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Exploring Hydrodynamic Modeling of Texas Bays

with focus on Corpus Christi Bay & Lavaca Bay

by

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Abstract

The work presented in this report is the basis for a portion of the author's dissertation research. On a grand scheme, this research will enhance the effectiveness of hydrodynamic modeling and data development for Texas waterbodies, as well as for TMDL modeling in the United States. As of yet, this work is unfunded, which allows the author great flexibility in his choice of subject, project, and timeframe. However, the search for funding is far reaching and constant. The results presented in this report will likely serve as the basis for future funding proposals.

The purpose of this project was ultimately to develop a hydrodynamic model of Corpus Christi Bay along the Gulf Coast of Texas. Field data has shown that seasonal hypoxia occurs near the benthic environment within the southern section of the bay near the interface with Laguna Madre. Previous modeling studies have not identified the causes of this hypoxia. However, the previous modeling attempts were 2D in nature and used simplified inputs and boundary conditions. A sophisticated 3D model incorporating a wide range of environmental variables will likely reveal those factors leading to the hypoxia.

In order to develop such a model, much environmental and spatial data needed to be collected. This data includes information on regional wind patterns, tidal data, river inflow data, and weather data. It also was necessary to develop a methodology for bathymetry data generation using the ArcView/ArcGIS software, to develop a methodology for adjusting the bathymetry to include changes, and to develop a methodology for linking the generated bathymetry into the ELCOM hydrodynamic model. It was also necessary to develop a methodology for displaying and processing the ELCOM model results in the ArcView/ArcGIS system. Such a representation will be useful in disseminating the model results in a form that will allow a greater number of users to view, manipulate, and make decisions based on this data.

Finally, the robustness of the ELCOM model needed to be ascertained. Hydrodynamic models should produce accurate results with any set of spatially consistent input data. To test the robustness of the ELCOM model, model runs were to be developed with spatial input data identical in every way, except for the data orientation with respect to the model grid. A methodology for creating, comparing, and displaying results in various spatial orientations needed to be developed and tested. For this purpose, Lavaca Bay was used as the study area. Lavaca Bay contains two approximately linear features in its bathymetry that would suggest the data orientation might affect the model results.

The author hoped that working on this project would provide him with insight into all aspects of the hydrodynamic modeling process. Although modeling results were not obtained, the basis for future modeling efforts was firmly developed. This project also generated ideas for other avenues of research which might be included in the author's dissertation. These ideas are presented in the final section of this report.

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Introduction – Hypoxia in Corpus Christi Bay

Corpus Christi Bay is a micro-tidal estuary located along the Texas Gulf Coast near Corpus Christi, TX and Port Aransas, TX. It is a primary bay that flows into the Gulf of Mexico through a ship channel, and exchanges flow Nueces Bay, Oso Bay, Laguna Madre, and Redfish Bay around its edges. Mustang Island is the barrier island that separates most of the bay from the Gulf of Mexico.

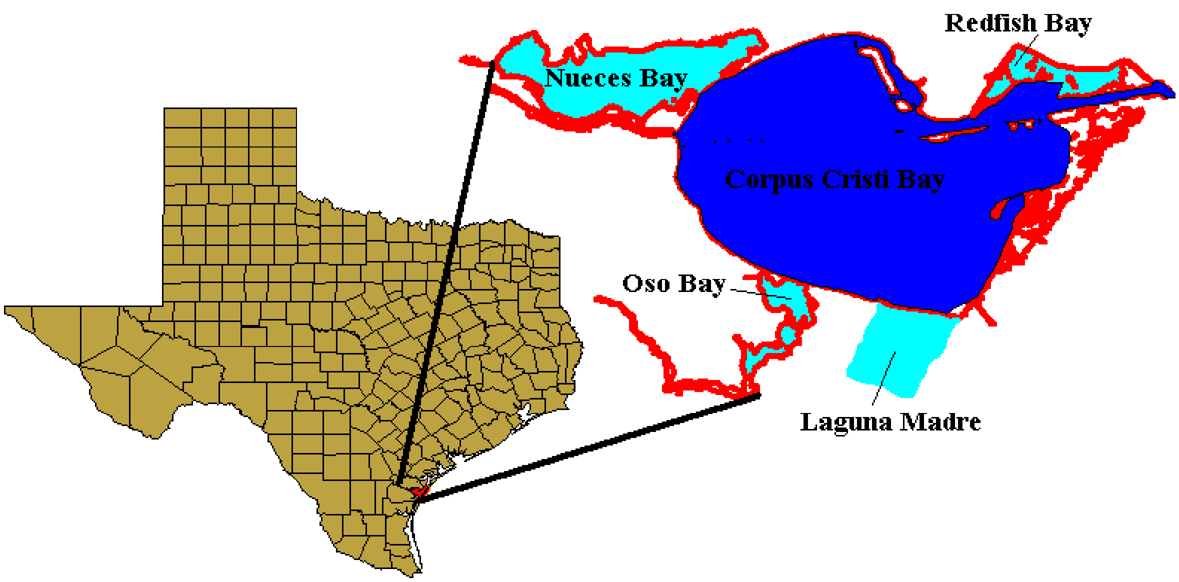


Figure 1 – Corpus Christi Bay, located along the Texas Gulf Coast

Hypoxia, operationally defined as a dissolved oxygen concentration less than 2.0 mg/L, has been observed periodically during the summer months in the southern part of Corpus Christi Bay (Ritter and Montagna, 1999). The hypoxia occurs only in the bottom most section of the water column, and only in the southern portion of the bay close to Laguna Madre. Periodic sampling has yielded an approximate region of the bay which is hypoxic during the summer months (Ritter and Montagna, 1999). Outside of this region, the bay waters are "estuarine hypoxic" which is a working definition signifying that the dissolved oxygen levels are low, but not less than 2 mg/l. The remaining part of the bay is normoxic and does not demonstrate a lack of dissolved oxygen above the benthos (Figure 2).

It is likely that the hypoxic develops due to the BOD of the benthos and the lack of oxygen transfer from the surface. This lack of transfer is suspected despite the fact that shallow estuaries like Corpus Christi Bay are often assumed to be completely mixed and uniform with depth. This assumption is valid for systems in which the wind stress at the surface generate enough turbulent motion in the water column so as to make the water column vertically homogeneous.

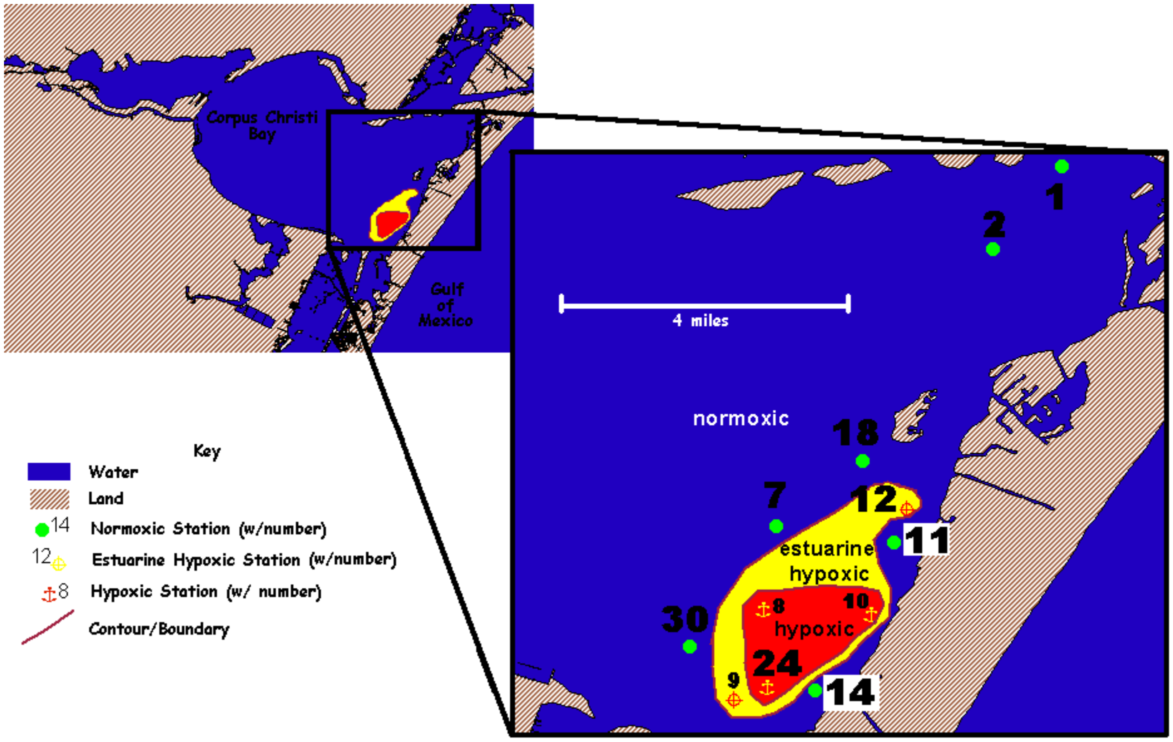


Figure 2 – Map of Corpus Christi Bay showing hypoxic, estuarine hypoxic, and normoxic zones. Numbers refer to sampling locations as developed by Ritter and Montagna (1999).

Other sources of turbulence that may lead to increased vertical mixing in the water column are local inflows to the bay and the general water circulation patterns in the bay. The surface thermodynamics are also important, although the evaporation at the surface often tends to produce more saline water at the surface then at depth. This yields density driven mixing, with water of greater density overlying water of lesser density, which is of course an energetically unstable situation.

The turbulence that leads to water column mixing is responsible for eliminating water column stratification. However, stratification is theoretically achievable if the environmental forcings contributing to the turbulence are temporarily relaxed. If the water column were stratified, then mixing of dissolved oxygen from the surface to the benthos becomes much more difficult. This theory is supported by the water column measurements, which show that hypoxia occurs only at locations where the water column demonstrates a salinity stratification (Figure 3). This modeling effort will attempt to identify the degree to which any environmental forcing relaxation contributes to turbulence reduction and the resultant stratification in the hypoxic regions of Corpus Christi Bay.

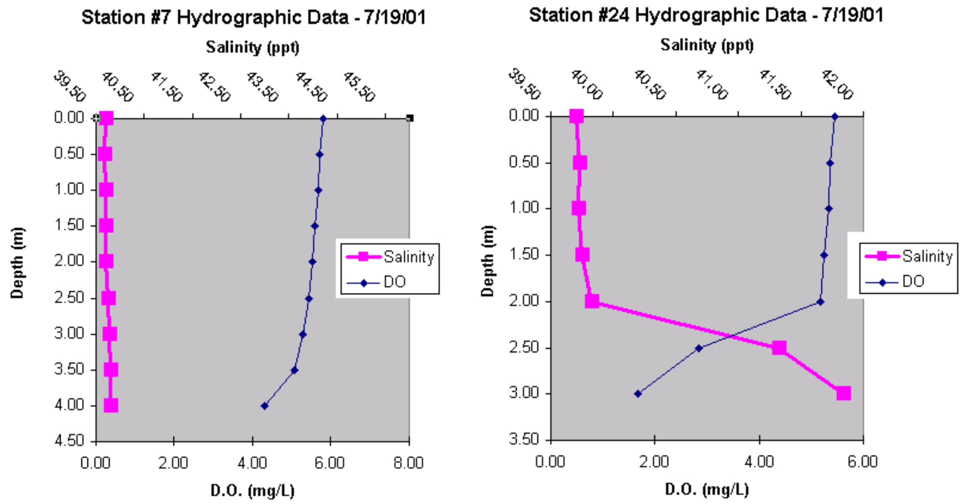


Figure 3 – Salinity and D.O. values vs. Depth for normoxic and hypoxic stations – stations with significant salinity stratification exhibit hypoxia. (Data sampled by author)

Aside from the relaxed environmental forcings, two other factors have been considered as contributing to the hypoxia in Corpus Christi Bay (Ritter and Montagna, George Ward, Personal communication). They are:

- Hypersaline groundwater inflow in the hypoxic region
- Hypersaline water influx from Laguna Madre or Oso Bay
- Bottom water stagnation due to depressions in the bathymetry

These possibilities are also to be addressed through modeling in this project. The existence of flow stagnation in the hypoxic region and influx from Oso Bay have been verified by previous modeling studies, however these studies did not address these topics with respect to hypoxia concerns.

TxBLEND Modeling – Corpus Christi Bay National Estuary Program

In 1997 the Texas Water Development Board (TWDB), in conjunction with the Corpus Christi Bay National Estuary Program, published the results of a modeling study on the estuaries along the Texas Gulf Coastal Bend. This modeling study included Corpus Christi Bay, Laguna Madre, Nueces Bay, Oso Bay, Redfish Bay, Aransas Bay, Copano Bay, Baffin Bay, and its smaller offshoot bays (Figure 4). For descriptive purposes, the aforementioned bays are referred to as the “estuarine system.” The purpose of the modeling effort was to determine the effects of structures and water use practices on the circulation and salinity patterns within the estuarine system. The model of choice is the 2-dimensional, depth averaged finite element model TxBLEND.

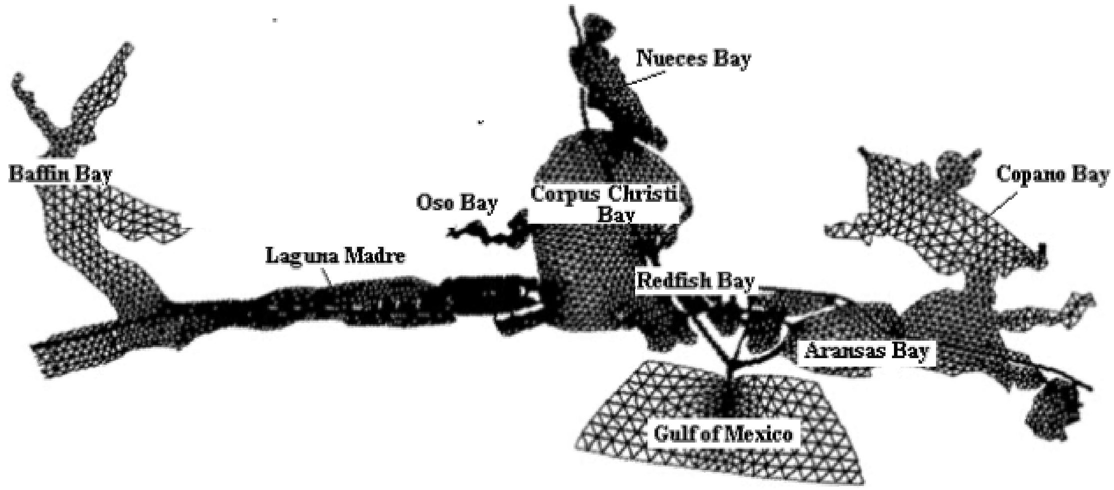


Figure 4 – TxBLEND Finite Element Grid w/ waterbody labels (modified from CCBNEP, 1997)

The TxBLEND finite element grid consisted of 8191 triangular computational cells across the entire estuarine system. The size of each cell is reflective of the level of detail required from the results. As shown in Figure 4, the smallest computational cells (yielding the most accurate results) are located at the interface between Laguna Madre and Corpus Christi Bay, between Nueces Bay and Corpus Christi Bay, and along the Corpus Christi Bay ship channel. These were the specific areas of most interest to the TWDB at the time of the modeling study. The computational cells overlying the region of hypoxia addressed in this work were approximately average in size and accuracy for the TxBLEND study. Due to the large size of the estuarine system and the specific interests of the TWDB, the finite element grid used does not provide much detail in the region of hypoxia in Corpus Christi Bay.

The TxBLEND model applies the wave continuity equation, the momentum equation, and the Convective-Diffusion Equation to solve transport and circulation problems. These equations, respectively, are given mathematically as (CCBNEP, 1997):

Eqn. 1
$$\frac{\partial^2 \xi}{\partial t^2} + G\frac{\partial \xi}{\partial t} - \nabla \bullet \left\{ \nabla \bullet \left(H\vec{V}\vec{V} \right) + gH\nabla\xi + \frac{gH^2}{2\rho}\nabla\rho + f \times H\vec{V} - HA \right\} + (G-\tau)\nabla \bullet \left(H\vec{V}\right) - H\vec{V} \bullet \nabla\tau = G\cdot(r-e)$$

Eqn. 2
$$\frac{\partial q_i}{\partial t} + \frac{\partial u q_i}{\partial x_i} + \frac{\partial v q_i}{\partial x_i} + gH\frac{\partial \xi}{\partial x_i} + \tau q_i = r_i$$

Eqn. 3
$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} - \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) = s$$

In these equations, most terms are defined in the standard nomenclature. However, it should be noted that ζ is the water surface elevation, τ is the bottom friction parameter, r_i represents forcing terms such as wind stress and the Coriolis parameter, and s is a source term for the substance considered in the C concentration term. The most interesting parameter in this set of equations is the parameter G, which is a nonphysical parameter included in order to force the wave equation to also satisfy the general continuity law in fluid mechanics. This parameter is system/model specific and is often determined by trial and error in order to produce the best, most stable model results. In a rough way of speaking, it is a "fudge-factor" term, which while computationally necessary, causes the modeling results to be dependant on non-environmental principles. This term slightly limits the credence of the model results, although it does provide a rough approximation of the errors obtained by representing a physical system in mathematical terms.

The main drawback of the TxBLEND study with respect toward its applicability in modeling hypoxia is that it is a depth averaged model. As such, it assumes the water column to be completely uniform in the vertical, therefore it assumes stratification in salinity and dissolved oxygen is not present. In order to accurately model vertical gradients in the water column, a 3-D model is needed.

The results of the TxBLEND study are useful, however, in that they demonstrate that the region of hypoxia in Corpus Christi Bay is also a region in which the water circulation is minimal (Figure 5). Also, the flows from Oso Bay and Laguna Madre are easily seen in the TxBLEND modeling results, which lends support to the theory that these flows affect the water column in the hypoxic region.

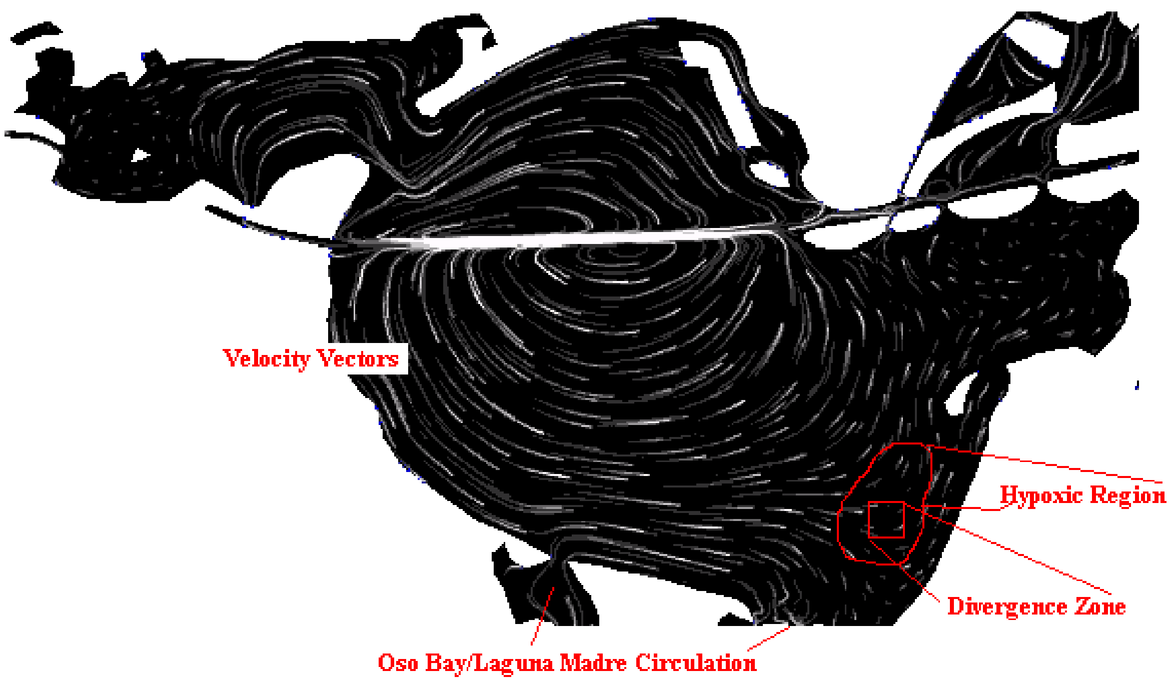


Figure 5 – TxBLEND Results showing Flow Stagnation in the Hypoxic Region, Circulation from Oso Bay to Laguna Madre

Another interesting result from the TxBLEND modeling is the depth averaged salinity values calculated for the Upper Laguna Madre/Southern Corpus Christi Bay area (Figure 6). These values are considerably lower than the measured values presented in Figure 3, suggesting that either the TxBLEND values are too conservative or that they did not consider the full affects of evaporation on shallow estuarine systems. Corpus Christi Bay and most of the other bays in the estuarine system are know to have salinities greater than the average marine environment because they receive relatively little freshwater inflow and because the bays are strongly evaporative. It is possible that the TxBLEND calculated salinities are from a period of low evaporation, which would cause the salinity values to be less than those measured in the summer (presented in Figure 3). However, the difference in salinities between Figure 3 and Figure 6 seems too significant to be due solely to a difference in seasonal evaporation.

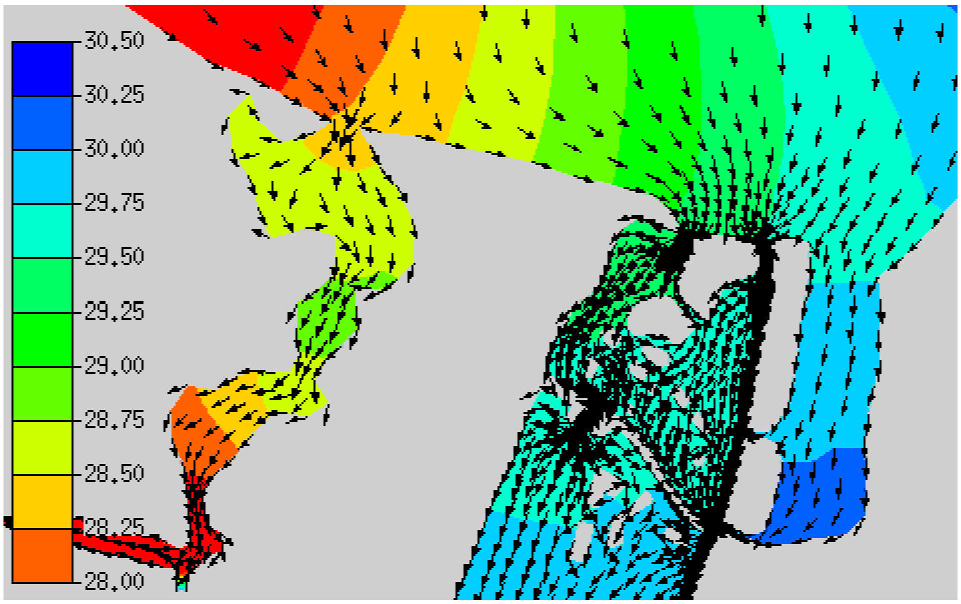


Figure 6 – TxBLEND calculated Salinities (ppt) for Oso Bay, South Corpus Christi Bay, and Laguna Madre. Salinities are much less than those presented in Figure 3 and measured in the hypoxic region. Note: The circulation flow between Oso Bay and Laguna Madre was not included in generating this plot (CCNEBP, 1997)

The TxBLEND modeling results, while questionable, are useful in supporting the hypothesizes leading to the cause of hypoxia in Corpus Christi Bay. However, the model itself is not capable of calculating the salinity gradients with depth that are necessary for truly understanding this complex system. For this, the 3D model ELCOM is required.

The *E*stuary and *L*ake *COM*puter Model (ELCOM)

The *E*stuary and *L*ake *COM*puter model (ELCOM) is a three-dimensional finite volume model developed by Dr. Ben Hodges at the University of Western Australia in 1999. It has been applied to the modeling of internal waves in Lake Kinneret, Israel (Hodges et al, 2000), modeling circulation patterns in Lake Maricaibo (in development), Venezuela, and modeling tidal influences on the Swan River Estuary in Western Australia (in development). The model has proven to yield extremely accurate results as compared to field measurements, and it is beginning to be used for modeling waterbodies in Texas and the United States.

The ELCOM model solves the Reynold's Averaged Navier-Stokes (RANS) equations for fluid flow using various turbulence modeling schemes. The model considers the affects of tidal flux, riverine flux, wind forcing, groundwater influx, and surface thermodynamics in predicting circulation patterns. It performs on a uniform X,Y grid with user-defined variable spacing in the Z (depth) direction. The numerical schemes used to solve the RANS equations are semi-explicit and second-order accurate in space. Unlike the TxBLEND model, the governing equations in ELCOM do not include any non-physical G terms. These equations are derivations of the basic equations of fluid mechanic, namely the continuity equation, the momentum equations, and the transport equations:

Eqn. 4
$$\frac{\partial U_\alpha}{\partial t} + U_j \frac{\partial U_\alpha}{\partial x_j} = -g\left(\frac{\partial \eta}{\partial x_\alpha} + \frac{1}{\rho_o}\frac{\partial}{\partial t}\int_{z'}^{\eta} \rho' dz\right) + \frac{\partial}{\partial x_1}\left(\nu_1 \frac{\partial U_\alpha}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\nu_2 \frac{\partial U_\alpha}{\partial x_2}\right) + \frac{\partial}{\partial x_3}\left(\nu_3 \frac{\partial U_\alpha}{\partial x_3}\right) - \varepsilon_{\alpha\beta} f U_B$$

Eqn. 5
$$\frac{\partial U_1}{\partial x_1} + \frac{\partial U_2}{\partial x_2} + \frac{\partial U_3}{\partial x_3} = 0$$

Eqn. 6
$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x_J}\left(CU_J\right) = \frac{\partial}{\partial x_1}\left(\kappa_1 \frac{\partial C}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\kappa_2 \frac{\partial C}{\partial x_2}\right) = \frac{\partial}{\partial x_3}\left(\kappa_3 \frac{\partial C}{\partial x_3}\right) + S$$

These equations are similar in appearance to those used in the TxBLEND model, except the ELCOM equations necessarily include terms related to the 3rd dimension. Also, The ELCOM transport equation (Eqn. 6) does not consider velocities and concentrations as non-conservative quantities in the advection term, as is considered in the TxBLEND formula.

In solving these equations, ELCOM requires numerous boundary conditions. These conditions may be temporally constant or variable, and may be either uniform or variable across the computational space. ELCOM models include numerous environmental forcing terms as boundary conditions. These terms are:

- Tidal Data
- Wind Data (Direction and Velocity)
- River Inflow/Outflow Data
- Evaporation/Precipitation Data
- Surface Thermodynamics Data (Air/water temperatures, solar radiation, etc)
- Salinity/Concentration data
- Groundwater inflow/outflow data
- Surface runoff data

Each of these datasets must be in a format readable by ELCOM, and the proper formatting is discussed in the next section.

ELCOM itself is a FORTRAN program, which produces results that may be analyzed using the MATLAB software. This software is a complete package for the analysis, processing, and display of mathematical quantities. The model user familiar with ELCOM can customize the model output in order to display the types of data desired. Some possible outputs derived within MATLAB are: circulation movies, surface plots, concentration vs.

depth plots for any location within the system, concentrations along a transect of the system, concentrations at a certain depth in the water column, etc. The connection with MATLAB gives the user the freedom to develop the results in manners most applicable to complete their tasks. This is a distinct advantage of other hydrodynamics models which include results-processing software.

Part 1 – Hydrodynamic Model Development – Corpus Christi Bay

The first step in developing an ELCOM model for Corpus Christi Bay was to gather data related to the geometry and environmental forcings within the bay system. Where possible, actual measured data is preferable over data predicted from equations. For example, in determining the cause of summer hypoxia, it is best to use tidal data measured during the hypoxia's existence rather than tidal data predicted from sinusoidal equations. However, often such data is unavailable or at best sparse. This is nearly always the case when wind data is considered. One may have a general idea of wind speed and direction across a bay, but the only available measurement is from one or few stations near the system. In such cases, the data needs to be interpolated based on scientific principles. The gathering and interpolating of environmental forcing data is discussed in the following sub-sections. In many cases, the methodology for obtaining data is discussed, although the data has not yet been obtained. Not all environmental forcing data was obtained for this project, and subsequently no ELCOM model results were generated. This is because the ELCOM model available to the Author has not yet been configured to run within the Windows computer environment. As such, the author decided to concentrate this semester efforts into processing some available environmental data and developing linkages between the ELCOM/MATLAB programs and the ArcView/ArcGIS programs.

Also, some of the environmental forcing data will be variable within the planned ELCOM runs. In such cases, the variables to be explored will be discussed. The first environmental forcing term that is included in a model has to be the bathymetry, because it is from the bathymetry that the model is framed.

Bathymetry Data for Corpus Christi Bay – GIS Development

ELCOM requires that the study area be divided into computational cells of equal width and length in the horizontal but of varying layer thickness within the vertical. This allows the user to partition the computational space in order to best meet the needs of the project. For example, if the benthic boundary layer is the focus of the modeling effort, then the bottom-most cells would best have much smaller thicknesses than the surface cells. This is yet another example of the flexibility inherent within ELCOM that allows the model to be adapted to simulate various aspects of environmental problems.

The horizontal dimensions of each cell must be equal, which requires the map view representation of the cell faces to be squares. This characteristic is a common characteristic of all Digital Elevation Models (DEMs) used and generated in the ArcView/ArcGIS software packages. DEMs are uniform planar grids that store the elevation of the land surface covered by each grid cell. DEMs have proven useful in automatic delineation of watershed boundaries for floodplain analysis and are very useful in the field of water resources engineering. This utility has been expanded in the sense that GIS software can be used to generate DEMs used as bathymetry files in ELCOM. The process for this generation is discussed in depth in the following section.

One notable benefit of using GIS to generate ELCOM bathymetry files is that it allows the user to easily modify the bathymetry based on spatial changes to the study area. For example, Corpus Christi Bay contains a set of ship channels that are included within the bathymetry. If one desired to model the circulation patterns within the bay without the presence of the ship channels, all that would be required is to remove the channels from the DEM. As shown in the following section, all that is required to do this is to combine a gridded representation of the channels with the existing DEM. The model user can make this modification in one step, and does not need to adjust the bathymetry values of each cell in the DEM individually. Therefore, the use of GIS to generate bathymetry files greatly enhances the user's ability to rapidly determine the affects of bathymetry changes on modeled systems.

Bathymetry data was obtained from the GEODAS data package (NOAA, 2001), available from the National Geophysical Data Center. This branch of the National Oceanic and Atmospheric Administration (NOAA) strives to provide global environmental and satellite data for use by scientists, politicians, and the general public. The GEODAS package is a formalized database of environmental data, including bathymetry data and soundings collected and reported since 1930. The program output may take on various forms. For this modeling effort, the program generated a text (.txt) file that contains the latitude, longitude, and water depth of every sounding available in the database.

This text file was converted into a database file (.dbf) in Microsoft Excel, and it was then imported as a table in ArcView. Using the "Add Event Theme" function, the *bath_points.shp* theme was created. This theme consists of a point for each sounding location (latitude and longitude), and the location is attributed with the reported sounding depth (meters relative to MSL).

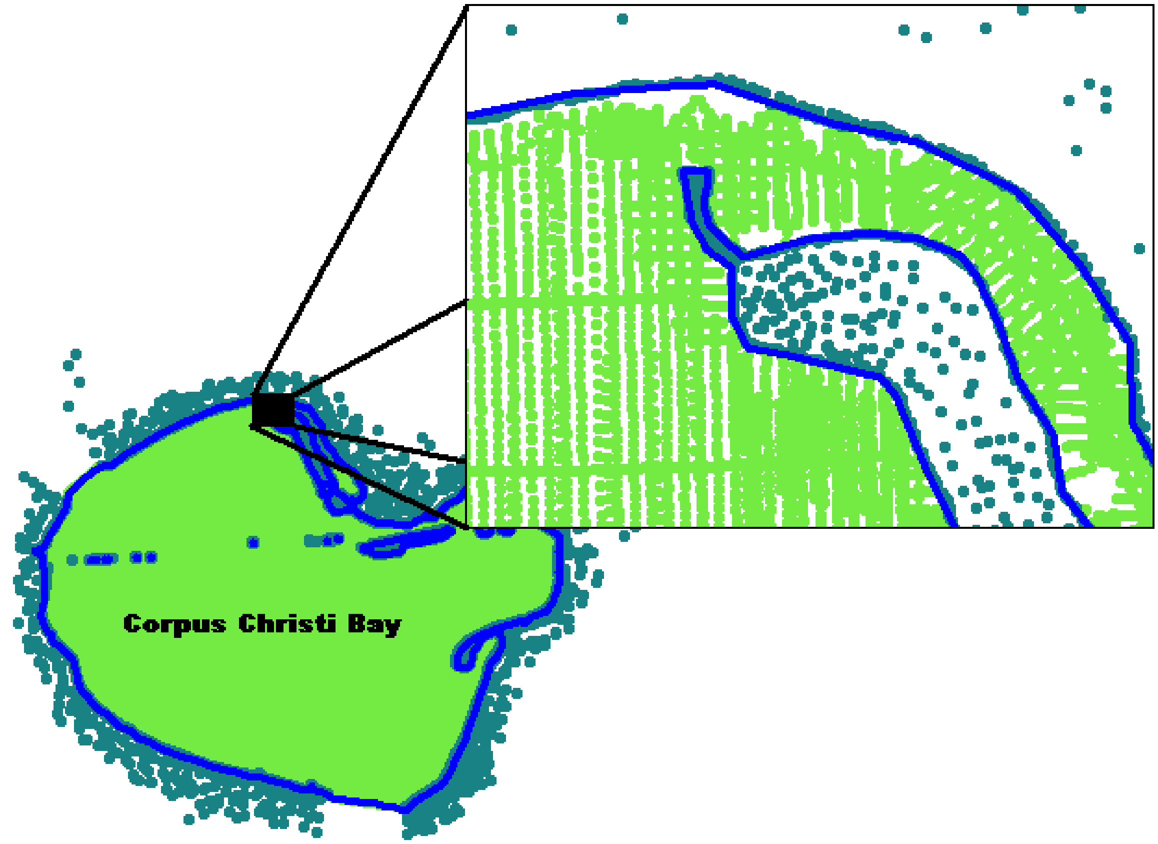


Figure 7 – Sounding points in the bath_points.shp theme

Nearly 147,500 soundings are included in the *bath_points.shp* theme, and these points were derived from numerous surveys. The consistency of these surveys was not investigated. On average, there is 1 sounding for each 2,500 m^2 area of the bay, corresponding to one measurement per each 50m x 50m surface area across the bay. This suggests that the bathymetry data justifies the generation of a bathymetry grid consisting of 50m cells. Such a grid would prove cumbersome in the ELCOM calculation process. A 250m grid was developed instead as a first attempt at setting up a working model of the Bay.

The shape of Corpus Christi Bay was obtained from the National Hydrography Dataset (NHD) published by the USGS. This dataset, in geographic projection, provided a polygon theme detailing the Bay boundaries as well as the many islands within the Bay. In order to incorporate the islands and bay boundaries in the interpolated bathymetry grid, "land" soundings were manually added to the *bath_points.shp* theme. These artificial sounding points (the darker dots in Figure 7) each have an elevation equal to that of MSL (0 meters). The artificial soundings were densely located along all edges of the bay and its islands, as well as sparsely located on the landmasses surrounding the bay. These points were added so that the grid interpolation procedure would generate a bathymetry grid containing the value "0" for land cells. These "0" valued cells would be recognized as land cells by ELCOM, and would not be included in the model calculations.

The addition of the artificial soundings also ensures that the bay bathymetry gradually slopes up to MSL along the bay edges. This gradual slope would not be present if the interpolation were performed without the artificial soundings. However, artificial soundings were not included at the interface between Nueces Bay and Corpus Christi Bay, nor at the interface between Laguna Madre and Corpus Christi Bay, because no such slope occurs at these locations. Artificial soundings were included at the interface between Corpus Christi Bay and Oso Bay, and that between Corpus Christi Bay and Redfish Bay. These points were included because bathymetry data suggested Oso Bay was significantly shallow at the interface, and because Redfish Bay is not likely to have an affect on the circulation patterns within Corpus Christi Bay (Paul Montagna, personal communication). These assumptions are to be verified by the modeling, and the bathymetry may be adjusted based on the preliminary modeling results.

The interpolation was performed with the "Interpolate Grid" function available with the ArcView Spatial Analyst Extension. The grid is developed with the Inverse Distance Weighted (IDW) interpolation technique, which makes use of the points closest to a given location in order to estimate the value of the elevation at that location. The bathymetries used here were created by accepting the ArcView IDW default parameters. These parameters are: "Nearest Neighbors, "12" neighbors, "2" power, and "no barriers."

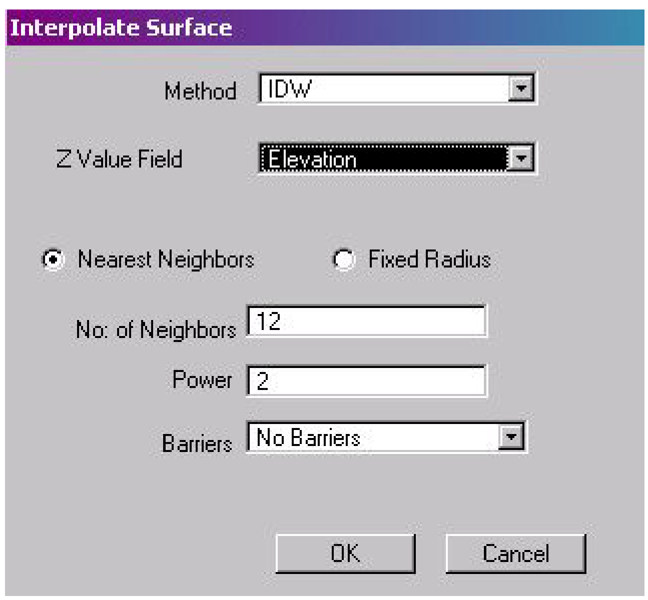


Figure 8 – ArcView Surface Interpolation Input Window (with default parameters)

The "Nearest Neighbor" method and the "12" specified neighbors requires that the interpolation at any point is driven by the 12 measurements nearest to the given point. The "2" power determines the weighting applied to each of the neighbors, and it describes the relative importance of a given measurement in an interpolation. With higher powers, the nearest neighboring points are given more influence in the interpolation scheme than are the farther neighboring points. The "No Barriers" specification means that the interpolation is not terminated at any set boundary other than the boundary of the overall grid. For these interpolations, this boundary was an arbitrarily defined rectangular polygon theme that encompassed the entire area of Corpus Christi Bay. The cell size of the interpolated grid is also determined by the user.

Although the sounding data adequately described the existence of the Corpus Christi Ship Channel, it did not include the intercoastal waterway that runs North-South through the Bay and into Laguna Madre. Because such channels can act as water conduits and greatly influence the movement of water through a system, the intercoastal waterway and ship channels were manually added to the bathymetry.

The location and width of the ship channels was approximated based on GIS data made publicly available from the Texas General Land Office (CITE). However, the TGLO data consisted of a line theme describing the channels. In order to add the channels to the existing bathymetry grid, it was necessary to convert the line theme to a polygon theme. This was achieved by manually drawing a polygon theme over the existing TGLO line theme (Figure 9).

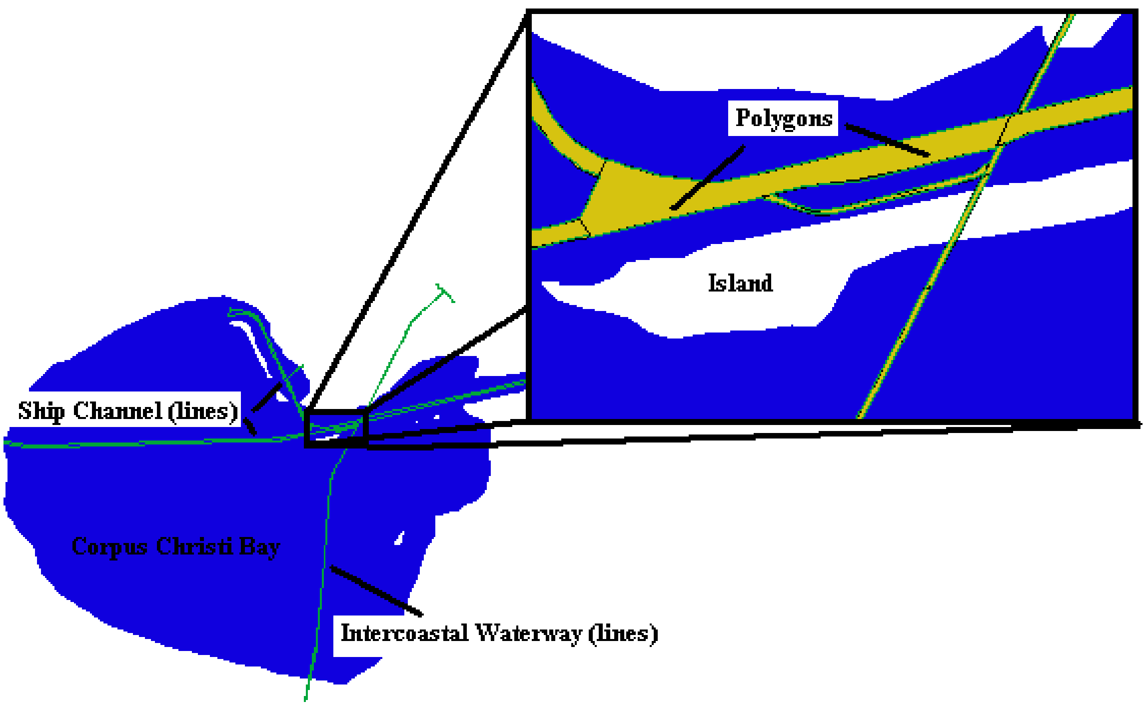


Figure 9 – Line and Polygon Representations of the Corpus Christi Bay Channels

A separate polygon was created for each discernible channel segment of a different depth. Therefore, channel segments corresponding to the Intercoastal waterway were transformed into one set of polygons, and segments corresponding to the deeper Corpus Christi Bay ship channel were transformed into separate polygons. Each polygon was then attributed according to the known depth of the channel (13.7 meters for the ship channel and 3.7 meters for the intercoastal waterway). Once attributed, the polygon themes were converted into a grid representation, where the grid is made up of 250m cells and is the same extent as the previously generated bathymetry grid. The resulting grid, however, did not present a continuous representation of the channels. This is because the channel width is too small relative to the size of the grid cells (Figure 10).

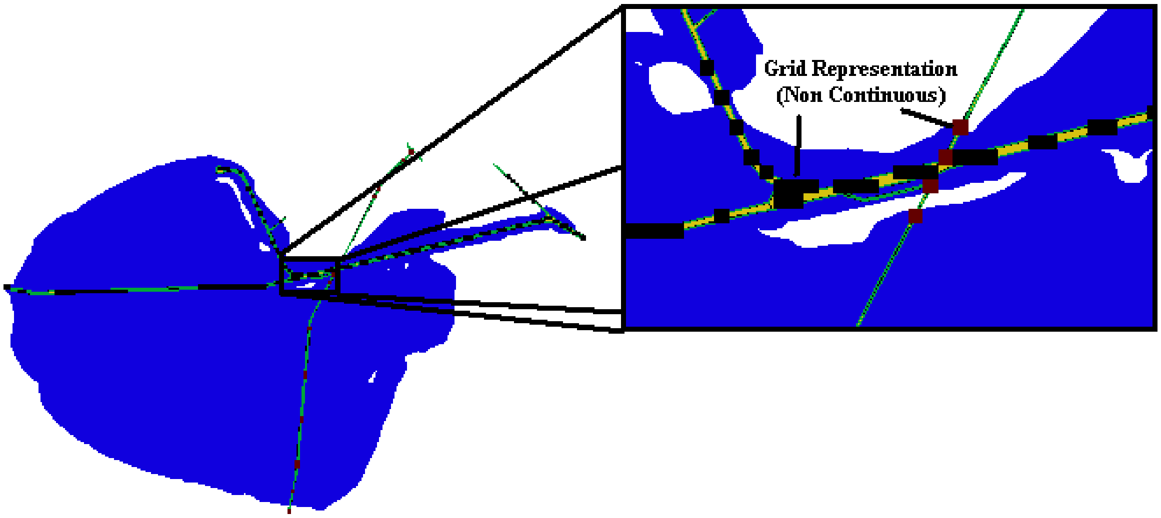


Figure 10 – Non-continuous grid representation of channels with 250m cells.

To fix this problem, the width of the channels had to be expanded, which introduced error into the bathymetry. However, the importance of this error may be negligible based on the distance between the main channels and the hypoxic zone. The other way to avoid such error is to use a higher resolution bathymetry grid, which will be attempted in future simulations.

To increase the channel widths, the polygon theme was buffered to a distance of 150m on each side, making the channel width 300m wider than the actual physical channels. When this buffered channel was converted to a 250m grid, the channel was continuous (Figure 10).

The gridded channels were added to the existing bathymetry in a two-step process. The first process is to generate a grid containing the existing bathymetry values for cells not overlain by the gridded channels. Cells that are overlain by the gridded channels are given the value “0”. This is achieved by creating a “mask” grid storing the value “1” for non-channel cells and “0” for channel cells. This mask grid is then multiplied by the existing bathymetry grid to produce the result of the first step. The second step is to alter the channel grid so that the channel cells contain their respective depth values, and all other cells contain the value “0.” This is achieved through linear manipulations of the *isnull* grid function in ArcGIS. Once this second grid is completed, the final bathymetry grid is created by adding the grids from step one and step two.

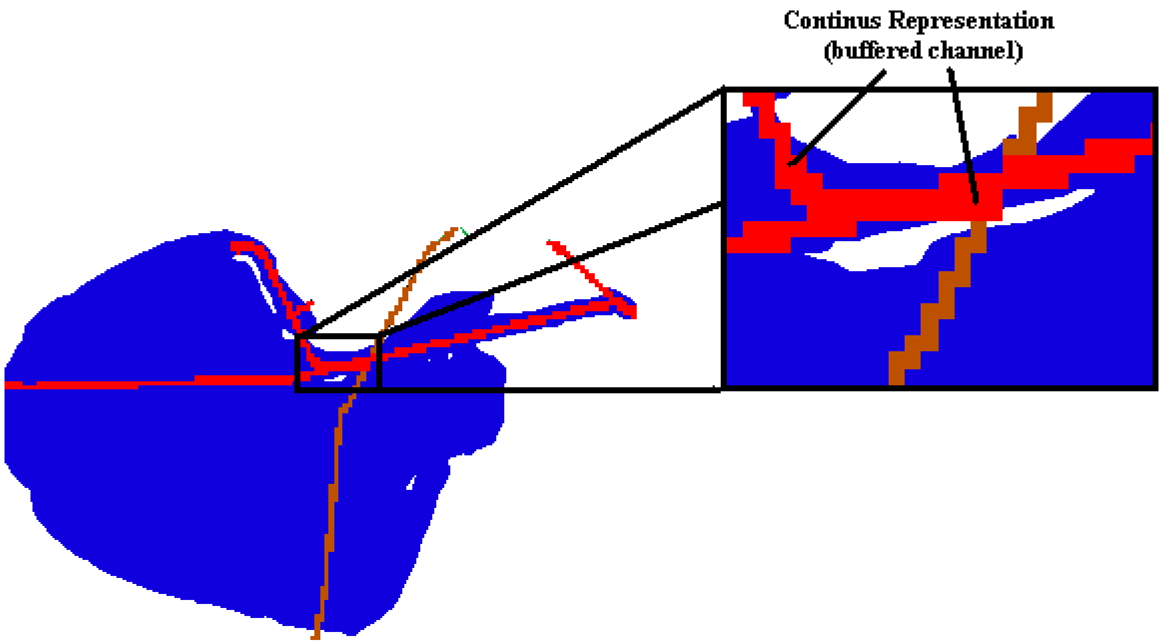


Figure 10 – Continuous Representation of the buffered channels (grid size = 250m)

The final product of all of these grid permutations is the corrected bathymetry of Corpus Christi Bay (Figure 11). However, this bathymetry is not yet in a format readable within ELCOM. The linkage between GIS and ELCOM in bathymetry formatting is discussed in Part 2 of this report.

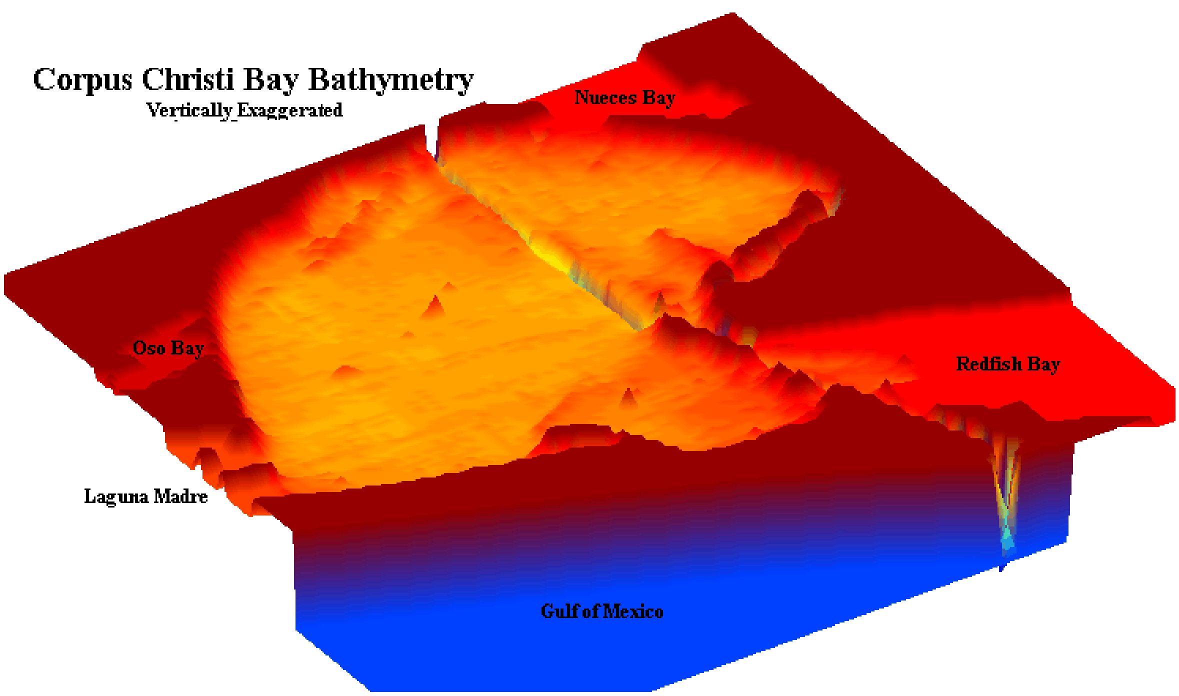


Figure 11 – GIS Processed Bathymetry of Corpus Christi Bay Region (Plotted in MATLAB)

Environmental Forcing Inputs – Boundary Conditions

After generation of the bathymetry, the remaining environmental forcing conditions need to be quantified. These forcings are both spatial and temporal in scale, and often the accuracy of the model depends on the forcings used. In this modeling effort, some forcings will be held constant, while the affects of changes in other forcings will be determined by the modeling. The best way to describe the environmental forcing conditions on Corpus Christi Bay is to group them spatially across the bay domain (Figure 12). Each of the 7 forcing groups shown in Figure 12 will be discussed in detail below.

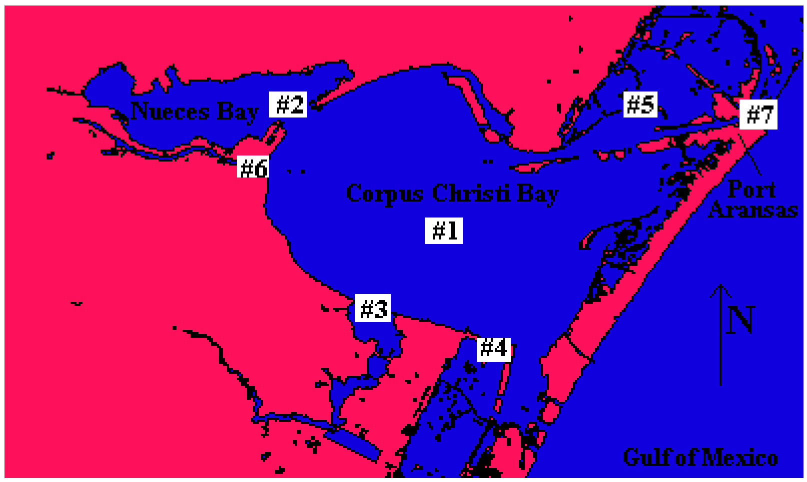


Figure 12 – Locations where various environmental forcings are applicable on Corpus Christi Bay

<u>Environmental Forcing Group #1</u> – Forcings On the Entire Bay (Surface or Bottom)

This forcing group applies to all regions of Corpus Christi Bay, although they may not be uniform across the bay extent. This group includes:

- **Precipitation**: this is potentially a source of freshwater to the system, which would tend to reduce surface salinities and possibly increase constituent concentrations in the water column (due to the deposition of trace chemicals from the atmosphere). This forcing is temporally highly irregular, and because hypoxia is observed in the summer dry months, precipitation will not be included in this modeling study.
- **Groundwater**: this potential inflow source could affect salinity concentrations near the benthos, and is a possible contributor to the hypoxia in the southern section of the bay. The groundwater inflow is not really quantifiable, however, and as such it will be included as a variable to be tested in the modeling runs. The groundwater inflow will be localized only to the hypoxic region, and the salinity concentrations in the flow will also be varied in attempts to match the field data.
- **Wind**: the wind field above Corpus Christi Bay is likely to be of vital importance in determining the bay's circulation patterns. The wind stress at the water surface contributed turbulent energy to the water column, and it dictates

currents and vertical mixing of constituents. Wind data may be spatially and temporally variable across the bay, and it is often only measured at spares locations. This is true for Corpus Christi Bay, where wind measurements are made only at the Corpus Christi Naval Air Station between Oso Bay and Laguna Madre. The wind fields over the bay have been assumed to be uniform, 17-28 mph, and from the southeast during the summer months (Ritter and Montagna). These values will serve as a baseline from which the effects of variable wind fields will be determined. It is also possible that the seasonal hypoxia is caused be a lee affect on the wind field due to the proximity of Mustang Island to the hypoxic region. The lee effect could significantly reduce the wind over the hypoxic area, therefore reducing the energy imparted into the system, therefore adding to the turbulence. A methodology to quantify this lee affect is underdevelopment (as a pet project of the author).

- **Evaporation/Surface Thermodynamics**: the rate of evaporation from the Corpus Christi Bay surface is a significant determinant of the salinity concentrations in the bay. During the summer months, evaporation causes the salinities in the bay to exceed those commonly found in the open ocean. In order to accurately model in the salinity distributions, either measured evaporation data or data from which evaporation may be estimated are required. In order to estimate evaporation, ELCOM requires solar radiation data, water/air temperature data, wind speed data, cloud cover, and other geographically significant factors. These factors are available from weather reporting services such as NOAA.

<u>Environmental Forcing Group #2</u> – Exchange between Nueces Bay and CC-Bay

This exchange between waterbodies is a significant source of fresher water into Corpus Christi Bay, and this inflow has been demonstrated to be significant from the TxBLEND modeling. The inflow will be estimated from the USGS gauged riverflow on the Nueces river, minus estimated evaporation losses.

<u>Environmental Forcing Group #3</u> – Exchange between Oso Bay and CC-Bay

This exchange between waterbodies is possibly a significant source of saline water into Corpus Christi Bay. Oso Bay is extremely shallow, which suggests it is hypersaline due to increased evaporative losses. The major flux of water, although likely affected by tides, is from Oso Bay into Corpus Christi Bay. This is because of the power plant located inbetween Oso Bay and Laguna Madre. This plant withdraws cooling water from Laguna Madre in discharges it into Oso Bay. This water transfer sets up a cycling of water from Oso Bay, into Corpus Christi Bay, past the hypoxic region, and into Laguna Madre. This circulation pattern is evident in the TxBLEND modeling. However, it is not known if the flows occur across the total depth of the water column. If the high salinity flows are mainly in the deeper regions of the water column, the flows might lead to stratification in the hypoxic region. This possibility is to be explored.

<u>Environmental Forcing Group #4</u> – Exchange between Laguna Madre and CC-Bay

As discussed in the previous section, water is thought to circulate from CC-Bay into Laguna Madre. However, it is possible that if this circulation is relaxed, hypersaline water from the shallow Laguna Madre could flow into Corpus Christi Bay and contribute to the stratification in the hypoxic region. This inflow could be tidally driven, as evidenced by the TxBLEND modeling. Possible values for the exchange will be derived from the input data used in the TxBLEND modeling.

<u>Environmental Forcing Group #5</u> – Exchange between Redfish Bay and CC-Bay

This exchange is likely to have only a minimal impact on flow within the hypoxic region (Paul Montagna, personal communication). The existence of the Corpus Christi Ship Channel and the islands about the channel are likely to block any North-South exchange from the hypoxic region to Redfish Bay. The modeling effort will include estimated exchange values spanning multiple orders of magnitude. This will support or refute the hypothesis regarding the importance of the exchange. Values will also be driven from the literature on the area.

<u>Environmental Forcing Group #6</u> – Exchange between the Ship Channel and CC-Bay

The Corpus Christi Ship Channel is likely to act as a conduit for water flow, which will greatly influence the circulation of water throughout the bay. This evidence is viewable in the TxBLEND results (Figure 5). However, the exchange between the Ship channel and the bay at the #6 location (Figure 12) is likely to be tidally driven. Because ELCOM uses tidal data to calculate flows, this environmental forcing will be determined by the model.

<u>Environmental Forcing Group #7</u> – Tidal Influences from the Gulf of Mexico

Tidal fluxes serve as inflow and outflow sources of water for the Corpus Christi Bay system. However, the tidal affect is felt mostly along the length of the ship channel, and is significantly reduced in other areas of the bay. This is especially true because Corpus Christi Bay is a microtidal system, where the maximum tidal range is only 1-2 meters. The tidal influence is input into ELCOM as a time series of dates and water surface elevations as measured at the Port Aransas station and provided by the Conrad Blutcher Institute. Tidal Records are available from many periods over the last century, and are especially detailed in the recent years. A sample tidal time series for 2001 is shown in Figure 13. This time series data is applied at the mouth of the ship channel, and will be supplement with tide data measured at the Corpus Christi Naval Air Station.

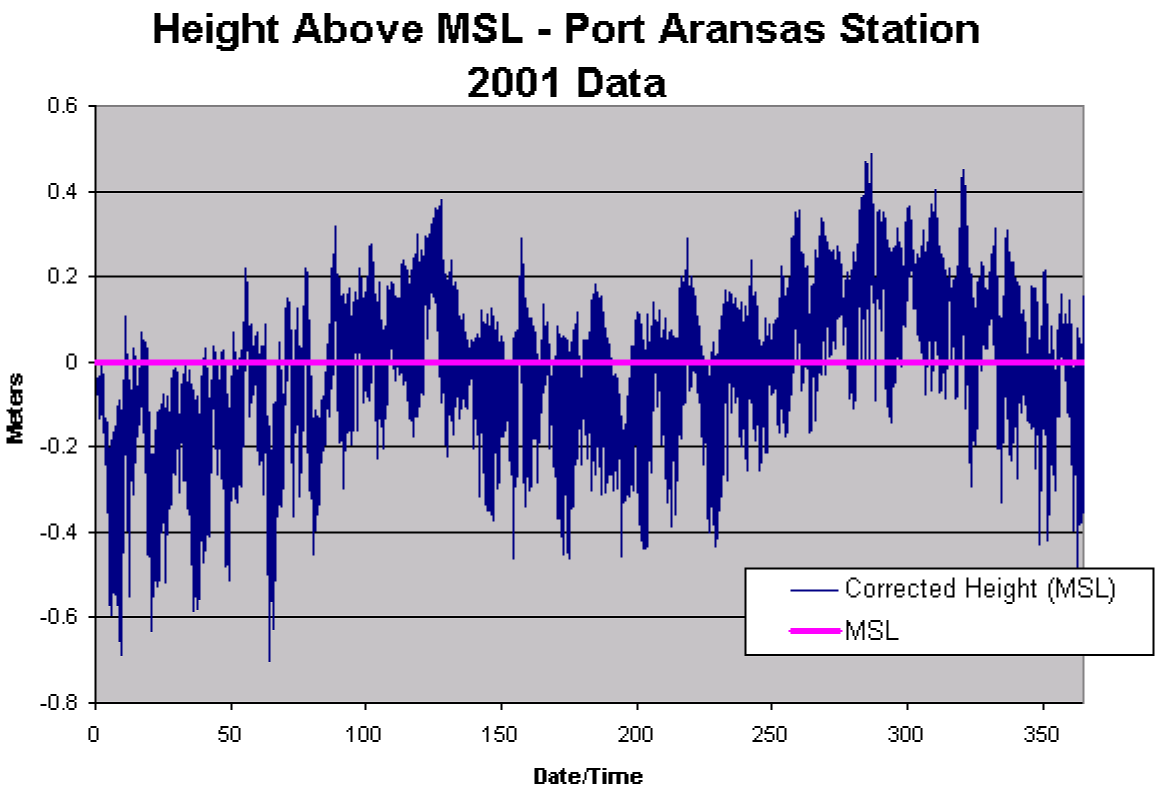


Figure 13 – Port Aransas Tidal Data for 2001 (Provided by the Conrad Blutcher Institute)

After collecting all applicable environmental data, the data files need to be organized in a format readable by ELCOM. This usually requires the generation of multiple text files of inputs, and knowledge of the grid cells to which the forcing conditions apply. This "location of grid cells" procedure is also made easier through the use of GIS software, and the methodology for doing so is similar to the methodology for adding the ship channel to the bathymetry.

Part 2 – Linking GIS and ELCOM

With the establishment of GIS processes for ELCOM bathymetry generation, the potential connection between the two programs is forged. However, a file linkage must be made in order to connect the GIS files to the ELCOM model. It is also potentially beneficial to develop a methodology for processing and/or displaying the ELCOM results in the GIS environment. This would allow more users to view, manipulate, and make decisions based upon the ELCOM model results. This is because most government agencies and consulting companies are using GIS systems to store data and solve environmental problems. Therefore, if ELCOM results were stored in GIS compatible formats, GIS users who do not have the ELCOM model would still be able to analyze the model and disseminate results. In this part of the report, connections between GIS and ELCOM are presented.

Formatting GIS Bathymetry Grids for use in ELCOM

ELCOM receives bathymetry input as a text file, and this text file is used in the ELCOM pre-processing program. This program "constructs" the 3-dimensional spatial domain over which the hydrodynamic calculations are made. A section of the bathymetry input file *250m_channel.txt* is given in Appendix E. This is the input file used in simulations including the ship channel. The sample only includes part of the actual bathymetry data.

All ELCOM bathymetry files contain a specific set of information in a specific arrangement and order. As shown in Appendix A, the file first contains information related to the specific model setup (i.e. title, user name, date, etc), followed by information describing the extent and geographic location of the bathymetry grid. The penultimate data specified by the file are the sizes of the 3-dimensional grid cells included in the model. ELCOM grid cells may have different sizes in each of the three principal directions (X, Y, and Z), and cell heights (Z values) do not have to be uniform across the depth of the waterbody. The user can tailor the vertical size of the grid cells in order to obtain the best resolution for the processes to be modeled.

The final section in the bathymetry input file specifies the bathymetry values for the waterbody. Specifically, a bathymetry value is included for each cell in the (X, Y) area domain. These values are listed by row, and are separated by spaces (space-delimited format).

```
! ------------------------------------------------------------------------ !
! x in rows (increasing down), y in columns (increasing across)            !
 BATHYMETRY DATA
9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999
9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999
9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999
```

Figure 14 – Section of Bathymetry Data Input file for ELCOM (Values shown represent land cells)

Unlike many hydrodynamic models, ELCOM places the grid origin at the upper-left corner, with the row number increasing downward and the column number increasing across from left to right. This, and the space-delimited nature of the input data allows for easy conversion of GIS raster bathymetry data into ELCOM format. GIS raster data is formatted in a similar manner to the data required by ELCOM.

GIS grids may be exported into an ASCII-raster format using the export functions in ArcView and ArcGIS. The exported files are text files with the ".asc" extension. These files contain all of the information used by the GIS system in order to properly orient the grid to a specific geographic location, as well as the value stored in each individual grid cell. As with the ELCOM bathymetry input file, the exported GIS grids use the upper left corner of the spatial domain as the domain origin.

```
ncols         96
nrows         89
xllcorner     1825214.78276
yllcorner     7161459.095
cellsize      250
NODATA_value  -9999
9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999
9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999 9999
```

Figure 15 – Section of Exported GIS Bathymetry Grid showing spatial reference information and some bathymetry values

The exported GIS grid ".asc" file may be combined with a user-specified input text file in order to produce a properly formatted ELCOM bathymetry input file. The user-specified input file must contain the ELCOM model setup information, as well as the Z-height values to be included in the model calculations. The size of the grid cells in the X and Y directions is determined directly from the ".asc" file, as is the number of rows and columns included in the grid. The text file combination is carried out by the stand-alone Visual Basic program ***Bathymetry.exe*** created by the author.

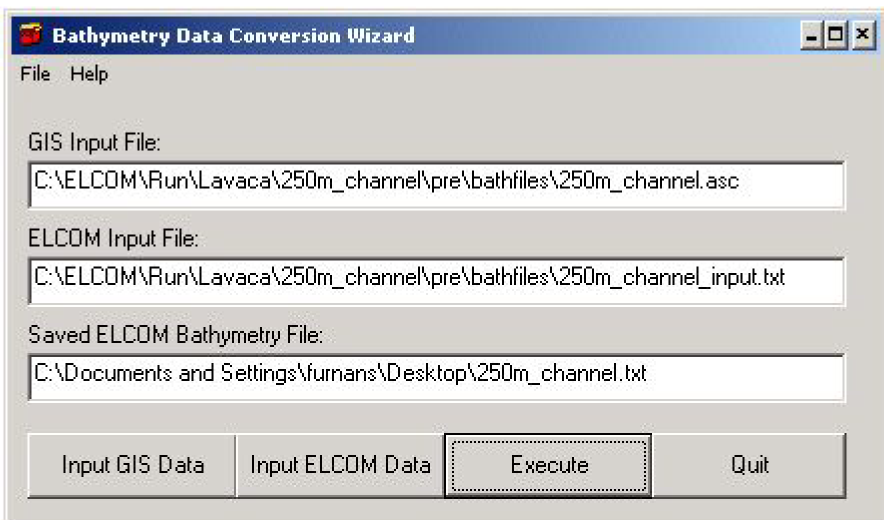


Figure 16 – Bathymetry.exe interface for converting GIS ".asc" files to ELCOM Bathymetry files

The ***Bathymetry.exe*** program works by extracting data from the GIS ".asc" file and the user-defined ELCOM input file, and then combining these extractions in the proper order. The output is a new text file suitable for use in the ELCOM pre-processing program. The program user can define the name and storage location of the new text file (Figure 16). The sample ELCOM bathymetry file *250m_channel.txt was* generated with the ***Bathymetry.exe*** program with the *250m_channel.asc* and *250m_channel_input.txt* given in Appendix A.

Conversion of ELCOM Results to GIS Format

ELCOM results, as generated from each model run, are stored in the **NET**work **C**ommon **D**ata **F**orm **(NETCDF)** format. This format of data storage is machine independent, and it allows for an easy exchange of information between various users and programs. For this work and most other previous ELCOM applications, the netcdf files are processed and the results are visualized using the Matlab 6.1 software package. Dr. Ben Hodges, as well as researchers at the University of Western Australia, have written numerous Matlab scripts for processing and presenting the ELCOM results. In order to convert these results into a GIS format, some of these scripts were modified and combined. The conversion script, ***elcom_to_gis.m***, is available from Dr. Ben Hodges at CRWR.

The conversion script makes use of the gridded nature of the ELCOM results, where at any give time step a model output (ex. U_VELOCITY) is calculated for each grid cell in the X-Y model domain. The output is stored as a series of multi-dimensional arrays within the Matlab variable "data." The arrays are either 1, 2, or 3 dimensional. The one dimensional arrays store data related to the time of the simulation results. 2-dimensional arrays store data that does not change with time, such as bathymetry. The first dimension in such arrays corresponds to the cell number in the y-direction of the grid, and the second number pertains to the cell number in the grid's x-direction. A three dimensional array follows the same format as the 2-dimensional array except that the result time is stored in the first dimension. Therefore a 3-dimensional array stores gridded time series data.

```
data =

             x: [91x98 double]
             y: [91x98 double]
             z: [91x98 double]
      S_HEIGHT: [91x98 double]
         BATHY: [91x98 double]
    U_VELOCITY: [100x91x98 double]
    V_VELOCITY: [100x91x98 double]
    W_VELOCITY: [100x91x98 double]
        HEIGHT: [100x91x98 double]
          time: [100x1 double]
      set_type: 'SHEET_2D'
           day: [100x1 double]
          year: [100x1 double]
```

Figure 17 – Sample ELCOM Data in Matlab – multiple arrays stored in the "data" variable.

The multidimensional array format of the ELCOM data is very similar to the format of raster data used in GIS programs. As described previously, raster GIS data was used to create the ELCOM bathymetry files from which the results in this project are based. Specifically, the GIS bathymetry grid was exported into an ASCII text file, which was then transformed into the ELCOM bathymetry file using the ***bathymetry.exe*** program. Because the ELCOM grid cell locations and sizes are determined from the bathymetry, the ELCOM results have the identical spatial references as the raster GIS data from which the bathymetry is created. Therefore, in order to correctly display the ELCOM results in GIS, it is necessary to run the ***bathymetry.exe*** in reverse. The ***elcom_to_gis.m*** Matlab script performs this data conversion for a specified array in the "data" variable, and couples the ELCOM data with the necessary spatial reference information of the GIS grid. The final product is an ASCII text file containing the desired model results. This text file may then be imported into the GIS system and saved as a GIS grid.

```
data = get_db(cellstr('../ncfiles/s7_avg.nc'),...
              cellstr(char('U_VELOCITY','V_VELOCITY')),[14:14]);

velocity = sqrt(data.U_VELOCITY.^2 + data.V_VELOCITY.^2); % get the velocity magnitude
nfiles = size(velocity,1)                          % get the number of time slices
velocity(find(isnan(velocity))) = -9999

for ii = 1:nfiles                                  % create a file for each slice
    fid = fopen(['Velocity',num2str(ii),'.asc'],'w');   % open the file
    fprintf(fid, '%-12.9s', 'ncols  96');
    fprintf(fid, '\n');
    fprintf(fid, '%-12.9s', 'nrows  89');
    fprintf(fid, '\n');
    fprintf(fid, '%-12.17s', 'xllcorner  182515');
    fprintf(fid, '\n');
    fprintf(fid, '%-12.17s', 'yllcorner  7161459');
    fprintf(fid, '\n');
    fprintf(fid, '%-12.14s', 'cellsize  250');
    fprintf(fid, '\n');
    fprintf(fid, '%-12.20s', 'NODATA_value  -9999');
    fprintf(fid, '\n');
    adjust = size(velocity,2)-1  % Elcom addes cells around the original bathymetry
    adjust1 = size(velocity, 3)-1 % GIS system parameters don't account for these cells
    for jj = 2:adjust
        for kk = 2:adjust1
            count = fprintf(fid,'%-12.4f',velocity(ii,jj,kk)); % print a line
        end
        fprintf(fid,'\n'); % end of line
    end
    fclose(fid)
end
```

Figure 18 – Sample elcom_to_gis.m script for 250m grid about Lavaca Bay

In the above sample conversion script, the U_VELOCITY and Y_VELOCITY data are extracted from the s7_avg.nc file at the 14th time step. The ".nc" file extension signifies the file is in netcdf format, and the "s7_avg" file name signifies that this is the depth averaged data reported at each grid cell spanning the study area. The U_VELOCITY and V_VELOCITY data are the calculated velocities in the U and V (X and Y) directions. These values are multiplied in quadrature to create the *velocity* array, which is also 3-dimensional (There is only 1 time series result in the array, however). This velocity array stores the magnitude of the velocity of the water movement in each grid cell. A similar calculation is necessary to determine the angle of this movement. From a combination of the magnitude and angle data, velocity vector data may be generated. Creation of the velocity vector data is not shown in Figure 18.

The format conversion begins with the replacement of the Matlab generated "Not a Number" (NaN) values in the array with the NODATA value used in the GIS grids. The conversion is carried out with the combination of the *find* and *isnan* functions incorporated within Matlab. The NODATA value is always –9999 and is set as such when the original bathymetry grid is exported from GIS into ASCII format. After adjusting the NaN values, a "for" loop is initiated which creates a separate ASCII file for each time step included in the conversion. Each ASCII text file is created with the name "VelocityX.asc" where "X" is the number of the time step data to be represented in GIS format and ".asc" signifies that the file is in ASCII format. The following steps provide the spatial reference data that allows the GIS system to display the results in their proper location. The required fields are those fields found at the beginning of all exported GIS grid files, namely "ncols," "nrows," "xllcorner," "yllcorner," "cellsize," and "NODATA_value." The numbers following each one of these fields are specific to the location and grid size for which the program is used, and the values may be obtained from the exported bathymetry ASCII file (See Figure 18). The "fprintf" statements print the specified text to the VelocityX.asc file, and the "/n" code specifies the location of an end of line character. The next step is to write the individual velocity values into the ASCII file, with each value separated by spaces. This is carried out with two nested "for" loops, with the first loop controlling the rows of data and the second loop controlling the data columns. It is important to note that not all of the rows and columns from the velocity array are included in the ASCII file. Specifically, the first and last rows and columns are excluded.

In generating output, ELCOM adds NaN valued rows and columns along the border of the study area. These values do not affect the display of data in Matlab scripts, but do affect the display of the results in GIS. The added rows and columns are evident in comparing Figures 17 and 15, where the former shows 91x98 sized arrays and the later specifies an 89x96 grid. If these extra rows are not removed, the GIS system will include only part of the study area in the imported grid. Also, each grid cell will contain a value other than the value ELCOM calculated for the spatial area of the grid cell; the value will be the value of the cell with the row number and column number one higher than its own.

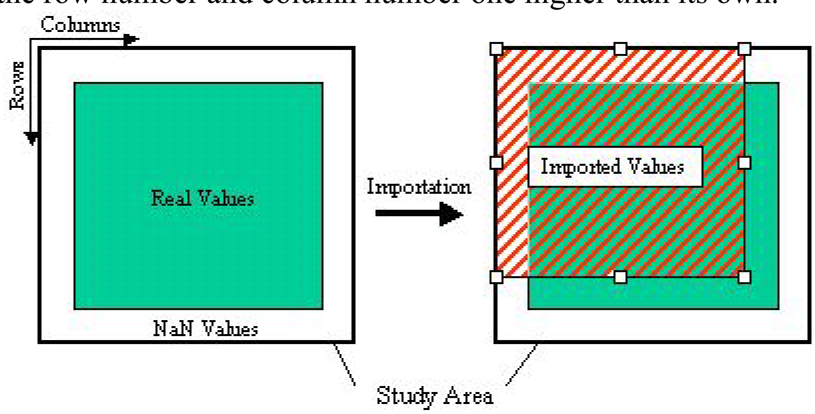


Figure 19 – Location of Imported Values Relative to Real Values if extra NaN Values are not excluded

When imported into a GIS system, an "uncorrected" ASCII file will display in a nonsensical manner. An "uncorrected" and "corrected" results display is shown in Figure 20.

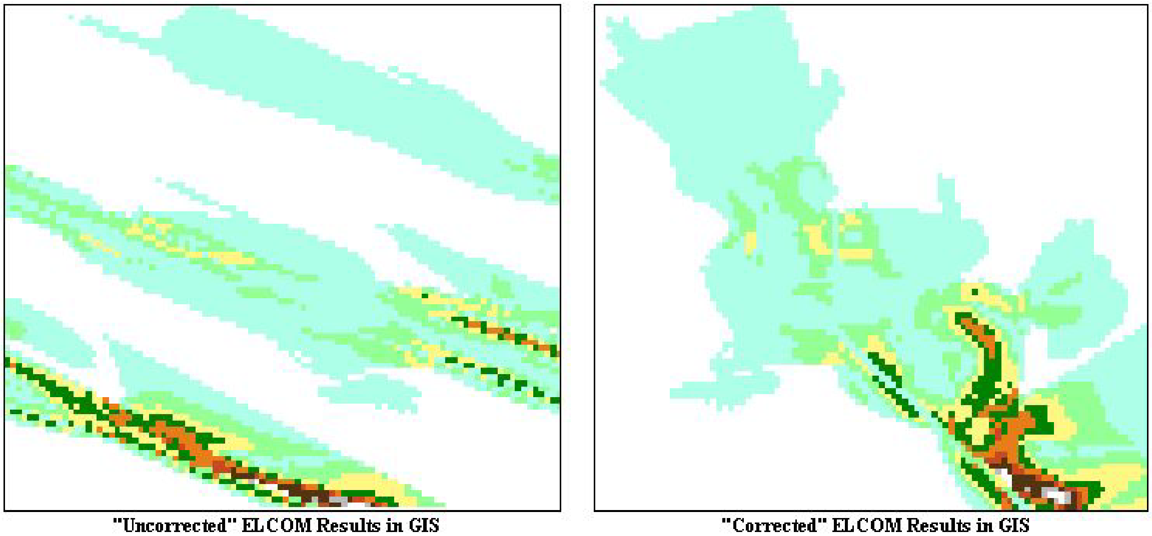


Figure 20 – ELCOM Results in GIS (Darker colors indicate greater velocity magnitudes)

Once stored as a GIS grid, the user may convert the model results in the more useful polygon format. This would be especially useful if the GIS grid contained concentration data, or other data based on one parameter. The drawback of using GIS grids to display modeling results is that the grids cannot be used to show water velocities, because velocities are two-parameter values requiring a magnitude and a direction. Methodologies for ameliorating this difficulty are under development.

Part 3 – Testing ELCOM Robustness

ELCOM is a rather untested hydrodynamic model – while it has been successfully applied to numerous study areas (Lake Kinneret, Lake Maricaibo, Swan River Estuary), each new application identifies minor difficulties and inaccuracies in the current program code. One characteristic that has not been adequately tested is the model robustness with respect to the orientation of the bathymetry data. This characteristic of the model is potentially important in systems such as Lavaca Bay and Corpus Christi Bay which contain "linear" features such as ship channels. The square grid bathymetry used in ELCOM simulations may not adequately represent these linear features, and this inaccuracy may increase the numerical diffusion involved in the calculation process.

In implementing a finite volume solution space on a 3D waterbody, the finite volume grid must be tailored to adequately describe the waterbody shape. This is easier to accomplish with smaller and smaller grid cells, however smaller cells requires more calculations when running the model. If the grid cells are too small and therefore too numerous, the computer on which the model is run will be overwhelmed by the calculation procedure. Therefore, it is necessary to use a grid size that does not overwhelm the computer but that also provides a fairly accurate approximation of the waterbody shape.

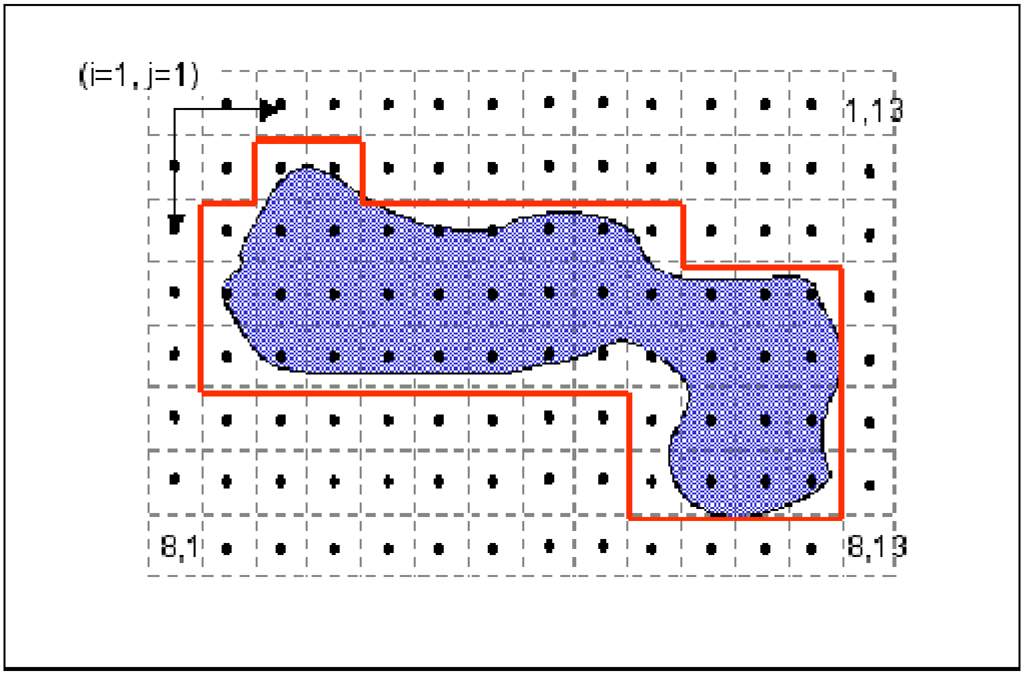


Figure 21 – Example Approximated shape (Red Outline) of the irregular waterbody (Blue)

As shown in Figure 21, the square box grid used in ELCOM is not always an accurate representation of the waterbody to be modeled. In this figure, a smaller grid size would better represent the waterbody, reducing the amount of space inside the red outline and outside of the blue waterbody. A non-uniform, or perhaps curvilinear grid may also more accurately represent the curves of the waterbody perimeter. However, the ELCOM model is not currently capable to perform calculations on such grids. Future modifications to the ELCOM code will likely incorporated such capabilities.

Linear features such as ship channels are often conduits for the transport of water through a waterbody. This was assumed true in developing an ELCOM model for Lavaca Bay, which contains numerous ship channels at various orientations with respect to North.

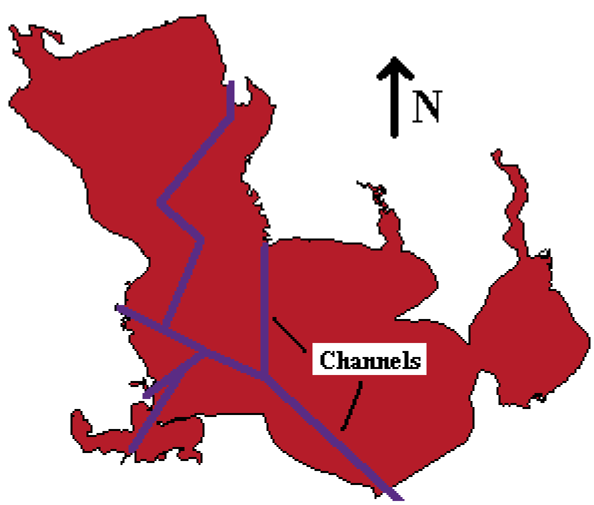


Figure 22 Ship Channels in Lavaca Bay, Orientations at angles with North

The width of each ship channel is constant along its length, and is directly related to the size of the ships desiring to use the channel. These channels are rarely greater than 30m wide, which presents a problem in terms of the ELCOM bathymetry grids. The bathymetry grids would have to have a grid scale equal to or less than the width of the channel in order to accurately represent the existence of the channel. This is not possible due to computational limitations. In order to include the ship channels in the bathymetry, it was necessary to increase the width of the ship channel so that it at least spans one grid cell.

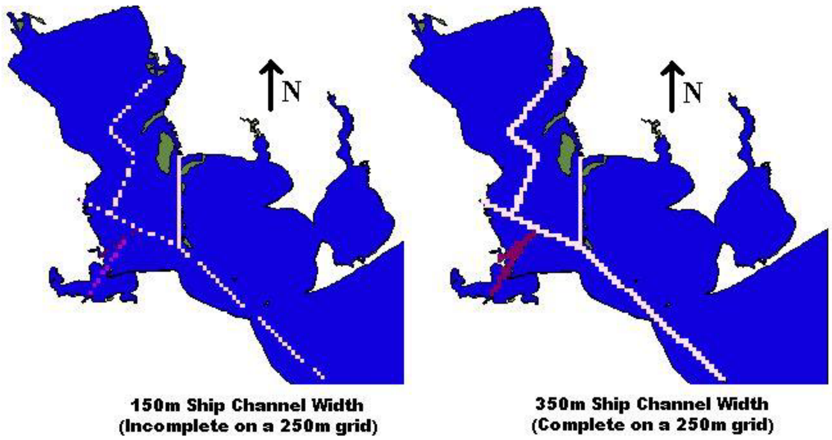


Figure23 Ship Channel Representations in Bathymetry Grids – Channels are discontinuous when with is less than 350m.

On a 250m grid oriented along the cardinal directions, a 150m wide ship channel is not continuously represented in the bathymetry. The ship channel width had to be increased to 350m in order to be represented continuously (Figure 23), which is a with an order of magnitude greater than the actual channel width. This is potentially an enormous error source for the modeling.

Also, even with a continuous channel, the direction of the channel with respect to the N-S grid cells gives the channel a "stair-stepped" appearance. Rather than being a smooth, continuous linear feature, the gridded channel is a series of stairs. Flow through this gridded channel must change direction at every "step," which increases the numerical diffusion of the results due to momentum losses that inevitably occur when flows are calculated to change direction.

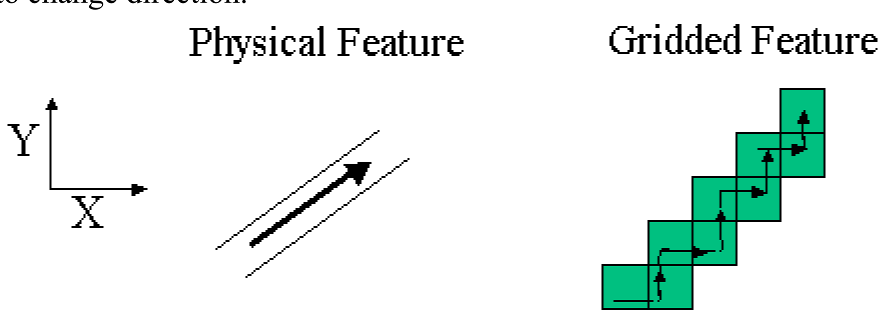


Figure 24 Representing "Diagonal" Linear Features with a Square Grid

One methodology for minimizing this momentum loss is to orient the main linear of the study area with respect to the grid. This can be accomplished by rotating the feature to a new coordinate axis shown in Figure 25. If the bathymetry grid is generated after the rotation of the linear features, the next bathymetry grid should represent these features in a way that more accurately reflects their actual physical characteristics. In such a case for Lavaca Bay, the "stair-stepped" shape of the main ship channel would be avoided, and the width of the channel could be reduced to the exact width of the grid cells.

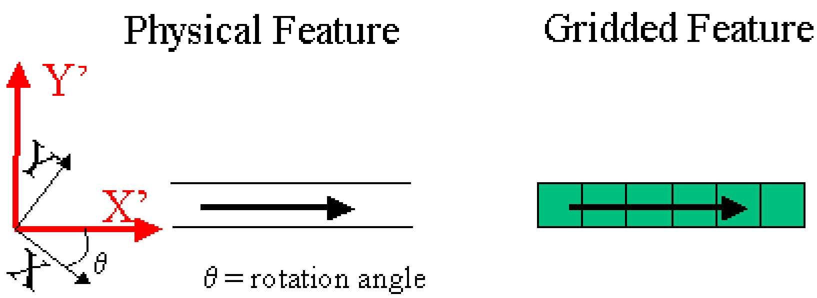
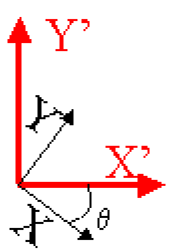


Figure 25 Rotated Linear Features may be Accurately Represented in Bathymetry Grids

The rotation of the bathymetry grid is easily carried out because the grid was generated based on sounding points attributed with latitude and longitude values. Within the ArcView/ArcGIS system, it is possible to employ a rotation algorithm to these points in order to re-orient the data to better represent any linear feature in the system to be modeled.

Rotation Methodology

The rotation of the sounding points used to generate the bathymetry files is really just a simple change axes transformation. Since the sounding points are referenced based on their latitude and longitude with respect to the {0,0} degree origin, the new coordinates with respect to an axis rotated about the origin are given mathematically as:



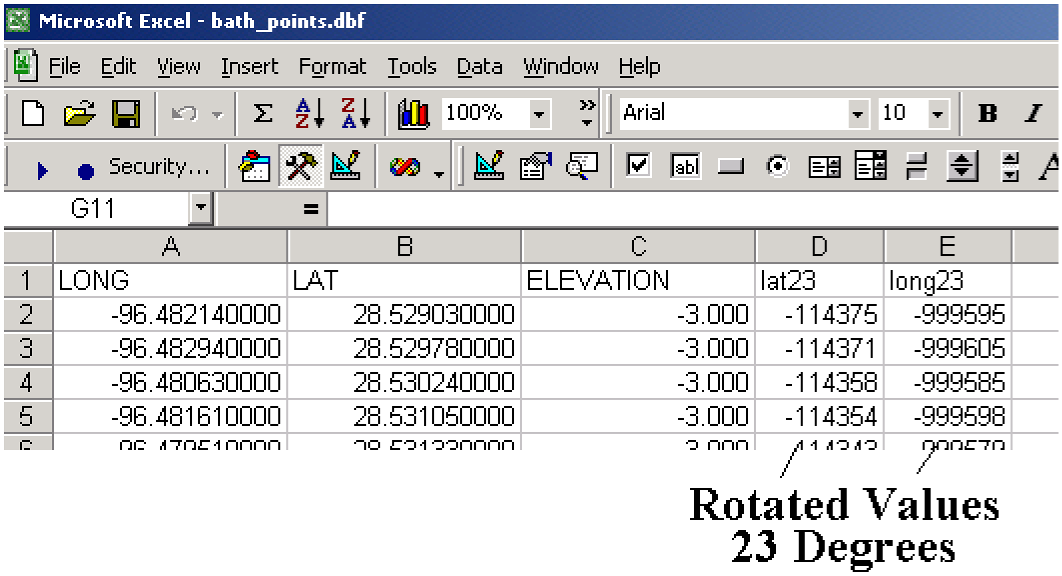
Coordinate Transformation:

$$X' = X\cos\theta - Y\sin\theta$$

$$Y' = Y\cos\theta + X\sin\theta$$

θ = rotation angle

This simple formula was incorporated into a Microsoft Excel Macro which is set to run on the .DBF file of the GIS shapefile describing the sounding points. This macro performs the coordinate transformation based on a user specified rotation angle, and added new fields to the spreadsheet containing the new latitude and longitude of the rotated points. However, the new latitude and longitude values are multiplied by 10000. This is in order to maintain the decimal digits of each value, which would be lost upon saving the modified .DBF file in Microsoft Excel.



	A	B	C	D	E
1	LONG	LAT	ELEVATION	lat23	long23
2	-96.482140000	28.529030000	-3.000	-114375	-999595
3	-96.482940000	28.529780000	-3.000	-114371	-999605
4	-96.480630000	28.530240000	-3.000	-114358	-999585
5	-96.481610000	28.531050000	-3.000	-114354	-999598

Figure 26 Microsoft Excel Rotation Spreadsheet

Once imported back into the GIS system, the newly rotated values need to be divided by 10000 in order to regain their correct decimal notation. The data then needs to be added as a new event theme, and the rotated bathymetry grids may be generated.

Original Points Rotated Points Interpolated Grid

Figure 27 Rotation of Points to Generate New Bathymetry – Lavaca Bay was rotated by negative 26 degrees in order to align the interface between it and Matagorda Bay to the horizontal grid cells.

Once the rotated bathymetry is incorporated into the ELCOM model setup, the ELCOM model can be run as before. However, it is important to adjust the North direction in the ELCOM input text file in order to account for the rotation of the north arrow. It is also necessary to adjust the direction from which the wind is blowing. This direction must be changed to reflect the rotated coordinate axes.

Data Comparison - Lavaca Bay Simulations

The differences in results between simulations using the rotated and non-rotated bathymetries may be assessed visually, however it would be preferable to make an assessment numerically. To do so, it is possible to use the ROTATE function in Arc/Info GIS to re-rotate results from an ELCOM run on rotated bathymetry. The re-rotation process, however, may resample the ELCOM model results when generating the re-rotated grid. This resampling may distort the ELCOM results and make them meaningless. This possibility needs to be explored.

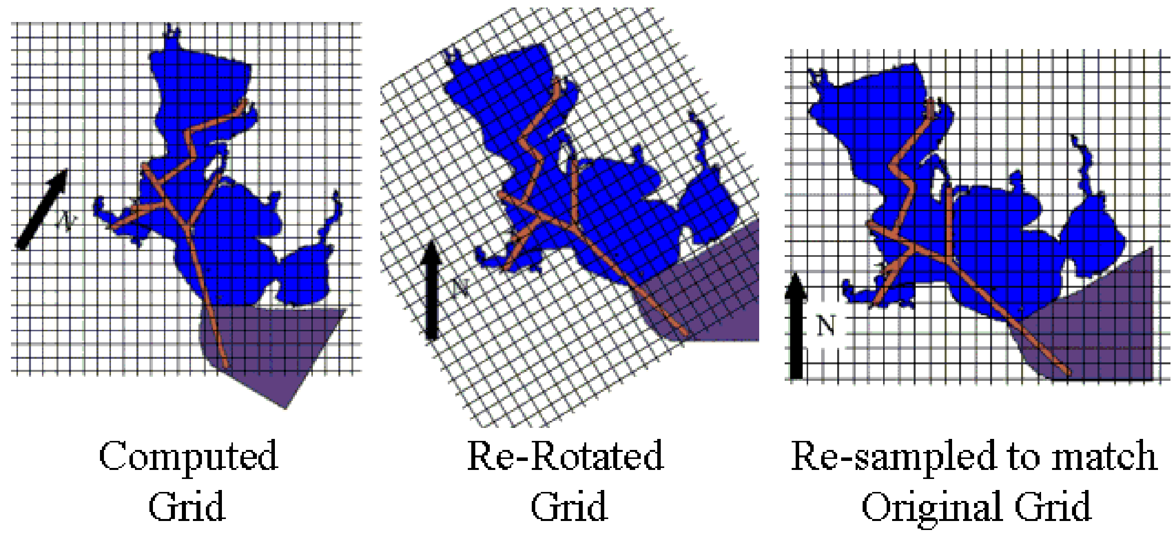


Figure 28 Re-rotation of grids may distort the values due to resampling.

Unfortunately, the semester ended before this re-sampling could be tested to determine if this were a viable comparison approach. This remains one of the avenues to explore as this project continues.

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- Ritter, C. and Montagna, Paul A. 1999. "Seasonal Hypoxia and models of benthic response in a Texas Bay." *Estuaries*. 22:7-20.