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PREDICTION OF INSTANTANEOUS CURRENTS IN SAN DIEGO BAY FOR NAVAL APPLICATIONS

by

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June 2004

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Naval operations are highly dependent upon environmental conditions that can either adversely affect successful completion or hinder the safety of personnel. Each warfare community has defined environmental thresholds and operating limits that restrict the execution of any intended maneuver. As the warfare environment continues to shift from open ocean to the littoral, environmental prediction and modeling efforts of the shallow water surroundings need to be developed in order to support these operations. A hydrodynamic model, Water Quality Management and Analysis Package (WQMAP), has been developed by Applied Sciences Associates, Inc. that is designed specifically to provide accurate littoral environmental prediction. WQMAP is one of several hydrodynamic models used operationally by the Naval Oceanographic Office (NAVOCEANO) to predict currents and water elevations in littoral regions. Implementations of shallow water hydrodynamic models in foreign waters are usually data-starved for model forcing and validation. In a series of studies, NAVOCEANO intends to model various bays within the continental United States, where sufficient data exists, to study the sensitivity of lack of data on model results. This study will utilize WQMAP to design a hydrodynamic model in San Diego Bay to predict currents in order to investigate the impact of grid resolution on model results, and to provide proper current predictions for Fleet training and operations.

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PREDICTION OF INSTANTANEOUS CURRENTS IN SAN DIEGO BAY FOR NAVAL APPLICATIONS

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ABSTRACT

Naval operations are highly dependent upon environmental conditions that can either adversely affect successful completion or hinder the safety of personnel. Each warfare community has defined environmental thresholds and operating limits that restrict the execution of any intended maneuver. As the warfare environment continues to shift from open ocean to the littoral, environmental prediction and modeling efforts of the shallow water surroundings need to be developed in order to support these operations. A hydrodynamic model, Water Quality Management and Analysis Package (WQMAP), has been developed by Applied Sciences Associates, Inc. that is designed specifically to provide accurate littoral environmental prediction. WQMAP is one of several hydrodynamic models used operationally by the Naval Oceanographic Office (NAVOCEANO) to predict currents and water elevations in littoral regions. Implementations of shallow water hydrodynamic models in foreign waters are usually data-starved for model forcing and validation. In a series of studies, NAVOCEANO intends to model various bays within the continental United States, where sufficient data exists, to study the sensitivity of lack of data on model results. This study will utilize WQMAP to design a hydrodynamic model in San Diego Bay to predict currents in order to investigate the impact of grid resolution on model results, and to provide proper current predictions for Fleet training and operations.

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I. INTRODUCTION

This study consists of a detailed analysis of tidal elevation and current data for San Diego Bay during the time period from January 1st, 2004 to January 31st, 2004 for the purpose of predicting the instantaneous currents within San Diego Bay to support for myriad of naval operations that are limited to water current thresholds. The hydrodynamic model utilized in analyzing these currents was a commercial off-the-shelf Windows based application called Water Quality Mapping and Analysis Program (WQMAP) that was developed Applied Science Associates, Inc. This program was developed specifically for marine and fresh water modeling applications.

A. OVERVIEW

The execution of any naval operation can be hindered by numerous environmental factors. Proper planning for these operations includes forecasting the environment of the area of operations. Each warfare area has defined environmental thresholds and operating limits that restrict the execution of any intended maneuver. Amphibious Assault Vehicles (AAV), Mechanized Landing Craft (LCM 6 and LCM 8), Utility Landing Craft (LCU 1646), AN/SLQ-48 Mine Neutralization Vehicle (MNV) aboard AVENGER Class Mine Countermeasures Ships (MCM) and OSPREY Class Coastal Minehunters (MHC), and EOD/Diver operations all have these water current thresholds. As the warfare environment continues to shift from open ocean to the littoral, environmental prediction and modeling efforts of the shallow water surroundings need to be developed in order to support these operations. Present Navy operational current prediction models consist of Wave Watch 3 (WW3) from Fleet Numerical Meteorology and Oceanography Command and Navy Layered Ocean Model (NLOM) out of the Naval Oceanographic Office. Both these models forecast for large scale or global regions and do not provide output for inner littoral bays and estuaries. A finer resolution model designed within specific bays is required to support mine warfare and diver operations within those explicit locations.

B. WATER QUALITY MAPPING AND ANALYSIS PROGRAM (WQMAP)

WQMAP is an integrated hydrodynamic and water quality modeling system designed for use within coastal and fresh water environments. This commercial off-the-shelf program was developed by Applied Science Associates, Inc. out of Narragansett, Rhode Island. WQMAP consists of three basic components: a boundary-fitted coordinate grid creation module, a three-dimensional hydrodynamics model, and a water quality or pollutant transport model. These models are executed on a boundary fitted grid system. They can also be operated on any orthogonal curvilinear grid or a rectangular grid, which are special cases of the boundary fitted grid.

1. WQMAP as a Hydrodynamic Model Choice

The WQMAP hydrodynamic model solves the three dimensional equations of the conservation of water mass, conservation of momentum, and the salt and energy equations. These solutions are computed on a spherical, nonorthogonal, boundary fitted grid system that is applicable for littoral regions and can also be predicted as two dimensional, vertically averaged circulations. The model can calculate a time varying field of surface elevations and/or velocity vectors. Environmental forcing inputs include tides, surface elevations, and wind fields. The model is configured to run in a vertically averaged mode or as a fully three-dimensional, baroclinic mode. A sigma stretching system is incorporated to diagram the free surface and bottom to resolve bathymetric variations. Calculations are achieved on a space-staggered grid system in the horizontal and a non-staggered system in the vertical.

2. WQMAP as Windows Platform

WQMAP requires an IBM-compatible 486 or better PC running Microsoft Windows 95 or higher, although a Pentium system is recommended. It also requires a minimum of 64 megabytes of RAM, 100 megabytes of free hard drive disk space, and a VGA color monitor. The system permits the user to directly create boundary fitted grid systems through a user-friendly Windows graphical interface which is controlled by pull down menus and point and click operations similarly found in most Windows-based applications. These boundary grids represent the area of interest from which the model predictions can be displayed in the form of time series plots, vector and contour plots, in addition to color animated displays. The software is developed for making new

applications to any geographic area with remarkable speed and simplicity. Supporting data is accessed through the location specific data sets, the geographic information system (GIS), or input through the menu windows.

a. Geographic Information System (GIS)

The program has a GIS base and can be set up for any number of regions in the world. The embedded GIS permits input, storage, manipulation, and analysis, and displays geographically referenced information. Moreover, the GIS is quick, interactive, and simple to use. GIS based data sets from other GIS based programs, such as ArcView, can be imported and displayed as well. The user can quickly change from one geographic location to another by simply "pointing" the display to the appropriate data set. These locations, as in any GIS location, are defined by a base map and a series of GIS layers of vector or raster data. The GIS can also be used to provide input data to the models. Everything from the location selection, grid design, selection of forcing data, to the display of the model run is controlled from the simple GIS user interface.

b. Graphical User Interface (GUI)

The WQMAP graphical interface permits every function (from boundary fitted grid creations, importation of open boundary conditions, and execution of the hydrodynamic model, to exporting either graphical or tabular results) to be extremely effortless. The program allows the user to display the results of any model calculations. The user opens a defined scenario and selects the variable (currents, temperature, surface elevation, salinity) and the vertical level. The results can then be animated, using either vectors or color contours, covering the model simulation period. The animation control allows forward, step forward, and rewind options. The animations can also be overlaid on the bathymetric data to allow the user to visualize the relationship between the predicted values (currents, salinity, and temperature) and the depth. The user can also choose a section view window (vertical cross section along user selected line) that permits any variable to be displayed along the section line at the same time as the grid view is animated. Time series data can also be plotted and exported from this section line as well.

C. PURPOSE

This study is concerned with the analysis of the WQMAP model current prediction of San Diego Bay. The focus was to characterize and predict the circulation of the bay where present day Navy operational current models cannot determine such parameters. If the modeled currents can be accurately determined, then the time frame where operational thresholds will be exceeded can also be determined, whether the planned operation is for mine warfare, diver operations, or in many situations, both. The objectives of this investigation are listed as follows:

- Assess the accuracy of WQMAP in determining current circulations within San Diego Bay.
- Operationally outline current threshold restrictions on mine warfare and diving operations for the same modeling period.
- To provide Naval Oceanographic Office an accurate current prediction boundary fitted grid by which future inner bay naval operations may be properly planned from.

II. MODEL

A. HYBRID ORTHORGONAL CURVILINEAR-TERRAIN FOLLOWING COORDINATE SYSTEM

Let (j, l, z) be the latitude, longitude, and height, and (x, h, s) be a hybrid coordinate system with a generalized orthogonal curvilinear coordinate system (x, h) in the horizontal and terrain-following s-coordinate in the vertical. The metric coefficients connecting (f, l) to (x, h) are defined by

$$g_{11} = (\frac{\partial l}{\partial x})^2 \cos^2 f + (\frac{\partial j}{\partial x})^2, \tag{1}$$

$$g_{22} = (\frac{\partial l}{\partial h})^2 \cos^2 + (\frac{\partial j}{\partial h})^2 \quad . \tag{2}$$

Let (z, H) be the surface elevation and bathymetry. $D = H + z$, is the total water depth. The s- and z-coordinates are connected by

$$s = \frac{z + H}{z + H}, \tag{3}$$

which makes $s = 1$ for the ocean surface and $s = 0$ for the ocean bottom.

B. GOVERNING EQUATIONS

The equations of motions and continuity are expressed in a hybrid orthogonal curvilinear-terrain following coordinate system (x, h, s) with (u, v, w) being the corresponding velocity components. In this coordinate system, the basic dynamical system is represented by Kantha and Clayson (2000).

$$R\sqrt{g_{11}g_{22}}\frac{\partial z}{\partial t} + \frac{\partial\left(uD\sqrt{g_{22}}\right)}{\partial x} + \frac{\partial\left(vD\sqrt{g_{11}}\right)}{\partial h} + R\sqrt{g_{11}g_{22}}\frac{\partial w}{\partial s} = 0, \tag{4}$$

which is the continuity equation,

$$\frac{\partial uD}{\partial t}+\frac{1}{\sqrt{g_{11}g_{22}}}\left[\frac{\partial\left(u^2 D\sqrt{g_{22}}\right)}{\partial x}+\frac{\partial\left(uvD\sqrt{g_{11}}\right)}{\partial h}+uvD\frac{\partial\left(\sqrt{g_{11}}\right)}{\partial h}-v^2\frac{\partial\left(\sqrt{g_{22}}\right)}{\partial x}\right]-fDV$$
$$+\frac{\partial uw}{\partial s}-fDv=-\frac{gD}{R\sqrt{g_{11}}}\left[\frac{\partial z}{\partial x}+\frac{D}{r_0}\int_s^0\left(\frac{\partial r}{\partial x}-\frac{s}{D}\frac{\partial D}{\partial x}\frac{\partial r}{\partial s}\right)ds\right]+\frac{1}{D}\frac{\partial}{\partial s}\left(A_v\frac{\partial u}{\partial s}\right), \tag{5}$$

which is the momentum equation in x -direction,

$$\frac{\partial vD}{\partial t}+\frac{1}{\sqrt{g_{11}g_{22}}}\left[\frac{\partial\left(uvD\sqrt{g_{22}}\right)}{\partial x}+\frac{\partial\left(v^2 D\sqrt{g_{11}}\right)}{\partial h}+uvD\frac{\partial\left(\sqrt{g_{22}}\right)}{\partial x}-u^2\frac{\partial\left(\sqrt{g_{11}}\right)}{\partial h}\right]+fDV$$
$$+\frac{\partial vw}{\partial s}+fDu=-\frac{gD}{R\sqrt{g_{22}}}\left[\frac{\partial z}{\partial x}+\frac{D}{r_0}\int_s^0\left(\frac{\partial r}{\partial x}-\frac{s}{D}\frac{\partial D}{\partial x}\frac{\partial r}{\partial s}\right)ds\right]+\frac{1}{D}\frac{\partial}{\partial s}\left(A_v\frac{\partial v}{\partial s}\right), \tag{6}$$

which is the momentum equation in h -direction. Here, R is the earth radius; r_0 (= 1025 kg/m^3) is the characteristic density for the seawater; f is the Coriolis parameter, g is the acceleration due to gravity, A_v is the vertical eddy viscosity. The transport equations for temperature and salinity are represented by

$$\frac{\partial S}{\partial t}+\frac{u}{R\sqrt{g_{11}}}\frac{\partial S}{\partial x}+\frac{v}{R\sqrt{g_{22}}}\frac{\partial S}{\partial h}+w\frac{\partial S}{\partial s}=\frac{1}{R^2 g_{11}}\left(D_h\frac{\partial^2 S}{\partial x^2}\right)+\frac{1}{R^2 g_{22}}\left(D_h\frac{\partial^2 S}{\partial h^2}\right)+\frac{1}{D^2}\frac{\partial}{\partial s}\left(D_v\frac{\partial S}{\partial s}\right), \tag{7}$$

$$\frac{\partial T}{\partial t}+\frac{u}{R\sqrt{g_{11}}}\frac{\partial T}{\partial x}+\frac{v}{R\sqrt{g_{22}}}\frac{\partial T}{\partial h}+w\frac{\partial T}{\partial s}=\frac{1}{R^2 g_{11}}\left(D_h\frac{\partial^2 T}{\partial x^2}\right)+\frac{1}{R^2 g_{22}}\left(D_h\frac{\partial^2 T}{\partial h^2}\right)+\frac{1}{D^2}\frac{\partial}{\partial s}\left(D_v\frac{\partial T}{\partial s}\right), \tag{8}$$

where D_h and D_v are horizontal and vertical diffusivities.

The three-dimensional hydrodynamic equations (4-6), contain both high-speed external gravity waves and slow propagating internal gravity waves. The equations of motion are broken up into vertically averaged equations and vertical structure equations, which are called the exterior and interior modes by the WQMAP documentation, respectfully. This approach permits the calculation of free surface elevation from the exterior mode and the three-dimensional currents and thermodynamic properties from the interior mode. The vertically averaged equations are obtained by integrating equations (4-6) from s =0 to s =-1.

C. VERTICAL AVERAGED MODE

Let (U, V) be the vertically averaged velocity components in (x, h) directions. Vertical integration of (5) and (6) leads to the momentum equations for (U, V),

$$\frac{\partial UD}{\partial t}+\frac{1}{\sqrt{g_{11}g_{22}}}\left[\frac{\partial\left(U^2D\sqrt{g_{22}}\right)}{\partial x}+\frac{\partial\left(UVD\sqrt{g_{11}}\right)}{\partial h}+UVD\frac{\partial\left(\sqrt{g_{11}}\right)}{\partial h}-V^2\frac{\partial\left(\sqrt{g_{22}}\right)}{\partial x}\right]-fDV$$
$$=-\frac{gD}{R\sqrt{g_{11}}}\left[\frac{\partial z}{\partial x}+\frac{D}{r_0}\int_{-1}^{0}\int_{s}^{0}\left(\frac{\partial r}{\partial x}-\frac{s}{D}\frac{\partial D}{\partial x}\frac{\partial r}{\partial s}\right)ds\right], \tag{9}$$

$$\frac{\partial VD}{\partial t}+\frac{1}{\sqrt{g_{11}g_{22}}}\left[\frac{\partial\left(UVD\sqrt{g_{22}}\right)}{\partial x}+\frac{\partial\left(V^2D\sqrt{g_{11}}\right)}{\partial h}+UVD\frac{\partial\left(\sqrt{g_{22}}\right)}{\partial x}-U^2\frac{\partial\left(\sqrt{g_{11}}\right)}{\partial h}\right]+fDV$$
$$=-\frac{gD}{R\sqrt{g_{22}}}\left[\frac{\partial z}{\partial h}+\frac{D}{r_0}\int_{-1}^{0}\int_{s}^{0}\left(\frac{\partial r}{\partial h}-\frac{s}{D}\frac{\partial D}{\partial h}\frac{\partial r}{\partial s}\right)ds\right]. \tag{10}$$

Vertical integration of (4) leads to

$$R\sqrt{g_{11}g_{22}}\frac{\partial z}{\partial t}+\frac{\partial\left(UD\sqrt{g_{22}}\right)}{\partial x}+\frac{\partial\left(VD\sqrt{g_{11}}\right)}{\partial h}=0\,, \tag{11}$$

which is the continuity equation for the vertically averaged mode.

D. MODEL NUMERICS

The surface elevation is solved implicitly whereas the density gradient, bottom stress, Coriolis, and advective terms are solved explicitly. The two-dimensional vertically averaged equations of continuity and motion are solved semi-implicitly. The momentum equations are substituted into the continuity equation to obtain a Helmholtz equation in terms of surface elevation. A staggered spatial discretization is established for the Arakawa Grid C system (Arakawa and Lamb, 1977) as displayed in Figure 1. The u and v velocities are defined, within a layer, in a staggered orientation in the horizontal direction, but determined at the center in the vertical direction. The vertical velocity ω is similarly defined at the center of a layer in the vertical direction in the center of the cell in the horizontal direction. The variables density, temperature, salinity, eddy diffusivity and eddy viscosity are also defined at the center of the cell. Time is discretized by means of a

three level scheme using a weighting factor of 1.5. The resulting numerical scheme is second order accurate in both space and time. The vertically averaged velocities are then determined from the vertically averaged momentum equations, using the surface elevation solve from the discretized Helmholtz equation.

The coefficient g_{11} is the metric tensor in x-direction and the coefficient g_{22} metric tensor in h-direction. These tensors permit the model to transform the user defined boundary fitted grid to a numerical grid employed for spatial discretization utilized in an Arakawa C Grid as displayed in Figure 2.

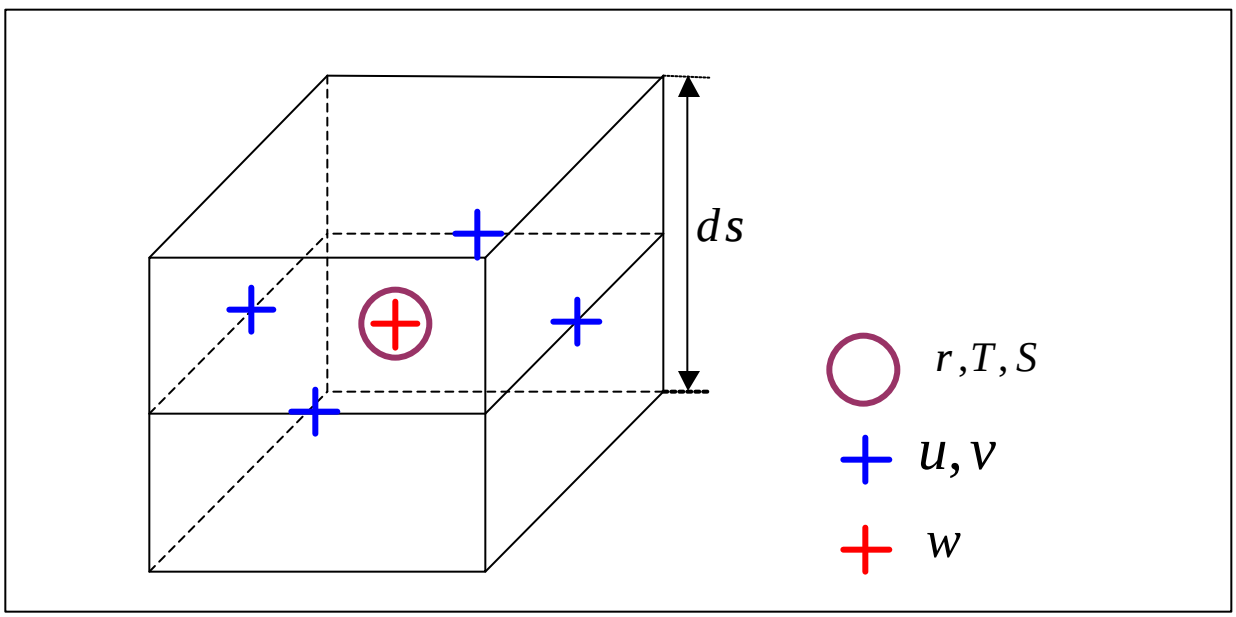

Figure 1. Arakawa 'C' Grid.

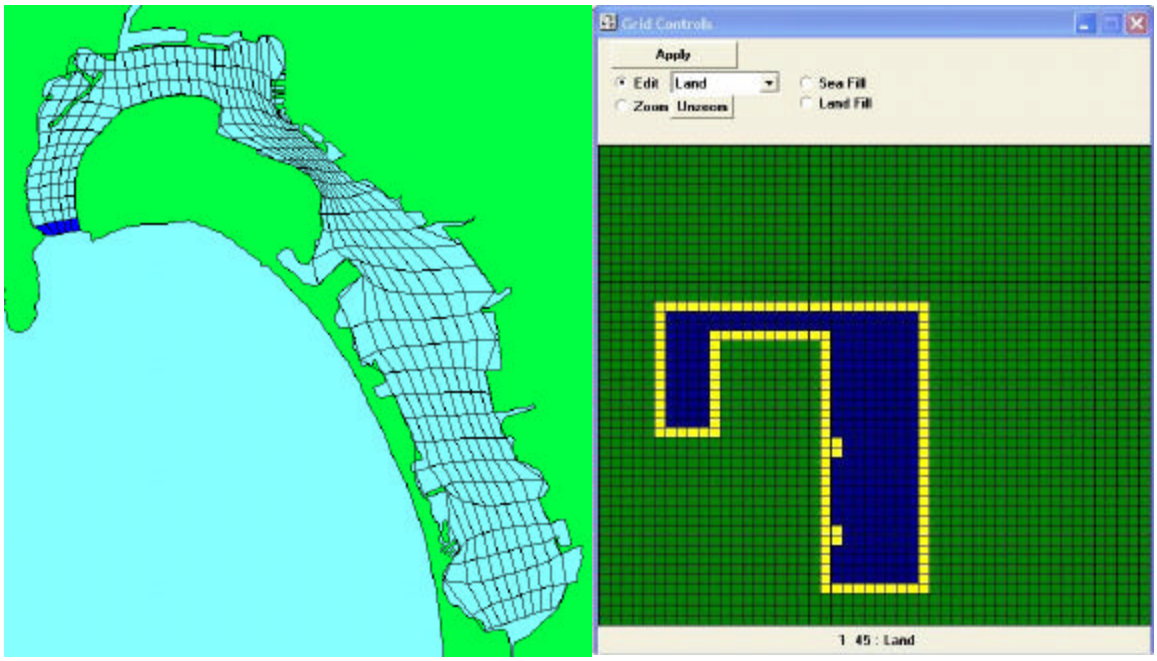

Figure 2. Grid Representation.

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III. BOUNDARY FITTED GRID CREATION

A. CREATING A NEW SCENARIO

The start of this process is to create a new scenario for the project. Scenarios consist of the same geographic location to be modeled. Each individual scenario can be either a hydrodynamic model or mass transport model (e.g., pollution tracking). The particular scenario can consist of either a two dimensional (2-D) vertically averaged model or a three dimensional (3-D) model. In addition, each saved scenario tracks the grid, bathymetry, open boundary forcing, and time frame of that particular scenario. If it was desired to run similar conditions but use different designed grids, then separated scenarios must be saved to keep these distinctions on record. Under the "File' menu, 'New Scenario' needs to be selected to start the process. Under a separate window the choice of either hydrodynamic model or mass transport model is made, as well as scenario name, and either a 2-D or 3-D model is to be used. If the model is 3-D, then the number of sigma levels also needs to be identified. For the purposes of this study, a 2-D hydrodynamic model was selected.

B. CREATING THE BOUNDARY FITTED GRID

Since WQMAP is a geospatial information system, the region which is to be hydrodynamically modeled needs to be identified with the appropriate map location file displayed as a GIS layer. WQMAP is supplied with one base map, or location, with the ability to input additional areas depending on the need of the user. This base map serves as the largest domain over which the hydrodynamic model will be implemented. Model locations vary from small rivers, lakes and estuarine systems with scales of kilometers, to bays, seas, and the continental shelf, with scales of tens to hundreds of kilometers. For each location, a geo-referenced shoreline and bathymetry is created from either magnetic data or charts. Base maps of small spatial extent may contain high-resolution characteristics (harbor shapes, piers, etc.). Conversely, large spatial extent base maps have less detail. For this study a small spatial extent ASA map file (.bdm) for the San Diego Bay was utilized.

Initial grid creation is rather simple. From the 'Grid' pull down menu, 'New Grid' is selected. The user clicks and drags the mouse drawing a box over the area to be modeled. A grid parameter window opens where, at a minimum, the grid resolution (Imax and Jmax) and the grid name need to be identified. The first grid generated was a coarse 50 by 50 grid. The four corners of the box identify the grid boundaries starting with the lower left at as (1,1), the upper left as (1,50), the lower right as (50,1) and the upper right at (50,50) as seen in Figure 3. The grid end points can then connected by selecting an 'Interpolate Points' command from either the 'Grid' pull down menu or by right clicking.

Once the grid borders are established, as displayed in Figure 4, the process becomes more complex. The user must strategically shape the grid to the general symmetry of the bay itself. This process requires the user to mentally picture the bay as a rectangular construct. The user accomplishes this by interpolating additional points around the general shape of the bay, and then strategically removing the excess over land (Figure 5). Once the general shape is determined, the user moves the symmetric grid points to conform to the bay's actual boundaries. Finally, the grid is ready to be processed. Under the 'Grid' pull down menu, the user selects 'Run Gridding Model'. WQMAP then creates the entire boundary fitted grid while calculating the spatial transform tensors of g_{11} and g_{22} for each grid cell. The boundary fitted grid that is seen by the user (Figure 7) is mathematically linked to the spatial discretized Arakawa C Grid as displayed in Figure 2.

Three separate grids were created for this study: a coarse resolution 50 by 50 grid (Figure 7), a medium resolution 100 by 100 grid (Figure 8), and a fine resolution 150 by 150 grid (Figure 9).

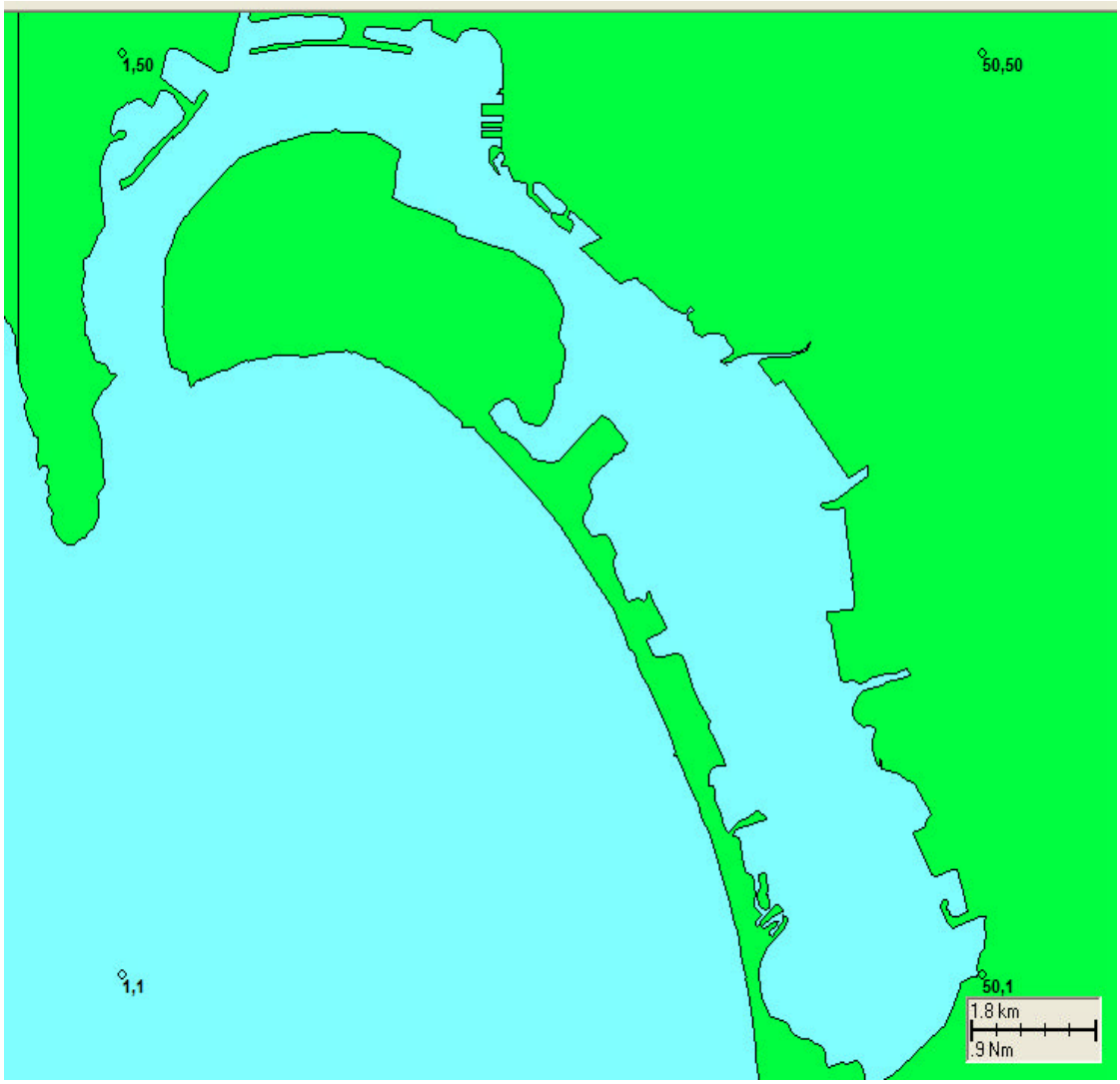

Figure 3. Initial Grid Creation.

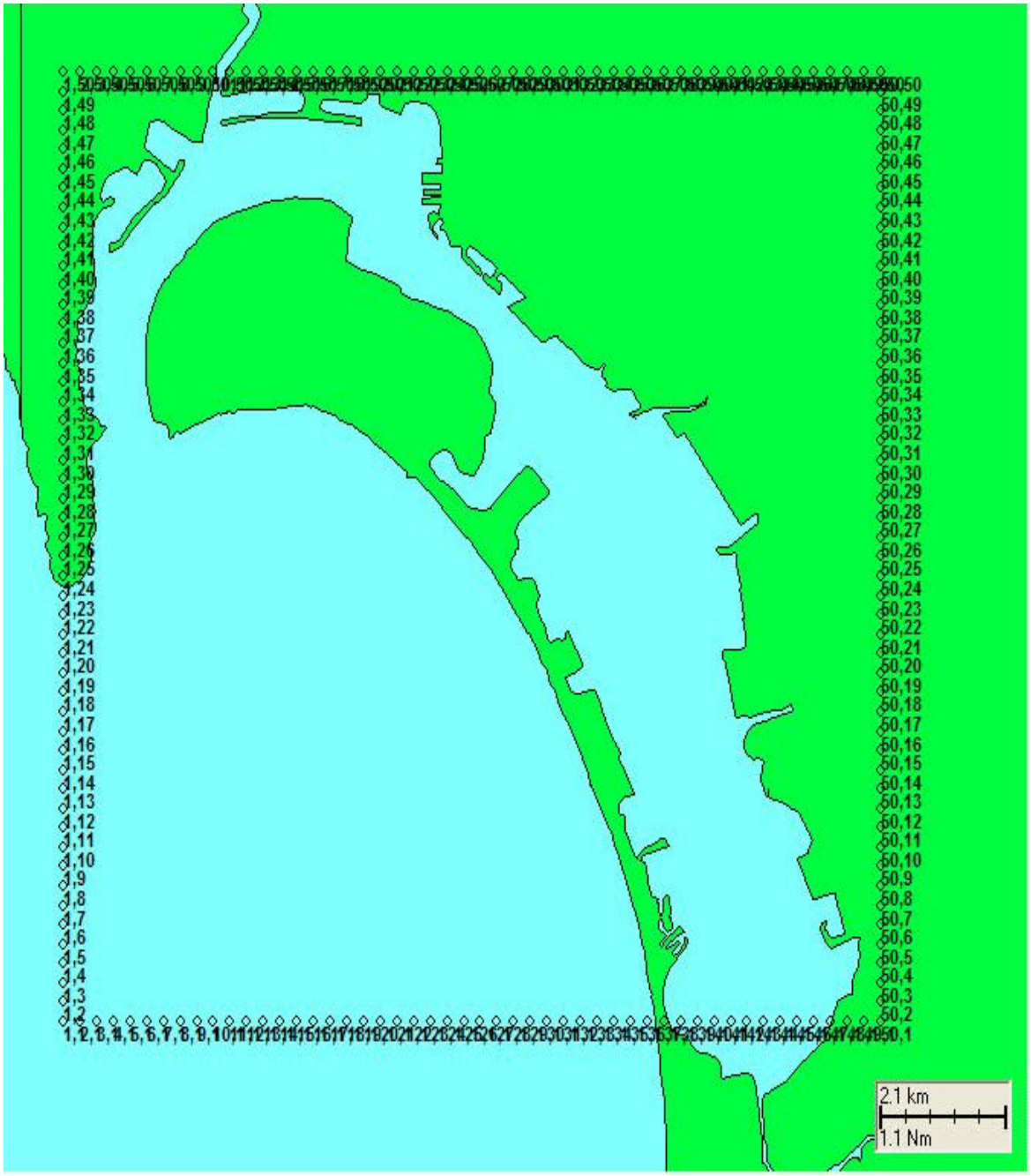

Figure 4. Interpolating Grid Boundaries.

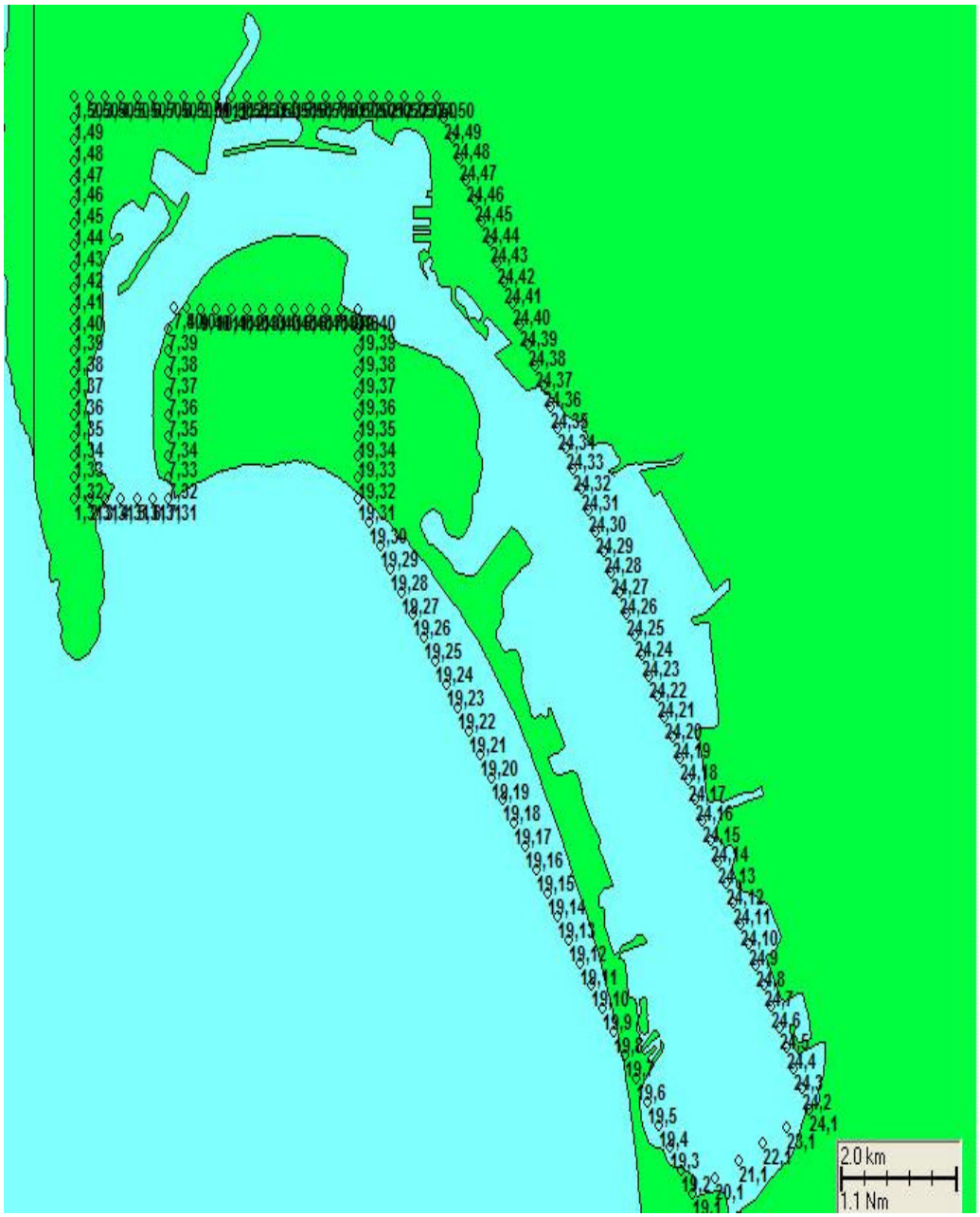

Figure 5. Forming Bay Symmetry.

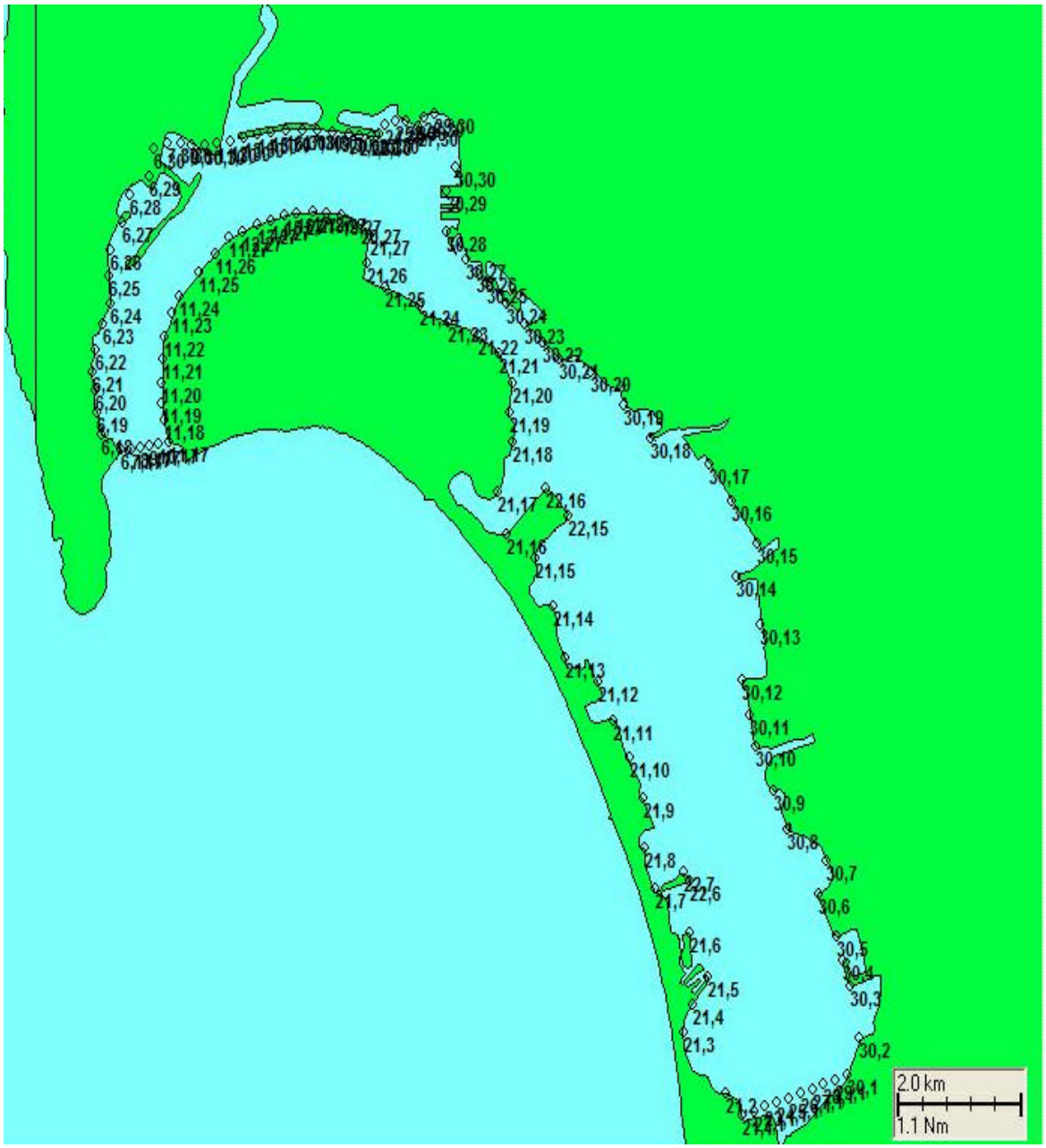

Figure 6. Aligning Grid to San Diego Bay Boundaries.

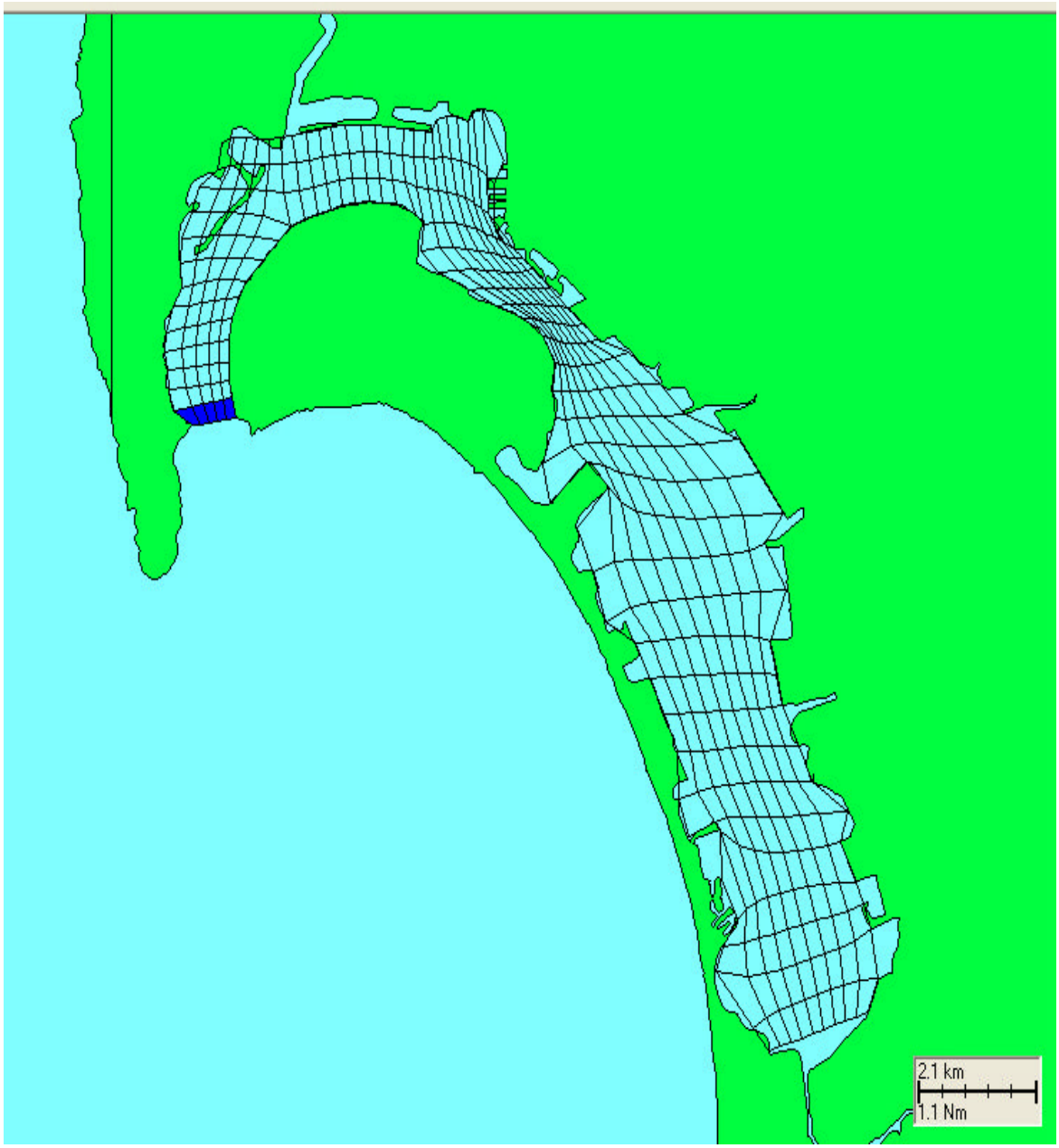

Figure 7. Coarse Boundary Fitted Grid

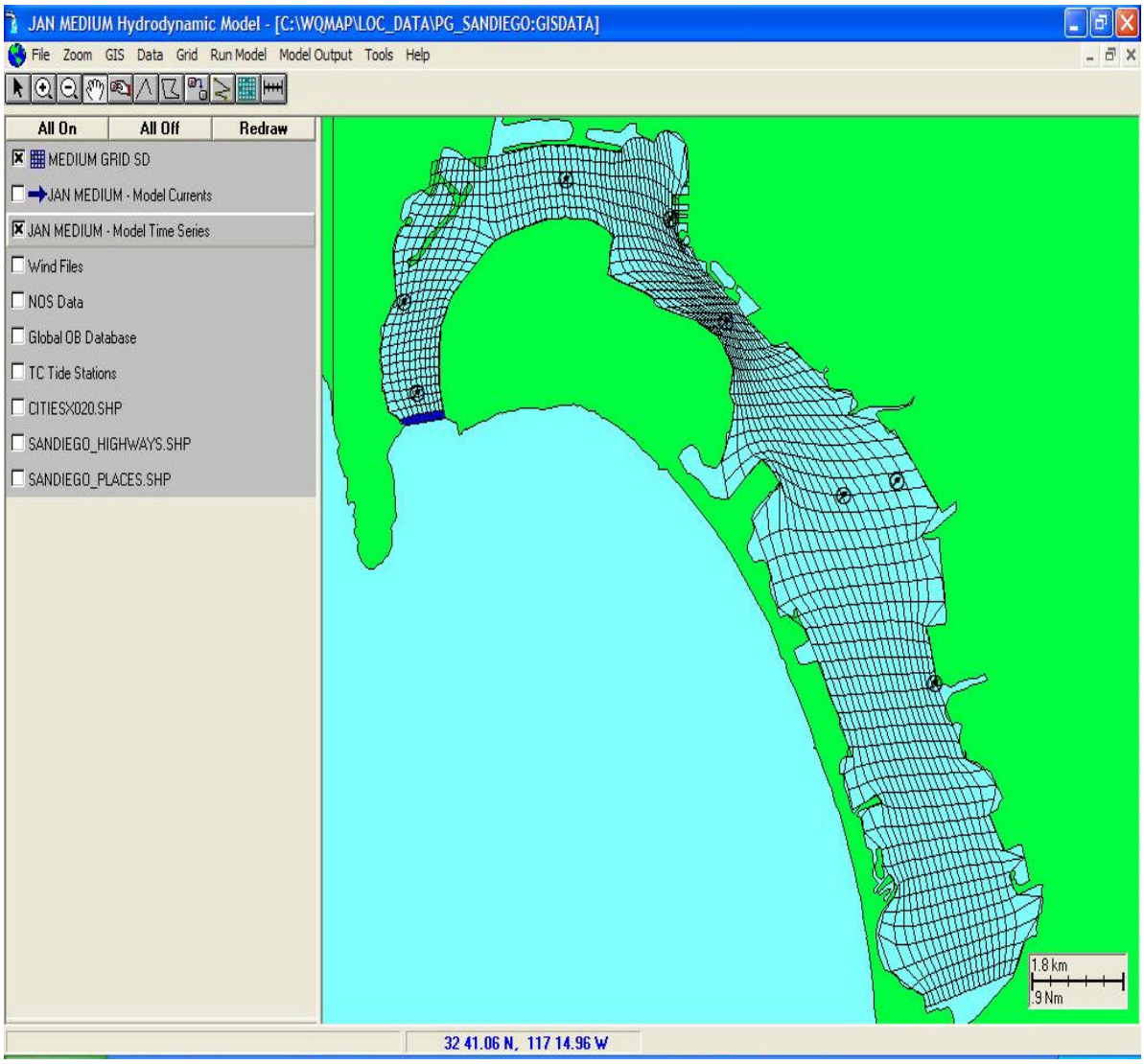

Figure 8. Medium Boundary Fitted Grid

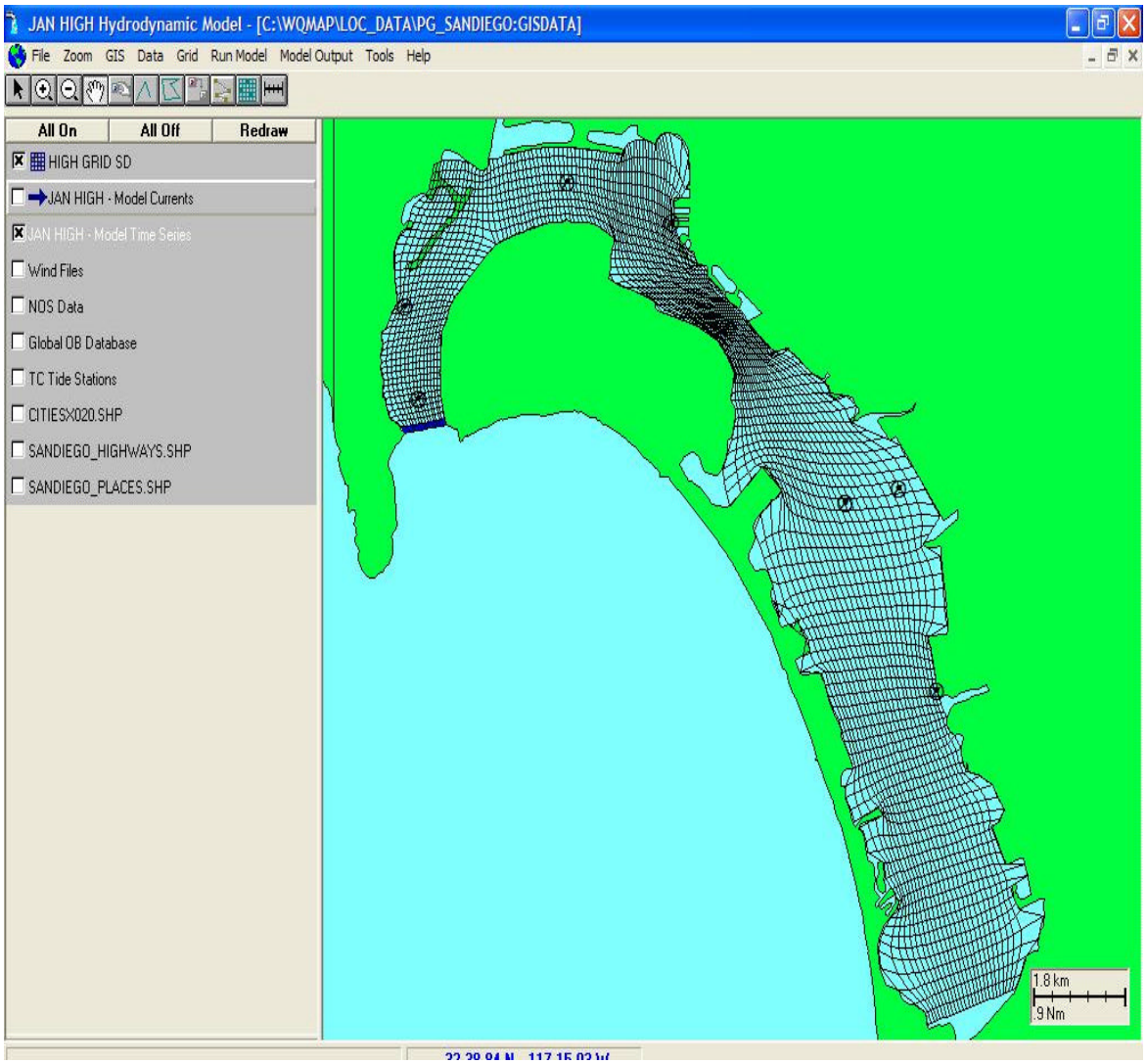

Figure 9. Fine Boundary Fitted Grid

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IV. DATA AND METHODS

A. DATA COLLECTION

1. Forcing Data

The blue shaded cells of Figures 7, 8, and 9 are defined as the open boundary conditions with the model. The land boundaries are assumed impermeable; hence the normal component of the velocity at those boundaries is set to zero. Tidal harmonic constituents or sea surface elevation can be an input as a function of time along the open boundaries. Such elevation data for the entrance to San Diego Bay was available the National Oceanographic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) website. A search was conducted for verified six-minute elevation data from time 0000 on 01 January 2004 to 2354 on 31 January 2004 for the San Diego Bay entrance (Station Identification Number 9410170). An example of the beginning of the data file that was returned is displayed in Table 1. Since this data was sampled once every 6 minutes for the month of January, the data set consisted of 7,440 lines of observed elevation data points. The file must be formatted such that WQMAP can import it as an Open Boundary Tidal Forcing file (.hst). The HST file is a time series file for tidal forcing, salinity and temperature to be linked to the blue open boundary cells. The HST layout consists of an ASCII format of year, month, day, hour, minutes, elevation (m), salinity (ppt) and temperature (°C). The data can be either comma or space delimited. This study was not concerned with salinity and temperature advection so those value could be omitted. The first 22 lines of the data file were deleted as well as the first 8 columns, which was merely the Station Identification Number. Then column 5 (a slash), column 8 (another slash), and column 14 (a colon) were replaced with spaces and then saved. Then the new file's last column was extracted. A Fast Fourier Transport was then conducted on the data set, and the high frequency signal that was present within the data set from winds, fronts, etc was filtered out. This new smoothed elevation data column was reinserted to the file. The file could then be saved with a *.hst extension and moved to the 'runhydro' sub-directory of the program directory.

```
Verified 6 minute Water Level Data (W1)

       Station   --   Unique seven character identifier for the station
       Date Time --   Date and time the data were collected by the DCP
       WL        --   Water level height

       Sigma     --   Standard deviation of 1 second samples used to
                      compute the water level height
       I         --   A flag that indicates that the water level value
                      has been inferred.
       F         --   A flag that when set to 1 indicates that the flat
                      tolerance limit was exceeded
       R         --   A flag that when set to 1 indicates that the rate
                      of change tolerance limit was exceeded
       T         --   A flag that when set to 1 indicates that the
                     temperature difference tolerance limit was exceeded

Data are in Meters above MLLW
Times are on Local Standard Time (LST)
9410170 SAN DIEGO, SAN DIEGO BAY , CA  from  20040101 to 20040131
Click HERE for further station information.------------------------------
Station Date       Time      WL    Sigma I F R T

9410170 2004/01/01 00:00   0.713   0.009 0 0 0 0
9410170 2004/01/01 00:06   0.727   0.007 0 0 0 0
9410170 2004/01/01 00:12   0.737   0.007 0 0 0 0
9410170 2004/01/01 00:18   0.754   0.011 0 0 0 0
9410170 2004/01/01 00:24   0.795   0.014 0 0 0 0
9410170 2004/01/01 00:30   0.835   0.013 0 0 0 0
9410170 2004/01/01 00:36   0.850   0.013 0 0 0 0
9410170 2004/01/01 00:42   0.867   0.009 0 0 0 0
9410170 2004/01/01 00:48   0.878   0.011 0 0 0 0
9410170 2004/01/01 00:54   0.899   0.009 0 0 0 0
9410170 2004/01/01 01:00   0.914   0.010 0 0 0 0
9410170 2004/01/01 01:06   0.929   0.008 0 0 0 0
9410170 2004/01/01 01:12   0.942   0.008 0 0 0 0
9410170 2004/01/01 01:18   0.968   0.008 0 0 0 0
9410170 2004/01/01 01:24   1.003   0.012 0 0 0 0
9410170 2004/01/01 01:30   1.056   0.010 0 0 0 0
9410170 2004/01/01 01:36   1.098   0.009 0 0 0 0
9410170 2004/01/01 01:42   1.103   0.011 0 0 0 0
9410170 2004/01/01 01:48   1.115   0.012 0 0 0 0
9410170 2004/01/01 01:54   1.131   0.010 0 0 0 0
9410170 2004/01/01 02:00   1.151   0.009 0 0 0 0
9410170 2004/01/01 02:06   1.169   0.012 0 0 0 0
9410170 2004/01/01 02:12   1.195   0.009 0 0 0 0
9410170 2004/01/01 02:18   1.220   0.011 0 0 0 0
```

Table 1. NOAA/NOS Verified 6 minute Water Level Data (Truncated) for Station 9410170 (San Diego Bay, Ballast Point.)

2. Verification Data

The original intent of this study was to compare the modeled output of currents within San Diego Bay from WQMAP to observed current data collected by an Acoustic Doppler Current Profiler (ADCP) from the same time frame. Such a data source was identified online with the San Diego Marine Information System (SDMIS). SDMIS has three ADCPs located with San Diego Bay. The first one was positioned at the SPAWAR Pier 160/A, the second was at the 10th Avenue Marine Terminal, and the third was located at the National City Marine Terminal. This information was available live online, but archived data was not. Contact with SDMIS revealed that the company InterOcean Systems Inc maintained the ADCPs and the database. Contact with the InterOcean Systems Inc Data Manager revealed that the T1 connection connecting the ACDPs to the mainframe computer was down for a period of about five months including the time frame of this study. As a second source of verification data, NOAA CO-OP Tide Tables for elevation and current (Tables 2 and 3, respectively) were obtained for the month of January 2004. These tables are valid for the entrance of San Diego Bay at Ballast Point. As a result, this is where the blue open ocean boundary cells have been positioned as seen in Figures 7, 8, and 9. The NOAA elevation tide table and NOAA current tide tables had to be converted into a time series table column-wise with the year, month, day, hour, minute, and height delimited by spaces. In addition, the elevation was converted from feet to meters and the current was converted from knots to meters per second.

Date	Day	Time	Height		Time	Height		Time	Height		Time	Height	
01/01/2004	Thu	04:46AM LST	4.9	H	12:12PM LST	0.8	L	06:04PM LST	2.9	H	10:51PM LST	1.8	L
01/02/2004	Fri	05:23AM LST	5.2	H	12:54PM LST	0.4	L	07:07PM LST	3.0	H	11:35PM LST	2.1	L
01/03/2004	Sat	05:57AM LST	5.3	H	01:29PM LST	-0.1	L	07:52PM LST	3.2	H			
01/04/2004	Sun	12:16AM LST	2.2	L	06:30AM LST	5.5	H	02:01PM LST	-0.4	L	08:27PM LST	3.3	H
01/05/2004	Mon	12:53AM LST	2.2	L	07:04AM LST	5.7	H	02:32PM LST	-0.6	L	08:59PM LST	3.4	H
01/06/2004	Tue	01:29AM LST	2.2	L	07:37AM LST	5.8	H	03:03PM LST	-0.7	L	09:29PM LST	3.5	H
01/07/2004	Wed	02:03AM LST	2.1	L	08:10AM LST	5.9	H	03:35PM LST	-0.8	L	10:00PM LST	3.5	H
01/08/2004	Thu	02:37AM LST	2.1	L	08:44AM LST	5.9	H	04:07PM LST	-0.8	L	10:33PM LST	3.5	H
01/09/2004	Fri	03:12AM LST	2.1	L	09:17AM LST	5.8	H	04:41PM LST	-0.7	L	11:08PM LST	3.6	H
01/10/2004	Sat	03:50AM LST	2.1	L	09:52AM LST	5.6	H	05:14PM LST	-0.6	L	11:45PM LST	3.6	H
01/11/2004	Sun	04:34AM LST	2.2	L	10:30AM LST	5.2	H	05:49PM LST	-0.3	L			
01/12/2004	Mon	12:25AM LST	3.8	H	05:31AM LST	2.2	L	11:13AM LST	4.7	H	06:25PM LST	0.1	L
01/13/2004	Tue	01:08AM LST	4.0	H	06:46AM LST	2.1	L	12:09PM LST	4.0	H	07:04PM LST	0.6	L
01/14/2004	Wed	01:56AM LST	4.2	H	08:19AM LST	1.9	L	01:32PM LST	3.3	H	07:50PM LST	1.1	L
01/15/2004	Thu	02:49AM LST	4.6	H	09:56AM LST	1.3	L	03:24PM LST	2.9	H	08:46PM LST	1.6	L
01/16/2004	Fri	03:44AM LST	5.1	H	11:16AM LST	0.6	L	05:15PM LST	2.9	H	09:55PM LST	1.8	L
01/17/2004	Sat	04:40AM LST	5.5	H	12:17PM LST	-0.3	L	06:38PM LST	3.0	H	11:04PM LST	2.0	L
01/18/2004	Sun	05:34AM LST	6.0	H	01:09PM LST	-1.0	L	07:36PM LST	3.4	H			
01/19/2004	Mon	12:07AM LST	2.0	L	06:26AM LST	6.3	H	01:56PM LST	-1.6	L	08:22PM LST	3.7	H
01/20/2004	Tue	01:03AM LST	1.9	L	07:15AM LST	6.6	H	02:39PM LST	-1.8	L	09:03PM LST	3.9	H
01/21/2004	Wed	01:54AM LST	1.7	L	08:03AM LST	6.7	H	03:21PM LST	-1.8	L	09:42PM LST	4.0	H
01/22/2004	Thu	02:42AM LST	1.6	L	08:48AM LST	6.6	H	04:02PM LST	-1.7	L	10:21PM LST	4.1	H
01/23/2004	Fri	03:29AM LST	1.5	L	09:32AM LST	6.3	H	04:40PM LST	-1.3	L	10:59PM LST	4.1	H
01/24/2004	Sat	04:17AM LST	1.5	L	10:16AM LST	5.7	H	05:18PM LST	-0.8	L	11:39PM LST	4.2	H
01/25/2004	Sun	05:09AM LST	1.6	L	10:59AM LST	5.0	H	05:54PM LST	-0.2	L			
01/26/2004	Mon	12:19AM LST	4.2	H	06:06AM LST	1.7	L	11:46AM LST	4.1	H	06:29PM LST	0.5	L
01/27/2004	Tue	01:02AM LST	4.2	H	07:17AM LST	1.7	L	12:42PM LST	3.4	H	07:04PM LST	1.1	L
01/28/2004	Wed	01:50AM LST	4.2	H	08:48AM LST	1.7	L	02:07PM LST	2.7	H	07:43PM LST	1.7	L
01/29/2004	Thu	02:44AM LST	4.3	H	10:36AM LST	1.4	L	04:35PM LST	2.5	H	08:38PM LST	2.1	L
01/30/2004	Fri	03:42AM LST	4.4	H	11:54AM LST	0.8	L	06:49PM LST	2.7	H	09:57PM LST	2.5	L
01/31/2004	Sat	04:39AM LST	4.6	H	12:41PM LST	0.4	L	07:35PM LST	2.9	H	11:11PM LST	2.5	L

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable).
All heights are in feet referenced to Mean Lower Low Water (MLLW).

Table 2. NOAA/NOS Tidal Water Level Data for Station 9410170 (San Diego Bay, Ballast Point.)

San Diego Bay Entrance (off Ballast Point), California

Predicted Tidal Current January, 2004
Flood Direction, 355 True. Ebb (-)Direction, 175 True.
NOAA, National Ocean Service

Day	Slack Water Time h.m.	Maximum Current Time h.m.	Veloc knots	Slack Water Time h.m.	Maximum Current Time h.m.	Veloc knots	Slack Water Time h.m.	Maximum Current Time h.m.	Veloc knots	Slack Water Time h.m.	Maximum Current Time h.m.	Veloc knots	Slack Water Time h.m.
1		236	1.1	533	858	-1.4	1302	1541	0.8	1821	2057	-0.7	2344
2		320	1.2	611	942	-1.7	1343	1630	1.0	1921	2147	-0.7	
3	26	358	1.2	646	1020	-1.9	1418	1710	1.2	2010	2230	-0.8	
4	102	432	1.3	719	1054	-2.1	1450	1747	1.3	2051	2308	-0.8	
5	136	503	1.3	751	1128	-2.2	1520	1820	1.4	2128	2343	-0.8	
6	207	531	1.3	822	1200	-2.3	1550	1851	1.4	2203			
7		16	-0.8	237	558	1.3	852	1232	-2.3	1621	1921	1.4	2236
8		49	-0.8	306	624	1.3	922	1305	-2.3	1651	1951	1.4	2309
9		123	-0.8	339	653	1.3	953	1339	-2.3	1723	2021	1.3	2343
10		200	-0.8	416	725	1.2	1026	1415	-2.1	1756	2053	1.3	
11	19	241	-0.8	501	804	1.1	1103	1454	-1.9	1830	2128	1.2	
12	58	329	-0.8	559	851	0.9	1147	1539	-1.7	1908	2210	1.1	
13	143	426	-0.9	714	954	0.7	1245	1632	-1.3	1951	2302	1.1	
14	234	535	-1.0	853	1126	0.5	1409	1739	-1.0	2041			
15		7	1.0	331	650	-1.2	1041	1326	0.6	1604	1858	-0.8	2141
16		119	1.1	430	802	-1.6	1204	1458	0.8	1749	2017	-0.7	2247
17		227	1.2	526	906	-2.0	1305	1604	1.2	1907	2126	-0.8	2351
18		326	1.4	620	1001	-2.4	1356	1657	1.5	2006	2224	-0.9	
19	49	419	1.6	711	1051	-2.7	1442	1744	1.8	2055	2314	-1.1	
20	140	507	1.8	759	1137	-2.9	1525	1827	1.9	2139			
21		0	-1.2	228	552	1.9	845	1221	-3.0	1607	1908	2.0	2220
22		43	-1.2	314	635	1.8	929	1303	-2.9	1647	1948	1.9	2300
23		125	-1.3	400	716	1.7	1012	1343	-2.7	1724	2027	1.7	2338
24		208	-1.2	447	758	1.5	1053	1423	-2.3	1801	2105	1.5	
25	18	252	-1.2	537	841	1.2	1134	1503	-1.9	1835	2143	1.3	
26	58	339	-1.1	637	930	0.9	1218	1545	-1.5	1910	2225	1.1	
27	143	433	-1.0	754	1034	0.5	1311	1633	-1.0	1947	2315	0.9	
28	234	539	-0.9	946	1217	0.3	1432	1735	-0.6	2032			
29		23	0.7	333	658	-1.0	1143	1412	0.4	1634	1859	-0.4	2136
30		143	0.7	434	815	-1.2	1248	1529	0.6	1819	2029	-0.4	2258
31		249	0.8	530	916	-1.4	1330	1621	0.9	1924	2136	-0.5	

All times listed are in Local Time, and all speeds are in knots.

Table 3. NOAA/NOS Tidal Current Data for Station 9410170 (San Diego Bay, Ballast Point.).

3. Bathymetry

In order to properly prepare WQMAP to execute the hydrodynamic model, the bathymetry of San Diego Bay was incorporated into the newly formed grid. The file format used for the bathymetry consisted of three columns of longitude, latitude, and depth at those coordinates in meters. West longitude and south latitude are denoted as negative values. The file has a depth point file (*.dpt) extension and it has to reside in the 'runhydro' sub-directory of the program directory. Under the 'Grid' menu, 'Grid Parameters' was selected. The same window that was used to create the new grid appeared except it allowed for insertion of a default depth of 10 meters, an ETOPO2 (Global Two Minute Elevations) data set, or a specific depth point file via a pull down window. Once the desired depth point file was selected, the 'Fill Depths' button was selected. The program then inserts the averaged depth value for each grid point. The bathymetry file loaded into San Diego Bay is seen in Figure 10.

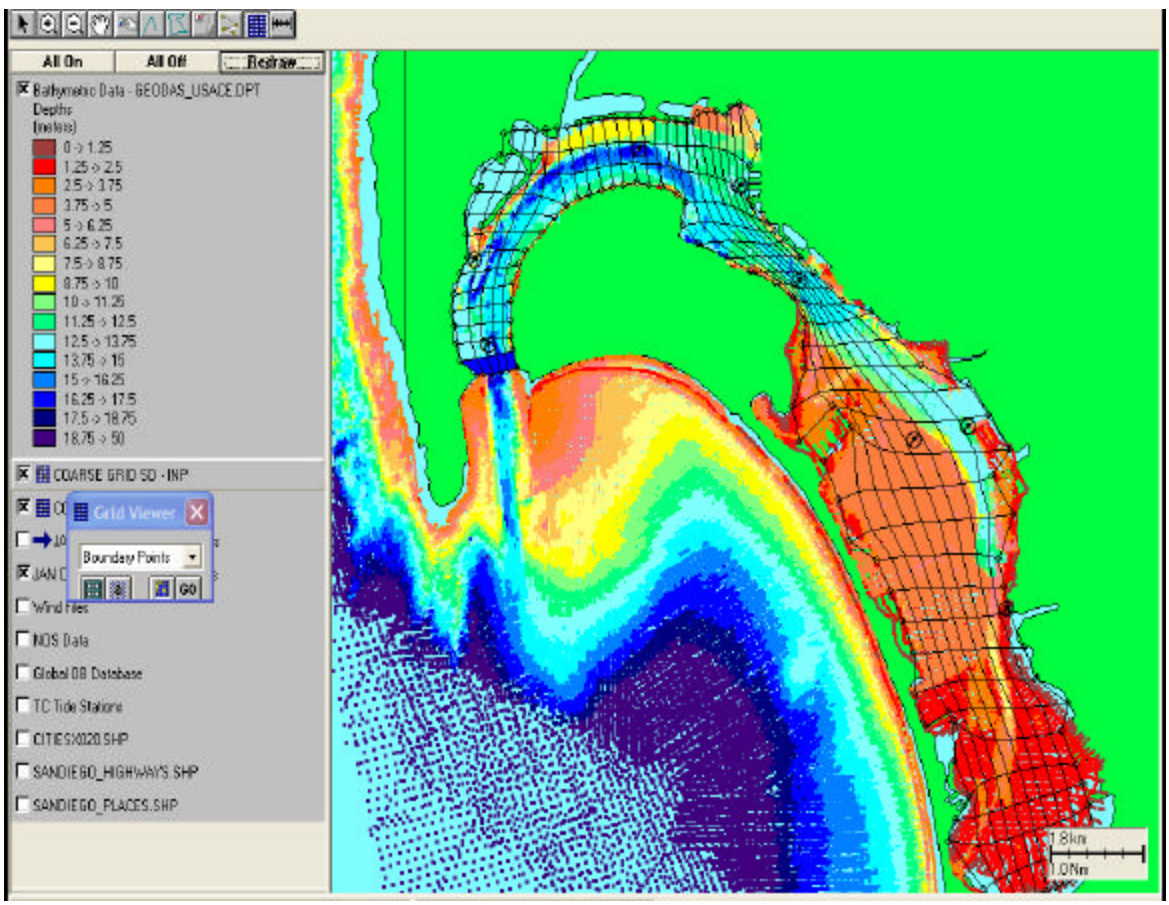

Figure 10. San Diego Bay Bathymetry

B. HYDRODYNAMIC MODEL EXECUTION

The program must have the desired forcing data file (*.hst) selected for the blue open boundary cells as displayed in Figure 7. Under the 'Data' menu, 'Select Cells by Region' is chosen, followed by sub-directory choice of 'Boundary Cells'. The mouse pointer turns into a cross symbol. A simple geometric shape is then drawn around the blue open boundary cells. A separate window appears giving the operator the option of selecting either 'Tidal Constituents' or 'Time Series File' choices. The selection of 'Time Series File' followed by the choice of the desired Open Boundary Tidal Forcing File (*.hst) from a pull down window places the file time series contents for the forcing elevation to the blue open boundary cells. With the boundary fitted grid designed; the bathymetry is loaded into the grid. Finally the desired forcing data is then obtained, formatted and assigned to the open boundary cells; then the hydrodynamic model is ready for execution. Under the 'Run Model' menu, the 'Hydrodynamic Model' choice starts the process. The separate window that opens has three separate option tabs, Model Run Control, Model Parameters, and Physical Parameters.

1. Model Run Control

Within this section the run length of the model is determined. The start time and end time are entered as date and time. The interval for the current time series and the interval for current field output, each in minutes, are also specified here. Due to time constraints, the program that allows for modeling using a file with a wind time series at the surface boundary was not able to be utilized for this analysis. The run time for this study began on 0000 January 1st, 2004 and ended on 2354 January 31st, 2004. Interval for the current field time series and the interval for current field output were both set to six minutes.

2. Model Parameters

Details specific to the modeling numerics are stipulated within this section. Inputs by the user for number of Z grids (3-D only) as well as model time step, ramp time period and residual start time in minutes are to be provided. The model can be run in a baroclinic process with prognostic terms for salinity and temperature and the advection time step in minutes can all be chosen. The hydrodynamic model as a baroclinic process

was not run in this study. The time step was set to six minutes and the ramp time period and residual start time were set for one day (1,440 minutes).

3. Physical Parameters

All physical parameters that affect the hydrodynamic model are defined here. This section requires wind drag coeffient, vertical viscosity (m^2/sec), vertical dispersion (m^2/sec), horizontal dispersion (m^2/sec), and the bottom drag coefficient to be specified. If salinity and temperature advection are to be modeled, initial temperature in degrees Celsius and initial salinity in parts per thousand (ppt) can be stipulated as well. This study utilized the default values as follows: wind drag coefficient 0.0014, vertical viscosity 0.005, vertical dispersion 0.001, and horizontal dispersion 1.0, and the bottom drag coefficient 0.003.

4. Output Time Series Sites

Output time series locations are added before a model is run by choosing the 'Add Time Series Site' from the 'Data' menu. Manually clicking on the grid will produce a time series location at that point. The hydrodynamic model can run with no time series locations, but no graphical or ASCII output files can be created from the model run until a time series site is specified. Eight specific time series sites were determined and are seen in Figure 11. Station 1 will bear the most significance to this study since it is the first WQMAP model time series site so close to the verification data (NOAA Tide Table Prediction for San Diego Bay Entrance, Ballast Point).

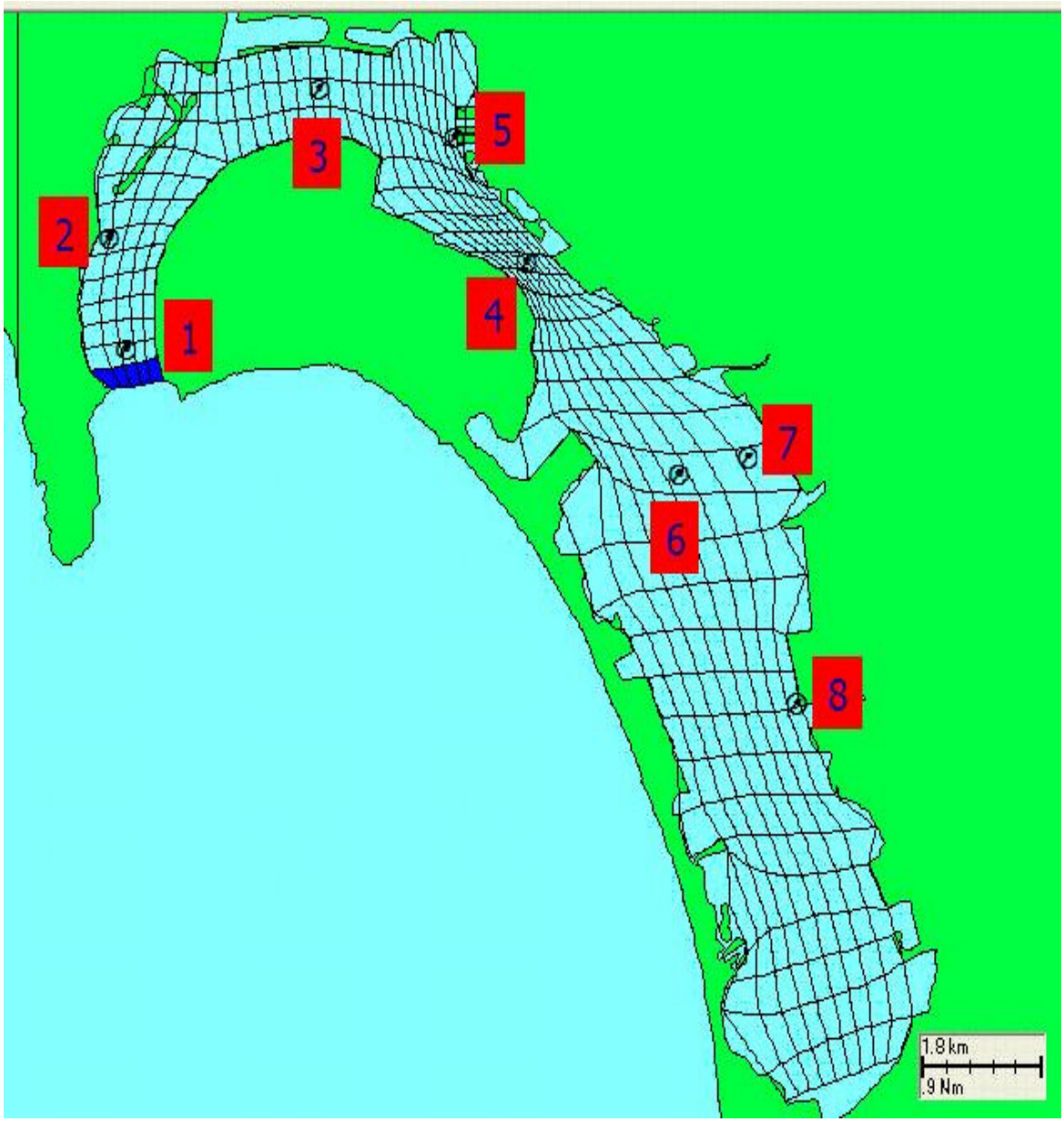

Figure 11. Time Series Sites

5. GUI Results

Once all model parameters and settings are provided, a click of the hydrodynamic model button at the top of the window starts the process. The model calculates the elevation, east-west velocity (u), and north-south velocity (v) for each grid point during each time step. It then creates a new GIS layer for the modeled currents. With his layer activated, the program can animate the modeled current speeds and directions with vector arrows over the time period modeled (Figure 12). A graphical output of the current time series can also be viewed for any time series site that was pre-specified. Figure 13 is the modeled output for Station 1 that was located one grid point north of the bay entrance blue open boundary cells.

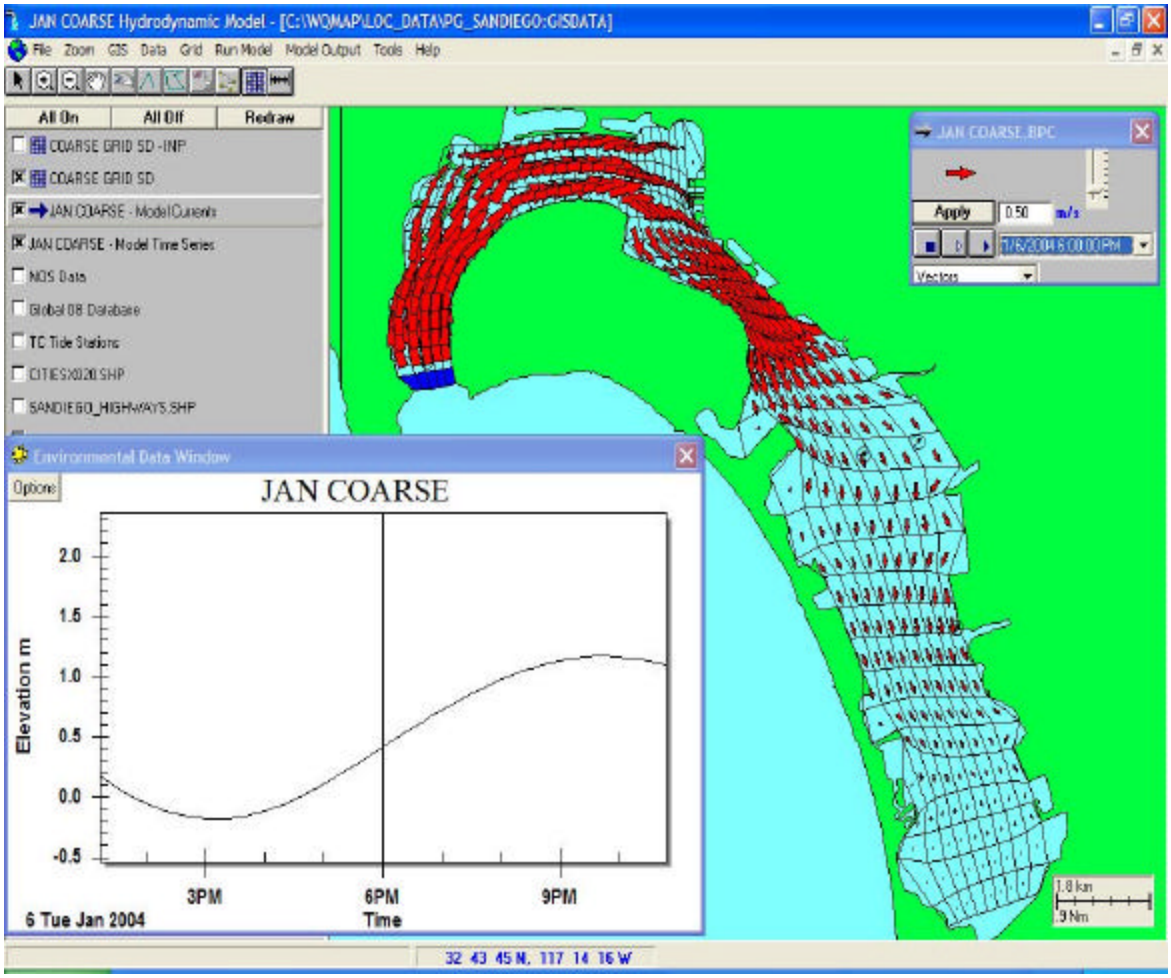

Figure 12. Animation Screenshot of WQMAP Modeled Current 0600 January 6th, 2004

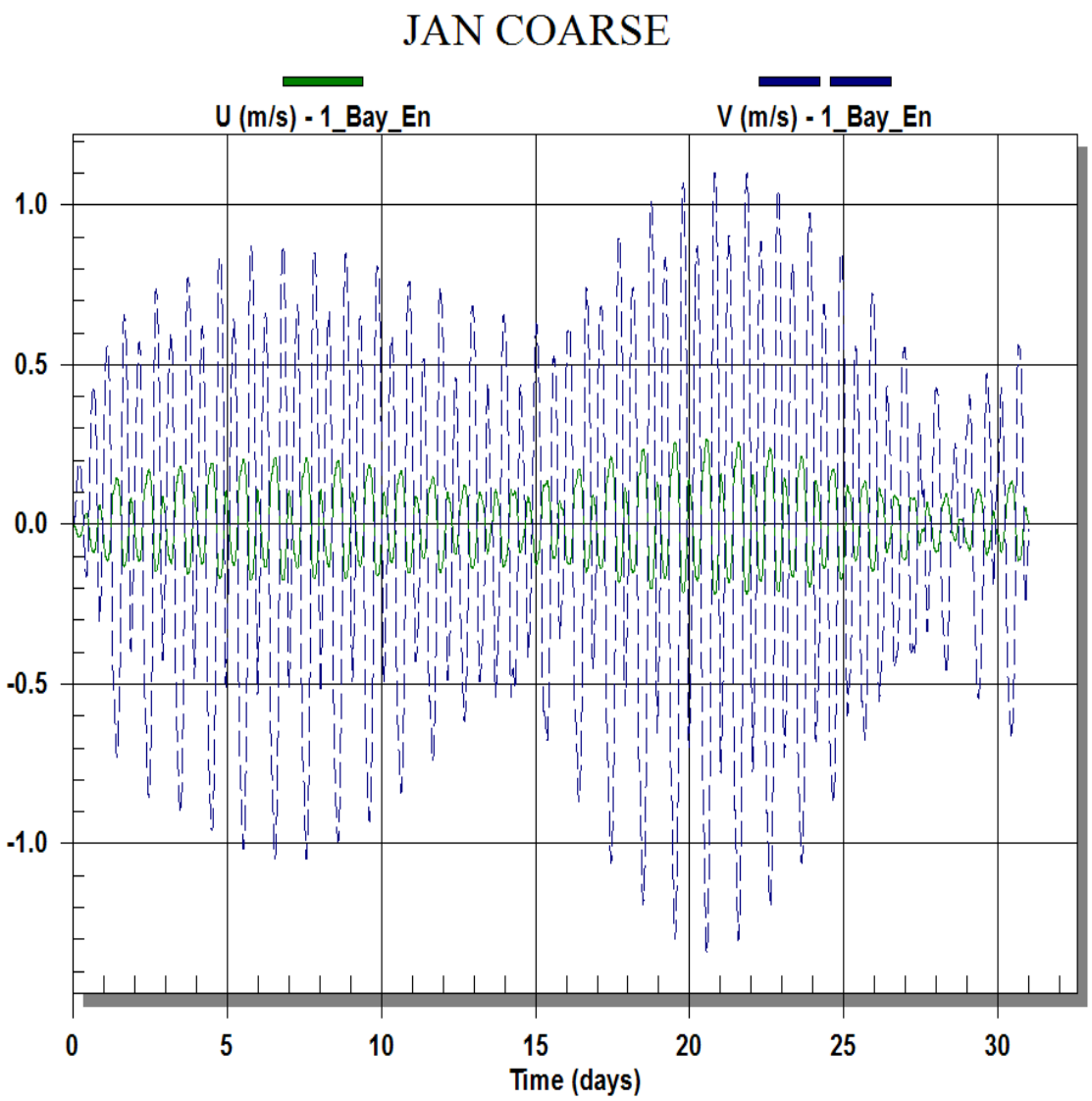

Figure 13. Station 1 WQMAP Modeled Current January 2004

C. DATA PROCESSING

1. WQMAP Output Files

The time series graph seen in Figure 13 can also be exported as data files. The u velocity and v velocity can be exported separately in a file as shown in Table 4. The file includes summary information about the model run, grid size and time series site information. The output data follows in columns of year, month, day, hour, minute, and u velocity. The output files for u and v velocities for each time series site were produced for each resolution grid covering the elevation forcing data for January 2004.

```
RUN  : JAN COARSE
GRID : COARSE G
IMAX :      51
JMAX :      51
KMAX :       1
NSEQ :          354
NTSR :            8
TSR: I,J =   9 19 : 1_Bay_En
DATE                1
2004  1  1  0  0  0.00000
2004  1  1  0  6 -0.00003
2004  1  1  0 12 -0.00007
2004  1  1  0 18 -0.00013
2004  1  1  0 24 -0.00022
2004  1  1  0 30 -0.00035
2004  1  1  0 36 -0.00050
2004  1  1  0 42 -0.00070
2004  1  1  0 48 -0.00094
2004  1  1  0 54 -0.00122
2004  1  1  1  0 -0.00155
2004  1  1  1  6 -0.00194
2004  1  1  1 12 -0.00238
2004  1  1  1 18 -0.00288
2004  1  1  1 24 -0.00345
2004  1  1  1 30 -0.00408
2004  1  1  1 36 -0.00478
2004  1  1  1 42 -0.00556
2004  1  1  1 48 -0.00641
2004  1  1  1 54 -0.00735
2004  1  1  2  0 -0.00835
```

Table 4. WQMAP Modeled U Velocity for Station 1, Truncated Output File

2. Rotational Matrix

WQMAP's output for the u velocity is positive for the east direction and negative for the west direction. Similarly, the v velocity is positive in the north direction and negative in the south direction. The NOAA Tide Table data used to verify the WQMAP's model of Station 1 is in reference to a positive value for the flood direction of 355° True and a negative value for the ebb direction of 175° True. This orientation of flood and ebb directions needs to be applied to the WQMAP u and v velocity output data sets. Note that each time series site has a different flood and ebb direction than that of Station 1. Different re-orientation calculations have to be made with each time series site. Such a re-orientation is conducted using the rotational matrix method. As visualized in Figure 14, the positive x direction lies eastward and the positive y direction lies northward. If the axis were rotated ? degrees clockwise, maintaining their respective orthogonality, the new axis' direction would lay in the x′ and y′ directions. Given that the u velocity lies in the x direction and the v velocity lies in the y direction, each time series site flood direction (v′) would be located in the y′ direction once the angle ? for each station is determined.

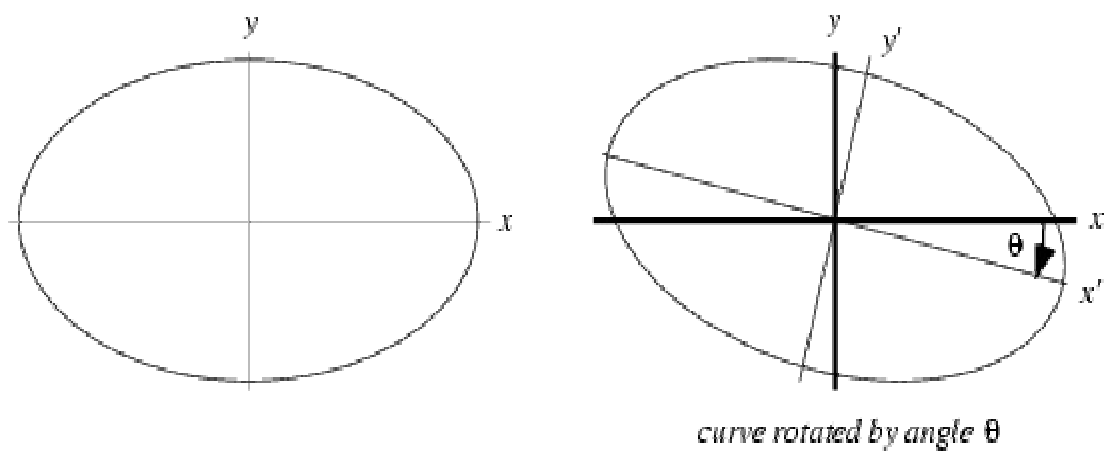

Figure 14. Rotational Matrix Visualization.

Define α as the counter-clockwise direction from x to x′ then α = 360° - ?. The rotated axis' velocities could be calculated using the values of u and v for each matching instant in time by using the rotational matrix calculations:

$$u' = u\cos a + v\sin a \tag{12}$$

$$v' = v\cos a - u\sin a \tag{13}$$

The resultant calculations provide positive values of v′ as a flood current and negative values of v′ as an ebb current. Each time series of the site u and v output files were summarily imported and the rotational matrix calculation for each station was conducted after measuring the angle α at each station.

IV. RESULTS

A. DIFFERENCE BETWEEN DIFFERENT RESOLUTION GRIDS

The WQMAP modeled current results for each grid resolution for Station 4 (San Diego-Coronado Bridge) are displayed in Figure 15. The difference in the modeled currents between each grid is so fine that a superposition plot of all three grid results cannot be discerned visually. A plot of the difference between each resolution is provided in Figure 16 where the medium grid modeled currents is used as a reference between the other two grids. The maximum difference between the medium grid and the coarse grid currents is 0.05 m/s. The maximum difference between the medium grid and the fine grid currents is slightly less at 0.04 m/s. The medium to coarse grid current difference has root mean square error of 0.0222 m/s whereas the fine to medium difference in currents has a root mean square of 0.0164 m/s. Given these values of maximum current differences as well as the root mean square error, the current prediction is for any grid resolution selection correlates reasonably well. All future comparisons to model output will be made with the fine resolution grid. Since it allows nearly the same grid modeled output correlation while providing more grid cell time series site selections for either future comparisons or operational planning needs.

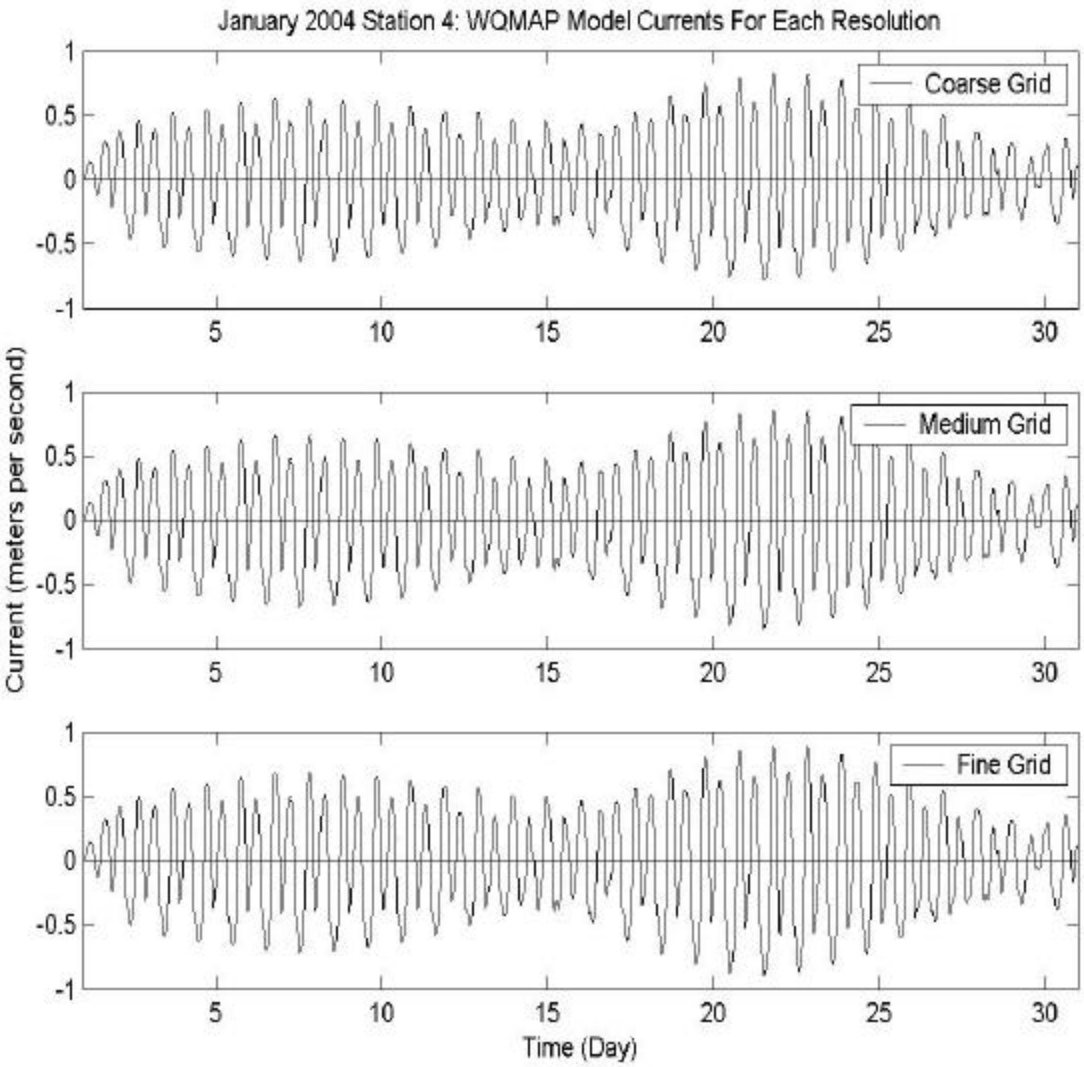

Figure 15. WQMAP Modeled Currents for Station 4 (San Diego Bay Entrance)

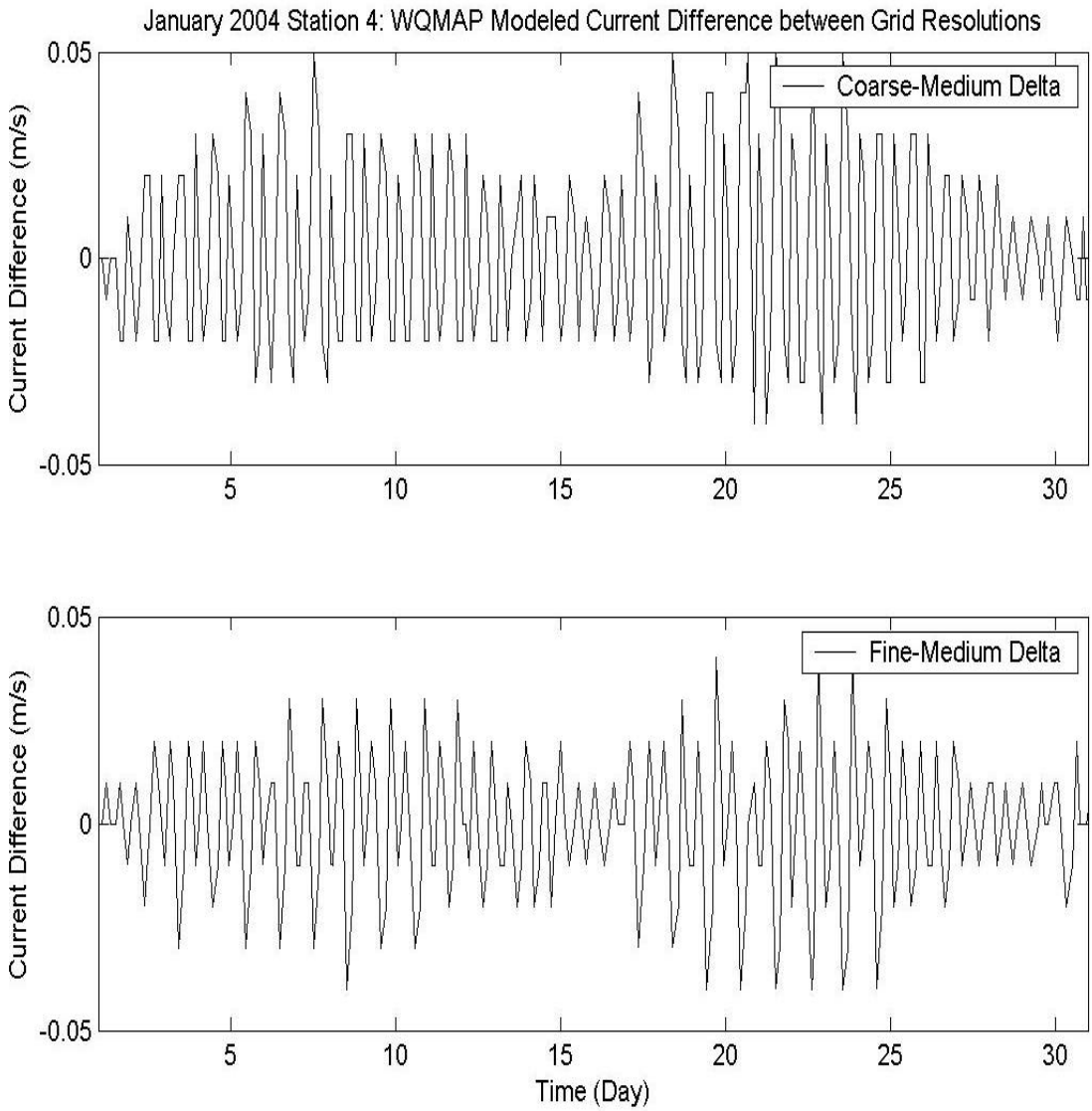

Figure 16. Difference in Modeled Current Between Grid Resolutions at Station 4.

B. COMPARISON OF TIDE TABLE DATA TO MODELED CURRENTS

Direct comparison of WQMAP fine resolution grid modeled output for Station 1 (San Diego Bay Entrance) and NOAA tide table data for the San Diego Bay entrance is displayed in Figure 17. The model output is highly in-phase visibly with the NOAA tide table data. Modeled results are slightly over predicted in the flood currents and similarly under predicted in ebb currents. The initial large error in amplitude and phase is seen at the beginning of the model run and is primarily due to the ramp up time needed for the model to initialize. The model elevation forcing was already in place at the instant of the model run but initial current speed for the model initialization was zero meters per second. After a period of one day, the model nearly perfectly matches the phase and amplitude of the verification data. The mean relative error between the modeled currents and the NOAA tide table data set was 4.1% as determined using equation (14)

$$\text{mean relative error} = \frac{1}{\mathrm{M}} \sum_i \frac{\left| v^{WQMAP}(t_i) - v^{NOAA}(t_i) \right|}{\left| v^{NOAA}(t_i) \right|} \tag{14}$$

where M is the total number of data points, v^{WQMAP} is the WQMAP modeled current, and v^{NOAA} is the NOAA tide table current.

Also, an over-prediction trend is observed in WQMAP modeled currents occur during flood conditions, while an under-prediction trend in modeled currents is seen during ebb conditions. This trend is identical to the difference between the actual water level (verified water level used for open boundary cell forcing) and the NOAA tide table data (verification data source) seen in Figure 18. These results are acceptable from a operational consideration to validate the WQMAP fine resolution grid modeled currents to the NOAA tide table data for the San Diego Bay entrance at Ballast Point.

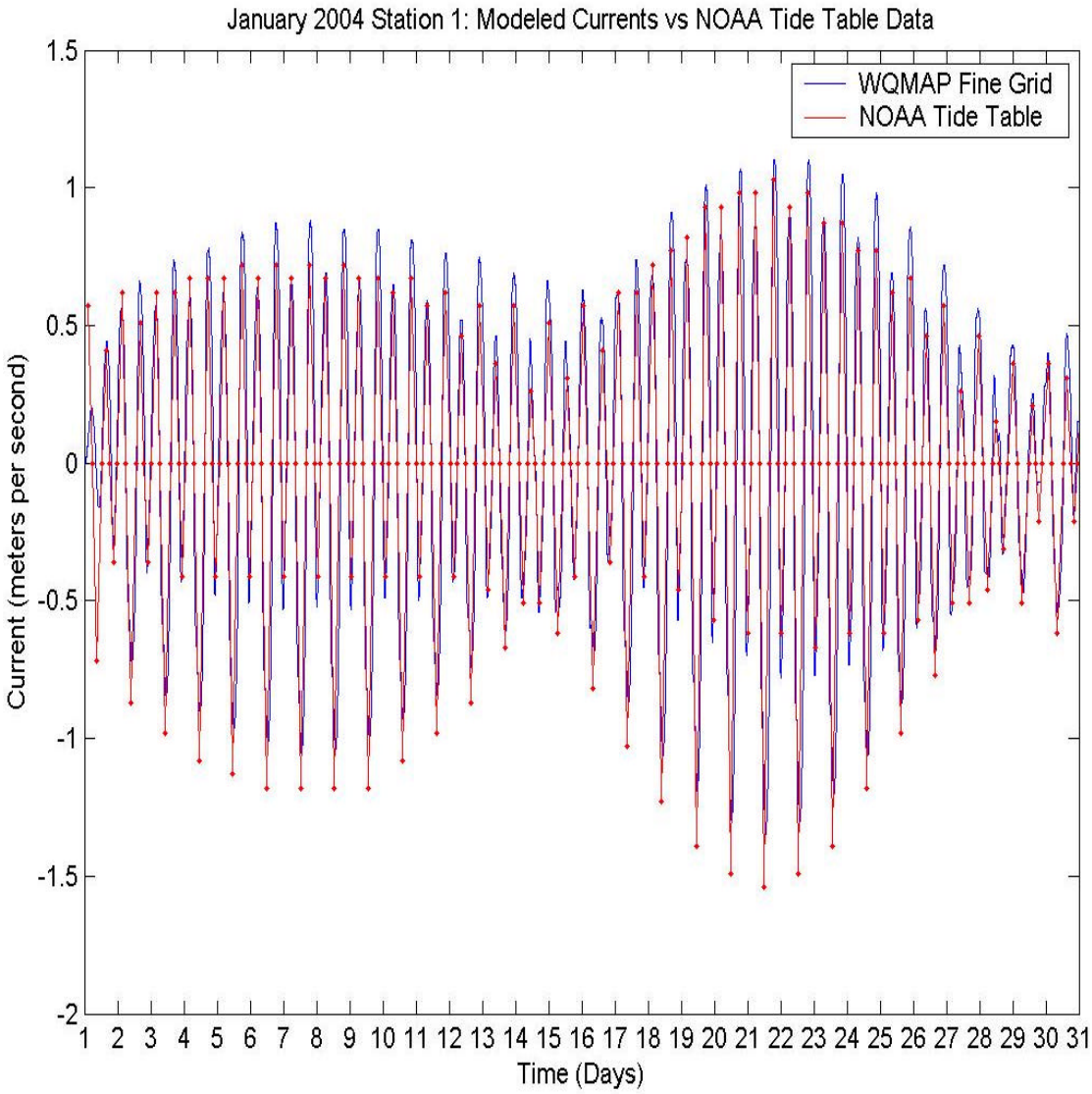

Figure 17. WQMAP Modeled Currents and NOAA Tide Table for San Diego Bay Entrance.

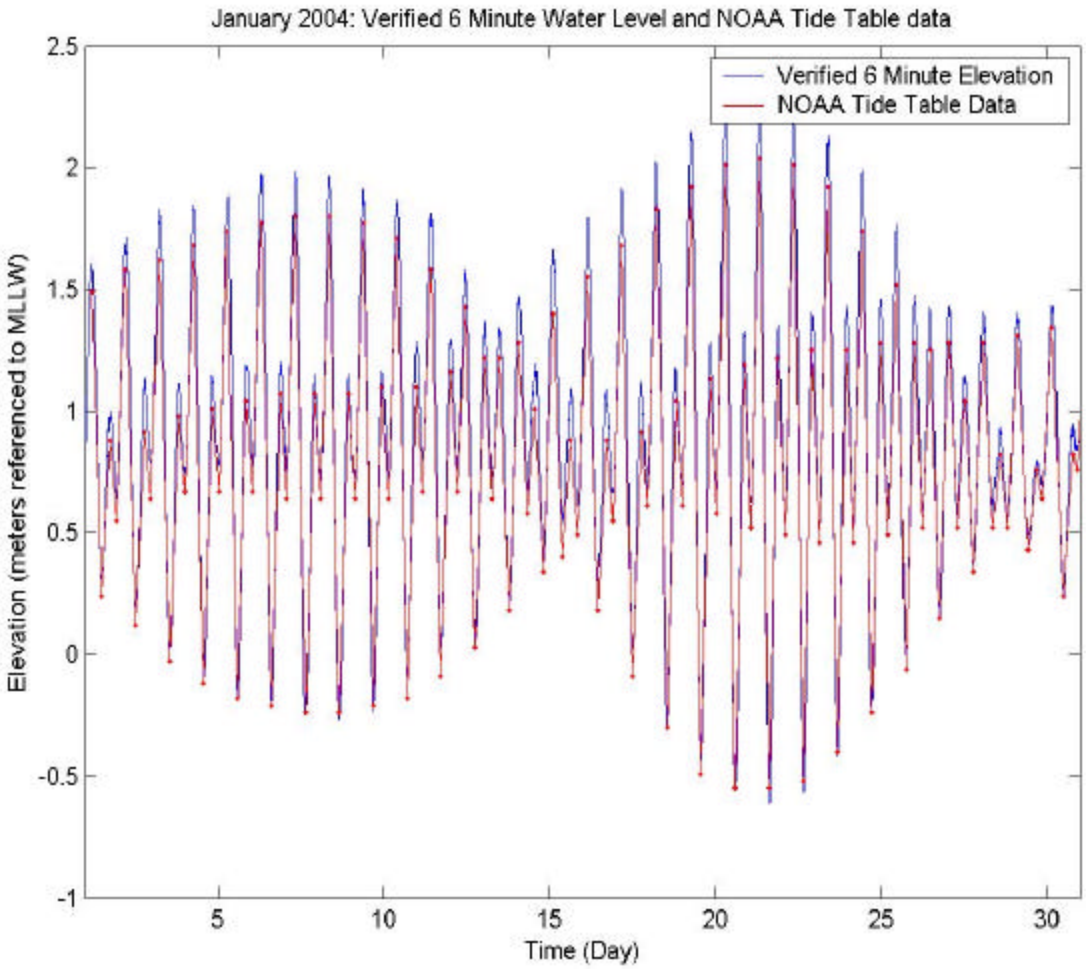

Figure 18. Plot of Verified Six Minute Water Level VS NOAA Tide Table Data for January 2004.

C. STATIONS FURTHER FROM BAY ENTRANCE

The time series sites of Station 2, Station 5, and Station 8 were specifically chosen in anticipation of ADCP validation data from InterOcean Systems, Inc. archived from the SDMIS website. Despite this lack of validation data, a subjective look at modeled results further from the bay entrance will be performed. In comparing Figures 10 and 11, bathymetry remains constant through the main channel of the bay from Station 1, through Station 3, up to Station 4. Through normal coastal processes of dispersion and friction, it is expected that current flow should decrease along those grid points as distance increases away from the mouth of the bay. By Station 6, this is much more anticipated due to the significant decrease in the depth of the bay at that point. Furthermore, the phase of the currents (timing of slack water as well as flood and ebb currents) should remain constant for all stations within the bay. Figure 19 is a plot of the fine resolution grid modeled currents for Station 4 compared to the NOAA tide table data that is valid for the Bay Entrance near Station 1. It is visually evident that the model is correctly decreasing current amplitude for time series location while properly maintaining the phase when compared to the bay entrance data. Figure 20 is a plot of the fine resolution grid modeled currents for Station 6 also compared to the bay entrance NOAA tide table data set. The expected result of a larger decrease in current for this station due to additional dispersion, friction, and decrease in water depth is also visually evident while maintaining the expected phase lock throughout the bay.

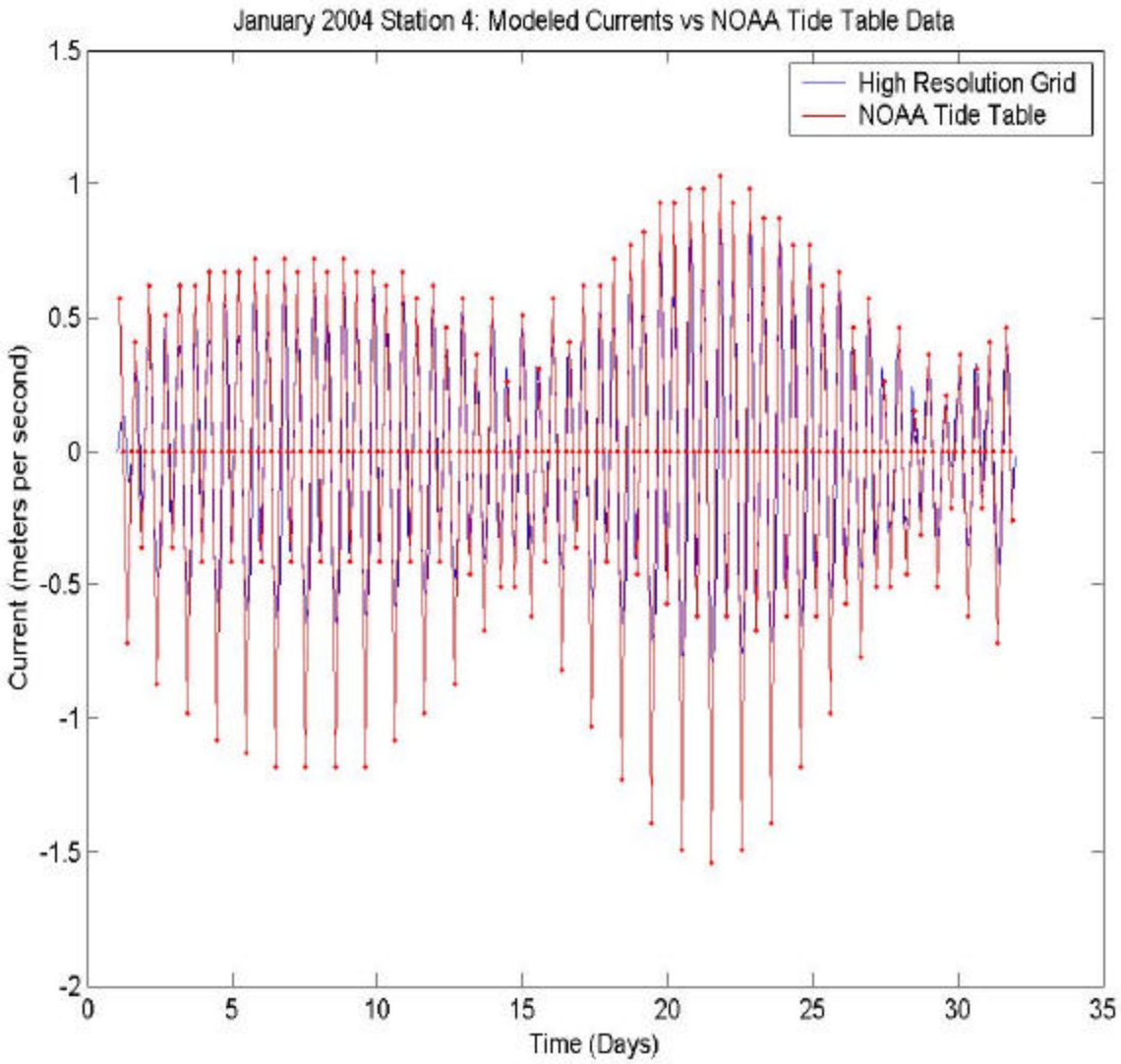

Figure 19. Station 4 Modeled Currents vs NOAA Tide Table Data for San Diego Bay Entrance.

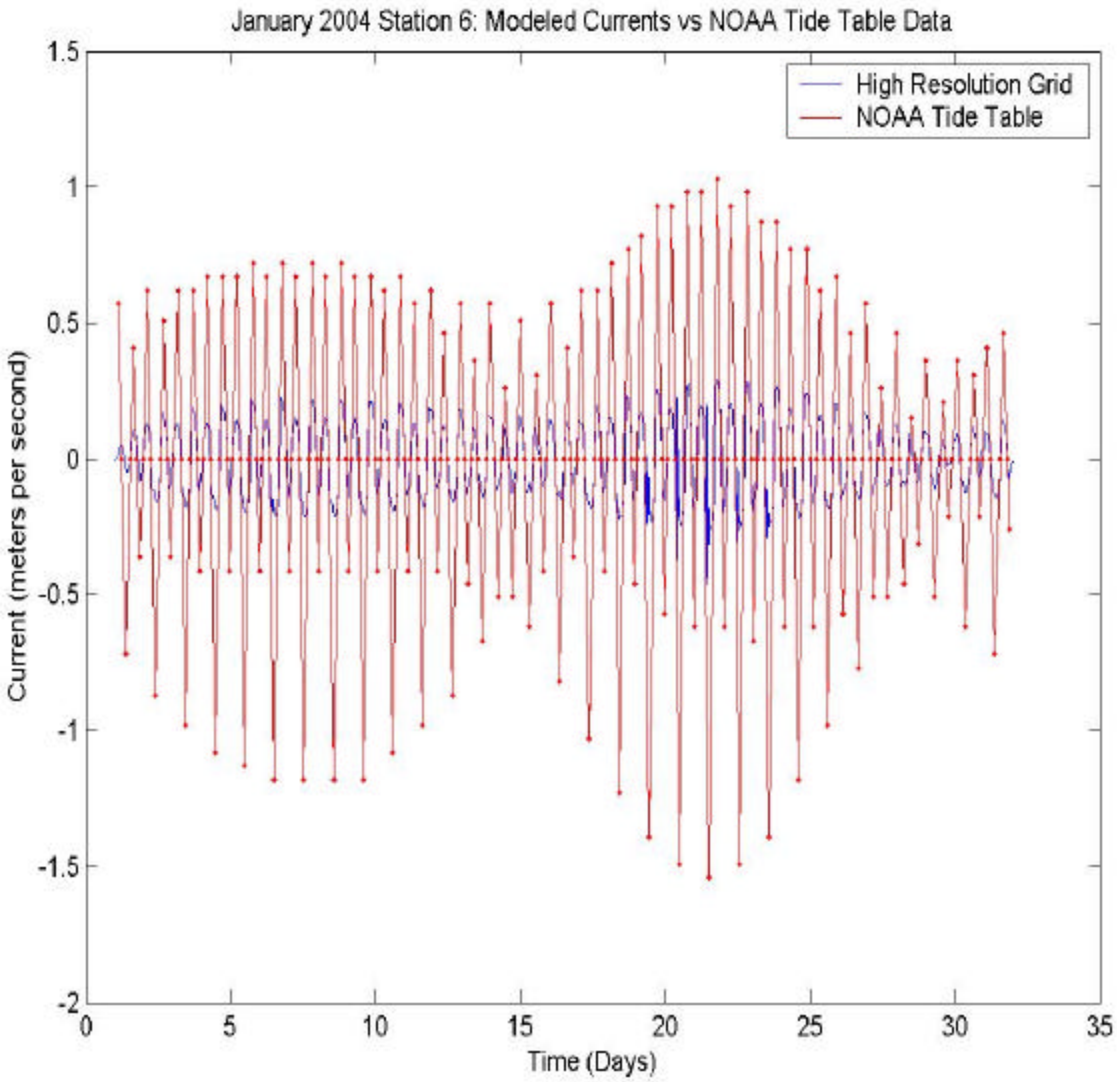

Figure 20. Station 6 Modeled Currents vs NOAA Tide Table Data for San Diego Bay Entrance.

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V. CONCLUSIONS

A. NEED FOR ADCP DATA

Despite that Station 1 had a relative error of 4.11% validates the model well for operational considerations; determining the relative error for other stations within the bay is in order to attest the effectiveness of this study. The validation of this model is imperfect without proper real time observed current results from an ADCP. Despite the strong correlation Station 1 had to the NOAA tide table data, real time data for Station 1 is necessary to assess the model's true correlation to verified results at the same location. Proper time series analysis for coherence and phase comparison to the NOAA tide tables cannot be conducted given the varying time step of the tide table data. Consistent real time data of current with a constant time step will be able to provide such an analysis. WQMAP permits the user to self define the time step interval for the model and for the output time series itself. Whatever ADCP data time step that may be available or obtained can be matched by the hydrodynamic model within the 'Model Run Control' initial settings. Furthermore, validation for any other station or time series site cannot be conducted at all without such validation data. An additional study should be planned and conducted utilizing the boundary fitted grids created within this model using coordinated matching forcing data from the NOAA CO-OPS verified elevation data portal and verification data obtained by placing additional ADCPs at key stations of interest with San Diego Bay.

B. APPLICATION OF MODELED RESULTS

1. MIW Exercise

Assuming the modeled results of this study were fully validated, a simple application of the modeled environment is in order is illustrate its potential as an environmental planning aid for the warfigher. A simple mine warfare operation was conducted within San Diego Bay on 21 January 2004. The scenario is that just a day before, a freighter exiting the bay was seen discharging several large objects in the vicinity of the Coronado Bridge (Station 4) as it steams outbound for sea. An AVENGER Class Mine Countermeasures Ship (MCM) is dispatched to locate and

identify the mine like objects utilizing its AN/SQQ-32 Variable Depth Minehunting Sonar along with the AN/SLQ-48 Mine Neutralization Vehicle (MNV). The current thresholds for these assets are operationally sensitive, so a fictitious and current limit of 2 knots will be used as an operational current threshold in this example. Figure 21 illustrates what the operational windows are, marked in green, given the threshold limits to the MCM, marked in red, using the NOAA Tide Table data set. The MCM can operate within this threshold all morning until 1110. Minehunting operations would be able to resume again around 1345 with no other restrictions for the rest of the day. Compare this scenario with the modeled output from WQMAP for Station 4 for the same day (Figure 22). There is no timeframe that restricts minehunting operations using the WQMAP modeled data set since the predicted currents do not exceed the operational threshold for that location.

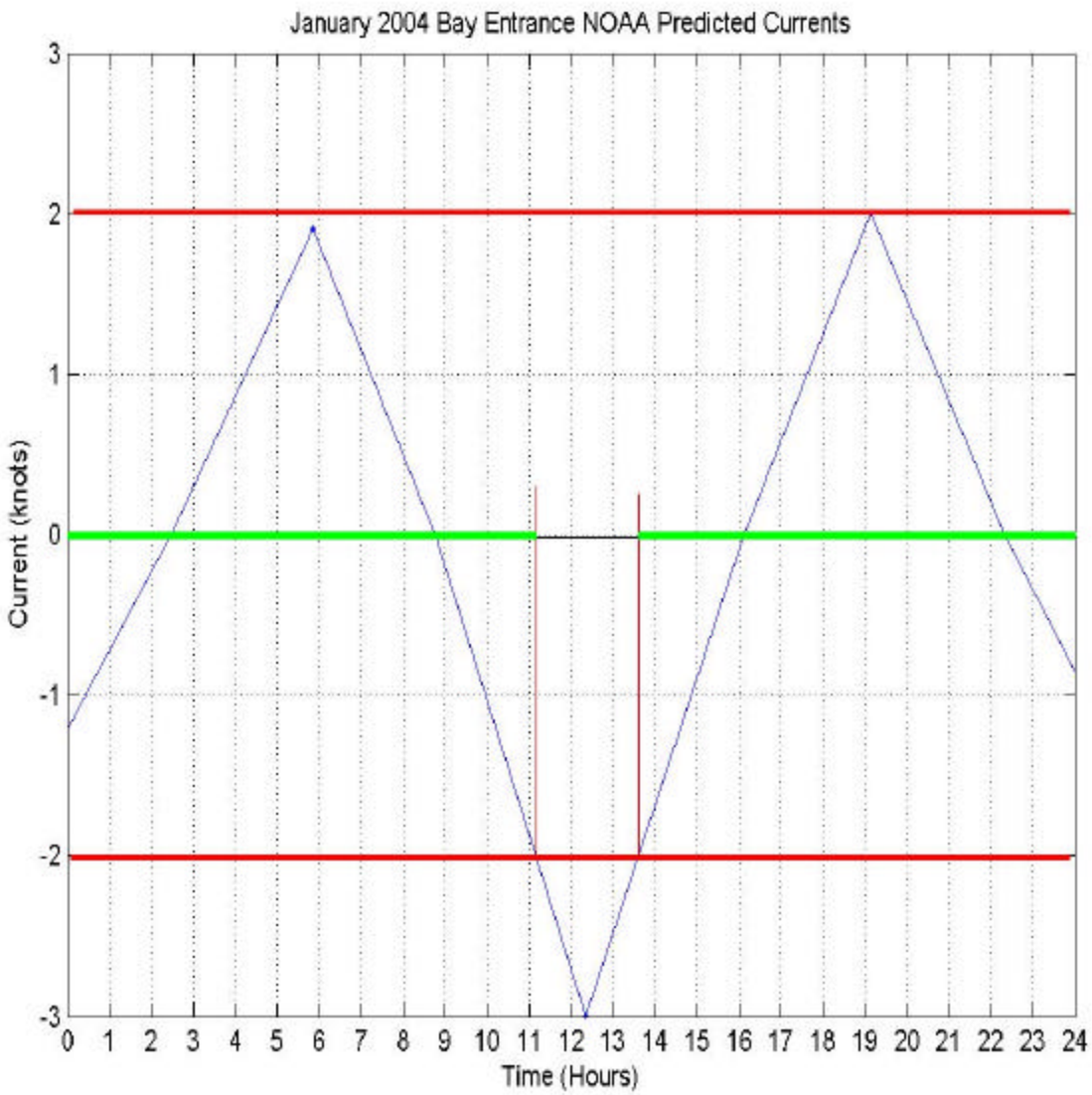

Figure 21. Operational Example of MIW Exercise for 21 January 2004 at Station 4 Using Fictitious Current Threshold of 2.0 knots using NOAA Tide Table Data.

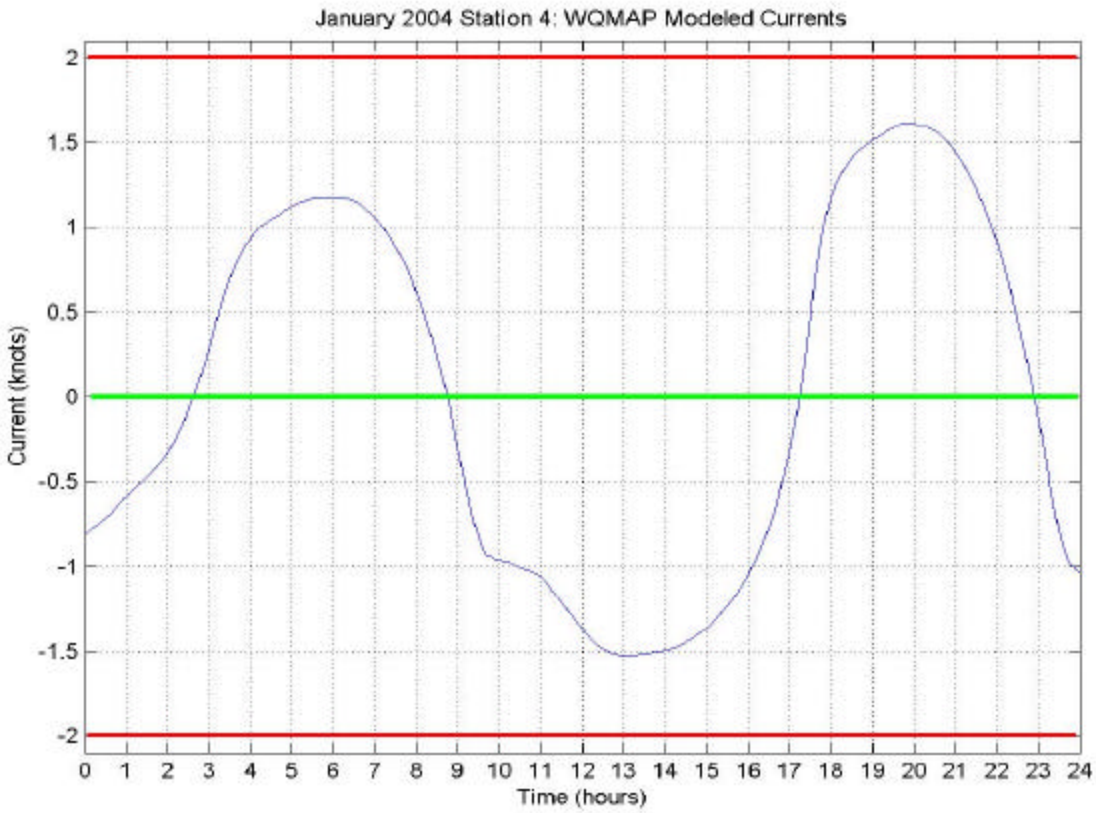

Figure 22. Operational Example of MIW Exercise for 21 January 2004 at Station 4 Using Fictitious Current Threshold of 2.0 knots using WQMAP Fine Resolution Grid Modeled Currents.

2. EOD Operation

An additional and more useful example is to extend the same operation on the same day to include diving operations. One option to mine neutralization is to recover the mine using an Explosive Ordnance Disposal (EOD) team. The scenario continues with the MCM finding and identifying a mine like object as an actual mine. The mine was found near a structural pylon of the Coronado Bridge so detonating it using the MNV is not a desirable option. An EOD team is dispatched to retrieve the mine. Their operational threshold for currents is also operationally sensitive so a fictitious limit of 0.5 knots will be used for this example. There are four operational windows for diving operations in this scenario using the NOAA Tide Table data set (Figure 23). They range from 0130 to 0320, 0800 to 0920, 1530 to 1655, and 2130 to 2330. Again, compare these windows to those found using the WQMAP modeled currents (Figure 24) for the same location and the operation picture changes. The revised operational windows due to the modeled currents are 0130 to 0310, 0810 to 0910, 1650 to 1730, and 2230 to 2320. The first two windows were reduced slightly. More crucial changes occurred to the last two windows. The third window prediction was moved forward in time by an hour and twenty minutes and was reduced in duration from an hour and twenty-five minutes down to just forty minutes. Such changes in operating windows are crucial to successful operational planning to ensure mission success and safety to all personnel involved. This example clearly illustrates the value added this hydrodynamic program can provide to effective mission planning.

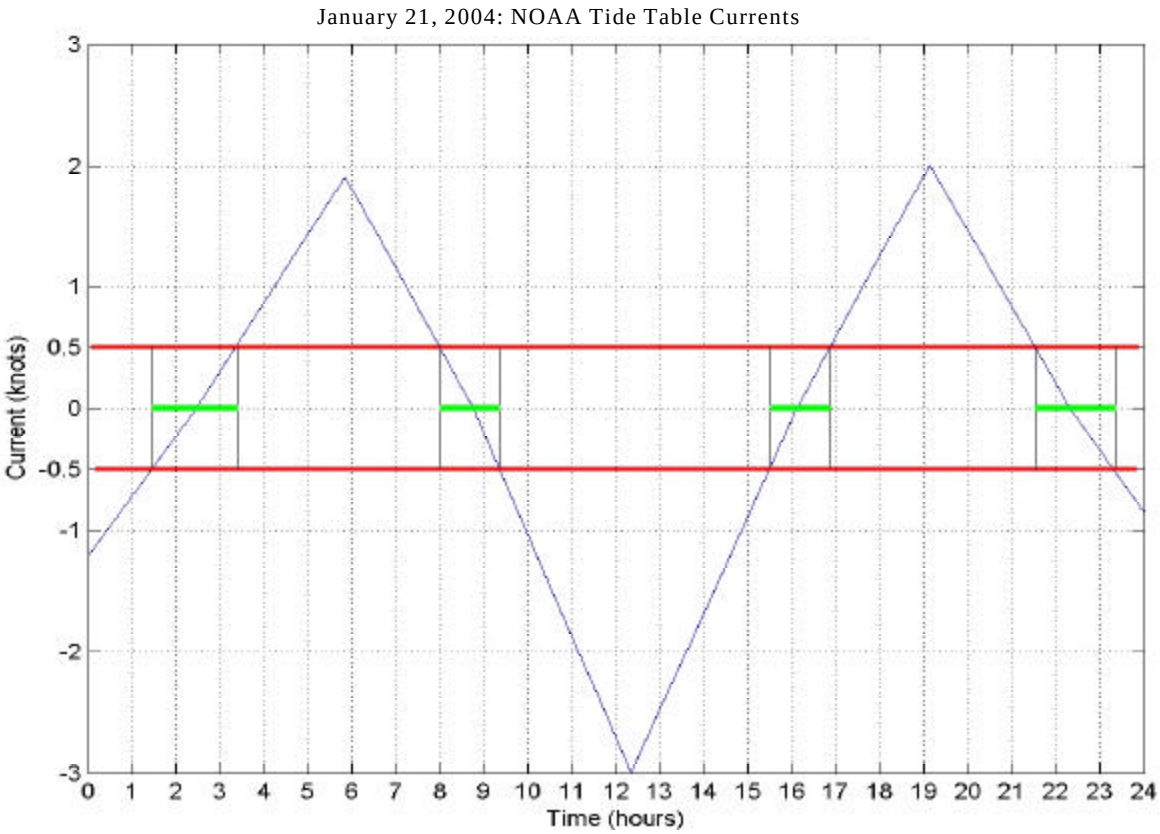

Figure 23. Operational Example of EOD Exercise for 21 January 2004 at Station 4 Using Fictitious Current Threshold of 0.5 knots using NOAA Tide Table Data.

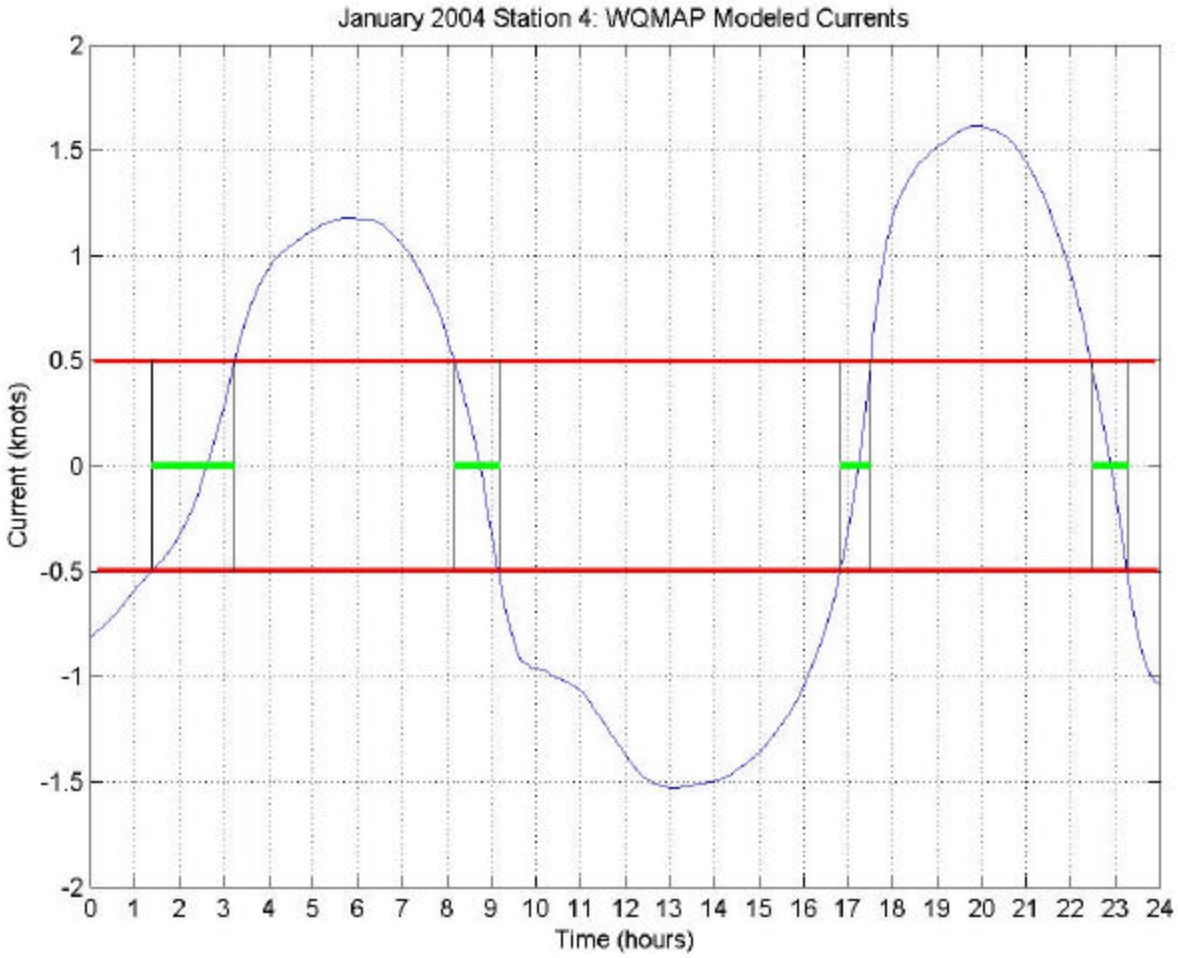

Figure 24. Operational Example of EOD Exercise for 21 January 2004 at Station 4 Using Fictitious Current Threshold of 0.5 knots using WQMAP Fine Resolution Grid Modeled Currents.

C. FUTURE APPLICATION USING FLEET SURVEY TEAM ASSETS

As the warfare communities continue to advance in the realm of littoral warfare, so will the support for those communities. There continues to be an increasing demand to better model the much more complex coastal environment. WQMAP boundary fitted grids can be developed for any coastal region, bay, or estuary. The current use of the Naval Oceanographic Office's Fleet Survey Teams (FST) can readily provide what is needed to validate these models for each littoral grid that may be needed. The primary mission of the FST is to obtain bathymetric data for navigational chart development. This same bathymetry can by imported into a boundary fitted grid of the same region to help model this environment. The FST can facilitate a successful model validation for a coastal area of interest by obtaining elevation data during a survey period to be used as forcing data for the open boundary cells defined within the model. Lastly, the FST, by adding an ADCP to their inventory, can obtain verification data during their time frame of their hydrographic survey. With proper planning, this NAVOCEANO asset can be providing the warfare communities more than just an improved navigational product. The FST's mission in conjunction with the Naval Oceanographic Office's Modeling and Forecasting Divisions will be able to produce a series of small, PC-based current prediction models that will be an invaluable benefit to future and unpredictable Naval operations.

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