution of Sediment	Redistribution of Sediment	Redistribution of Sediment	Redistribution of Sediment
	Degradation of Critical Habitat	Degradation of Critical Habitat	Degradation of Critical Habitat	Degradation of Critical Habitat

Increased Pollution (D3:P1-4): Describes the time-dependent, in situ concentration and molecular form of the most ecologically-important (and regionally significant) forms of dissolved pollutants and toxicants.

Suggested State Variable(s): Heavy Metals (nM or ppb)
Dioxins/Furans (nM or ppb)
Pesticides (nM or ppb)
Pharmaceutical Residues (nM or ppb)
Petrochemical Toxicants (nM or ppb)

Increased Dredging (D1:P2-3; D3:P1-4): Describes either the time or financial investment associated with ship channel excavation, or the amount of sediment removed, re-suspended, and/or re-deposited as a result of such excavations.

Suggested State Variable(s): Total Suspended Sediment (mg L^{-1})
Quantity of Excavated Sediment (tons or m^3)
Excavation Effort (\$ day^{-1}, tons day^{-1}, or m^3 hr^{-1})

Increased Fishing Effort (D1:P3; D2:P3; D3:P1-4): Describes the amount of time and/or financial resources dedicated to fishing interests. Frequently some surrogate is used relating to a given combination of inputs into the fishing activity, such as the number of hours or days spent fishing, numbers of hooks used, kilometers of nets used, etc. As an example, the European Union defines fishing effort as fleet capacity (Gross Tonnage = GT or Engine Power = kW) multiplied by the number of days at sea dedicated to fishing (time = t); the formulas are GT x t and kW x t.

Suggested State Variable(s): Time-investment in fishing (hrs or days)
Financial-investment in fishing ($)
Fishing fleet weight capacity (Gross Tonnage)
Fishing fleet power capacity (kW)

Increased Boat Traffic (D3:P1-4): Descibes either the number, the weight, or the power of vessels traveling to (or through) an area per unit time. Boat traffic can also be described using the mean distance traveled per vessel per unit time.

Suggested State Variable(s): Number of vessels in area (unitless)
Weight of vessels in area (tons)
Power of vessels in area (kW)
Time spent in area (hrs or days)
Distance traveled per excursion (km)
Number of marinas/ship docks (unitless)
Number of vessel departures/returns (unitless)

Time spent during departure & return (hrs or days)

<u>Introduction of Non-native Species (D1:P3; D2:P2-3; D3:P1-4)</u>: Describes the quantification and monitoring of non-native species present within the ecosystem. Species survey methods (identification and enumeration) are usually required to determine the presence of non-native species, then quantify non-native species dominance using standard species richness, evenness, biodiversity, and community similarity indices.

Suggested State Variable(s): Counts of individual species (unitless)
Total number of individuals in the survey (unitless)
Species Richness (unitless)
Area of survey (km^2 or ha)
Area of species coverage (m^2, km^2, or ha)
Index of Diversity (unitless)
Index of Evenness (unitless)
Index of Dominance (unitless)
Index of Community Similarity (unitless)
Time elapsed between surveys (hrs, days, or years)

<u>Increased Development (D1:P1,3; D3:P1-4)</u>: Describes the time-dependent changes to land use, specifically as it relates to urban/agricultural development of previously undeveloped land. Note that the *type* of development is as critical as the *amount* of developed land; thus, it is often difficult to reduce "development" to a singular state variable. Care should be taken to accommodate the disparate ecological effects of particular development efforts.

Suggested State Variable(s): Total land area (km^2 or ha)
Total area of undeveloped land (km^2 or ha)
Total area of developed land (km^2 or ha)
Type(s) of developed land (unitless)
Time elapsed between development surveys (days or years)
Financial investment in new developed land ($ $year^{-1}$)

<u>Redistribution of Sediment (D1:P1,3; D2:P2-3; D3:P1-4)</u>: Describes how sediments are redistributed (either by natural or anthropogenic means), typically as a measure of coastline changes (e.g. coastal erosion) or sediment accumulation from fluvial inputs. However, redistribution of sediments can also be accomplished by extreme climatic events (e.g. hurricanes) or human-related endeavors (e.g. deposition of dredge-spoil).

Suggested State Variable(s): Deposition rates (cm day^{-1}, or m $year^{-1}$)
Volume of displaced sediment (m^3)
Weight of displaced sediment (tons)
Total suspended sediment (mg L^{-1})

Sediment grain size (variable, usually □m to mm)
Sediment grain density (g mL^{-1})
Settling velocity (cm sec^{-1} or m hr^{-1})
Land elevation/bathymetry (m)
Coastline complexity/rugosity (unitless)
Time elapsed between surveys (days or years)

<u>Decreased Land Elevation (D2:P2)</u>: Describes the vertical changes in land elevation, compared either to mean sea level (standard survey methods) or the geoid (high-resolution satellite altimetry), caused by any number of factors, including erosion, subsidence, sea level rise, increased development, or reduced sediment deposition.

Suggested State Variable(s): Land elevation (m or km)
Time elapsed between surveys (days or years)
Subsidence rates (cm day^{-1} or m $year^{-1}$)
Erosion rates (cm day^{-1} or m $year^{-1}$)
Sea level rise (cm day^{-1} or m $year^{-1}$)
Deposition rates (cm day^{-1} or m $year^{-1}$)

<u>Degradation of Critical Habitat (D1:P1-3; D2:P1-3; D3:P1-4)</u>: Describes the reduction of critical habitat areas in affected ecosystems. This reduction can be either geographic (i.e. reduction of habitat area), functional (i.e. depressed ecological function), or a combination of both. Geographic degradation of critical habitat can usually be quantified more easily than functional degradation; however, state variables should be chosen carefully to provide insight into both features of habitat degradation.

Suggested State Variable(s): Types of habitat (unitless)
Valuation of habitat criticality (variable)
Idealized ecological services of each habitat (variable)
Actual ecological services of each habitat (variable)
Total area surveyed (km^2 or ha)
Total area of each habitat type (km^2 or ha)
Time elapsed between development surveys (days or years)

CURRENT RESEARCH

As a critical part of the Integrated Ecosystem Assessment (IEA) effort, the Mississippi Sound/Bight region was selected in order to explore the parameterization and execution of coupled hydrodynamic/ecosystem-function models to: 1) incorporate ground truth data into the coupled models of the system (*i.e.* data infusion); 2) capture historical dynamics to test the fidelity of hindcast models (*i.e.* model calibration); 3) provide predictive analyses of ecosystem response to modeled perturbations and ameliorative management efforts (*i.e.* model forecasting);

and 4) develop management strategies for appropriate response(s) based on predicted effects and risk assessment (*i.e.* the Ecosystem Approach to Management, or EAM).

It is against this complex ecological backdrop that the effects of the ultimate environmental perturbation, the Deepwater Horizon (DwH) oil spill, must be integrated. Crucial for the assessment and management of these MS Sound/Bight ecosystems, post-DwH, is a holistic and integrated analysis of DwH impacts on the hydrography, chemistry, and biology of this nGoM region, including the implications on and feedbacks from the society and economy in the region. Such an ambitious analysis requires: 1) large and diverse data sets encompassing pre- and post-DwH conditions within the MS Sound/Bight; and 2) close coordination among multidisciplinary approaches and perspectives.

The ecosystem-integrated approach is ideally suited for the assessment of the environmental impacts of the DwH accident, generally in all affected nGoM ecosystems, but specifically in the MS Sound/Bight. The models developed thus far can treat the oil spilled by the accident as a chemical driver and explore cascading impacts on the biological/ecological components of the ecosystem , as well as feedbacks between all processes. In this way, it shall be possible to implement current efforts of ecosystem-integrated research to include the analysis of environmental and human impacts from the DwH accident. The broad goal is to use the IEA framework to build an ecosystem modeling tool specifically designed to make use of ongoing research and monitoring related to DwH (with the outcome being a broader capitalization on the unprecedented amount of research planned or ongoing in other regions of the nGoM).

Development of an ecosystem model is a by nature a collaborative activity that capitalizes on multiple sets of expertise, as well as multiple sets of perspectives about model input data and model output. Model development is a cyclical process involving numerous opportunities for external review and comment separated by model refinement and data analysis. Currently, the emphasis of the NGI Eco-Modeling Group is on understanding oil spill impacts at the ecosystem level which requires that group members both integrate ongoing research into the model, as well as look at synergistic effects that extend across individual impacts in the MS Sound/Bight region. This effort is nearly complete and has focused on a workshop approach that was centered on a core team for model development. More specifically, model development was structured around three workshops from 2011-2012. These model workshops were intended to bring together a wider group of researchers with modeling expertise to obtain input on model development and to peer-review the results in real-time.

MODEL PROGRESS

Workshop/Conference 1: Model Development/Selection (Completed)

This workshop was convened as a starting point for the development of a conceptual ecological model built from existing efforts and mapping the path for an Integrated Ecosystem Assessment (IEA) of the nGoM. A conceptual model was used to design a quantitative model based on an energy transfer framework and was also used as a module for a larger Earth Systems Model comprising physical, biological, and social-economic parts.

The workshop was held January 26-27, 2011, at the Gulf Coast Research Laboratory in Ocean Springs, MS and was attended by 43 people from a variety of agencies and backgrounds; nearly all of which are involved in some form of quantitative modeling of living systems. The intent of the workshop was to benefit from the collective experience of the attendees, as well as the core modeling group, to acquire expert input on what needs to go into a general ecological model of a coastal watershed prior to addressing a particular question(s). The workshop's emphasis on discussions by the modeler attendees directed the workshop towards identifying practical issues of model development such as the model framework, temporal/spatial scale, model complexity, model linking, and computational logistics. Ultimately, the results of this workshop were used to: 1) inform the process of selecting an ecological model appropriate for the IEA tasks; 2) identify the fundamental elements of the model which can be modified for tasks specific to IEA/EAM needs; and 3) assemble the data necessary to engage in a significant modeling effort, using the MS Sound/Bight ecosystem as a regional test-case.

Key Products of Workshop/Conference 1

1) "Off-the-shelf" models may not provide complete functionality, but developing a comprehensive model from scratch may be too time- and resource-intensive. Consider the basic customization of existing models (e.g CASM), coupled with existing hydrodynamic models of the MS Sound/Bight (e.g. FVCOM).

2) Modeling efforts will naturally be constrained by model/data availability, as well as the demands associated with model customization vs. model innovation
    i) Model inventory is needed
    ii) Data inventory is needed
    iii) Use a modular approach, beginning with a simplified test case as a proof-of-concept

3) Scale of investigation is not fixed and may change across the sub-modules
    i) Use a flexible approach which requires careful examination of feedback mechanisms on a limited geographic/temporal scale to maintain workability
    ii) Map out functional groups based on relevant and workable scales

4) Input–Output variables must include estimates of ecosystem function and ecosystem services
    i) Model simulations to first focus on ecosystems of limited scope (for manageability)
    ii) Provide appropriate linkages between ecological & hydrodynamical models
    iii) Subsequent model validation will allow within-site simulations (and comparisons)
    iv) Successful validation will ultimately allow across-site simulations (and comparisons)

<u>Model/Data Inventory (Completed)</u>

Subsequent to Workshop 1, a thorough list of the available environmental data, as well as information relevant to feedbacks with economical and societal issues, in three representative ecosystems of the nGoM, Barataria Bay (Louisiana), Mississippi Sound (Mississippi), and

Perdido Bay (Florida) was compiled. The large data sets extending several years before the DwH oil spill and post-accident surveys, in combination with all the other DwH-related work done by many others, constituted a substantial data set to explore with rigor the environmental, societal and economic impacts of the accident. Ultimately, these data were used to focus the scope of the ecological model, specific to the MS Sound/Bight for initial model customizations (eventually, the ecological model will be broadened to include the Barataria and Perdido Bay sites as well).

After careful review of the available hydrodynamic models available for the MS Sound/Bight region-of-interest, FVCOM was selected as the physical model to which the EM would be coupled. Based on power, scalability, and ease-of-use, the Fulford et al. (2010) Trophic Simulation Model (TroSiM) was selected as the ecological model for the MS Sound/Bight region.

Model Parameterization (Completed)

In order to limit the scope of the ecological model to the primary IEA/EAM objectives, it was determined that TroSiM would focus on two broad questions: 1) impacts of the DwH oil spill on fisheries production; and 2) impacts of the DwH oil spill on nearshore trophic structure. To this end, the modeling approach involved three main components:

1) Food web component – the existing TroSiM model would be optimized to contain only those functional groups germane to the initial simulation and calibration steps, offering dynamical food web interactions within MS Sound/Bight habitats, focusing primarily on the oyster reef habitat as the initial test case.

2) Hydrodynamic/water quality component – the existing FVCOM model grid, boundary conditions, and hydrodynamic code for the MS Sound/Bight region would be utilized to produce estimated flowfields (and other pertinent physical forcings), all of which shall be coupled to the ecological model.

3) Fisheries component – an addendum to the food web component, to allow for commercial fishing pools as a mortality source for fishable functional groups. Ultimately, this component will be driven by social-economic factors and shall therefore provide the linkage point to larger Earth Systems Models (in the future).

Within the model architecture of TroSiM, a wide variety of competition parameters and diet matrices required definition and quantification for each functional group selected within the model simulation. This is an extremely time-intensive exercise, as regional data or literature values must be used to quantify each competition parameter, specific to each exemplar or each functional group within the simulation, using values in keeping with the regional context (*e.g.* the temperature-dependent growth rate for the Eastern Oyster, *Crassostrea virginica*, may differ significantly between the MS Sound and Chesapeake Bay). Notwithstanding, the parameterization of the following functional groups, selected for customization within TroSiM, has been completed:

- Phytoplankton (3 exemplars)
- Periphyton (1 exemplar)
- Submerged Aquatic Vegetation (1 exemplar)
- Emergent Plants (1 exemplar)
- Zooplankton (3 exemplars)
- Zoobenthos (Eastern Oyster + 2 additional exemplars)
- Pelagic Omnivorous Fish (3 exemplars)
- Pelagic Piscivorous Fish (1 exemplar)
- Benthic Omnivorous Fish (2 exemplars)
- Heterotrophic Bacteria (1 exemplar)

Workshop/Conference 2: Model Refinement (Completed)

The goal of Workshop/Conference 2 was to provide an initial presentation of the TroSiM model structure and to obtain feedback from workshop/conference participants that was used to refine and verify the model structure. This workshop/conference was conducted at the Northern Gulf Institute (NGI) Headquarters at Stennis Space Center, MS on 30 July 2012 and was attended by a subset of attendees from Workshop/Conference 1, as well as the core IEA/EAM team and members of the DwH oil-spill research community. Feedback from Workshop/Conference 2 was used by the IEA/EAM team to further refine model structure, model output, and model input to maximize the integration of current research with model-based analyses to assist with final model refinements.

Workshop/Conference 3: Model Validation (tentatively scheduled for late September 2012)

During the model validation phase of this investigation, TroSiM shall be used to address the probable impacts of the DwH oil spill (Table C-4), such as: 1) trophic perturbations caused by functional group mortality due to oil exposure; 2) alteration in marine microbial processes particularly due to the assimilation of petroleum-based carbon; 3) habitat loss and redistribution of important ecosystem component species; 4) recruitment impacts in apex predators caused by exposure of early life stages to surface oil; and 5) cascading effects of the near absence of fishing mortality during the summer-fall of 2010.

The goal of Workshop/Conference 3 will be to obtain feedback on model output associated with the primary drivers identified at the Workshop/Conference 1. The model framework will be close to completion at this point and the focus will be on input/output data. Discussion of input data will be intended to complete a data inventory and data pedigree with the objective of identifying key data gaps for future work. Discussion of output data will be intended to judge output utility for understanding ecosystem responses to the oil spill and to further refine output to increase this utility. The outcome of Workshop/Conference 3 will be a close-to-functional model that incorporates both new data on the DwH oil spill, as well as existing peer-review research on ecological impacts of oil spills in other regions. This workshop will be attended by the core NGI Eco-Modeling Group, as well as by modelers and members of the management community that represent potential end-users of the model. Their collective input will provide both technical and practical advice on the model structure and output that will be used to further refine the model for future applications of TroSiM.

Table C-4. Example list of probable drivers of oil spill impacts matched to hypothesized ecological outcome and a resulting model relationship.

Candidate drivers	Probable ecosystem impact	Model relationship
Oil induced population mortality	Trophic disruption	Functional group response to oil exposure based on toxicity assays; field work
Enhancement of microbial processes	Decreased carbon cycling; bottom-up trophic enhancement ;hypoxia	Include oil-based carbon as a food source in the model with factors for bioavailability based on dispersant use
Habitat loss (coastal; deep water)	Longer –term reductions in productivity; redistribution of predators	Multi-year effects of sub-optimal habitat based on habitat quality sub-modeling
Reductions in primary productivity	Regime shifts in secondary consumers; loss of productivity	Alterations of food web base and bottom-up effects
Recruitment limitation in 2010	Year-class loss; reduced prey base in coastal food web in 2010	Alteration of biomass in early-life sub-pools and examination of trophic connectivity of sub-pools
Freshwater diversion	Bivalve mortality; habitat alteration	Oyster reef mortality based on sub-model of salinity impacts on oyster reef community.
Boom/barrier deployment	Reduced productivity edge effects	Spatial component of core model to examine key issues such as coastal emigration.
Dispersant use	Transmission through the food web, toxicity	Results of toxicity assays and oil distribution maps used to structure mortality functions.

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Appendix D: Perdido Bay

Integrated Ecosystem Assessment/Ecosystem Approach to Management – Report Phase II

By Just Cebrian and Bart Christiaen, Dauphin Island Sea Lab

Introduction

Perdido Bay is a shallow estuary that lies on the border between Florida and Alabama. On the southern edge, Perdido Bay is connected to the Gulf of Mexico through Perdido Pass and the Intracoastal Water Way, which links Lower Perdido Bay with Big Lagoon and Mobile Bay. On the northern edge the bay is fed by the Perdido River, which drains an area of 3000 km^2. Perdido Bay is approximately 50 km long, has an average width of 4 km and is on average 2 m deep. Perdido Bay is impacted by several anthropogenic stressors, including increased shoreline and watershed development, stormwater run-off, septic tanks, effluent from waste water treatment, industrial discharges, agriculture and silviculture.

Despite its relatively modest size (approximately 130 km^2), Perdido Bay encompasses a wide range of habitats, each of which is impacted differently by anthropogenic stressors. The bay can be divided into 3 distinct geographic regions: Upper Perdido Bay (north of the bridge of route 98), Middle Perdido Bay (between the bridge and Inerarity Point) and Lower Perdido Bay, which includes the areas around Ono Island and Perdido Pass. These regions are fringed by a series of bayous and lagoons, each with varying degrees of anthropogenic disturbance. Lower Perdido Bay is highly developed and receives significant amounts of stormwater run-off. It is also the part of the bay with the highest salinity, as it is closest to the Gulf of Mexico. Perdido Pass has a relatively good water quality compared to the rest of Perdido Bay. This allows for the presence of patchy seagrass beds in the shallow areas near Ono Island and Big Lagoon. Middle Perdido Bay includes the deepest parts of the estuary. This area is often strongly stratified, especially during periods of increased precipitation, when the lighter fresh water from run-off and river discharge overlays the heavier, more saline water from the Gulf. The deeper parts of Middle Perdido Bay can become hypoxic when stratification is strong and water temperatures are high. The upper parts of Perdido Bay are less developed, but receive significant amounts of run-off from agricultural activities in nearby Baldwin County (AL). Upper Perdido Bay receives nutrients from a couple of point sources, including a paper mill which discharges into the bay through Elevenmile Creek and a sewage treatment plant which discharges through Bayou Marcus Creek. This area is more susceptible to phytoplankton blooms than the other parts of the bay.

The small bayous and lagoons surrounding Perdido Bay are very different in their physiochemical characteristics and size. Some of these systems, such as Tarkiln Bayou and State Park lagoon, are relatively pristine. They contain submerged aquatic vegetation and are surrounded by significant amounts of maritime forest and/or salt marsh. Others, such as Kees

Bayou and Ingram Bayou are moderately impacted by either stormwater run-off or fertilizer. They still retain many characteristics from the healthy sites, such as fragmented seagrass beds or fringing marsh vegetation. Some bayous and lagoons are severely impacted by stormwater run-off, shoreline modification and fertilizer from golf courses or agriculture. Examples of these heavily impacted sites are Gongora, Weekly Bayou and Bayou Garcon.

During the last 50 years, the area surrounding Perdido Bay has experienced rapid growth in the human population and a dramatic increase in development. This trend is still ongoing. Between 2000 and 2010, the population in Baldwin County has increased by 30% and the populations in the cities of Gulf Shores and Orange Beach, which are located near Lower Perdido Bay, have increased by 93% and 44% respectively. The increasing development of the watershed and the negative environmental impacts that follow are a serious concern for management. The construction of houses, condominiums and marinas has greatly increased the amount of impervious cover, which results in increased stormwater run-off. This usually leads to increased turbidity, higher nutrient concentrations, decreased water quality and eventually loss of seagrass.

Perdido Bay was selected as a representative system for generating an Integrated Ecosystem Assessment (IEA) for the Gulf of Mexico. In a preliminary report, we identified pressures and drivers for IEA based on a 10 year dataset collected in three shallow coastal lagoons surrounding Perdido Bay. In this report, we will extend the driver and pressure analysis to the entire Perdido Bay, and provide data to develop indicators that reflect ecosystem attributes specific to Perdido Bay. In order to do so, we will start at small spatial scale (coastal lagoons) and work our way up to the entire Perdido Bay.

Bayous and Lagoons

Over the past 10 years, we have been studying the impacts of human development in 3 shallow coastal lagoons in the Perdido Bay area: State Park, Kees Bayou and Gongora. While these lagoons connect to the same body of water (Lower Perdido Bay) and experience similar tidal cycles, each is impacted differently by human activities (Figure D1).

State Park (30.308° N, 87.403° W) is our most pristine site. This lagoon is located in Big Lagoon State Park, and is entirely surrounded by salt marsh and maritime forest with no residential development. The bottom is more than 60% covered by patches of shoalgrass (*Halodule wrightii*), interspersed with shoots of widgeon grass (*Ruppia maritima*) and turtle grass (*Thalassia testudinum*). The lagoon has a surface area of 22659m², an average depth of 0.4m and is connected to Big Lagoon Sound through a substantial gap in a sandbar. The lagoon is also connected by a small channel to a brackish lake surrounded by marshes. During high rainfall events the lagoon receives pulses of high dissolved organic matter (DOM).

Kee's Bayou (30.310° N, 87.469° W) is more impacted by human influences as compared to State Park. This lagoon is surrounded by houses and a road on the northern and the eastern sides, while the southern and western sides are bordered by salt marsh. The lagoon has a surface of 30208 m², an average depth of 0.47 m and is connected to Big Lagoon Sound by a narrow channel that passes through a neighboring lagoon. The bottom of the lagoon is covered with a small patch of shoalgrass (less than 5%) which, over the years, has been increasingly surrounded by a sizable bed of widgeongrass (up to 25%, but highly variable). This lagoon has a sandy bottom layer that is usually covered by finer sediments. These sediments are easily stirred up, which leads to adverse conditions for seagrasses (through increased turbidity). This lagoon is bisected by a channel, and is periodically dredged.

Gongora (30.305° N, 87.424° W) is our most impacted site. This narrow lagoon is bordered by houses on the northern and eastern sides, and fringed by salt marsh on the southern and western sides. The northern tip of the lagoon is connected through a small culvert to an 18-hole golf course. The lagoon has a surface of 9841 m², an average depth of 0.48m and is connected by a small channel to an adjacent lagoon. The bottom of the lagoon is bare, and the sediment ranges from sandy (at the mouth) to muddy (at the northern end). The lagoon is frequently dredged, and over the years, the entire eastern shoreline has been replaced by bulkheads.

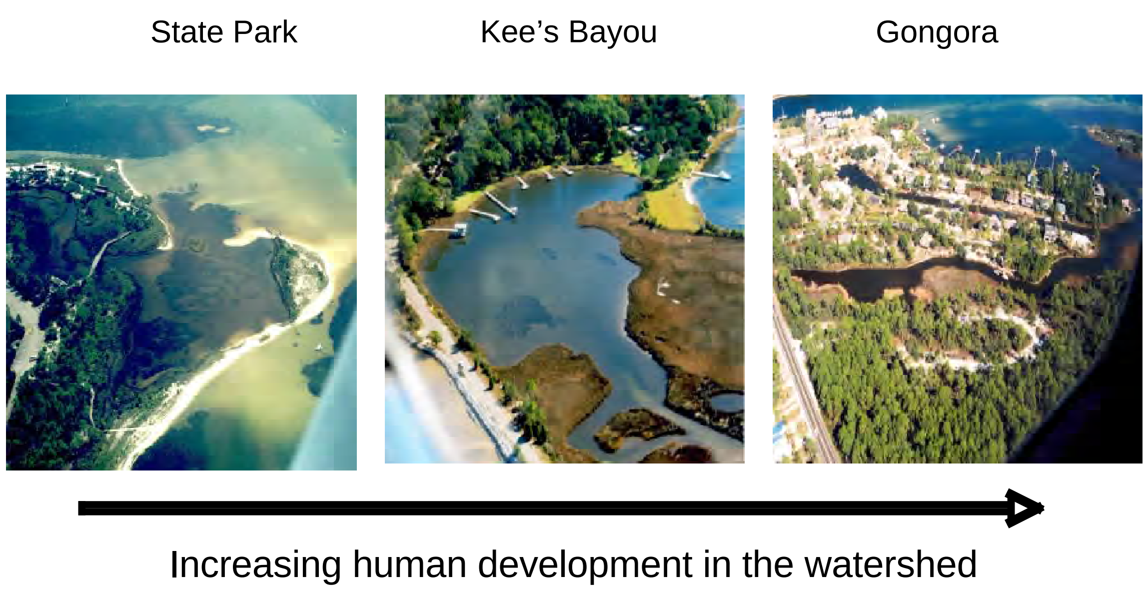


Figure D1: Watershed development in the 3 lagoons studied

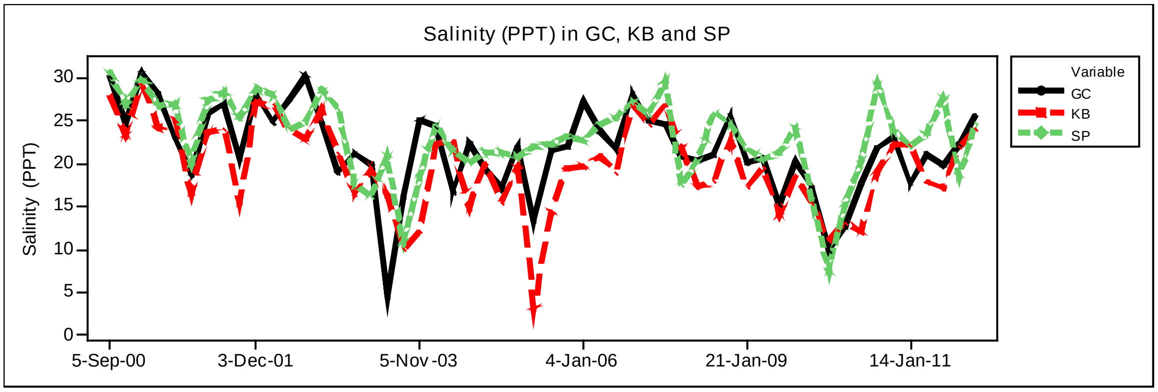
Methods:

We sampled 45 times from October 2001 to April 2012. During each round of sampling, all three lagoons were visited within a 10 day period. We only sampled on days with cloud cover of less than 10 percent to be able to compare incubations for community metabolism among sites. At each site, we measured rates of benthic daytime net primary production, gross primary production and community respiration, in both seagrass patches and bare sediment. In addition, we collected measurements of producer biomass (seagrass aboveground, seagrass belowground and benthic microalgae measured as chlorophyll), secondary production (biomass of benthic invertebrates), refractory organic matter (detritus > 0.5 mm diameter), environmental parameters (average water depth, temperature, salinity, %DO in the water column), water quality parameters (nutrients, particulate organic matter and light attenuation in the water column) and meteorological data (wind speed, wind direction, seasonal changes in PAR and precipitation, from the weather station at Pensacola NAS).

Results:

State Park, Kees Bayou and Gongora are connected to Lower Perdido Bay, and have similar physical characteristics. This is illustrated by the time series of salinity and temperature in Figures D2A and D2B. These results are not surprising as all three lagoons are equally shallow, have a similar tidal regime and are located relatively close to each other. Despite these similarities, the lagoons are quite different in their biogeochemical characteristics. State Park has significantly lower nitrogen load as compared to Kees Bayou and Gongora (4.2 kg N Ha^{-1} y^{-1}, compared to 25.7 kg N Ha^{-1} y^{-1} and 27.7 kg N Ha^{-1} y^{-1} respectively). This difference in nutrient loading results from the gradient in intensity of watershed development between the lagoons. Although the nutrient loading is significantly different among the sites, there is no difference in average DIN concentration (Figure D3B). Most likely, the majority of inorganic nutrients are rapidly assimilated by resident communities of primary producers, which results in the consistently higher chlorophyll concentrations in Gongora, our most impacted site (Figure D3A). The higher chlorophyll and higher particulate organic matter in the water column of Gongora cause more light attenuation, which prohibits the establishment of seagrass at this site. These factors profoundly alter the ecological functioning, metabolism and nutrient cycling in Gongora.

State Park and Kees Bayou receive significantly different nutrient loads but nutrient and chlorophyll concentrations are very similar between these sites. However, benthic communities are very different. Our results indicate a long term decline in seagrass biomass in the vegetated areas of State Park and Kee’s Bayou (Figure D4A). This decline was most pronounced in State Park. The decline in seagrass biomass did not result in a reduction in areal coverage in either site. In Kees Bayou the seagrass bed even increased in size. This was likely due to a change in the dominant seagrass species, from shoalgrass to widgeongrass. The widgeongrass bed in Kees Bayou appears to change on a seasonal basis: during winter the grass disappears almost completely, only to reappear and completely overgrow the water column during the warmer periods of the year.



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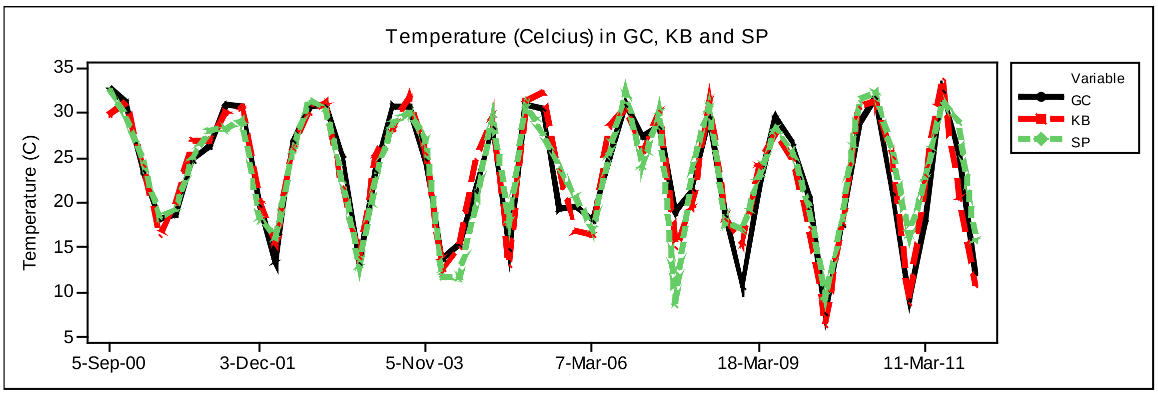

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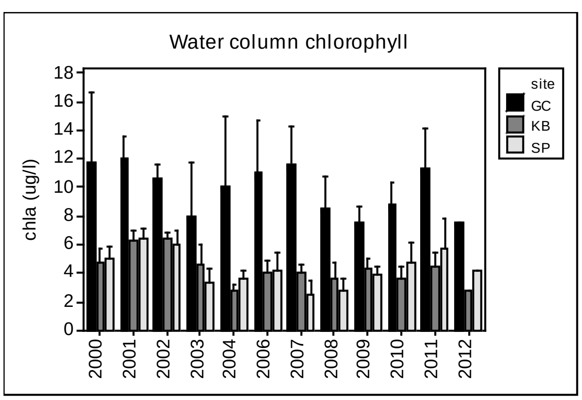
Figure D2: Temperature and salinity follow similar patterns in each of the lagoons.



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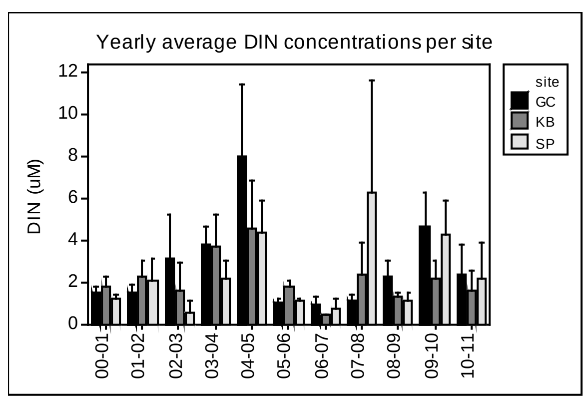
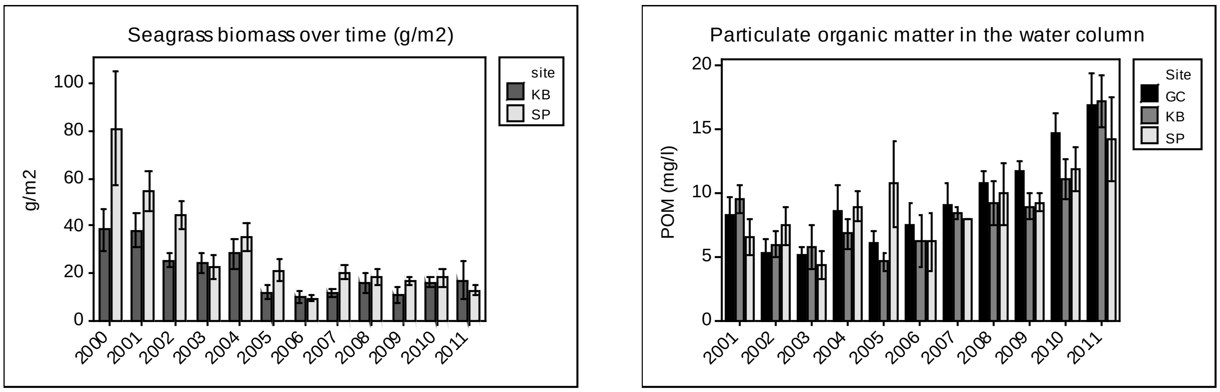


B

Figure D3: Although there are no significant differences in DIN concentrations between the sites, water column chlorophyll is consistently higher in Gongora, the most impacted site.

The shoalgrass bed is perennial, both in State Park and Kees Bayou. Shoalgrass has a more robust system of roots and rhizomes and easily survives the colder months. The decline in seagrass biomass from 2000 to 2010 is coincident with a relatively large increase in human population in the neighboring towns of Orange beach and Gulf Shores. It also corresponds with a gradual increase in particulate organic matter in the water columns of each lagoon (Figure 4B).

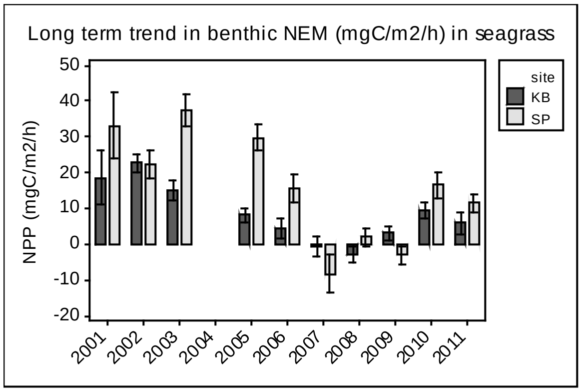


A

B

Figure D4: A gradual decrease in seagrass biomass over time in both State Park and Kees Bayou correspond to an increase in particulate organic matter in the water column in each lagoon. Error bars = 1SE.

There is a long term pattern in benthic net ecosystem metabolism (NEM) in both the seagrass beds from Kees Bayou and State Park (Figure D5A). NEM is the net effect of production and respiration for all biological components in an ecosystem. A positive NEM indicates that the system is autotrophic, which means that the combined photosynthesis rate of all biological components exceeds the community respiration rate. A negative NEM is an indicator of a heterotrophic system, where community respiration exceeds in-situ primary production. Our measurements of benthic NEM represent a theoretical maximum rate because we measured at optimal conditions (clear skies, daytime measurements only).



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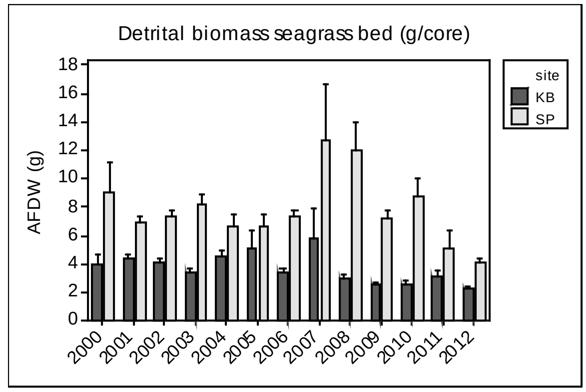


B

Figure D5: patterns in NEM and detrital biomass in the seagrass beds of State Park and Kees Bayou. Error bars = 1SE.

Daytime benthic net ecosystem metabolism (benthic NEM) declines from 2001 to 2007, and slowly starts to increase from 2008 to 2011. The decrease in benthic NEM does not overlap well with the decline in seagrass biomass. However, there seems to be an inverse relationship between benthic NEM and the amount of detritus in the sediment in State Park (Figure D5B). Benthic NEM might also be influenced by meteorological forces, since years of high NEM seem to correspond with years of higher river discharge in the Perdido River.

Conclusion:

The gradient in human disturbance over the three lagoons has a clear impact on ecosystem functioning. Seagrass cannot establish itself in Gongora, while the seagrass bed in Kees Bayou has wildly different characteristics from the seagrass bed in State Park. In addition, there seems to be a long-term trend in seagrass biomass and metabolism, which is partly caused by more intense shading over time. This indicates that there could have been an increase in stormwater run-off, associated with the increase in human population in the areas surrounding the lagoons (Gulf Shores and Orange Beach). The interannual decline in benthic NEM in the seagrass beds of State Park and Kees Bayou is an indication that the carbon metabolism of these seagrass beds has changed over the years. It is not clear if this is a function of human disturbance (increased human population) or natural variability (interannual changes in precipitation and river discharge). Most likely, meteorological forcings and anthropogenic disturbances are compounding factors influencing submerged aquatic vegetation and benthic metabolism in shallow coastal lagoons.

Extrapolation to larger spatial scale

Because of their relatively low flushing rates and proximity to land, small embayments are potentially more vulnerable to excessive inputs of nutrients and organic matter than the larger bodies of water they are connected with. So if our goal is to extend the driver and pressure analysis to larger spatial scale, we need to detect if:

- Shallow embayments and lagoons are more impaired in water column quality compared to the larger bodies of water they are connected with;
- There are differences in the degree of impairment between three embayments with different degrees of anthropogenic disturbance and different flushing rates;
- Shallow embayments react faster and more intense to changes in the watershed than the bodies of water they are connected with.

Methods:

In order to answer these questions, we set up permanent monitoring stations inside and outside the three lagoons from the long-term monitoring project (State Park, Gongora and Kee's Bayou). The distance between each pair of stations is approximately 100 m. These stations are sampled on a bi-monthly basis. Each sample event consists of a ten-day deployment of a YSI-6600 within and outside the embayment, combined with 12 additional water samples (3 replicate water samples within and outside the embayment at the start and the end of each deployment). Specific parameters we measure include temperature, salinity and DO (YSI-6600), light attenuation (LICOR), dissolved and particulate nutrients, total suspended solids, chlorophyll and abundance of heterotrophic microbes in the water column. These parameters function as a proxy for habitat quality for primary producers within the lagoons. Sampling for this component of the project started in July 2011 and continued through summer 2012.

Results:

Our results indicate that the water columns in shallow bayous and lagoons have significantly different physical characteristics than the water bodies they are connected to. The temperature is generally higher, while dissolved oxygen concentrations are lower. These features are most pronounced during summer. They are likely the consequence of lower flushing rates and increased benthic-pelagic coupling. The oxygen concentration in these systems shows pronounced diurnal cycling. When the temperature is sufficiently high, the water column goes from super-saturation during daylight hours to completely hypoxic at night (Figure D6).

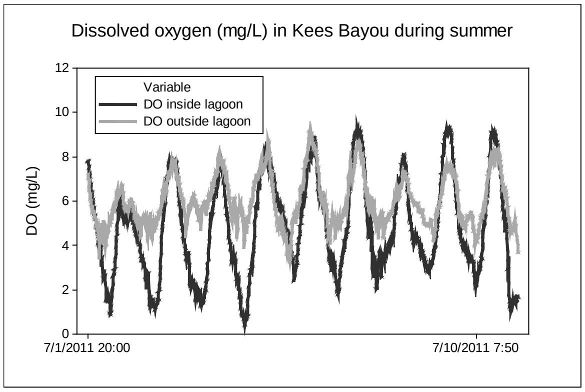
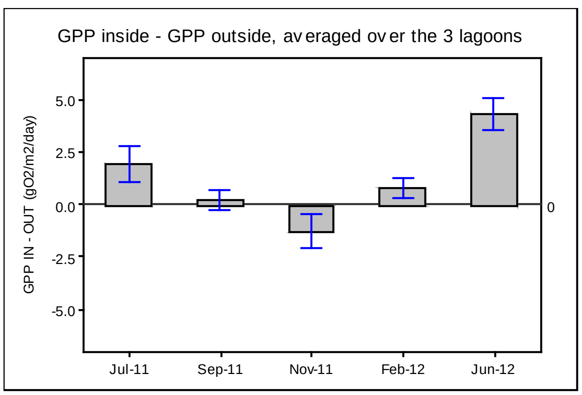


Figure D6: Dissolved oxygen concentrations in the water column in Kees Bayou during July 2011. Diurnal cycles of dissolved oxygen are more pronounced inside the lagoon.

These cycles occur in each of the lagoons, regardless of the degree in human disturbance. They are probably a natural feature of shallow lagoons along the NW Gulf of Mexico. The local fauna is most likely adapted to these short term shifts in oxygen concentrations.



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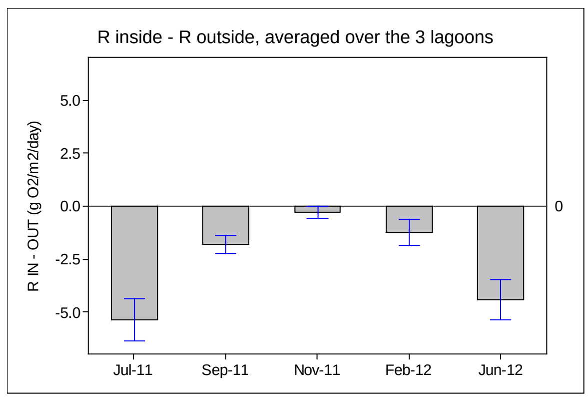

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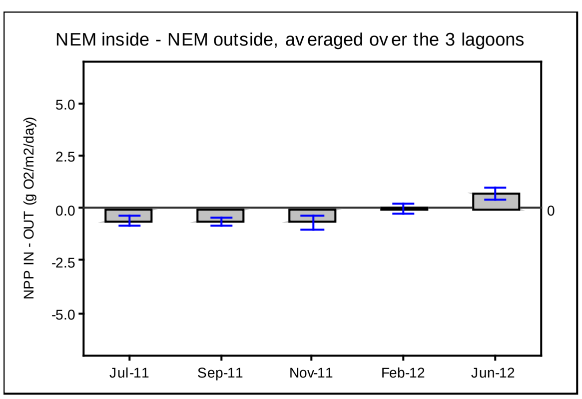
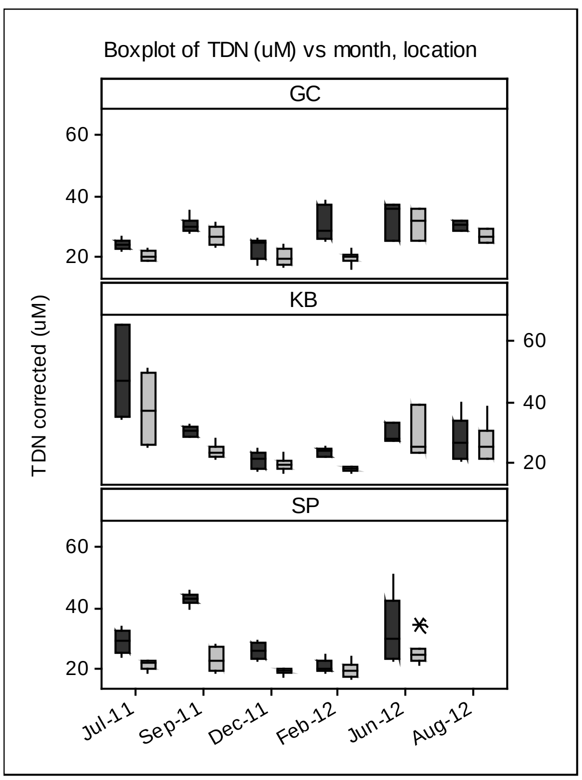


C

Figure D7: On average, there is more primary production (GPP) and respiration (R) inside than outside the lagoons during the warmer months of the year. This difference disappears during winter. Net ecosystem metabolism (NEM) is equal inside and outside the lagoons. Error bars = 1 SE.

The daily cycles of DO can be used to estimate ecosystem metabolism. When we compare ecosystem respiration (R), gross primary production (GPP) and net ecosystem metabolism (NEM) inside and outside the lagoons, we find that respiration (expressed as a negative flux) and gross primary production are significantly higher within the lagoons during the warmer months of the year (Figure D7). NEM is equal within and outside the lagoons. This suggests that there is more biological activity inside the lagoons, compared to their immediate environment, but that there is no difference in net production of organic matter.

Nutrient concentrations were always higher within each of the lagoons (Figure D8A). The magnitude of this difference varies over time, but the differences seem highest in Kees Bayou during summer and in State Park at the beginning of fall. Despite the differences between the lagoons and their immediate environment, there is no clear trend in nutrient concentrations between lagoons with different degrees of human disturbance. However, there is a trend in water column chlorophyll. Chlorophyll concentrations are highest in Gongora, the most impacted site (Figure D9A). This is consistent with the data from the long term monitoring project. These results suggest that nutrients are rapidly assimilated and end up in local populations of primary producers, such as phytoplankton, benthic microalgae and (in case of State Park and Kees Bayou) seagrasses and their epiphytes.



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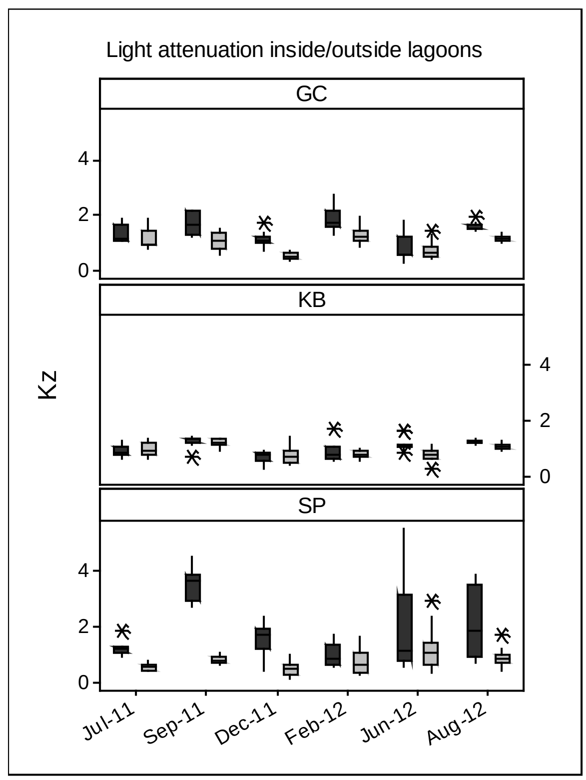
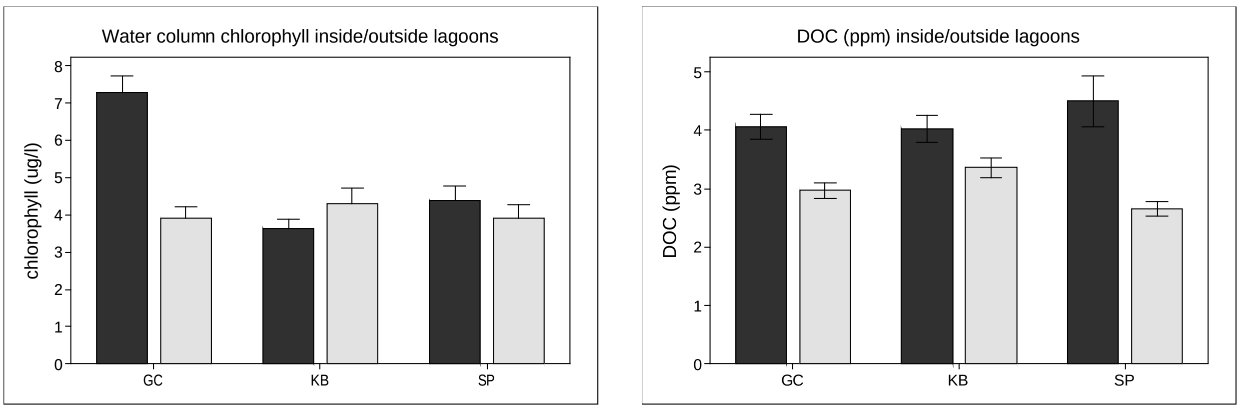


B

Figure D8: Total dissolved nitrogen (A) and light attenuation (B) inside (dark grey) and outside (light grey) the three lagoons in Lower Perdido Bay.

Dissolved organic carbon (DOC) concentrations were consistently higher within the lagoons (Figure D9B). The concentration gradient is most pronounced for State Park, the least impacted site. This is not surprising as seagrasses and salt marsh plants exude large amounts of labile organic carbon. During periods of high precipitation, State Park also receives significant amounts of tannins, which leach out from the surrounding maritime forest. During these periods, the water turns brown and attenuates more light. This is what caused the high light attenuation coefficient in State Park during September 2011, June 2012 and August 2012 (Figure D8B).



A B

Figure D9: Average water column chlorophyll concentrations (A) and average DOC inside (dark grey) and outside (light grey) each of the lagoons. Error bars = 1SE.

Conclusions:

Small bayous and lagoons are more likely to be impacted by increases in nutrient load, dredging and shoreline modification that the larger bodies of water they are connected with. Their water column is usually less transparent and often contains more chlorophyll, dissolved nutrients and DOC. These systems are highly dynamic: they respond very rapidly to anthropogenic disturbances. This makes them interesting sites for long term monitoring: small bayous and lagoons can serve as early indicators for changes in ecosystem health on larger spatial scales. For example: the decline in seagrass biomass in State Park and Kees Bayou (Figure D4A) could indicate that seagrass populations in Lower Perdido Bay are becoming vulnerable to the effects of the increasing human population in the cities of Gulf Shores and Orange Beach.

Perdido Bay

Up until 2012, most of our data was collected in Lower Perdido Bay. In order to extend our analysis of drivers and pressures to represent Perdido Bay as a whole, we conducted a literature study and started a survey of Upper and Middle Perdido Bay. We collect water samples at 4 stations along the length of Perdido Bay and in 6 bayous surrounding Middle Perdido Bay (Figure D10). We sample these stations on a seasonal basis from spring 2012 to winter 2012. Specific parameters we measure include temperature, salinity and DO (Hach 40d), dissolved and particulate nutrients, DOC, total suspended solids, chlorophyll and abundance of heterotrophic microbes in the water column.

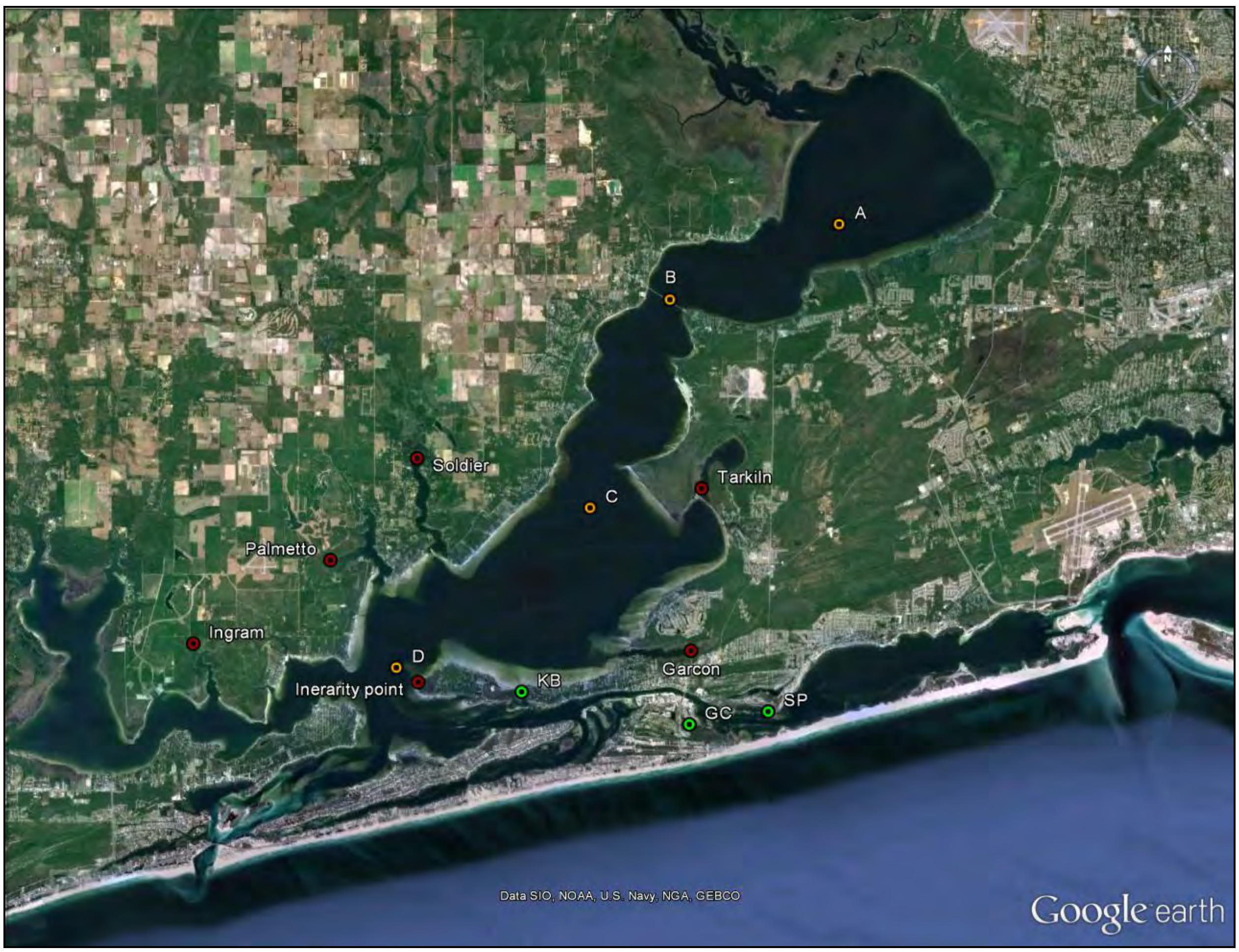
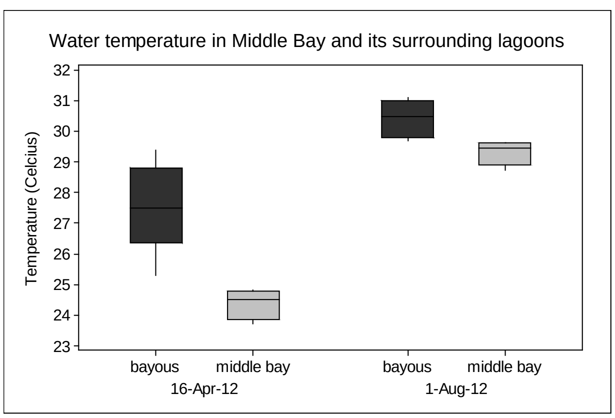


Figure D10: Sample sites for the Perdido Bay survey. Sites A, B, C and D are sampled at 0.5 m depth and near the bottom of the water column. The other sites are sampled in the middle of the water column since they are shallow and well mixed.

Preliminary results:

Results from April 2012 and August 2012 show stratification in the lower parts of the bay: there was a distinct halocline at sites B, C and D. However, in station A the water column is shallower and well mixed. There was also a horizontal gradient in salinity, ranging from 9.0 PPT in Upper Perdido Bay to 29.1 PPT near Inerarity Point. The water temperature was more or less homogeneous throughout the bay. However, there was a distinct difference in water temperature between the bay and the smaller bayous and creeks (Figure D11A). The differences were more pronounced during spring, indicating that the water in the smaller bayous and creeks warms faster than the water in the Bay. The higher temperature in the water column of the small bayous has the potential to increase microbial respiration, which will make these sites prone to strong diurnal shifts in oxygen concentration. This corresponds with the data from the spatial extrapolation of State Park Lagoon, Gongora and Kees Bayou.

The upper parts of the bay had higher concentrations of chlorophyll (Figure D11B) and DOC compared to the lower parts of the bay. The elevated chlorophyll concentrations were more than likely the result of nutrient rich effluent discharged through Elevenmile Creek and/or Bayou Marcus. Another potential source of nutrients for Upper Perdido Bay is agricultural run-off that enters the bay through the Perdido River.



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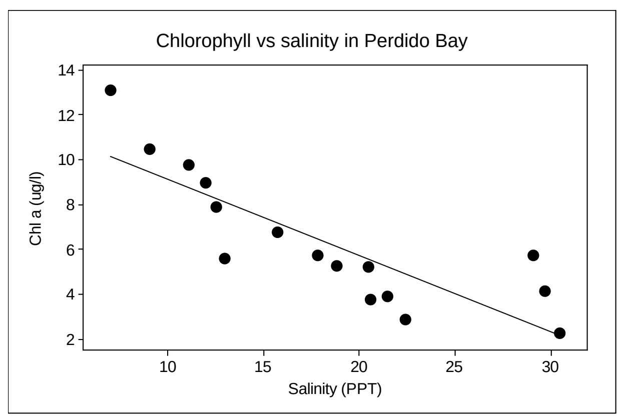
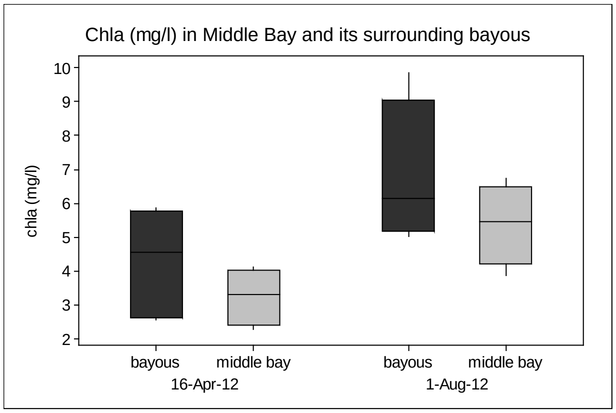


B

Figure D11: There was a difference in water temperature between Perdido Bay and its surrounding bayous; the difference was larger in spring (A). Preliminary results reveal a significant correlation between salinity and chlorophyll throughout Perdido Bay (B).



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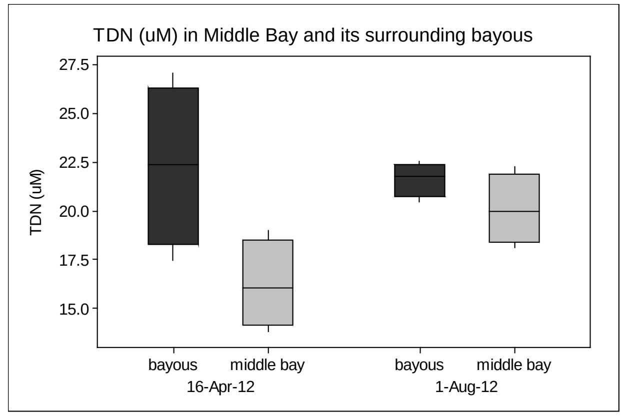

B

Figure D12: There was a difference in water column chlorophyll (A) and total dissolved nitrogen (B) between Middle Perdido Bay and its surrounding bayous.

Chlorophyll concentrations in the small bayous surrounding Perdido Bay were slightly elevated compared to Middle Bay, especially in Bayou Garcon, Bayou Ingram and Soldier Creek (Figure D12A). Total dissolved nitrogen was also higher in the bayous than in Middle Perdido Bay (Figure D12B). These results correspond with the data from the spatial extrapolation of State Park Lagoon, Gongora and Kees Bayou. Small bayous and lagoons are in close contact with the land and proportionally receive more runoff than the larger bodies of water they are connected with. Because of the relatively low flushing rates, local phytoplankton populations are able to utilize a large fraction of nutrients that are coming into these systems, which enables them to maintain a higher biomass than the phytoplankton populations in the bay.

Analysis of drivers and pressures for Perdido Bay

Regardless of the spatial scale of our analysis, the majority of pressures on the ecosystem in Perdido Bay are driven by “human-related processes”. Increased nutrients, increased pollution and altered riverine input are the dominant pressures in Upper and Middle Perdido Bay. Increased urban and coastal development is the most important pressure for the individual lagoons and the lower part of Perdido Bay. In certain bayous, increased dredging can be another pressure of importance. In Upper Perdido Bay, increased nutrients and increased pollution are driven by trade/industry (and agriculture). In Lower Perdido Bay, these pressures are mainly driven by the increasing size of the local population and tourism/recreation. Increased boat traffic and increased fishing are important pressures for the seagrass beds in Lower Perdido Bay. The seagrass beds in this area are usually found in very shallow water and are therefore prone to prop scars. This pressure is driven by tourism/recreation, since local people are aware of the location of seagrass beds.

There are two pressures that are driven by climate related processes in Perdido Bay. Altered riverine discharge is mostly a function of interannual variability in precipitation. The amount of discharge from the Perdido River has a direct impact on stratification in Middle Perdido Bay, and can be conducive to the development of hypoxia near the bottom of the water column. The effects of river discharge can be felt all the way down in Lower Perdido Bay. The long term dataset in the small lagoons illustrates that during peak flow, the salinity in the small lagoons in Lower Perdido Bay can drop to less than 5 PPT. Extreme weather events can drive critical habitat degradation. Hurricanes have a negative impact on water quality by increasing stormwater and sewage run-off through flooding and high levels of precipitation. However, the decrease in water quality is only temporary, and the long-term impact on seagrass beds is probably negligible compared to other (human related) pressures. Extreme events can also degrade marsh habitat through erosion. This seems to be of minor importance in Lower Perdido Bay, since the majority of salt marsh has been destroyed by development. The wetlands in Middle and Upper Perdido Bay are more sheltered and therefore better protected against the effects of erosion.

Table 1. Updated Analysis of Drivers (Columns) and Pressures (Rows) for Perdido Bay (P)

PRESSURES	DRIVERS									
	Hydrologic Modifications			Climate			Human-Related Processes			
	Exploration & navigation canals	Flood levee & dam construction	Freshwater diversion	Sea Level Rise/Subsidence	Extreme Weather Events	Variability	Local Population Size	Trade/Industry	Socio-Political-Educational Perceptions	Tourism/Recreation
Altered riverine input						P				
Increased nutrients (point and non-point)							P	P	P	P
Increased pollution (point and non-point)							P	P		P
Increased dredging							P			
Increased fishing effort										P

PRESSURES	DRIVERS									
	Hydrologic Modifications			Climate			Human-Related Processes			
	Exploration & navigation canals	Flood levee & dam construction	Freshwater diversion	Sea Level Rise/Subsidence	Extreme Weather Events	Variability	Local Population Size	Trade/Industry	Socio-Political-Educational Perceptions	Tourism/Recreation
Increased boat traffic (wakes, grounding, and anchoring)										P
Increased urban/coastal development							P		P	P
Critical habitat degradation					P					