Galveston Bay Ecosystem Model Phase 1

Final Report

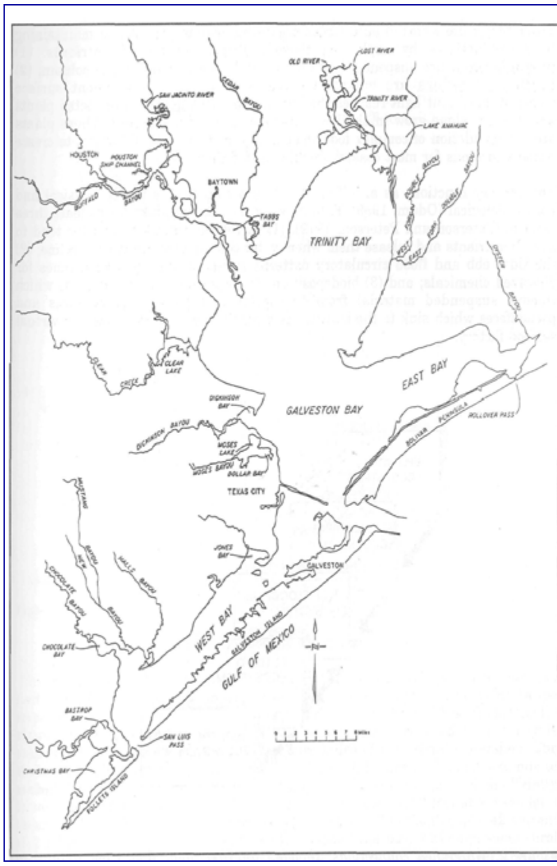
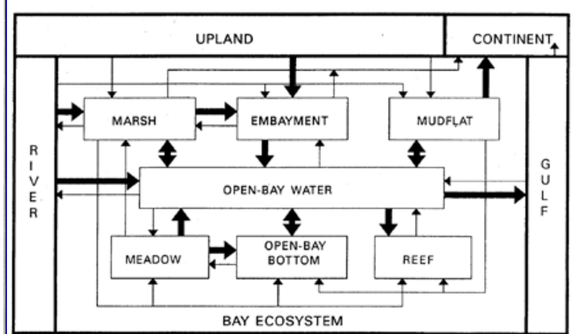
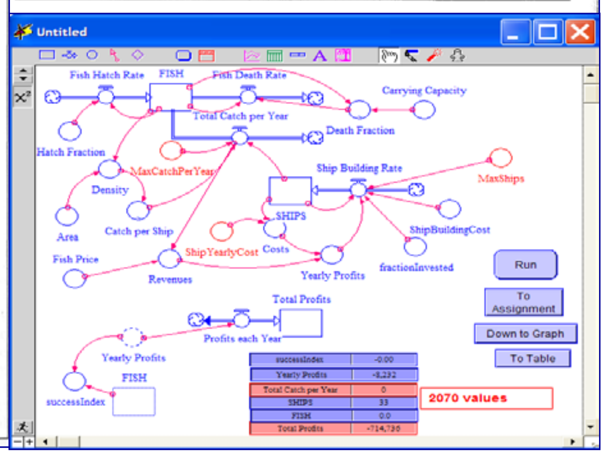


Figure 7. The import-export relationships between habitat components of the bay ecosystem and adjacent ecosystems. Major material flow is shown by a heavy line, moderate flow by a thin line; minor flows have been omitted.





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Executive Summary

The objective of the Galveston Bay Ecosystem Phase 1 project was to begin the process of developing an ecosystem modeling toolkit for Galveston Bay by working through a "mediated" modeling approach using an expert panel of participants who assisted in the development of 1) key resource management questions that need to be answered, 2) reviewing and updating a conceptual model of Galveston Bay to insure that it incorporates critical processes that are linked to these questions and 3) identify critical data gaps and information needs that need to be addressed in order to populate future model parameters and address data requirements, and 4) evaluating the suitability of existing models as tools to accomplish future modeling projects and informing management decisions.

The Environmental Modeling Workgroup (EMWG) was established to accomplish the four goals outlined above. In addition, the EMWG was established to 1) provide a forum for GBEP to evaluate current and ongoing ecological modeling projects, 2) develop questions for model interrogation based on best available science and conceptual models, 3) determine the need for future modeling projects and support to address the information needs of GBEP and partner organizations and 4) identify and help secure funding and resources to produce, maintain and modify modeling tools in support of management goals.

The EMWG held three workshops. Direct benefits of this project included a better understanding of the need to develop ecosystem models that can be used to evaluate processes and stressors affecting important natural resources of Galveston Bay. The EMWG was able to prioritize several potential modeling projects that are were needed to address critical resource management questions and needs. Notable accomplishments brought about by this process include the following:

1. Establishment of the Ecological Modeling Work Group – EMWG.

The group can serve as an ongoing informal workgroup of the GBEP that will recommend, review and evaluate future modeling projects. Members of the group included members with expertise in modeling and/or use of models to evaluate management options. It is recommended that the group meet quarterly or as frequently as needed. The first meeting in 2011 will be held between January and April 2011.

2. Review and confirmation of the Galveston Bay conceptual model.

The EMWG met and reviewed the Galveston Bay conceptual model. In addition, other Texas estuarine models were evaluated including the "Corpus Christi Bay" model. Based on input from various members it appears that the conceptual model is still valid and describes the major processes within the estuary fairly well. However, as specific modeling projects evolve it may be necessary to fine tune or update certain components of the conceptual model or add finer details to meet project objectives.

3. Establishment of desirable traits of ecosystem models

Various desirable attributes of simulation models were discussed during the several workshops. The most desirable traits included reasonable accuracy (as measured against reality during validation process), parsimony (simplest model that predicts with reasonable accuracy best), applicability (Is it the appropriate model?), transparency (others can see logic and data input of the model, along with model calculations), and ability to be interface with other models to receive input or provide output. In addition, in order for end users to use these models, they must be affordable and user friendly.

4. A review of major types of modeling approaches and products available for ecosystem modeling.

Several types of modeling approaches and platforms were discussed during the project. These ranged from specialized models to general purpose systems models. Although we cannot advocate any particular modeling platform, several software packages that are currently being used by agency staff should be considered for future quantitative use due their wide availability, relatively low cost and ability to share input and output.

5. A review of current ecosystem modeling efforts within the Galveston Bay watershed.

During the workshops a variety of current and proposed modeling efforts were identified in the Galveston Bay watershed. The majority these efforts fell into three categories. These included 1) ongoing regulatory required TMDL and watershed water quality modeling (e.g. dioxin, bacteria, dissolved oxygen) on a segment by segment basis, 2) hydrological modeling associated with freshwater inflow studies, 3) experiment fisheries modeling (e.g. EwE) and 4) coastal climate change/flood modeling by NOAA and other organizations (e.g. SLAMM modeling).

6. Prioritization and identification of ecological modeling projects.

Considerable effort was placed on developing a priority list of potential ecological modeling projects. This was a very difficult but essential task for the group. Due to the diversity of backgrounds and missions of some members affiliated organizations the list of topics was diverse. However, after multiple criteria the list was shortened to 2-3 main topics. The criteria that was used included 1) management need, 2) feasibility of accomplishment, 3) importance of the resource to the functioning of the Galveston Bay ecosystem, 4) complexity of the task and possibility of local/regional management intervention, 5) availability of modeling approaches and 6) whether any organization was conducting or would likely conduct such a modeling effort in the near future. The three priority modeling project areas selected for further consideration included:

1. Oyster Ecology and Reef System Modeling
2. Habitat alteration (terrestrial and wetland) and effects on Galveston Bay
3. Interaction of Climate Change with 1 & 2.

Based on the results of three workshops and efforts of the EMWG, it is strongly recommended that continued efforts are needed to pursue the development and production of proposed ecosystem based models recommended in this report. The recommended modeling projects are feasible based on available data and literature. These modeling projects would generate useful forecasts for management agencies, identify possible mechanisms by which resources are influenced, and help direct future research and monitoring. The eventual production of the proposed ecological models will help determine the critical pathways and processes that influence the important resources of Galveston Bay. These models will in turn will help guide and prioritize future monitoring and research. Creating an ecosystem model for one or more the priority project identified will assist GBEP in defining and attaining Galveston Bay Plan goals including protection of critical resources such as wetlands, important fisheries and improving water quality. Once set up, these models can also be used to evaluate future proposed scenarios involving multiple stressors including the projected changes in sea level and land use, and resulting impacts on critical resources such as freshwater inflow, water quality, wetlands, oyster reefs, fisheries, and colonial waterbirds.

Acknowledgements

I would like to thanks the members of the Environmental Modeling Work Group (EMWG) who contributed many hours to this effort and have agreed to continue working as members of the EMWG. I particularly thank Dr. Bob McFarlane who provided additional information and guidance regarding the Galveston Bay Conceptual Model he authored. This critical document served as the basis for this project and will likely also provide useful guidance during future ecosystem modeling efforts. Current members of the EMWG are listed in Appendix 1. The conclusions and opinions although developed with the input of the EMWG, primarily represent those of the author.

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Introduction and Background

Historical Use of Models

The management of environmental resources has relied on models as early as the 1920's. Simple models such as the Streeter Phelps Dissolved oxygen model have been used to model dissolved oxygen levels in streams and regulate the discharge of point source effluent (Schnoor 1996). Since then the complexity of management issues and needs have increased and include estimation and control of loading of conventional and toxic compounds from point and non-point sources, including air deposition, agricultural and urban runoff. In response to the complexity of these issues water quality models have increased both in complexity and scope and can now even deal with entire watersheds (Chapra 1997; EPA 2001; Singh and Frevert 2006). Recent modular modeling systems that incorporate geospatial data including watershed characteristics can also integrate the influence of pollutants that bioaccumulate in food chains (Clough 2009). In addition, a variety of water quality models have been developed to evaluate specific water quality issues including sediment loading, point source loads, heavy metals, with the frequent goal of estimating total maximum daily loads (TMDL)(Lung 2001). Most recently the EPA and National Research Council listed and reviewed water quality models (Committee on Models in the Regulatory Decision Process 2007; Wool 2010). Their list included various water quality models including AQUATOX, BASS, WRDB, WCS, LSPC, WAMView, SWMM, EPDRiv1, QUAL2K, CONCEPTS, EFDC and WASP. Most recently, the HGAC hosted a water quality modeling workshop where commonly used water quality models were reviewed (Petersen 2010). Some water quality models that have been used within the Galveston Bay watershed include LDC, BLEST, SELECT, HSPF, SWAT, SWMM, QUAL-TX/QUAL-2K, WASP, Tidal Prism/Box Model and EFDC. Common pollutants and processes simulated by these models include bacteria, conservative parameters, dissolved oxygen, nutrients, sediment, temperature, toxic compounds, and pesticides. Ultimately water quality models are dependent upon linkages with hydrodynamic models which simulate important physical stream, lake and estuarine processes including streamflow, tides, mixing and density stratification (Martin and McCutcheon 1999; Zhen-Gang 2008). For example oil and hazardous spill response models integrate the influence of marine currents, physical attributes and weathering processes to evaluate impacts from spills on natural resources (Guillen et al. 2004; NOAA 2006a; Texas General Land Office 2011).

Prior to the development of most environmental models, sociologists, economists, and natural resource managers had developed simple population models to evaluate the influence of limited resources on populations of single species. Some of the earliest attempts to develop explanatory models of animal population growth centered on the demographics of human beings. In 1798 English economist Reverend Robert Malthus in "An Essay on the Principle of Population" concluded that unchecked population growth would ultimately lead to poor environmental conditions for the existing citizens of a country (Malthus 1798). He concluded that without war or disease outbreaks overpopulation was inevitable due to limited resources including food unless proper steps were taken to reduce growth. At that time the British were in the process of conquering India and therefore sufficient evidence of impacts of overpopulation in that country supported his theories. The “Malthusian Model” was powerful. It was intensively debated since it generated dire predictions about the fate of mankind. Demographic models suddenly moved from an abstraction to concrete reality and attracted the attention of various related disciplines including economists and biologists. Economists used the model to show that the when the supply of labor is high the result will be lowered wages due to intense competition for economic resources. Charles Darwin incorporated the struggle for food into the centerpiece of his theory of evolution of species. Economists, life insurance companies, epidemiologists, and governments later modified these techniques to arrive at age and sex specific schedules of mortality. Demographic data (age, sex, deaths and births) was typically displayed in a life table which contained equations to calculate various age specific population parameters (e.g. death, birth). These were then used to calculate sex specific survivorship curves for various age groups.

The life table was introduced to ecologists in 1921 by Raymond Perl. (Pearl 1928) described three general types of survivorship curves which ranged from high to low juvenile mortality that was often correlated to parental care. Biologists and natural resource managers began the development of various simple population models early in the 1920’s to evaluate the influence of limiting resources on single populations. The two most basic population models including the density independent and dependent (logistic) models have served as the framework for much of the current population models that incorporate age or size specific data (Krebs 2001.).

(Russell 1931) recognized that a stock of fish (or wildlife) could be divided into animals of a size (or age) that is liable to capture (already recruited into a fishery) and those smaller (younger) than this limit. He also considered only complete stocks so that emigration and immigration were irrelevant. Russell (1931) focused on processes that would induce a gain in the population and what would lead to a loss. He summarized stock biomass dynamics as:

$$S_{t+1} = S_i + (A+G) - (C+M)$$

Where S_i is the stock biomass in year i, A is the sum of the initial weights of all individuals recruiting to the stock each year, G is the sum of the growth in biomass of individuals already recruited to the stock, C is the sum of all fish caught, and M is the sum of the weights of all fish die of natural causes during the year.

Ecosystem Modeling

For many years the management of wild populations of fish and wildlife has traditionally relied on modifications of Russell’s single species population models (Haddon 2001). Unfortunately, these approaches neglect the complex interactions of various trophic levels and changes in environmental conditions. (Haddon 2001) describes this more complex situation by including the physical and biological interactions of a single stock of fish (Figure 1). What was needed was a merging of environmental and biological processes into a comprehensive “ecosystem” model.

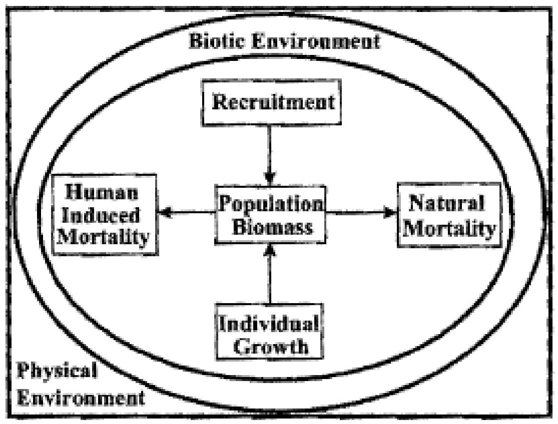

Figure 1. Interaction of single species stock with other organisms and the physical environment (from Haddon 2001).

For example, blue crabs play a key role in estuarine environments, supplying a critical food source to many inhabitants including the endangered species such as Whooping cranes. It is believed that blue crab populations may be adversely impacted by overfishing and/or reduced fresh water inflow. Therefore, predictive modeling tools are needed that can incorporate the often non-linear interactions inherent in ecological processes that may materialize as a result of management action. In recent years, several types of ecosystem models have been developed to accomplish the task of integrating the impacts of multiple stressors (Plaganyi 2007). Two notable approaches include EcoPath with EcoSim (EwE) and Atlantis modeling software packages developed for fisheries assessment.

In recent years, ecosystem modeling tools such as the EcoPath with EcoSim (EwE) ecosystem based stock assessment modeling tool have been developed that can characterize interactions between natural predator-prey systems and fishing pressure (Christensen and Walters 2004; Christensen et al. 2004). More recently EwE has added a spatial component Ecospace to evaluate loss of habitat and fishing sanctuary policy options. The model utilizes two master equations which it uses to conduct an ecosystem trophic mass balance analysis with a dynamic modeling capability for exploring past and future impacts of fishing and environmental disturbances as well as for exploring optimal fishing policies. This model focuses on the construction of marine food webs in order to evaluate the impacts of fishing pressure or other stressors on these trophic interactions.

The two master equations used by EwE are:

1) Biomass Term: Production = catches + predation mortality + biomass accumulation + net migration + other mortality

2) Energy Balance Term: Consumption = production + respiration + unassimilated food

Recent use of this model has demonstrated the utility of EwE in detecting less obvious implications of adoption of fishery regulations. For example, EwE predicted that reduction in red snapper shrimp trawl bycatch, may actually cause negative impacts on several valued species including Gulf menhaden, red drum, red snapper by allowing recovery of two competing catfish species including sea catfish and gafftopsail catfish (Walters et al. 2008).

Atlantis is another ecosystem model that considers all parts of marine ecosystems including biophysical, economic and social interactions. Originally focused on the biophysical world and then later fisheries it is now being used for multiple applications including addressing climate change questions and affects on fisheries (CSIRO 2010). Atlantis is a deterministic biogeochemical whole of ecosystem model. Its overall structure is based around the Management Strategy Evaluation (MSE) approach, where there is a sub-model (or module) for each of the major steps in the adaptive management cycle (Figure 2). Unlike EwE, Atlantis typically requires extensive amounts of environmental data and has a very steep learning curve. The NMFS Galveston laboratory hosted a workshop on this software during 2010. One of the members of EMWG, Mr. Glen Sutton, attended this workshop.

Similar ecosystem models like EwE and Atlantis are needed to evaluate fluctuations in fish and wildlife populations in estuaries due to the interaction of multiple stressors including fishing pressure and environmental fluctuations. Currently, the relative and cumulative influence of each of these factors on fish and wildlife survival is poorly understood. This lack of knowledge on interactions could translate into uninformed management decisions that may not access risk accurately. For example, it would unwise to reduce fishing pressure if the main factor affecting fish stock abundance is water quality, habitat loss or fresh water inflows. In addition, the reduction of dominant members of a trophic level can have major impacts on predators and prey as previously documented by (Walters et al. 2008). Reduced abundances of prey species can also impact endangered species such as wading birds (e.g. blue crabs and whooping cranes).

Conceptual Models

Prior to constructing any quantitative model it is necessary for produce a conceptual model which describes the major features of a system (Grant and Swannack 2008). Once the conceptual model is completed formal quantitative model construction can continue through a logical series of steps which includes data assembly (parameters, process definition), calibration, refinement and validation (Figure 3). To insure full acceptance of the model, especially when regulatory or legal decisions may depend on the output of the model, it is suggested that all stakeholders and experts participate in the development of the model including the original problem definition and conceptual model. This process is called “mediated modeling”(van den Belt 2004).

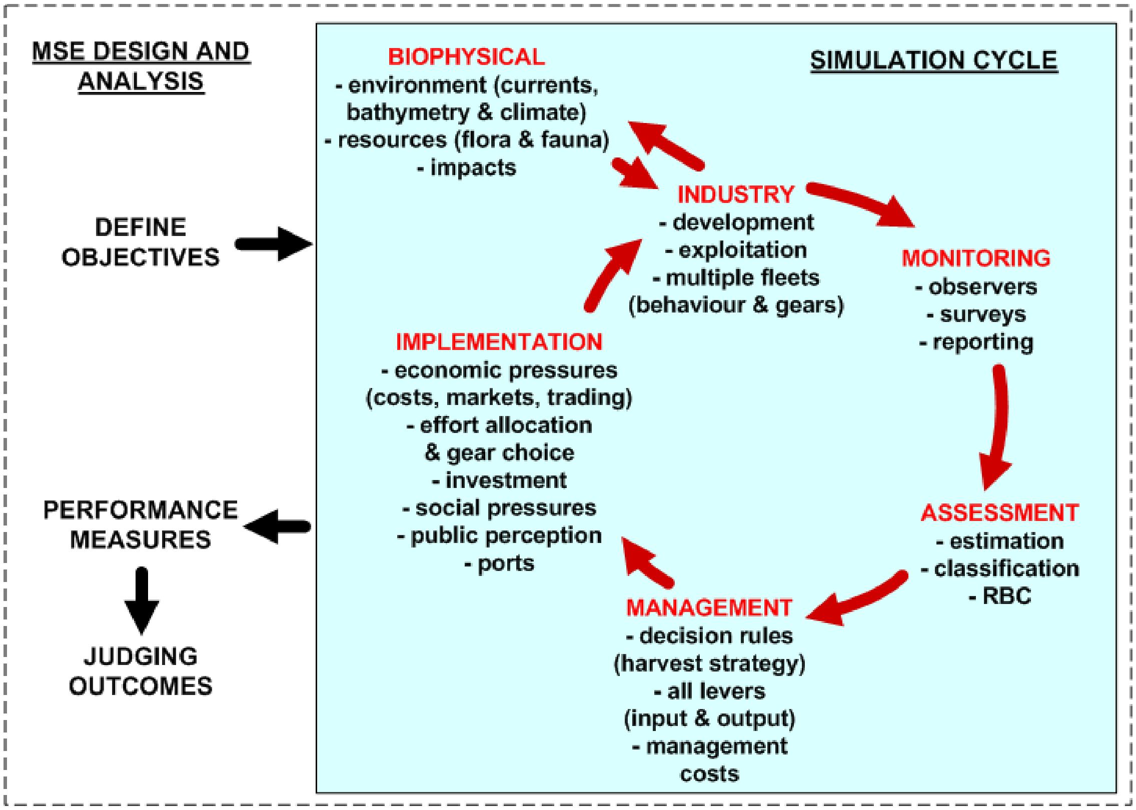

Figure 2. Atlantis model structure - based on the management strategy evaluation cycle (from CSIRO 2010).

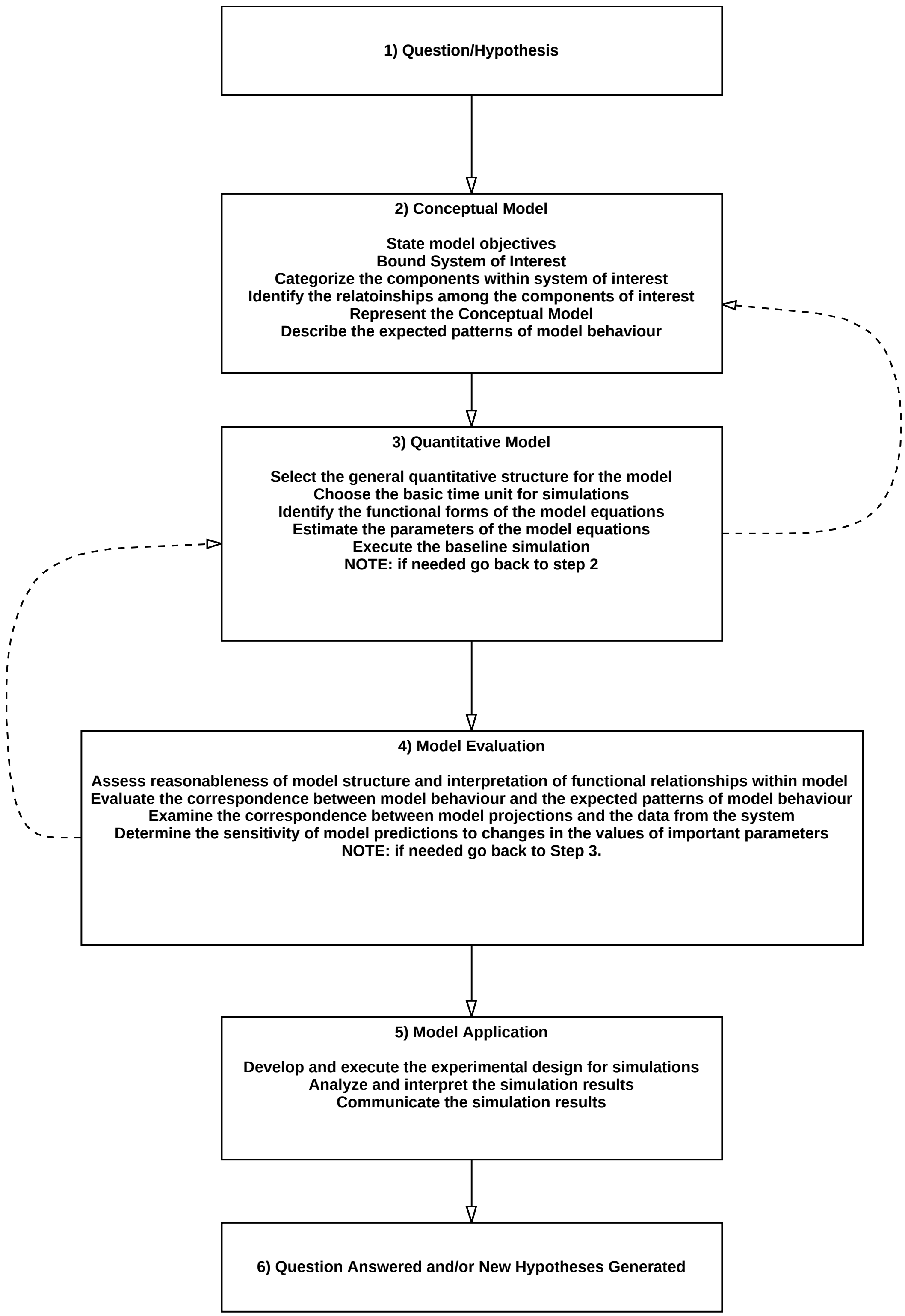

Figure 3. Steps in systems modeling starting with development of the conceptual model (after Grant and Swannack 2008).

Although no comprehensive quantitative ecosystem model exists for Galveston Bay, a conceptual model was produced with funding from *Galveston Bay National Estuary Program (GBNEP)*, the predecessor organization to the Galveston Bay Estuary Program (GBEP). The current conceptual model describes the major processes and components of the Galveston Bay ecosystem (McFarlane 1993). The conceptual model highlights important linkages between various ecosystem trophic levels including benthos, plankton, nekton, and nutrient inputs. The model was intended to serve as the baseline model for communicating key processes to decision makers, scientists and the public for future use in development of monitoring programs, quantitative models and management. What was needed is to revisit and review this conceptual model since it has been nearly 20 years since the original publication data and additional published scientific literature may be available that might update our present knowledge of how estuaries function. It was necessary to review the applicability of the conceptual model to Galveston Bay before any new future modeling efforts can begin. Additional conceptual models have been developed for Texas Bays (Montagna et al. 1996). Although similar in scope and purpose to the Galveston Bay model, the Corpus Christi Bay conceptual model contained additional graphical representations that were used to illustrate in non-technical terms important components and processes within Corpus Christi Bay to the general public. Another smaller and simpler conceptual model for the Sabine Lake estuary in Texas was produced by (McFarlane 1996). These three conceptual models represent the spectrum of conditions that may exist in most Texas estuaries with the exception of the Laguna Madre hypersaline system.

Recently conceptual models have been developed for estuarine systems that implicitly incorporate global climate change and water management as major components and drivers of the system (Davis et al. 2005). They attempted to establish possible mechanisms that could alter the normal processes within an estuary under future climate change scenarios. Another recent development in the field of ecosystem modeling is the attempt to address not only quantitative relationships but also include economic valuation of those resources so that fluctuations in key resources can be used to evaluate changes in ecosystem services. One software package, InVEST has been developed for quantifying ecosystem services produced under different scenarios (Daily et al. 2009).

Probably the most successful attempt to establish an institutional and widely acceptable conceptual model for estuaries is the “OzCoast system” developed in Australia (Harris et al. 2002; OzCoasts 2011; Ryan et al. 2003). The OzCoast system was developed as part of the initial 'Conceptual Models of Australian Estuaries and Coastal Waterways' project. The objectives of the project included:

• Integration of hydrological, biological, and geosciences perspectives regarding the relationship between the physical 'form', and the environmental 'function' of all Australian estuaries and coastal waterways (through collaboration with researchers).

• Enhancement of cross-disciplinary communication of scientific concepts, in order to give managers a broader and more comprehensive view of estuarine function, at a scale appropriate to environmental resource management.

A final report that describes their classification system and respective conceptual modeling process is described by (Harris et al. 2002). In addition, the resulting conceptual models are also represented as an interactive web production, linked to the OzEstuaries database (http://ozestuaries.org)(Ryan et al. 2003). The Conceptual Models were developed with close linkages to their 'Indicators of the Condition and Vulnerability of Estuaries and Coastal Waterways' project, which is also available as an interactive web production via the OzEstuaries database.

The conceptual models in their report were representations of real-world systems. They represented a synthesis of knowledge for each type of coastal waterway, and were intended to be visually stimulating to managers and users and easier to understand than the complex diagrams often used to represent environmental systems. Geomorphology and sediment type were used as the common 'base layer' in the conceptual models, because sediment is the fundamental, underlying substrate upon which all other estuarine processes depend and operate. Seven coastal waterway classes were identified, each having a distinctive suite of physiological parameters based on the relative combinations of wave, tide, and river influence, providing the first comprehensive classification of all the coastal waterway types found in Australia. The coastal waterway classes comprise:

- Embayments and Drowned River Valleys
- Wave-dominated Estuaries
- Wave-dominated Deltas
- Coastal Lagoons and Strandplain-associated Creeks
- Tide-dominated Estuaries
- Tide-dominated Deltas
- Tidal Creeks

Geomorphic conceptual models were eventually developed for each of the seven types of Australian estuaries and coastal waterways. Each conceptual model is comprised of a three-dimensional block diagram depicting detailed summaries of the structure, evolutionary characteristics, and geomorphology of each coastal waterway type, which are “overlain” with flow diagrams that depict some of the important biotic and abiotic processes, namely: hydrology, sediment dynamics, and nutrient dynamics. Their conceptual models provided strong evidence that estuaries (both wave- and tide-dominated) are the most efficient 'traps' for terrigenous and marine sediments, and these are depicted as providing the most significant potential for trapping and processing of terrigenous nutrient loads. They predicted that intertidal areas, such as mangroves and saltmarshes, and also the central basins of wave-dominated estuaries and coastal lagoons, are likely to accumulate the majority of trapped sediments and nutrients.

The conceptual model diagrams developed by the Australian government, with overlays representing environmental processes, were intended to be used as part of a decision support system for environmental managers, and as a tool for comparative assessment in which a more integrative and shared vision of the relationship between components in an ecosystem can be applied. They provide a framework for organizing knowledge, in order to help end users understand important components and processes that link these together. In this way, coastal managers are able to consider the dynamics of coastal ecosystems at temporal and spatial scales appropriate to making management decisions. In addition, gaps in knowledge can be filled by additional research and monitoring. According to the Australian government it was intended that the conceptual models presented should continually evolve and be improved through ongoing testing and review by coastal managers and researchers.

Management Needs

The Galveston Bay Estuary Program of the Texas Commission on Environmental Quality is charged with implementing the Galveston Bay Plan (The Plan), a comprehensive conservation management plan for Galveston Bay (GBEP 2001; GBNEP 1994). Based on scientific research and monitoring the Plan is designed to protect and restore Galveston Bay. It identifies problems, solutions and actions to rectify the Bay's growing needs. One key element of the Plan is to promote and fund sound monitoring and scientific studies that increase the ecosystem level understanding of the interactions between the ecosystem's biological, physical and chemical processes. The purpose of improving this understanding is to inform resource managers, decision makers and the public with the sole expectation of enhanced future management of the Galveston Bay ecosystem. Although GBEP funded research and monitoring activities are selected with input from various subject matter experts who serve on the Monitoring and Research Subcommittee (M&R), it has been recognized that more refined conceptual and/or quantitative models and tools are needed to guide and assess future research and monitoring. In particular, more refined tools and indicators are needed to monitor progress in implementation of the Plan. Past indicators such as acres of wetlands created, or amounts of restoration projects funded do not likely fully characterize the impacts of management actions on Galveston Bay ecosystem services and critical natural resources and environmental quality.

Future modeling tools should be able to incorporate complex, often non-linear and usually cumulative interactions inherent in ecological processes that may materialize as a result of various management options. Galveston Bay resource managers and planners need a tool to evaluate the potential cumulative impacts of various changes in land use and habitat, point and non-point discharges, freshwater inflow, global climate change, commercial and recreational fishing, and the introduction of invasive species. Many of these "causative factors or stressors" interact and influence ecosystem components that are measured or monitored using various "response indicators" including water quality variables, animal density and species composition, specific land use and habitat. However, these response indicators may themselves influence other response variables. For example, the influence the influence of freshwater inflow has been primarily evaluated indirectly by changes in salinity and nutrients. However changes in salinity and nutrients subsequently influence the distribution of estuarine organisms both directly and indirectly by influencing prey or predator organisms and available habitat. The original causative factor, freshwater inflow, can also interact with other causative factors such as point and non-point source loading. An excellent example of these types of interactions involves the question of nutrient loading and responses to these two factors in urban estuaries such as Galveston Bay. In this case freshwater inflow has been decreasing, but overall nutrient loading may be increasing due to loading from the local urban watershed, which may also be increasing. The exact interaction of these two factors is difficult to evaluate given current approaches. The use of ecosystem models to predict and guide research and monitoring could aid in answering these difficult questions.

Systems Modeling

In recent years there has been an expansion of more comprehensive watershed and ecosystem based models that have been developed to evaluate multiple stressors and environmental impacts at the watershed or larger scale (EPA 2001; Plaganyi 2007). Some notable examples include SWMM, BASINS/AQUATOX, EFDC, EcoPath/EcoSim, ATLANTIS, NSpect, and others (Christensen and Walters 2004; EPA 2001; Eslinger et al. 2005; Fulton et al. 2004; Kianirad et al. 2006; NOAA 2004; NOAA 2006c; Park and Clough 2009; Plaganyi 2007; Sutton and Guillen 2009; Tetra Tech 2007). Most of these models and modeling platforms have been developed to evaluate a suite of specific impacts such as non-point source loading, development of TMDLs, evaluating changes in fishing pressure and habitat on fish stocks, and estimating impacts of nutrients and toxic compounds on receiving streams. These models can be classified into a few major applications including the evaluation of 1) habitat needs by wildlife, 2) land use non-point source loading relationships, 3) evaluating bioaccumulation ecological/human risk models, 4) watershed impacts using modular models that can incrementally incorporate various stressors and output and 5) multispecies fisheries models that can incorporate other stressor impacts (e.g. water quality, currents, variable recruitment). The value of these models is that they are “tailor-made” to deal very efficiently with specific questions and may be well known in terms of their applicability and acceptability within specific disciplines of experts. Their major limitations are 1) they sometimes lack sufficient flexibility to incorporate additional stressors or endpoints, or unique management questions not addressed by standard output and 2) generally are not widely available known except to the specific disciplines and 3) may not be easily translatable into knowledge that can be used by managers and 4) may appear to be “black boxes” to all others not involved in the modeling effort.

Over the last 20 years graphical icon based “systems” modeling platforms including *STELLA*, *Madonna, PowerSim*, *Simile*, *Vensim* and *Goldsim* have been released. These software packages show promise as a more flexible, adaptable, and transparent modeling platform and approach for evaluating ecosystem changes (Hannon and Ruth 1997; Richmond 2004). All of these programs adopt the systems modeling approach (Odum and Odum 2000). These programs utilize graphical user interfaces and “flow diagrams” and animated graphics to illustrate model pathways and linkages, while providing access to the background programming language used by the programmer to construct the model. The “systems modeling” approach which these models utilize has many advantages (Meadows 2008). (Ackoff 1979) an operations theorist quoted by (Meadows 2008) observed that:

"Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other. I call such situations messes… Managers do not solve problems, they manage messes."

System modeling attempts to simulate and predict the behavior of the "system". A "system" is defined as an interconnected set of elements that is coherently organized in a way that achieves something. Therefore a system must consist of three things including *elements*, *interconnections* and a *function or purpose* (Meadows 2008). For example, the elements of the human circulatory system contain heart, veins, arteries, and capillaries. They interrelated through the physical flow of blood and dissolved substances. The function of this system is to transport nutrients and oxygen to body tissues and wastes and carbon dioxide to the lungs and kidneys for excretion. What is important is that management agencies usually focus on the elements of the system, such as nutrient levels, or individual fish species abundance, and less on the interconnections such as nutrient dynamics, or predator prey interactions. Even less focus has been placed on the function of particular systems, such as estuaries or wetlands. Only recently has the concept of "ecological services" entered into the environmental lexicon. In the case of wetlands several functions are apparent including nursery habitat, water quality improvement and flood prevention. In any case, a particular system can be logically defined by the individual trying to describe and understand it, if they incorporate the principles of elements, interconnections and function in their definitions. These systems can range in size from an individual body, population, community, watershed, up to oceanic regions or entire planet. Also, the systems can be scaled down and treated as modular subsystems, which fit into a larger system. For example, an oyster reef is a smaller system which is connected to the larger estuarine system, which in turn is connected to the larger nearshore oceanic system. The treatment of each component as a subsystem within a larger framework allows would be modeler's flexibility to create the entire ecosystem model in a stepwise fashion as resources and understanding of all ecosystem components are attained.

Recently, EPA researchers have started a project that uses the systems modeling software package, *Simile*, to develop estimates of Tampa Bay, Florida ecosystem services (Russell 2010)(Figure 4). The project is in the beginning stages and will take a few years to complete. The organized their ecosystem within the model into terrestrial, open water, and wetland compartments (Figure 4). They are attempting to use this model to evaluate the affects of currently predicted land development and climate change scenarios on these ecosystem services (Figure 5). We spoke to the group and they have indicated that they will be willing to share information about their progress to date and plans for the future including logistical issues regarding use of the *Simile* software platform.

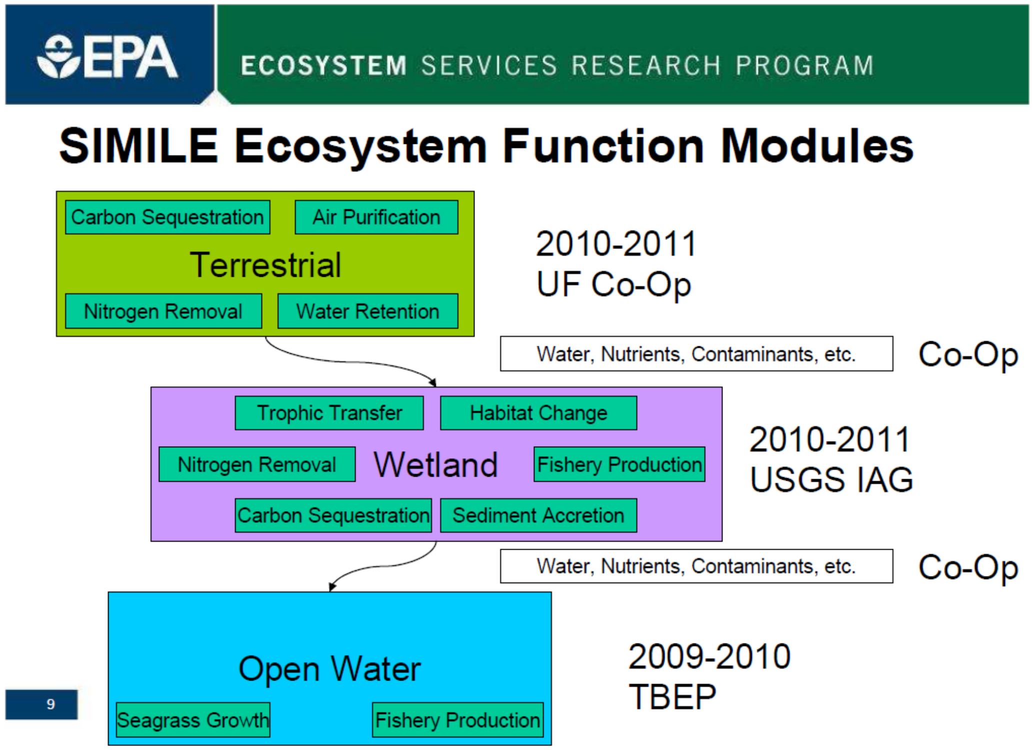

Figure 4. Conceptual model of Tampa Bay developed using the Simile software modeling platform (Source: Russell, 2010).

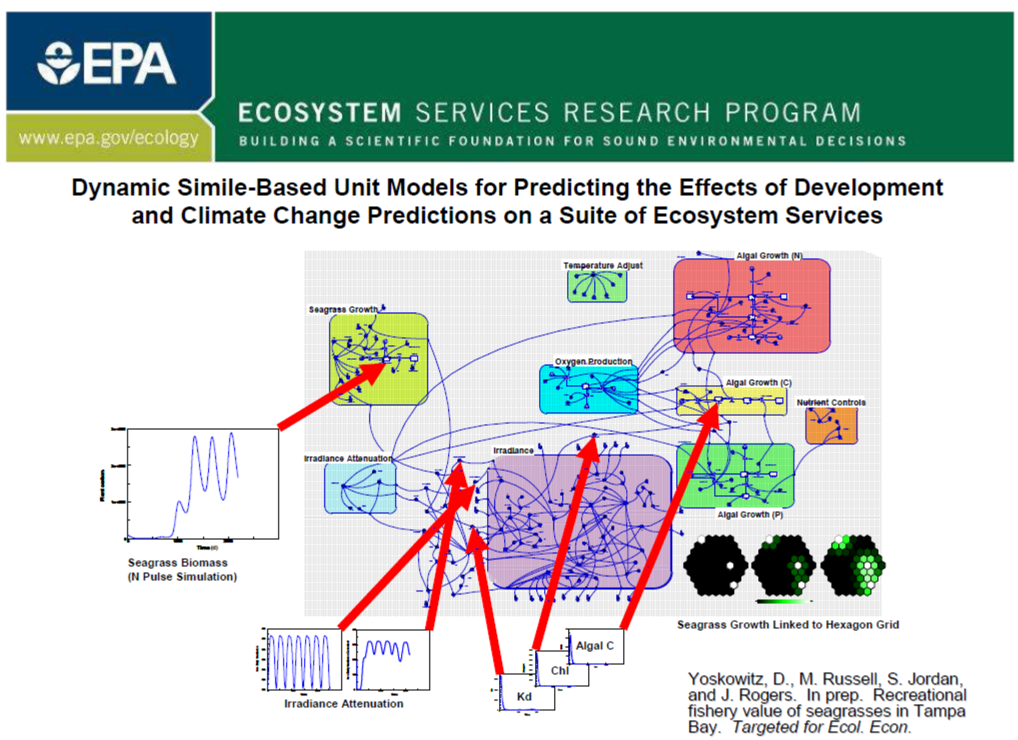

Figure 5. Tampa Bay Simile systems model used to evaluate ecosystem services (Source: Russell, 2010).

Dynamic systems model development for describing complex ecological systems continues to increase in popularity and popularity. However, it is critical that users both in research and management understand both the benefits and limitations of systems-based software. It is difficult for example to evaluate the comparative accuracy and applicability of different modeling platforms and approaches. Few comparative studies have been conducted. (Rizzo et al. 2006) translated a Surface Wetness Energy Balance (SWEB) model for canopy surface wetness into four systems modeling software packages and evaluated their strengths and weaknesses based on 'novice' user interpretations. They found expression-based models such as *Simulink* and *GoldSim with Expressions* were able to model the SWEB more accurately; however, stock and flow-based models such as *STELLA*, *Madonna*, and *GoldSim with Flows* provided the user a better conceptual understanding of the ecologic system. Although the original objective of their study was to identify an 'appropriate' software package for predicting canopy surface wetness using SWEB, their outcomes suggested that many factors must be considered by potential users and stakeholders when selecting a model because the modeling software will become part of the model and of the calibration process. Other factors and constraints to model selection may include user demographics, budget limitations, built-in sensitivity and optimization tools, and the preference of user friendliness vs. computational power. They concluded that the current multitude of closed proprietary software may present a disservice to the modeling community, creating model artifacts that originate somewhere deep inside the undocumented features of the software, and masking the underlying properties of the model (Rizzo et al. 2006).

The scope and specificity of the modeling question may also influence the applicability of selection of certain modeling software packages. (Edelfeldt and Fritzson 2005) evaluated two ecological models of nitrogen processes in treatment wetlands using the *MathModelica Model Editor* software package, three ecological modeling tools and one application specific (wastewater modeling package). This included the *PowerSim*, *STELLA*, *Madonna*, and *WEST* (wastewater model) modeling software packages. They compared the output between models. The results they obtained varied considerably depending on the complexity of the model and modeling tool. The similarities between these category types were apparent. When modeling, they point out that one of the main decisions is between trying to capture system complexity or utilize a simple approach. A complex model or tool may provide more possibilities to detail a simulation of a process or a system. However, the price of this complexity and flexibility is lack of simplicity. It may not be necessary or even possible to describe a system detailing many parameters, and a simpler model may often be enough. This consideration must always be taken in account when modeling. Most (if not all) models are simplifications of real life, and it is only the level of simplification that has to be decided. They concluded that the more complex nitrogen model was best simulated in the *MathModelica Model Editor*, as the *Model Editor* or the *WEST* software package (Edelfeldt and Fritzson 2005).

Since Galveston Bay may be experiencing possible impacts associated with some combination of all of the stressors listed, an ecosystem modeling approach is needed to evaluate cumulative and synergistic effects. In order to initiate this process it was first necessary to 1) review and/or modify a conceptual model for Galveston Bay 2) identify critical questions regarding the Galveston Bay system that may benefit from evaluation using a simulation model and 3) identify critical data needed to construct the model. These steps must be conducted prior to embarking on any future ecosystem modeling.

Objectives

The objective of this project was to begin the process of developing an ecosystem modeling toolkit for Galveston Bay by working through a "mediated" modeling approach using an expert panel of participants who would assist in developing 1) key resource management questions that need to be answered, 2) reviewing and updating a conceptual model of Galveston Bay to insure that it incorporates critical processes that are linked to these questions and 3) identify critical data gaps and information needs that need to be addressed in order to populate future model parameters and address data requirements, 4) evaluating the suitability of existing models as tools to accomplish future modeling projects and informing management decisions (van den Belt 2004).

Recommendations for future model development were based on the importance of the resource, ecosystem services that are provided, ability to serve as an indicator of overall ecosystem health of Galveston Bay, identification of model parameters, ability to acquire specific data and solicited input from subject matter experts. An environmental modeling workgroup (EMWG) was established to provide input on ecosystem processes and review available data and parameters. The process relied on a mediated modeling approach which incorporated the following steps through a series of workshops (van den Belt 2004).

1. Preparation – Relevant stakeholders with technical knowledge were invited to participate. Baseline information was established and additional information was gathered. Critical questions were identified and candidate modeling approaches were explored.

2. Workshops - A series of 3 workshops were held and aimed at fostering learning about models among stakeholders. Through mediation by the principle investigator the participants developed a problem definition which evolved into a conceptual model which will be used to develop a quantitative model. The participants were introduced to the concept of various what-if scenarios that will be used in future scenario evaluation phases.

3. Follow-up – Upon acceptance of a conceptual model and if sufficiently developed quantitative model exists, the EMWG will continue to guide and development of the ecosystem model. In addition, the focus will be on translation of technical information into information that can be communicated to a wider audience. It is anticipated this audience could be attendees at the next State of the Bay Conference and/or the Galveston Bay Estuary Program Advisory Board.

It was not the intent of this project to develop an ecosystem model but rather 1) review and/or refine existing conceptual models, 2) identify key management questions that could be addressed by ecosystem models, 3) identify key data gaps in regards to state variables and processes, 4) identify and evaluate potential ecosystem modeling approaches and 5) establish a long-term advisory group and approach to continue to develop, implement and advocate an ecosystem modeling approach. It was intended and hoped that the ecosystem modeling product eventually produced by this group will be a management resource tool that will be available to all participants and fully documented to allow workgroup members or anyone to update and expand the capabilities of the modeling approach to deal with future issues. It is also hoped that a more permanent EMWG group will be created that will meet regularly and help guide and support ongoing ecosystem modeling development.

Methodology

One of the main objectives of this project was to develop a recommendation on an ecosystem modeling topic, approach and software supported by local stakeholders and sufficient to answer a set of identified management questions including those of the Galveston Bay Plan. The recommendation was to be based on the identification of model objectives, resources importance, parameters, ability to acquire specific data, and solicited input from subject matter experts. In order to accomplish this objective we organized and facilitated an expert modeling working group (EMWG) to assist in model software selection, parameter development and to evaluate data availability. The overall process we followed is described as "mediated modeling" which involves technical input on model parameters, constraints, and documentation at various critical steps. This process insures full stakeholder involvement and input, which increases the likelihood of ownership and acceptance of the final product**.** Subject matter experts were selected by the principal investigator and approved by the GBEP Project Manager based on their subject matter expertise and/or knowledge of key components of the Galveston Bay ecosystem including hydrology, water quality, primary producers, critical resources, and habitat. Due to the limited budget, sources of membership included local and regional experts who currently serve on GBEP Monitoring and Research Advisory Committee (M&R Committee), the San Jacinto/Trinity River Galveston Bay SB3 BBEST (Bays and Basins Expert Science Team), HGAC Clean Rivers Monitoring partners, Gulf of Mexico Alliance (GOMA) technical experts and regional scientists employed by state and federal water quality and natural resource agencies.

One of the major tasks of the EMWG was to identify critical resource management questions that would be candidates for model interrogation. This was accomplished by development of a candidate list of key priority questions which was voted upon by the EMWG. These questions were evaluated based on several criteria. Appropriate hypotheses were developed that can be examined through an ecosystem model. Key attributes that were used for selection of priority questions were importance of the resource to the overall functioning of Galveston Bay, ecological services provided, availability of appropriate data, management priorities, and feasibility of being able to accomplish this task within a reasonable period of time.

The first step toward ecosystem model development was the review and evaluation, and/or refinement of a conceptual model of Galveston Bay and identification of key ecosystem components and processes that will require parameterization and data acquisition. Future selected modeling software output will be compared to this conceptual model to determine how well these models capture key processes and address important resource questions within Galveston Bay. The EMWG reviewed the current Galveston Bay Conceptual Ecosystem Model as well as other conceptual models developed for Texas bays to determine whether modifications or refinements are necessary (McFarlane 1993 and Montagna et al. 1996). Candidate modeling approaches and software used in the literature and in other similar ecosystems were identified for their appropriateness at simulating the Galveston Bay system based on key conceptual model processes.

Another major task inherent in the development of future ecosystem models was the identification of critical data gaps that need to be addressed to support further model development. The need for additional data was in part guided by the development of key research modeling questions, which were developed by the EMWG. Expert knowledge along with a cursory literature review of published data in bay systems including electronic data sources from various resource agencies including the HGAC, TPWD, TCEQ, TWDB, NMFS/NOAA, USFWS, and USGS, were the primary sources evaluated. With the assistance of the EMWG we evaluated the current state of knowledge and data as it applies to the Galveston Bay system that is needed to support development of future ecosystem models. Data gaps were identified and potential solutions (e.g. additional data collection, use of data from similar systems) were evaluated and documented.

One of the most important products produced from this project was the identification of pilot case study scenarios to evaluate the utility of selected candidate models at addressing critical natural resource questions. Some preliminary scenarios that were evaluated included the role of nutrients and freshwater inflow, fishing pressure, wetland habitat loss, oyster reefs, land use changes and loss of wildlife and wetland habitat, and persistent contaminants on key components of the estuarine ecosystem. Ultimately the EMWG developed 2-3 case studies and discussed the potential utility of various models in addressing these issues. This evaluation focused on the known traits and limitations of these models. This in turn was coordinated with the previously described task of identifying data availability to support future modeling efforts.

In addition to identifying potential case scenarios we also developed a strategy for facilitating the development of an ecosystem model by various stakeholder groups and resource management agencies. This was accomplished primarily through the establishment of an EMWG and candidate ecosystem modeling projects. These future modeling efforts will hopefully be guided by and with the input of the EMWG. The resulting ecosystem model will empower Galveston Bay stakeholders with the ability to carry on adaptive ecosystem management with the support of a flexible modeling system that has received scientific review and input by subject matter experts. Ultimately this will result in greater acceptance of a model which will be understood by all reviewers and future users. The modeling tool can be shared and utilized by various stakeholders to evaluate various future management efforts. The EMWG is anticipated to meet quarterly with to accomplish the extended modeling goals identified during this project. The principal investigator George Guillen has volunteered to continue this effort as an informal workgroup of the GBEP. It is anticipated that this effort will provide a platform to attract additional resources beyond the scope of this project.

Direct benefits of this project included development of a better understanding of the processes affecting important natural resources of Galveston Bay. Knowledge of the critical pathways and processes that influence important resources in Galveston Bay as defined in the Galveston Bay Conceptual Model were used for defining candidate ecosystem modeling projects. It was hoped that these candidate modeling projects will in turn help guide and prioritize future monitoring and research. Eventual creation of an ecosystem model will assist GBEP in execution of the Galveston Bay Plan including protection of critical resources such as wetlands and important fisheries. The information learned from the modeling effort can be used for adaptive management in the area of water quality, freshwater inflows, fisheries regulations, and habitat protection. The resulting model should assist in the identification of important causal variables while identifying important data gaps. This in turn should guide future environmental monitoring efforts. Methods used and knowledge gained from the model may be extended to other bay and estuaries along the coast to implement similar models.

One of the primary goals of the EMWG was to develop a clearer understanding of data needs and potential modeling tools that can help address critical information needs. IN addition, we wanted to be able communicate the performance traits of any candidate modeling approach including limitations, applicability and predictive power. The intent is for the EMWG to continue beyond the scope of this project to begin implementation of the ecosystem modeling efforts and assist in selection of future ecosystem modeling projects.

Results

The first major task that was accomplished was the selection of the EMWG membership. This list of members and technical expertise areas are listed in Appendix 1. The membership consisted of representatives who have a broad range of expertise and have many years of practical experience working on Galveston Bay and related coastal issues including conservation of natural resources, water quality, and hydrology. In addition to informal conversations between EMWG members, there were three formal meetings held on October 7, November 19, and December 10, 2010. In addition, there is a planned meeting for January to April 2011 and continued meetings beyond the scope of this project. EMWG membership is totally voluntary and open to new members with a desire to help and contribute to the ongoing efforts.

First Workshop

During the first meeting on October 7, 2010, the agenda consisted of presentations from George Guillen on the overall mission of the group including objectives and timelines including the need to establish a long-term EMWG beyond the scope of the project. Other topics that were discussed were an overview of current modeling activities in

Galveston Bay and a review of the Galveston Bay conceptual model and related modeling efforts (e.g. Corpus Christi). Potential modeling objectives were also discussed. Several major observations and conclusions were made at this meeting and are summarized (Table 1). The major discussion which was mediated by George Guillen included an overview of the mission of the group. The primary reason for modeling was also explained. A list of reasons for modeling in general was outlined for the group (Table 2).

One of the main reasons for conducting modeling in the environmental field is the lack of data and the increased complexity observed at higher levels of organization (Figures 6 and 7). For the purposes of the Galveston Bay program and affiliated organizations the most important reasons for modeling include a better understanding of the system, increasing our ability to make accurate predictions, in order to manage the system more effectively. Management of a highly complex system such as Galveston Bay requires simulation models in order to understand the interaction and feedback mechanisms of multiple stressors on the functioning of the estuary. For example, several system wide issues have recently emerged, that will challenge Galveston Bay managers in the future. These include continued projected urban growth, associated continued loss of critical wildlife habitat, changes in freshwater inflow, and global climate change and predicted sea level rise (Houston-Galveston Area Council 2007; Region H Planning Group 2011; Warren Pinnacle Consulting Inc. 2011) . Population in Region H is projected to grow from approximately 6.0 million in 2010 to approximately 11.3 million in 2060. The interaction of these factors will likely result in an increased rate of loss of wetlands due to apparent sea level rise and in increased demands for land, water and fisheries which in turn will negatively affect freshwater inflow, estuarine nursery habitat and water quality. However, the ability to predict the exact impacts remain problematical due to lack of data and a poor understanding of how the rates and amounts of material transferred through food webs and biogeochemical pathways will be altered under future scenarios.

A recent example of the inability to fully address the complexity of ecosystems is the recommendation of ecological freshwater inflow needs for Galveston Bay (Trinity-San Jacinto-Trinity Bay and Basins Stakeholders Committee 2010). With passage of Senate Bill 3 (S.B.3) in 2007, the Texas Legislature created a stakeholder process that would produce science and policy based environmental flow regime recommendations to protect freshwater inflows. Advisory committees were created to oversee implementation of the process. The bill also created seven bay/basin stakeholder groups (BBASC) and bay/basin expert science (BBEST) teams. The primary task of the BBEST was to provide a consensus based recommendation on environmental flows to the BBASC, who review and submit these with modification for policy implications to the TCEQ and other science advisory groups to review. Based on these recommendations and reviews, TCEQ will adopt rules establishing environmental flow standards for the bay/basin area, including a set-aside of un-appropriated flows.

Table 1. Key concepts discussed at the October 2010 meeting of EMWG.

Topic/Question	Key Concepts Developed
1) Availability of data may limit the ability to conduct ecosystem modeling	1. Past, recent and projected land-use data and status of wetlands are available from multiple sources including the NOAA Coastal Geospatial Data (NOAA 2011), National Wetlands Inventory (U.S. Fish and Wildlife Service 2011), GBEP funded studies (e.g. Jacobs and Webb), HGAC LULC (Houston Galveston Area Council 2010a; Houston Galveston Area Council 2010b; Houston Galveston Area Council 2011; Meyer 2008; NOAA 2011) 2. Benthic organism data is limited, some available from TCEQ SWQMIS, past NCCA surveys, and studies by past university investigators. Some published studies on converting wet weight to dry weight for secondary production and energy flow modeling (EPA 2010; Houston Advanced Research Center 2010; Ricciardi and Bourget 1998) 3. Data on seagrass distribution and species composition is limited in Galveston Bay. Past studies document the extent and distribution and recent changes were noted (Pulich and White 1990; Sheridan et al. 1998) and Leslie Williams TWPD and current projects by A. Quigg for freshwater species. 4. Fisheries data collected by TPWD coastal fisheries limited to open bay environments and oyster reef. Little data collected in tributaries, and insufficient monitoring in tidally influenced rivers by either TPWD coastal or inland tributaries. Historically fisheries effort data (commercial) has been collected. 5. Few or limited wildlife surveys have been conducted in Galveston Bay watershed. Long-term monitoring data of sufficient quality not collected for waterfowl.

Table 1. Continued

Topic/Question	Key Concepts Developed
2) Management Question Definition 1. What are the key questions models can help us answer? 2. What is success? 3. How would you measure it? 4. The value of a resource in terms of the "ecosystem services" may help define the ultimate management question.	1) It is imperative to clearly define the management question that needs to be answered by the modeling. This in turn will focus modeling 2) No one model, even an "ecosystem" model can address all questions. 3) A modeling "tool-kit" may be more appropriate, similar to approach used by: a) NOAA internal modeling tool kit used to assess fisheries. b) EPA water quality modeling tool kit c) NOAA coastal habitat models 4) Current research suggests that wetlands and oyster reefs have high levels of ecosystem services. Example services: water quality improvement, storm surge protection, nursery habitat, primary production 5) Regulations and policy require GBEP and other agencies to monitor progress towards meeting goals of the Galveston Bay Plan. GBEP has developed several indicators that are tracked by HARC and also reports on various "administrative" performance indicators (e.g. number of grants awarded, leveraged grant funds and wetlands created). Are these the appropriate indicators? What do they really tell us about the health of the system? Modeling should inform us on the more appropriate indicators to use.
3) What are the major features of the current conceptual model and are modifications necessary?	Current Galveston Bay Conceptual Model was developed by Dr. Bob McFarlane with significant input from subject matter experts with extensive review (McFarlane 1993). Two major food webs present: 1. detritus based (wetlands, submerged grass) 2. phytoplankton (water column) EMWG needs to review conceptual model to determine if model needs to be updated. Other conceptual models in Texas include: 1. Corpus Christi Bay NEP (Montagna et al. 1996) 2. Sabine Lake has a simple conceptual model (McFarlane 1996) 3. Mission/Aransas NERR developing conceptual model of Aransas/Corpus Christi Bay – Sally Morehead contact. – P. Montagna pers. comm.

Table 1. Continued	
Topic/Question	Key Concepts Developed
5) Modeling Complexity What should be included in the ecosystem model? How much detail? What are the important components?	Ecosystem models should focus on connections (processes) between important components in system Should attempt to capture energy transfer in addition to material. Energy can be related indirectly to dollar equivalents through economic models (ecosystem services). Hard to estimate many parameters of complex models are extremely difficult to estimate due to lack of data. This is especially true in terms of process parameters. Law of Parsimony – models should be as simple as possible. Those that capture essential properties of system should be selected over those that try and capture all processes but may be impossible to implement in the end. Need to be able to communicate model to the public. If model to complex this may be difficult
6) Major tasks to be accomplished	1. Review and/or if needed suggest modifications to conceptual model 2. Select major questions to be evaluated 3. Define appropriate indicators using existing and conceptual model to guide us. This should include indicators/processes that can be equated to <u>ecosystem services</u> 4. Define gaps in data in terms of indicators 5. Develop a strategy or approach for merging cause and effect data sets collected at different scales (e.g. freshwater flow, nutrients and salinity, primary production, fish)
7) Goals for EMWG	1. Develop an ecosystem model incrementally through cooperative process involving Galveston Bay technical experts and stakeholders 2. Identify priority questions that need to be investigated 3. Learn more about the Galveston Bay ecosystem through model output 4. Benefits a. emergent properties b. creation of new hypotheses c. stimulation and focusing of research and monitoring approaches d. greater and better, clearer communication to stakeholders and scientists.

In the case of the Galveston Bay BBEST, there was no clear scientific consensus on the amount and frequency of water needed for Galveston Bay, due in part to lack of data and an insufficient knowledge about the influence of freshwater inflow on primary production and other trophic levels within Galveston Bay (Trinity-San Jacinto-Trinity Bay and Basins Stakeholders Committee 2010). Therefore it was almost impossible to make conclusive recommendations on the relationship of these ecosystem components and freshwater inflow.

Table 2. Reasons for modeling.

1. Define a problem
2. Organize our thoughts
3. Understand our data and associated system
4. Communicate and test our understanding of the system
5. Make predictions about the system (establish hypotheses)
6. Redefine the problem when predictions don't match data observed or system behavior
7. Manage the system of interest

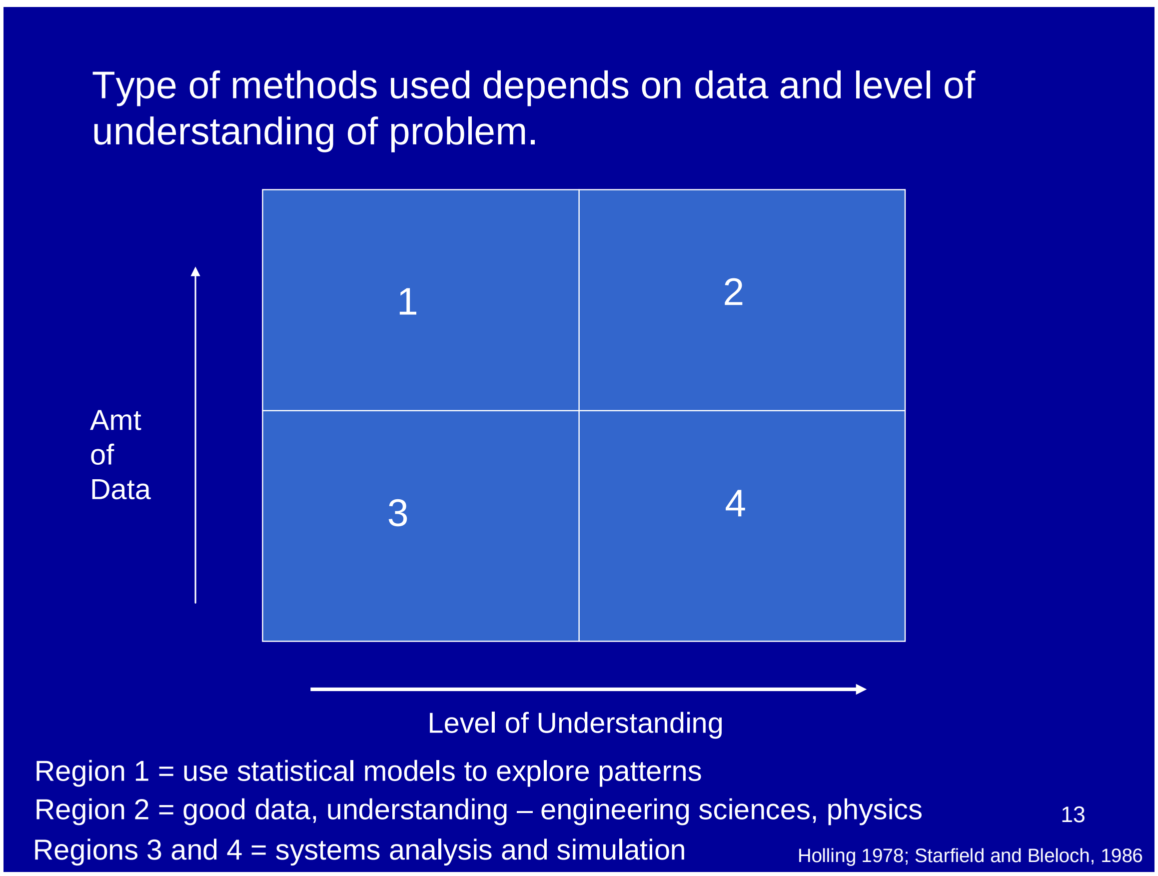

Figure 6. Decision tree for selection of analytical tools (Holling 1978; Starfield and Bleloch 1986).

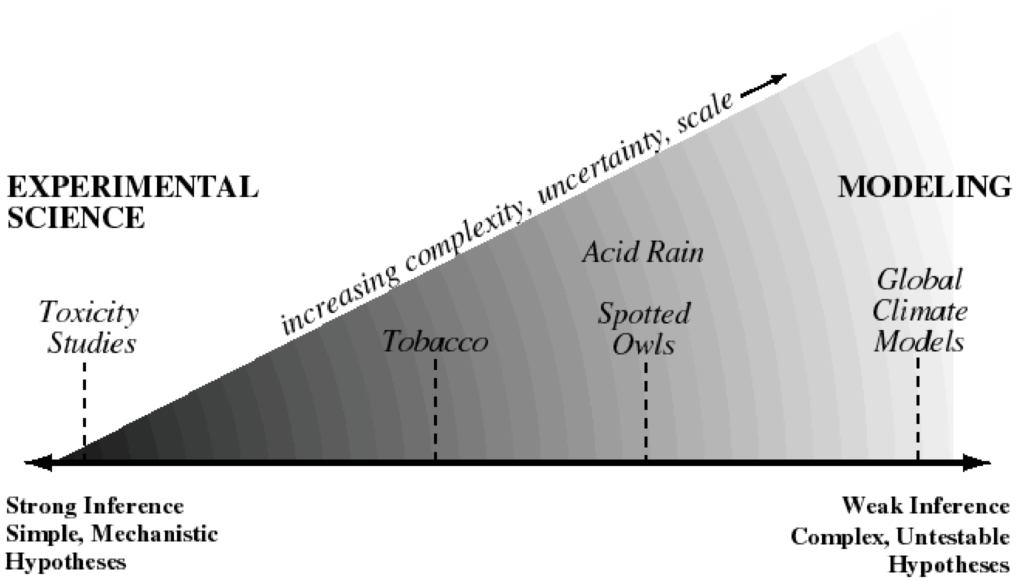

Figure 7. Relationship of system complexity to research approach used (Bradshaw and Borchers 2000).

The key recommendations that were produced from the first workshop meeting of the EMWG are summarized below.

1. There is a need to briefly review the Galveston Bay conceptual model to see if any modifications are needed. The current Galveston Bay Conceptual Model was developed by Dr. Bob McFarlane with significant input from subject matter experts with extensive review (McFarlane 1993). Dr. McFarlane explained the process that was used to develop the model and the input he sought and received from various subject matter experts. He documented the presence of two major interconnected food webs that dominate the Galveston Bay ecosystem (Figure 8). This includes a detritus based (mudflats, wetlands, submerged grass) and phytoplankton (water column) based webs. The group concluded that the EMWG needs to review the conceptual model to determine if it needed to be updated. There was also a discussion about other conceptual models that may be useful in formulating an ecosystem model for Galveston Bay.

The other conceptual models in Texas that were discussed include:

a). Corpus Christi Bay NEP (Montagna et al. 1996)

b). Sabine Lake has a simple conceptual model
(McFarlane 1996)

c). Mission/Aransas NERR is developing conceptual model of Aransas/Corpus Christi Bay – Sally Morehead contact. – P. Montagna pers. comm.

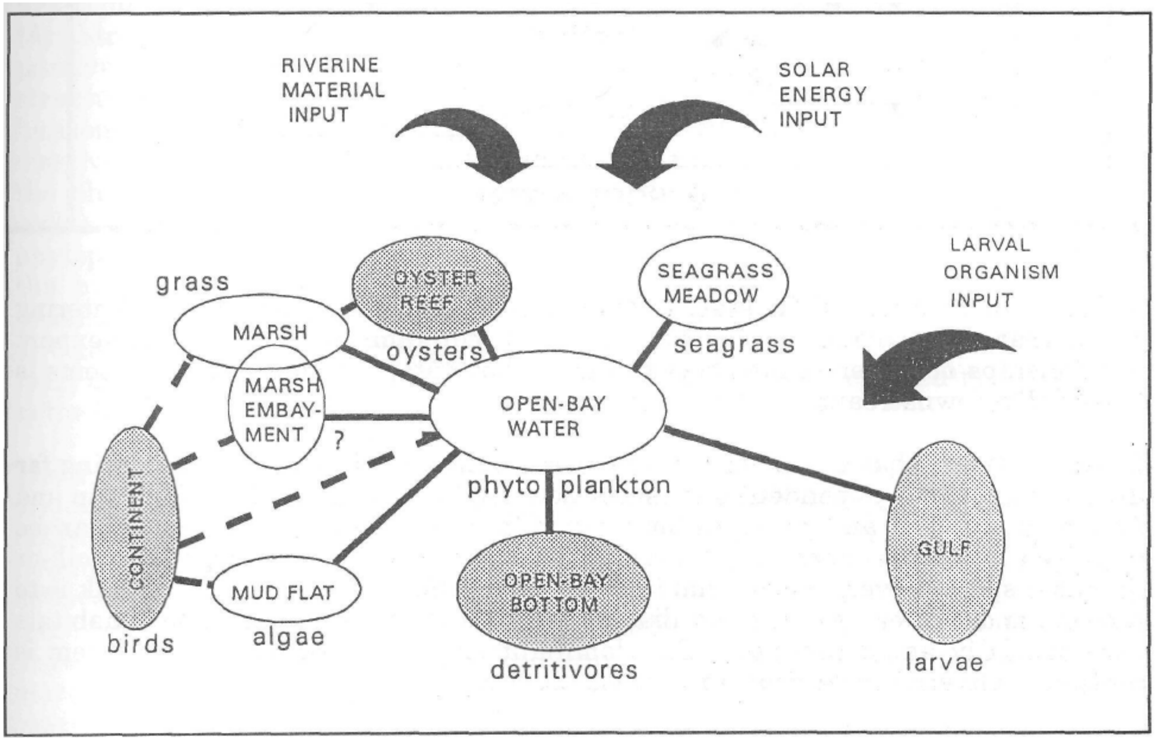

Figure 8. Web of estuarine habitats, highlighting dominant producer organisms and associated autotrophic habitats (open ellipses) or consumers in heterotrophic habitats (shaded ellipses). The principal external inputs are also indicated *(arrows)* from (McFarlane 1996).

2. It is imperative to clearly define the management question that needs to be answered by the modeling. This in turn will focus modeling.

There was considerable discussion about the need to clearly define the management questions that GBEP and their partners wish to answer through modeling. This will guide the selection of the final ecosystem model that will be developed. Depending on the question this may also dictate the simplicity and specificity of the model. The membership suggested that EMWG should consider a simpler scenario that can be addressed relatively easily that is also meaningful to management.

2) No one model, even an "ecosystem" model can address all questions.

Despite the desire to adopt a comprehensive modeling approach that can be used to build components of a conceptual model it was recognized by the EMWG that no one model can be used to address all issues. In general several classes of models have been developed. These include:

1. Water quality models – e.g. TMDL, permits, watershed non-point source loading
2. Fisheries Ecosystem models – EwE, Atlantis. Incorporate water quality, fisheries.
3. Habitat/Wildlife models - various

Many of these models have or are capable of interfacing with GIS and obtain spatial data input and also provide output to these platforms to post process data using shape files. There is a range of models that explicitly address habitat wildlife relationships ranging from simple response surface empirical models such as

3) A modeling "tool-kit" may be more appropriate, similar to approach used by:

a) NOAA internal modeling tool kit used to assess fisheries.

b) EPA water quality modeling tool kit. Their web site has a list of available models (Wool 2010). Most of these with the exception of the BASINS watershed model are models that target specific pollutants and are used for conducting TMDLs and point source modeling.

c) NOAA coastal habitat models

Several agencies sponsor and/or make available a variety of modeling tools that can be used in coordination or separately to deal with specific questions. For example, NOAA NMFS maintains a library of fishery modeling software for various fisheries. NOAA also maintains a library of spatial models designed to address a variety of issues including non-point source runoff, coastal flooding risks and wetland evaluation (NOAA 2006b)

4) Current research suggests that wetlands and oyster reefs have high levels of ecosystem services.

These components of the estuary may be logical targets for development of ecosystem models since loss of these services may result in critical damage to the estuarine ecosystem as a whole. Oysters, *Crassostrea viriginica*, are considered a keystone species. A keystone species is a species that has a disproportionate effect on its environment relative to its biomass. Such species plays a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community. Both of these systems have been conceptually described in various publications including the current Galveston Bay conceptual model developed by Dr. Bob McFarlane which included significant input from subject matter experts (McFarlane 1993). The conceptual model provided examples of a connectivity sub-model for oyster reefs and the life cycle of oysters (Figures 9 and 10). The primary process depicted is the import of nutrients and materials to the reef from external open water systems (Figure 9). One major process that is referred to in the oyster life cycle model is the influence of parasites such as Dermo on oysters (Figure 10).

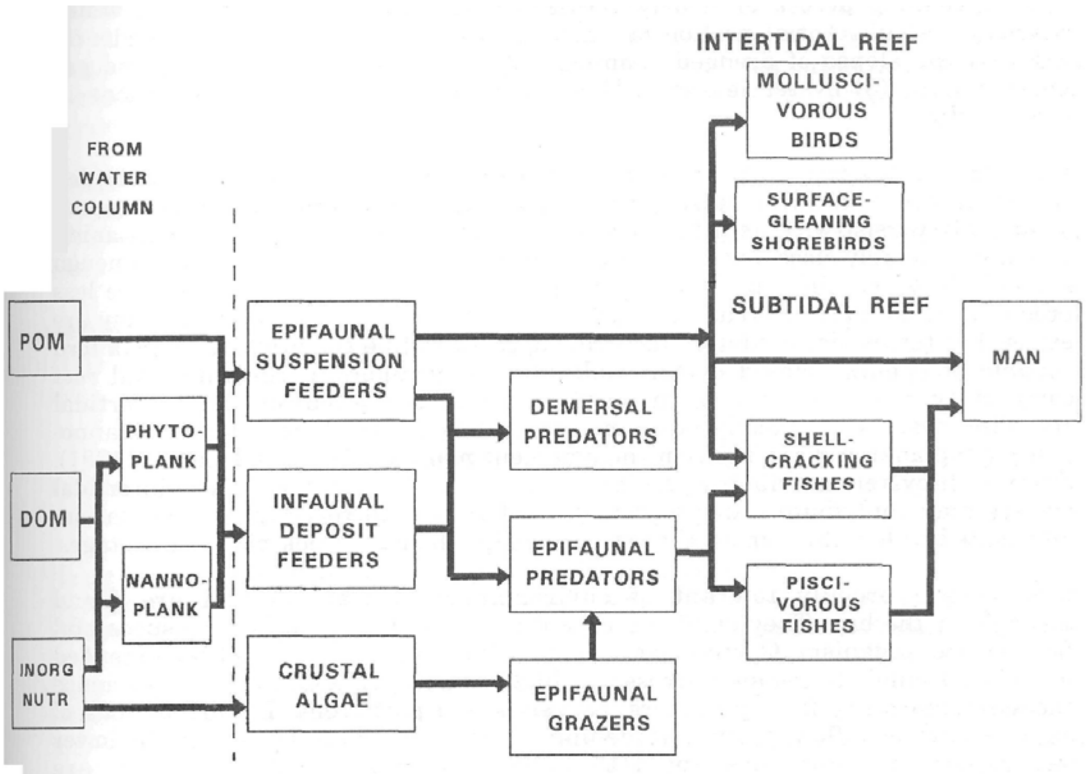

Figure 9. Connectivity model of Galveston Bay oyster reefs. From McFarlane (1993).

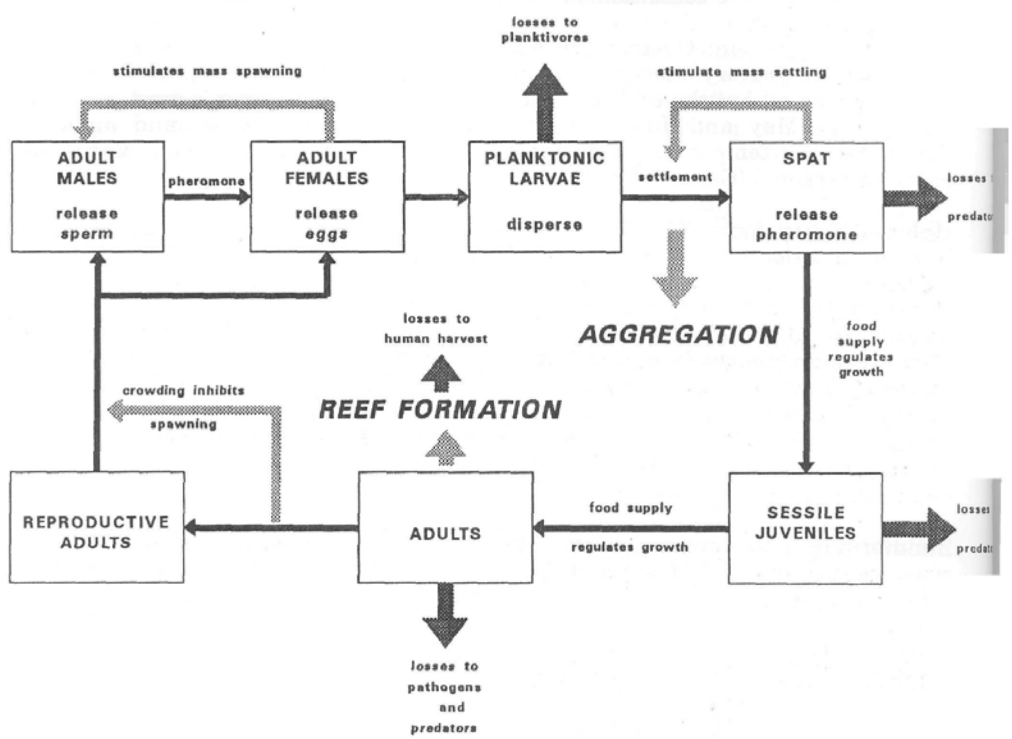

Figure 10. Oyster life history sub-model. From (McFarlane 1993).

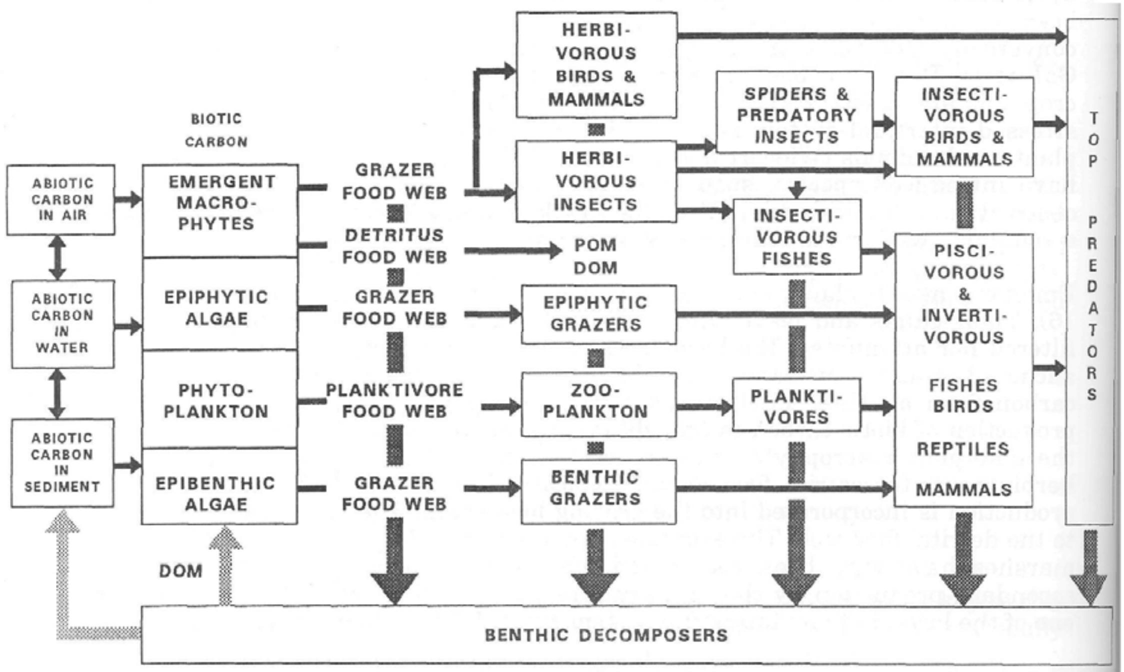

Figure 11. Connectivity model for estuarine wetlands. From McFarlane (1993).

At the meeting Dr. Jan Culbertson from Texas Parks and Wildlife Department announced that she had developed a proto-type oyster model for Matagorda Bay that focused on oyster parasites. She volunteered to present the details of this model to members of EMWG at a future meeting. Her model was developed using the STELLA modeling platform. (McFarlane 1993) also provides a connectivity model for estuarine wetlands. In addition to this current effort there have been past attempts to relate oyster population processes and parasitism to channelization, climate, latitude and freshwater inflow (Klinck et al. 2002; Powell 2003; Powell et al. 1994). Recently (Santopietro et al. 2009) developed a STELLA model of the oyster fishery in Rapphannock River in Virginia to evaluate a state management strategy that allowed commercial harvest from some of the fishing grounds while maintaining the development of a potentially disease tolerant broodstock population in nonharvested sanctuaries (Figures 12 and 13). Their STELLA model of the oyster fishery linked the biological system, the state management program and harvest effort. Their model results predicted that despite various management options high natural mortality rates caused by disease and predation are shown to severely reduce the number of juveniles that reach maturity. They concluded that recovery of the public oyster grounds using the native species is thus of doubtful value without a truly disease tolerant strain.

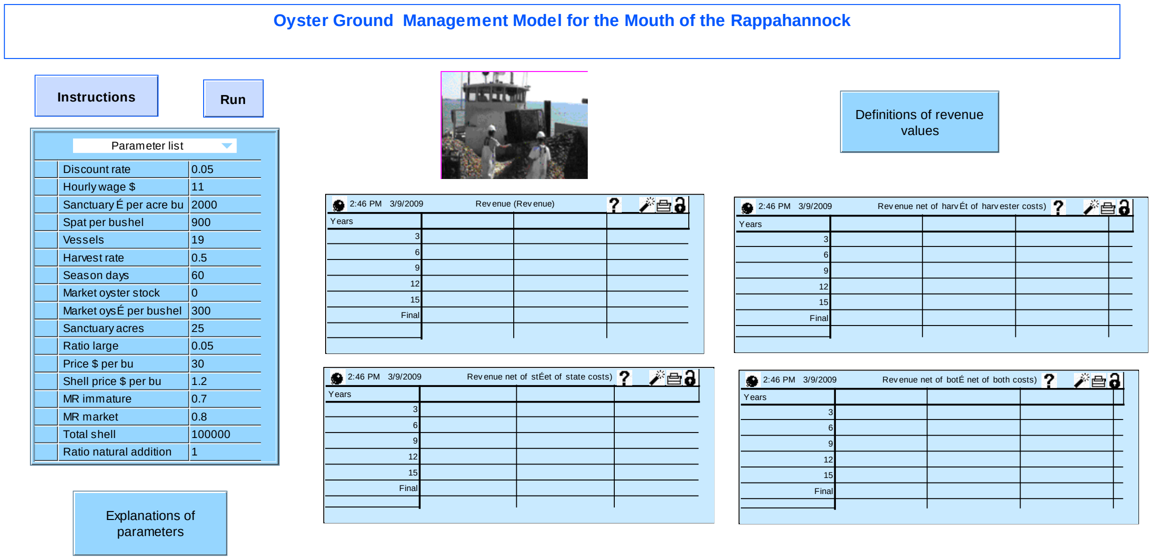

Figure 12. Example interface for Oyster Management model of the Rapphannock River created in STELLA software platform. Source: (Santopietro et al. 2009).

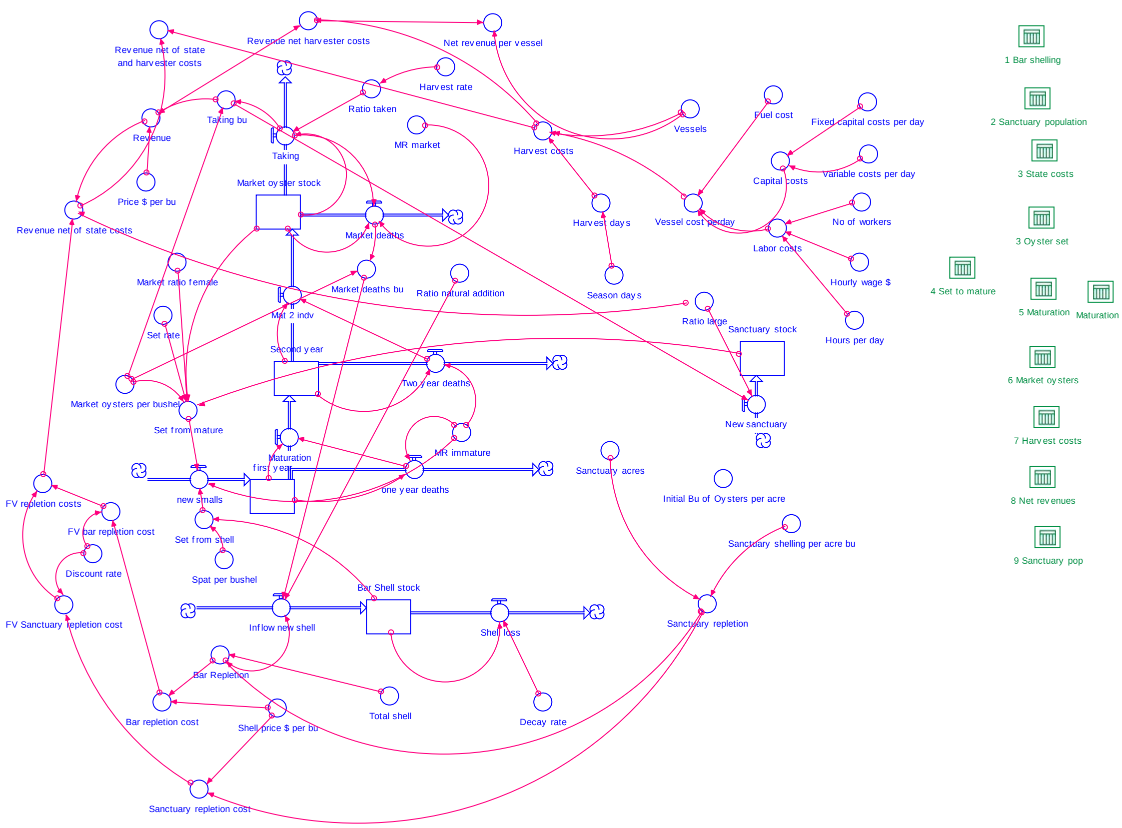

Figure 13. Example map layer for Oyster Management model of the Rapphannock River created in STELLA software platform. Source: (Santopietro et al. 2009).

Second Workshop

On November 19, 2010 the EMWG met again to discuss assigned tasks assigned at the October, 2010 meeting. In attendance at that meeting were Glen Sutton, Mustafa Mokrech, Tyra Booe, Robert McFarlane and Jim Webb and George Guillen. The primary purpose of this meeting was to continue to develop modeling goals and topics. This step was called the problem definition phase. Various problems or management questions were discussed and are listed below (Table 3).

Table 3. Potential Problem Definitions for focusing future modeling efforts.

Topic	Management Question
Habitat Loss	How much has occurred? What type has been lost? Is this question being addressed by past of future efforts (GBEP or non-GBEP funded)?
Freshwater Inflow and Effects	What role does GBEP have or EMWG? (e.g. SB3 Process)
Water Quality	Beyond TMDLs what else is there to do?
Fisheries	TPWD is the state lead. EcoPath Model has been developed. TPWD usually uses traditional single species models. Is there a role for EMWG?
Social/Economic Characterization	Economics? Ecosystem services? Public Health?
Monitoring Needs - Indicators	Do we have adequate indicators to evaluate the major components and processes of Galveston Bay to assess trends and whether the system is healthy?
Education of managers and the public	We need a system that can translate technical information into a form that managers can use to make decisions.
Redirecting research and monitoring	Models should inform and help focus research and monitoring

One of the issues identified and discussed by the EMWG was the appropriateness of current indicators used by GBEP and other agencies to assess the health of Galveston Bay. The EMWG conducted a lengthy discussion on the current indicators used to monitor Galveston Bay and their relative status and quality. A review of these indicators and monitoring programs are summarized in Table 4.

Table 4. List of current indicators and comments on status.

Indicator	Comment/Status
GBEP indicators – synthesis of agency monitoring programs with some derived metrics	The HARC supports this database. http://galvbaydata.org Modeling could help test our understanding of how these metrics describe key functions of the Galveston Bay system.
Indicator bacteria: Fecal coliforms *E. coli* – freshwater *Enterococcus* - marine	TMDLs, GBEP funded projects, TCEQ routine monitoring, CRP monitoring, DSHS shellfish monitoring provide data to this metric. Monitoring is done at different scales, making it difficult to assess short-term trends and responses to changes in hydrology and loading. Major issue: 1) relating levels of indicators to true risk and human pathogens and 2) determining sources. These are national issues being considered by EPA and at the State level. Information is needed to address this. Modeling contribution probably minimal at this time.
Water and sediment quality – e.g. nutrients N, P, Chlorophyll-a	Texas along with other states and EPA are trying to develop nutrient criteria. Current monitoring focuses on only certain forms of N and P. No silica is collected even though diatoms require this. Also, other pigments needed to characterize community dynamics. No sediment nutrient chemistry is collected either in a routine basis although sediment regeneration of certain chemicals is well known. Routine sampling conducted at only very coarse time and spatial scales (e.g. quarterly). Conducted by TCEQ and CRP partners primarily. Major problem is lack of sufficient temporal and spatial modeling and appropriate chemical forms to detect response from nutrients on phytoplankton community. Derivation of this relationship would help both programs engaged in nutrient criteria derivation and determination of the impacts of freshwater inflow. Dr. Quigg is conducting studies on freshwater, salinity, nutrient, primary production relationships. Modeling could help better define the possible relationship of nutrient levels, turbidity and phytoplankton response.

Table 4. Continued

Fisheries Data	Primarily monitored by TPWD. Random sampling grid. Fishery independent: Bag seine (single tow), trawls (single tow), and oyster dredge. Fishery Dependent: catch primarily evaluated by including recreational creel surveys, and landing statistics for shrimp, crabs and oyster dredging. Effort data for commercial fishing is largely lacking. Consequently, CPUE is difficult to estimate. In addition, fishery trends are difficult to evaluate since effort has changed over time. Finally it is difficult to correlate fishery independent estimates of abundance with fishing mortality. Recently TPWD has enacted new regulations that will allow derivation of blue crab effort. This makes it very difficult to utilize and evaluate the relative influence of fishing versus other sources of mortality to finfish and harvested shellfish. Preliminary EcoPath modeling was conducted by Mr. Sutton at TPWD. Preliminary results indicate that freshwater inflow may also be a major factor influencing interactions between finfish trophic groups and trends in blue crabs. One of the major areas where modeling would help address information needs includes oyster dynamics in relation to freshwater inflow, parasitism and harvest. Jan Culbertson – TPWD has recently developed a STELLA based model for Matagorda Bay and Eric Powell has developed models for oyster populations in Galveston Bay that includes mortality estimates based on freshwater inflow and channelization. Recent STELLA models have been developed for the Chesapeake Bay region for oyster management.
Colonial waterbirds and other wildlife	Colonial waterbird counts made by a variety of professionals and volunteers each year including nest counts and individual counts. The effort expended and methodology is not consistent however and many logistical issues and statistical issues surrounding the accuracy of these estimates exist.
Invasive plant and animals species	Few data exists for many species due to limited monitoring of terrestrial habitat, and tidal streams for biota.

Table 4. Continued.

Benthic soft and hard bottom communities	Very limited data exists in terms of routine monitoring of soft-bottom communities which is the most common community in estuaries. Fewer than 10 sites within the Galveston Bay system are monitored routinely more frequently than quarterly each year by TCEQ. Periodically more sites are randomly selected and sampled each year. This data collected by TCEQ has been supplemented periodically by special studies conducted by EPA EMAP, and more recently National Coastal Condition Assessment studies. A few special studies conducted as part of Master theses and Doctoral dissertations provide snap shots of spatially intense data. Virtually nothing is known of the benthic organism population fluctuations on oyster reefs.
Seagrasses	A few studies have been conducted over multiple years that document the extent of seagrasses. These have been summarized in the Galveston Bay Status and Trends reports and State of the Bay reports
Wetlands	The status of wetlands has been documented in various GBEP proceedings and the National Wetland Inventory. Most recently GBEP funded studies by Drs. Jim Webb and John Jacob to assess the status and distribution of wetlands (Jacob and Lopez 2005; Webb 2005). Also, the HGAC has implemented a GIS tool that allows users to track land use changes. In addition, more recent spatial data on the distribution of wetlands have been captured by the Coastal Change Analysis Program (C-CAP). http://www.csc.noaa.gov/digitalcoast/data/ccapregional/
Oyster Reefs	GBEP and its predecessors, and TPWD have mapped oyster reefs in Galveston Bay. TPWD is currently mapping these areas.
Contamination of seafood – pathogens and toxics	The distribution of toxic compounds such as PCBs and Dioxin has been a major issue in Galveston Bay. Due to the lack of routine monitoring and poor understanding about the possible pathways it is difficult to evaluate the ultimate sources and transport mechanisms and effects on aquatic communities and humans. Modeling may be useful in identifying possible pathways in organic pollutant transport to target in future monitoring.

Table 4. Continued.

Features or resources of interest that are not being characterized (under monitored or not monitored) a. New generation synthetic organic compounds b. Land use changes at smaller time steps c. Point source loads – corrected d. Non-point source loads – updated for new land use e. Atmospheric loading and deposition d. Zooplankton e. phytoplankton	Many variables that may influence of the health of Galveston Bay are not being monitored or are rarely monitored. These are listed below: a) New generation organic compounds – e.g. estrogen mimics. Rationale: Compounds appear to be ubiquitous and in many cases cause changes in sex ratios of alteration of secondary sex characteristics of fish and wildlife. b) Land-use is now being monitored more frequently with the expanded use of satellites, aerial photography and LIDAR. Historically time steps often ranged between a few to several decades. More frequent steps are needed to relate changes to variations in water quality etc. c) Point source loading – trends in basin. Data is collected by TCEQ and EPA on self reporting data from various facilities. However, many errors are present. Other than targeted TMDLs there has not been a long-term trends assessment of this data. This loading may be crucial in understanding nutrient dynamics in Galveston Bay. d) Non-point source loading. It has been many years since the early 1990's since the last comprehensive non-point source loading study was done for the Galveston Bay watershed. e) Atmospheric loading and deposition. Currently there is virtually no atmospheric depositional monitoring of nutrients and other chemicals. Only a few studies conducted in the late 1990s and a few recent modeling studies provide data for loading estimates (Park et al. 2001). f) Zooplankton data other than information retained from HL&P power plant studies in the 1970s and 1980s is very limited to a few data sets. g) Only chlorophyll-a is routinely monitored by TCEQ and CRP partners. Recently Dr Quigg through funding from GBEP and GOMA has initiated phytoplankton studies to evaluate the seasonal response to hydrological conditions.

In addition to these indicators and associated monitoring programs the EMWG reviewed the original conceptual model goals from (McFarlane 1993) which could serve as a model for future model development. An excerpt of the overall goal for the conceptual model is provided below:

The goals 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, non-technical 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 its connections to adjacent habitat. (3) Simple technical models useful to decision makers, resource managers and by users describe the interconnectedness of the ecosystem.

Several selected secondary goals of the conceptual model listed by (McFarlane 1993) that apply as well to the task of development of an ecosystem model include:

Provide an "ecological manual" for the estuary that will simplify the real ecosystem while preserving essential features and improve communication between decisions makers, advisors and the public

Assist in the development of appropriate segmentation schemes, monitoring programs, assessment of cumulative impacts, qualitative and semi-quantitative models, and predictive quantitative computer based models which may be needed to meet program goals.

Codify scientific knowledge and theoretical constructs regarding the estuary to achieve scientific consensus improve communication and transfer this knowledge to other users of the bay.

It was felt that the goals are still valid for any future modeling effort and represent broad goals for ongoing monitoring efforts. These fall into the general categories of description, prediction and conceptualization of the system alone and with human interference or management actions applied. Based on our review of table 4 and examination of several conceptual modeling diagrams from (McFarlane 1993) the group considered whether we were monitoring the correct variables. An excellent example that was used is the information depicted in figure 6 from the original conceptual model document (Figure 8 this report). For example, many major processes illustrated in figure 8 are currently not being monitored and consequently it is difficult to provide input into any future quantitative model. Some examples include 1) quantification of the input of larval stages of fish and shellfish entering seagrasses and estuaries in general from the Gulf of Mexico, 2) quantification of riverine material input and 3) quantification of wading bird grazing impacts on soft bottom intertidal sediment communities. Several key diagrams in the Conceptual Model report were critically evaluated to determine what other key processes are not being considered in current monitoring and research programs. This included the relationship between larval settlement and recruitment in relation to freshwater inflow, microorganism communities in both natural and perturbed environments, various toxic chemicals and their potential receptors, and energy and material flow between upland, estuarine and near coastal environments.

The work group also a discussed the main resource management issues that affect Galveston Bay in order to select a suite of possible future modeling projects. The first topic discussed was our current approach to the analysis of the effects of freshwater inflow does not incorporate the complex interactions of freshwater inflow, sediment and nutrient transport, and influence on estuarine circulation. Some members stated that evidence from up and down the coast suggests that changes in salinity associated with altered freshwater flows seem to only exert localized changes in biota in the zone of highest dilution. Examples were given for both the Corpus Christi Bay and Matagorda Bay systems. Dr. McFarlane pointed out that current monitoring data does not seem to support the hypothesis that organisms are responding to changes in salinity in a predictable manner. This is because freshwater inflow as an independent variable influences salinity, nutrients and suspended solids.

In other words, x = freshwater inflow, $y1$ = salinity, $y2$ = nutrients and $y3$ = SS. Therefore:

$$y1 + y2 + y3 = x$$

This is also not a simple straight forward relationship since additional variables including flow duration, magnitude and frequency of the magnitude of hydrological events can also influence salinity, nutrients and sediment load.

Dr. McFarlane also led a discussion on the lack of correlation between salinity and many estuarine biota. He argued that oyster infection rates do not appear to be correlated with salinity. He explained that one possible hypothesis is that most estuarine organisms are widely tolerant of salinity fluctuations and therefore the primary mechanism by which freshwater inflow influences biota is through increased loading of nutrients and sediment which drives the phytoplankton based food web and provides essential sediment needed to stabilize shallow deltaic based wetlands.

Factors such as wind can re-suspend sediments, while high flows of freshwater in local bayous may even increase sediment loads of highly reduced marsh sediments thereby temporarily increasing deadly hydrogen sulfide concentrations and causing fish kills. This was observed during several recent hurricanes. Given that most Gulf of Mexico estuaries are very shallow with weak astronomical tides the role of wind is often overlooked as a significant factor influencing estuarine circulation.

In terms of water quality it appears that other than some limited cases of contamination by toxic compounds near industrialized sectors of the estuary, the main issues seem to be focused on indicator bacteria and lack of sufficient dissolved oxygen (hypoxia) in the tidal tributaries. In addition, the role of nutrient loading into the system and subsequent hypoxia events and/or harmful algal blooms is poorly understood.

Several members discussed the problem of lack of sufficient fisheries effort data to describe the influence of commercial fisheries on stocks of fish and shellfish. Some members argued that there does not seem to be a relationship between catch or even crude measures of catch per unit effort (CPUE) based on limited commercial fishing effort data and fishery independent estimates of abundance. A modeling project may be warranted to see if this pattern could emerge given various levels of commercial fishing effort. Another way of saying this is what level of fishing pressure would be needed to manifest a subsequent change in fishery independent measures of abundance.

Due to limited time considerations, Glen Sutton who was scheduled to give a presentation on the EcoPath model he has developed instead gave a brief overview and agreed to provide a more in depth presentation at a later date. Based on discussions of these topics the group adjourned and agreed to take a vote on a short list of topics that will be that outlined by the facilitator. In addition, the above the group critically evaluated several potential modeling topics.

Third Workshop

At the third and final workshop of the year that was held on December 10, 2010 the EMWG group met to refine modeling objectives and reduce the original candidate list to 1-3 feasible projects. Several criteria were used including likelihood of success, importance of the resource and whether management actions could change the state of the resource. In addition, Dr. Mustafa Mokrech agreed to present a management model he co-authored. The following members of EMWG attended this meeting:

George Guillen – EIH
Mustafa Mokrech - EIH
Jim Webb
Tyra Booe - TAMUG
Lisa Gonzalez - HARC
Robert McFarlane
Ligata Kukleye - TAMUG

At the beginning of the meeting the group tabulated the results of the votes for topics to be considered by future modeling projects Table 5. These topics were further explored and rational for each discussed along with reasons for each. These discussions are summarized in Table 6.

Table 5. Results of survey of candidate modeling projects.

Project	Votes
Habitat Loss	3
Climate Change	3
Water Quality	3
FW Inflow	1
Oyster Reefs	3

Table 6. Candidate list of ecosystem modeling projects.

Proposed Project	Justification	Issues/Comments
Climate Change Impacts	Major Driver Top down impacts on all systems - Influences sea level - Effects habitat (see Habitat Change) - Effects society ability to deal with changes in flood risk, etc.; resiliency Examples: Loss Wetlands → Decline in viability of wildlife and fisheries	Dependent upon IPCC predictions, need to modify for local conditions, challenge is to scale down meteorology Funding available Models available (e.g. Dr. Mokrech, CLIMSAVE model, UK *Coastal Simulator Model* developed at Tyndall Centre for Climate Change Research; Consequences of coastal change predicted by coastal simulator including impacts of sea-level rise and climate change, coastal management, coastal erosion (Mokrech et al. 2007a; Mokrech et al. 2007b) Many agencies already involved (e.g. NOAA, EPA)
Habitat Change Impacts – inclusive Subcategories: Oyster Reef Wetlands Estuarine Regularly Flooded Intermittently flooded Freshwater Tidal Non-tidal Open Water Open Bay Embayements Islands Upland Prairie Urban areas	Causative Factors: Climate Change Causative Factors: Urbanization Keystone species, indicator, ecosystem services: water quality, fisheries. Ecosystem services: water quality, flood protections, nursery habitat Fisheries Production; shrimp Bird sanctuary, habitat Ecosystem services: flood protection, water quality Human habitat; resiliency issues, green space	Immediate and long-term problems, funding and resources available Data available, extremely important issue for fisheries, water quality, environmental flows Data available, extremely important issue for fisheries, water quality, environmental flows Data available from both TPWD and others Colonial water bird counts but data accuracy, methodology issues. Endangered habitat, data available Data available

Proposed Project	Justification	Issues/Comments
Oysters and associated Reef General Model	Keystone Species Influenced by changes in freshwater inflow, water quality, harvesting	Existing modeling existing Monitoring by TPWD, Dermo watch Biology understood but more research needed
Water quality Alteration – general model and/or specific topics	Water quality influenced by: Freshwater inflow Point source loading Non-point source loading Atmospheric Deposition	All of these issues are influenced by management actions including water diversions, permitting and development and can be manipulated. Modeling provides useful information on future directions needed to control these sources of stress.

Dr. Mustafa Mokrech also provided a presentation on a modeling project he had worked on previously in England. He described the Tyndall Climate Change Simulator and Management Tool that was developed in the United Kingdom by him and his colleagues at the Tyndall Climate Change Research Group (Mokrech et al. 2007a; Mokrech et al. 2007b). He demonstrated how this tool which has a GIS interface and user friendly console can be used to simulate various management response scenarios that could be implemented in response to varying levels of climate change predicted by the most recent IPCC report and resulting sea-level rises. The purpose of the model was to inform local and regional managers on potential options that can be used to combat the impacts of sea level rise. The Climate Simulator and Management Tool appeared to be a very reliable tool for predicting possible community impacts and how these impacts could be reduced or mitigated by various management approaches. In addition, the model could be used to evaluate other stressors such as land-use change, subsidence etc. Overall the EMWG was generally impressed with the flexibility of the model and the ability to be adapted to various coastlines. Dr. Mokrech mentioned how the modeling approach has been extended to parts of African coastline and how it has been expanded and is being modified for various European scenarios (Mokrech et al. 2007b). Dr. Jim Webb asked Dr. Mokrech how much time and effort would it take to construct a model similar to one used in England that could be applied to Galveston Bay. Dr. Mokrech indicated that it would likely take at least 2 years with funding needed for reprogramming ranging up to $1.5 M. However, this is a very rough estimate and would ultimately depend on available resources in terms of background data.

A general discussion about how to prioritize the proposed modeling projects brought up at the workshop and voted upon by the membership. Based on the results displayed in Table 5, the EMWG had identified 5 potential future modeling projects. This included climate change, land-use alteration, oyster and oyster reef management, water quality (nutrients and toxic compounds) and freshwater inflow. Freshwater inflow alone received the lowest number of votes but was recognized as having many links to the other potential projects. For example freshwater inflow affects nutrients and toxic compound levels, oyster survival, and is in turn influenced by and is affected by land-use alteration, particularly changes from pervious to impervious surfaces. Members of the EMWG mentioned that in regards to climate change (an independent causal variable) the modeling question is usually a “top down”, (e.g. what global warming causes in terms of habitat loss, disease etc). In contrast modeling questions such as habitat loss (a dependent variable) the question usually takes the form of a “bottom up” topic, such as what is causing it? However, sometimes the question may take the form of a “top down” scenario. For example what does habitat loss lead to (e.g. reduction in wading birds)? Note, the causes of climate change as it applies to Galveston Bay Ecosystem modeling is a top down exercise that we would not likely pursue because the manipulation of causative variables that influence and cause climate change are beyond the scope of future climate change modeling projects at the local level.

The EMWG also discussed was the final priority ranking of potential modeling projects in terms of probability of negative effects occurring within a short versus long time period, and whether practical management alternatives are possible. A specific example that was discussed was the likelihood of experiencing negative effects from urbanization and habitat loss versus seeing an effect from climate change within the next 10-20 years. The most current population, water use and transportation projections indicate that population growth in the near future will exert tremendous pressure in terms of urban development, transportation, infrastructure and water use long before global climate change will likely exert projected impacts. Therefore land-use management and urbanization ranked higher in terms of immediate risks to the Galveston Bay ecosystem. In addition, land-use alteration ranked higher because local communities have more control over causative factors such as community development, and water use are comparison with global climate change.

Indicators that are currently used to assess the Galveston Bay ecosystem in the Status and Trends project were discussed. As mentioned in the first workshop, there are concerns by the GBEP that they may not be tracking the most appropriate indicators to assess the ecological health of Galveston Bay. According to Ms. Gonzalez who coauthored the GBEP indicators report, many of the current ecological indicators serve as high level ecological functions (Gonzalez and Lester 2008; Lester and Gonzalez 2005). An example of an ecological indicator is the number of individual commercially and recreationally important finfish species. However, intermediate trophic levels such as zooplankton, phytoplankton and benthos that represent important pathways between stressors and targets (e.g. nekton) are rarely or never monitored. Although there are only limited data from these trophic groups to inform modeling exercises, it may be possible through modeling to estimate a plausible range of parameter values (e.g. mortality, growth) that would support observed relationships between higher trophic levels and lower primary production. This approach is basically used by the fisheries ecosystem modeling using Ecopath with Ecosim (EwE) as a means to “balance” the trophic levels for which data is limited (Sutton and Guillen 2009; Walters et al. 2008).

By the end of the workshop the EMWG membership had generally agreed upon several recommendations. The EMWG recommended that:

1) Two to three ecosystem modeling projects should be pursued. These include one that focuses on oyster reef ecology and general land-use alteration including loss of green space, prairie and wetlands. Oysters which are a keystone species are the ideal system to evaluate for estuaries due to the linkages with other important components of the system including the open water plankton community and the feedback mechanisms that exist. Oyster reefs provide habitat for fish, wildlife and other biota, filter the water column and alter currents. In turn, oysters are affected by freshwater inflow and salinity, primary production, water quality and pathogens which are also secondarily influenced by the salinity. A modular modeling approach that could be built upon and expanded to other systems would also be desirable. Land-use alteration analysis with an emphasis on predicting impacts on critical habitats such as wetlands is the second modeling project recommended. Land-use alteration affects remaining green space including wetlands, prairies and forests which in turn influences ecological services such as reduction of non-point source runoff, fishery production and air quality improvement. The third modeling project would involve the evaluation of climate change effects including sea level rise and how it would affect critical resources including oyster reefs, wetland and seagrasses. An additional modeling component would be to evaluate how different management options in response to sea level rise would affect these resources and human society.

2). Funding should be pursued by GBEP and other resource agencies and organizations to support these and other proposed future modeling projects.

3) Future modeling efforts should consider various selection criteria including model simplicity and ability to provide sufficient data based on current and near future monitoring data, model economic costs (user license costs, developer costs and ongoing support), data and algorithm transparency, transferability (ability to share with others and have others modify), and expandability. Modeling tools need to provide simple but useful user interfaces that managers can use to interrogate the model with various options. Managers will need to be able to evaluate a range of actions that can be used to deal with future issues while receiving sufficient feedback from the model to understand repercussions of each alternative. Currently there are many candidate software packages that would meet these criteria.

4). The EMWG strongly recommended that the GBEP continue the EMWG process as a voluntary advisory group to the GBEP Monitoring and Research Committee. The group should meet at least quarterly or more frequently as needed to discuss modeling needs, seek funding opportunities and to provide a forum for the presentation of current and future modeling results.

The facilitator announced at the end of the meeting that future meetings will be held in 2011. The EMWG recommended that at the next meeting Dr. Jan Culbertson be invited to present her Oyster Model. Dr. Guillen also mentioned that Dr. Paul Jensen had volunteered to present recent water quality modeling experiences in the Galveston Bay watershed. The workshop adjourned.

Discussion and Recommendations

The three workshops were highly successful in developing a greater understanding of the need for ecosystem models for use by GBEP and other resource agencies. Direct benefits of this project included a better understanding of how ecosystem models can be used evaluate and clarify the processes affecting important natural resources of Galveston Bay. In addition, through the workshop process the EMWG was able to prioritize several potential projects that are currently not being conducted but are needed to address critical resource management questions. Notable accomplishments brought about by this process include the following achievements.

1. Establishment of the Ecological Modeling Work Group – EMWG.

The group will serve as an ongoing informal workgroup of the GBEP that will review and evaluate future modeling projects. Members of the group include members with expertise in modeling and/or use of models to evaluate management options. Another primary goals of the EMWG will be to identify resources including funding to meet future GBEP ecosystem modeling needs. It is expected that the group will meet quarterly or more frequently as needed. The first meeting in 2011 will be held between January and April 2011.

2. Review and confirmation of the Galveston Bay conceptual model.

The EMWG met and reviewed the Galveston Bay conceptual model. In addition, other Texas estuarine models were evaluation including the “Corpus Christi Bay” model. Based on input from various members it appears that the conceptual model is still valid and describes the major processes within the estuary fairly well. However, as specific modeling projects evolve it may be necessary to fine tune or update certain components of the conceptual model or add finer details to meet project objectives.

3. Establishment of desirable traits of ecosystem models

Various desirable attributes of ideal models were discussed during the several workshops. The most desirable traits included reasonable accuracy (as measured against reality), parsimony (simplest model best), applicability (is it the appropriate model), transparency (others can see logic and input of the model along with model calculations), and ability to be interface with other models to receive input or provide output. This may range from formal software integration to being able to translate output or input file formats. Other important desirable features include reasonable costs for the model developer, and ability to share produced models with other developers and/or users at little or no cost. In order for end users to use these models, they must be affordable and user friendly. For example, some software developers provide free “viewer” software versions at no cost so developers can share models to end users such as agency managers. The ability to integrate output into web applications is also highly desirable.

4. A review of major types of modeling approaches and products available for ecosystem modeling.

Several types of modeling approaches and platforms were discussed during the project. These ranged from specialized models to general purpose systems models. Although we cannot advocate any particular modeling platform, several software packages that are currently being used by agency staff should be considered for future quantitative use due their wide availability, relatively low cost and ability to share input and output. Two particular modeling platforms were identified including STELLA and EcoPath with EcoSim (EwE), due to the fact that TPWD staff is currently using these models for specific applications, including oyster reef management and blue crab population modeling. A list of some popular modeling platforms and a short description is provided in Appendix 2.

5. A review of current ecosystem modeling efforts within the Galveston Bay watershed.

During the workshops a variety of current and proposed modeling efforts were identified in the Galveston Bay watershed. The majority these efforts fell into three categories. These included 1) ongoing regulatory required TMDL and watershed water quality modeling (e.g. dioxin, bacteria, dissolved oxygen) on a segment by segment basis, 2) experiment fisheries modeling (e.g. EwE) and 3) coastal climate change/flood modeling by NOAA and other organizations (e.g. SLAMM modeling) (Warren Pinnacle Consulting Inc. 2011). Several new initiatives were identified including USGS SPARROW modeling associated with nutrient loading estimates for Texas Rivers and streams. The majority of TMDL related modeling efforts can be found on the TCEQ TMDL web site (http://www.tceq.texas.gov/implementation/water/tmdl/nav/tmdlbasins.html). The Texas Water Development Board also continues to support freshwater inflow modeling efforts in Galveston Bay. No new comprehensive modeling efforts were conducted during the SB3 environmental flow evaluation process, although the TWDB models TxBLEND (current model) and TxEMP (inflow model) using gauged and ungaged flows and precipitation were utilized to estimate salinity isopleths versus distribution of critical resources. This was done to assess risk levels at varying inflow levels and to estimate ideal conditions within Galveston Bay for certain species (e.g. oysters and submerged freshwater grasses) (http://midgewater.twdb.state.tx.us/); (Longley 1994). The availability of water given current and future permitted water rights is evaluated using the Water Rights Availability Model (WRAP) available from TCEQ (http://www.tceq.texas.gov/permitting/water_supply/water_rights/wam.html#used)

6. Prioritization and identification of ecological modeling projects.

Considerable effort was placed on developing a priority list of potential ecological modeling topics. This was a very difficult but essential task for the group. Due to the diversity of backgrounds and missions of some members affiliated organizations the list of topics was diverse. However, after multiple criteria the list was shortened to 2-3 main topics. The criteria that was used included 1) management need, 2) feasibility of accomplishing the model development, 3) importance of the resource to the functioning of the Galveston Bay ecosystem, 4) complexity of the task and possibility of local/regional management intervention, 5) availability of modeling approaches and 6) whether any organization was conducting or would likely conduct such a modeling effort in the near future. The three priority modeling subject areas selected for further consideration include:

1. Oyster Ecology and Reef System Modeling
2. Habitat alteration (terrestrial and wetland) and effects on Galveston Bay
3. Interaction of Climate Change with 1 & 2.

Justification for the proposed Oyster Reef Ecology System modeling project includes multiple reasons.

1. Oysters are a keystone species. Their presence dramatically affects the distribution of other organisms including primary producers and consumers by providing hard bottom habitat, filtering water, providing food for various aquatic and avian predators, and altering water currents

2. Adult oysters are sedentary and therefore serve as excellent sentinels of local water quality conditions.

3. Oysters are affected by fisheries, salinity, turbidity, temperature, and nutrient concentrations (indirectly).

4. Oyster pathogens are also differentially affected by the same variables

5. Oysters therefore integrate the effects of multiple stressors including freshwater inflow, harvest, climate change and pollution.

6. Oysters are commercially important at the local, state, regional and national level. They support a major seafood industry. This has become even more evident with the collapse of east coast oyster fisheries.

7. Management of many of these stressors previously mentioned is possible.

8. Management of oysters is of current and ongoing interest to TPWD, DSHS, TCEQ and TWDB (SB3 process).

9. Historical and current monitoring of oyster reefs, landings and pathogens is occurring but can be improved.

10. Many of the oysters life history parameters are well know or can be estimated through targeted research projects.

11. Modeling approaches by several investigators has been conducted over the last 10 years and may be applicable to current questions.

12. Funding for modeling efforts may be available directly and indirectly through multiple funding sources including TWDB (freshwater inflow studies), SB3 implementation, GOMA restoration funds, and NOAA restoration funds. Oyster restoration has become a major focus area in the Gulf of Mexico.

The were numerous reasons identified by the group that can be used to justify pursuing the development of a comprehensive ecological model dealing with the effects of land-use alteration with a focus on loss of green space (undeveloped land, native prairie, forests, islands, wetlands). They are listed below.

1. The threatened habitats including wetlands, islands, and prairie provide important ecosystem services including flood risk reduction, water quality improvement, support of fisheries species, habitat for wildlife including colonial waterbirds, and recreational opportunities. The loss of these habitats would likely have dramatic effects. Many organisms associated with these habitats would likely decline or disappear including up to 70% of the recreationally and commercially important species. Loss of dredge spoil islands and natural islands would lead to direct losses of nesting habitat for many migratory colonial waterbirds including state and federal listed species. In addition, species such as diamondback terrapin which avoid predators by living on these islands would likely decline.

2. Many of these habitats are irreplaceable once lost. Mitigation of their lost functions and services would be very difficult, costly and maybe impossible.

3. The habitats are affected by urbanization, freshwater inflow, water usage, subsidence, and climate change.

5. The habitats therefore integrate the effects of multiple stressors including freshwater inflow, sea level rise, and urbanization.

6. The resources and uses dependent on these habitats are commercially important at the local, state, regional and national level. The loss of wetlands would most likely translate into loss of property and natural resources.

7. Management of many of the stressors that affect these habitats although politically difficult is possible.

8. Management, preservation and restoration of natural habitats is of current and ongoing interest to local government, HGAC, NMFS, USFWS, TPWD, TCEQ and TWDB (SB3 process).

9. Historical and current monitoring and research projects documenting changes of land-use has been historically limited. However with the increasing use of GIS, LIDAR and satellite and aerial photography the situation is improving. Ground truth surveys of classification systems are probably needed for many areas.

10. Many of the attributes of these habitat types (soil permeability, chemical reactions, energy conversion have been estimated or can be estimated through targeted research projects.

11. Spatial mapping and non-point source pollutant and rainfall-runoff modeling approaches by several investigators has been conducted over the last 20 years and may be applicable to current questions.

12. Funding for modeling efforts may be available directly and indirectly through multiple funding sources including EPA, TWDB (freshwater inflow studies), SB3 implementation, GOMA restoration funds, NOAA restoration funds. Wetland restoration continues to be a major focus area in the Gulf of Mexico.

It was believed that climate change and associated sea level rise is a very important topic and potential modeling project. However, the ability to manage global climate change is limited at the local scale. However, the response to sea level rise will depend on various strategies including engineering and social responses. These responses will involve trade offs that influence other critical resources. For example, the building of levees and dikes to protect inland areas from intrusion of sea water as levels rise will protect private property but will limit the ability for wetlands and submerged grasses to migrate inland. However, policies and incentives that encourage the relocation of humans inland while leaving most the coastal intact in its former state would reduce this impact. The measure of coastal resiliency and tools to achieve it in response to storms and sea level rise has become a major management and research agenda topic at both all levels of government and internationally. Therefore the incorporation of a modeling project that evaluate the resiliency and relative impacts of various response measures to climate change in terms of overall benefits and costs is needed.   As previously mentioned modeling tools such as the methods developed by Dr. Mokrech in England may be needed to achieve this objective (Mokrech et al. 2007a). The protection and conservation priorities of the GBEP and partner organizations in regards to critical habitat and resources would need to be incorporated into this modeling approach if this project were to move forward. Currently the likelihood of funding for climate change modeling and related coastal resiliency activities looks promising. Organizations such as GOMA, NOAA and TGLO may have funding available for development of such a modeling tool.

Based on the results of three workshops and efforts of the EMWG it is strongly recommended that continued efforts are needed to pursue the development and production of proposed ecosystem based models recommended in this report. The recommended modeling projects are feasible based on available data and literature. These modeling projects would generate useful forecasts for management agencies, identify possible mechanisms by which resources are influenced, and help direct future research and monitoring. Currently the EMWG will continue to meet during 2011 and will continue as needed. The short term goal of the group will be to continue to clarify and assemble additional information in regards to the priority topic areas. The next meeting of the group will be between January and April 2011 and will likely continue through

2011. Researchers and scientists engaged with recent ecological modeling projects will be invited to present their methodology and results. Current members of EMWG will be encouraged to remain on the workgroup and will assist in further defining modeling goals and actively assist in identifying potential funding sources and participants to assist the goals of the group.

The eventual production of the proposed ecological models will help determine the critical pathways and processes that influence the important resources in Galveston Bay. These models will in turn will help guide and prioritize future monitoring and research. Creating an ecosystem model for one or more the priority project identified will assist GBEP in defining and attaining Galveston Bay Plan goals including protection of critical resources such as wetlands, important fisheries and improving water quality. The information learned from the modeling effort can be used for adaptive management in the area of water quality, freshwater inflows, fisheries regulations, and habitat protection. The proposed modeling projects and ongoing efforts by EMWG will likely result in the identification of important causal variables and processes that will help identify important data gaps and guide future environmental monitoring efforts. Methods used and knowledge gained from these future modeling are transferable to other Texas bay and estuaries. Once set up, these models can also be used to evaluate future proposed scenarios involving multiple stressors including the projected changes in sea level and land use, and resulting impacts on critical resources such as freshwater inflow, water quality, wetlands, oyster reefs, fisheries, and colonial waterbirds.

By the end of the project the EMWG had a clearer understanding of data needs and potential modeling tools that can help address critical information needs. In addition, we had identified the short-comings of the proposed modeling approaches. The intent is for this EMWG to continue beyond the scope of this project to begin implementation of the ecosystem modeling efforts.

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Appendix 1. List of Ecosystem modeling workgroup members.

Name	Affiliation	Subject Matter Expertise
George Guillen	EIH	Fisheries, Water quality, freshwater inflow
Glen Sutton	TPWD	Modeling, fisheries
Mustafa Mokrech	EIH	GIS, modeling, climate change
Bob McFarlane	Consultant	Ecology, conceptual modeling, freshwater inflow
Woody Woodrow	USFWS	Wildlife habitat
Mike Turco	UGSG	Hydrology, freshwater inflow
Jim Webb	TAMUG retired	Coastal wetlands, plant communities
Tyra Booe	TAMUG (A. Quigg student)	Phytoplankton, nutrients
Lisa Gonzalez	HARC	Ecology, water quality, data synthesis and trends
Ligita Kuklyte	TAMUG (Dr. Wood student)	Heavy metals, modeling
Paul Montagna	TAMUCC	Benthic communities, conceptual modeling, freshwater inflow
Jan Culbertsen	TPWD	Oysters, modeling
Jamie Schubert	TPWD	Coastal habitat, restoration
Paul Jensen	PBS&J	Water quality, modeling
Tom Calnan	GLO	Coastal habitat
Robert Burgess	TWDB	Coastal resources, water quality
John Jacob	Sea Grant	Wetlands and soils, community development
Linda Broach	TCEQ	Benthic communities, water quality
Joe Trungale	Consultant	Hydrology, freshwater inflow
Robin Brinkmeyer	TAMUG	Microbiology ecology

Appendix 2. List of modeling software and platforms discussed and/or used in the Galveston Bay watershed.

Model and/or Sponsor	Type	Media or Application
Load Duration Curves	Water Quality Model	Ambient water, simple with limited assumptions, used in bacteria TMDLs locally sediment
BLEST	Watershed Water Quality Model	Ambient water TMDLs bacteria
EFDC Model	Water and sediment quality model, hydrological component, rivers, lakes, and estuary	Very powerful platform, being used for some TMDLs in Galveston Bay. DO, nutrients, sediment, toxics, bacteria, temperature
BASINS	Watershed modeling platform, facilitates use of GIS data with various water quality and hydrodynamic models	Various water quality parameters, now uses open source GIS software. Not used much in Texas, but extensively in other states and countries.
AQUATOX	Bioconcentration model in water, sediment and organisms. Ecological risk	Water, sediment and biota. Free from EPA, limited support and training classes. Limited use in estuaries. Some “training” scenarios in Galveston Bay.
BASS	Ecological and human health risk bioconcentration model, metals and organics	EPA, free.
QUAL-TX, QUAL-2K	Lakes and River water quality model	Ambient water, TMDLs, DO, nutrients, sediment, toxics, bacteria, temperature
HSPF	Watershed, lakes, and River water quality model	Ambient water TMDLs, DO, nutrients, sediment, bacteria, temperature, evaluate land-use
N-SPECT (NOAA)	Non-point source loading watershed tool	Free, need ArcGIS, but new version will use open source free GIS like BASINS.
PRISM, tidal box model	Estuary, bay	Ambient water, TMDLs, sediment and bacteria
WASP	River and estuary water quality model, lakes	Ambient water, TMDLs, DO, nutrients, sediment, toxics, bacteria, temperature
SWAT	Watershed, lakes, and River water quality model	Ambient water TMDLs, DO, nutrients, sediment, bacteria, temperature, evaluate land-use
SWMM	Watershed and River water quality model	Ambient water TMDLs, nutrients, sediment, bacteria, evaluate land-use
SPARROW	Watershed model USGS	Nutrients, sediments
SELECT	Watershed Water Quality Model	Ambient water TMDLs, select

Appendix 2. Continued		
Model and/or Sponsor	Type	Media or Application
Simile. Commercial	Systems Icon Based Modeling Platform	Various, numerous ecological models have been developed. Education versions are free, but limited functionality. Being used by EPA for Tampa Bay model.
Madonna Commercial	Systems Icon Based Modeling Platform.	Differential equation model can be used in conjunction with STELLA. Relatively inexpensive
STELLA Commercial	Systems Icon Based Modeling Platform	Widely available. May be able to produce shareable user models, otherwise may be too costly. Being used by TPWD for oyster model.
Vensim Commercial	Systems Icon Based Modeling Platform	Widely available, used extensively in Europe. Some ecological and environmental models have been developed.
GoldSim Commercial	Systems Icon Based Modeling Platform	Expensive. But contains more features for contaminants modeling. High end model
PowerSim Commercial	Systems Icon Based Modeling Platform	Widely available.
SLAMM, Pinnacle Consulting	Hydrological, sea level rise	Sea level, land coverage.
TxBLEND, TWDB	Hydrological, currents	Coastal currents and tides
TxEMP (including rainfall/runoff) TWDB	Freshwater inflow optimization model to find salinity ranges supported of target organisms	Physical model, salinity and organism occurrence.
EcoPath with EcoSim (EwE) TPWD local user.	Trophic level model used to evaluate various fishery options, can indirectly evaluate other factors, e.g. habitat loss and freshwater inflow	Trophic level model, free with limited support. Sometimes buggy. Long tract record. Has been used in various Waterbodies and fisheries. Can handle various levels of data availability.
ATLANTIS, New Zealand	Fisheries Ecosystem Model, accepts environmental and biological data, very flexible	Free, but very steep learning curve. Requires considerable data to run.
VORTEX	Demographic Life History Model, used with endangered species to determine risk of extinction	Free. Specific application only. Can be used to evaluate loss of critical habitat. Learning curve. Some courses available
HEP (Habitat Evaluation Procedures) Models - FWS	Habitat Models for selected species	New GIS support, free. FWS recognized. Some application and can be used to evaluate loss of habitat.
EcoLogical (HGAC land use change predictive model)	Not really a model but display system to evaluate changes in habitat based on predicted changes and resulting changes in ecological services. Terrestrial only	Free from HGAC and online.