Final Report–Visualizing the Output Data of SUNTANS using ArcGIS

Dongyu Feng

Austin, United States

Abstract

This report discusses a method of using ArcGIS to visualize the results of a numerical model SUNTANS. ArcGIS is a powerful tool of visualizing and analyzing data. For both large and small study domain, it is able to present persuasive figures. By adding different layers, such as fresh water source and NHDPlus, the key features of results of a numerical model can be well presented. Meanwhile, the correctness of the model bathymetry and boundary conditions can be checked by comparing with the existing dataset. In the report, different model outputs, such as velocity, free surface elevation, temperature and salinity, are visualized. By analyzing the distribution and time variation of salinity, the conclusion that river discharge and tidal effect play a significant role in salt structure of San Francisco Bay is obtained. The results also suggest a comprehensive consideration of freshwater source. And a long-period run is needed to study the tidal effects.

Keywords: ArcGIS, SUNTANS

1 Introduction

San Francisco Bay is located in the state of California, surrounded by a contiguous region, covering somewhere between 400 and 1600 miles. Several estuaries in this Bay system serve as observational examples in the study of salt balance in estuaries. San Francisco Bay is also a mecca for sailors due to its strong wind system. The variability of San Francisco Bay is characterized by many mechanisms, such as tidal effects, freshwater discharge and exchange flow [1]. Therefore, it is valuable to study the hydrodynamic properties in this Bay system.

A three dimensional unstructured non-hydrostatic numerical model, SUNTANS (Fringer et al. [2]), is used to implement this study. This model allows a complete solution of the governing equation and solves on triangular mesh. Stacey et al. [3] tested the application of SUNTANS to San Francisco Bay and focused on South Bay. Both 2D and 3D validation of the model is provided. Chua et al. [4] did a similar study but focused on the northern reach. The northern San Francisco Bay is a partially-stratified estuary dominated by seasonal-varying freshwater discharge, while the south bay is mainly affected by tidal oscillation [4]. The visualization of SUNTANS has been implemented in the platform of MATLAB and python, which gives a conceptual understanding of the data. Geographic Information System (GIS) is considered as a powerful tool in presenting and processing data, and is thus capable of visualizing the data of various flow and climate properties of San Francisco Bay.

Before running a numerical model, GIS serves as a tool to check the input grid and bathymetry files. Its efficiency of loading and presenting data from various sources gives a clear view of the model frame and avoid primary mistakes, which may cause serious problems. In this report, to analyze the ability that GIS helps complete an analysis of numerical model, I start with its function of presenting existing data from various sources. Then, the visualization of the output data and related analysis is discussed. The advantage of GIS in visualizing SUNTANS is taken into account in the end.

2 San Francisco Bay and Model Setup

In this section, a more detailed introduction of San Francisco Bay system is presented including the characteristics of each composition. The model setup, which are the boundary and initial conditions are discussed.

In figure 1, a plot indicating different systems that comprise the whole San Francisco Bay area is presented. It is seen that there are basically five components, which are Pacific Ocean, Suisun Bay, San Pablo Bay, Central Bay and South Bay. The last two can also be combined and are called San Francisco Bay. There are mainly two rivers flowing into Suisun Bay, which are Sacramento and San Joaquin rivers, serving as large freshwater discharge. Napa River flows into San Pablo Bay at the entrance. The whole bay area is dominated by three large cities, San Francisco, Oakland, and San Jose. And the famous Golden Gate is the North American strait that connects San Francisco Bay to the Pacific Ocean.

Since the San Francisco Bay case of SUNTANS is only a test case introduced by its developers to test the model practicability, the boundary and initial conditions are assumed to be simple. For the boundary condition, there are three kinds of edges, which are closed boundaries, open or velocities specified boundaries and open or stage-specified boundaries. Since the values at the closed boundaries are considered zero, I only consider the boundary condition at the river mouth and coastal area. The background temperature is considered 0 in this study. QGIS, which is an open source software, is used to generate a shape file to specify the edge ID for the velocities specified boundary. The Sacramento river and San Joaquin river serve as two river discharge at this boundary. However, the river fluxes at these sites are set to be zero by the developers, which may distort the truth in estuary dynamics. Since we focus on the way that ArcGIS visualize the output data in this report, the introduction of model setup only assists to understand the results. In the stage-specified boundary, the background salinity is assumed to be 32 psu for the sea water. The harmonic analysis of tide is used to represent the tidal effects, where the oscillatory water level can be indicated as follows,

$$h = h_0 + hamp \times cos(\omega t) \tag{1}$$

where h is the surface elevation at the boundary. $h_0 = -5m$ is free surface at the initial condition. $\omega = \frac{2\pi}{12.42 \times 3600}$ is the tidal frequency. $hamp = 0.5$ is the tidal range. For the initial condition, the temperature and salinity are assumed to change linearly as the location approaches inland with the background value of 0 and 32 psu, respectively. The wind condition is also added to the model but details will not be discussed here. Baston and Harris [5] did a similar study with more realistic boundary and initial conditions in Pentland Firth and studied the effect of tidal flow.

With the information of San Francisco Bay and SUNTANS model setup, it is ready to analyze the model output data with the help of ArcGIS.

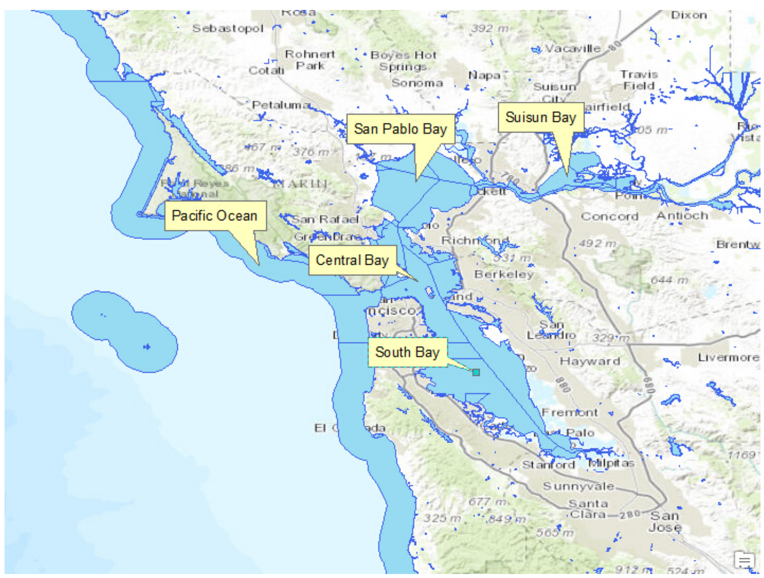

Figure 1: Detailed Composition of San Francisco Bay

3 Visualization of Model Grid and Bathymetry

In this section, the ability of ArcGIS in checking the model input data is discussed. Before a normal run, it is always thoughtful to check the input file in a different method to avoid basic mistakes. For example, the input bathymetry may be created using a certain script. Its correctness should not be taken as granted without comparing with the real topography. This process can be fulfilled by ArcGIS within seconds due to its large data source. The ability of presenting the grid is also valuable. Since the grid file of some of the numerical models is created by developers, the executors may lack the access to visualize the grid, which can be compensated by the efficiency of loading data in ArcGIS.

In this project, a two-dimensional run of the SUNTANS model in San Francisco Bay is accomplished. Since the data format is NetCDF, a matlab function is developed to decompose the data and transfer the original format to that of excel, which can be read by ArcGIS.

The data projection datum used by SUNTANS is "NAD_1983_UTM_Zone_10N" , and the earth datum is "D_North_American_1983". SUNTANS is a triangle unstructured model, comprised of Delaunay triangle grid, with Delaunay points at the indices of each triangle and Voronoi points at the nearly centered points. The grids are divided into three files, which are points, edges and cells. Since these files are generated using a specific tool related with SUNTANS, and the direct connections between cells and edges are the indices of Delaunay points, I will not visualize the triangle grid in ArcGIS. Instead, the Voronoi points of the San Francisco Bay, which represent the computing points of water properties at each grid are visualized in figure 2. This figure

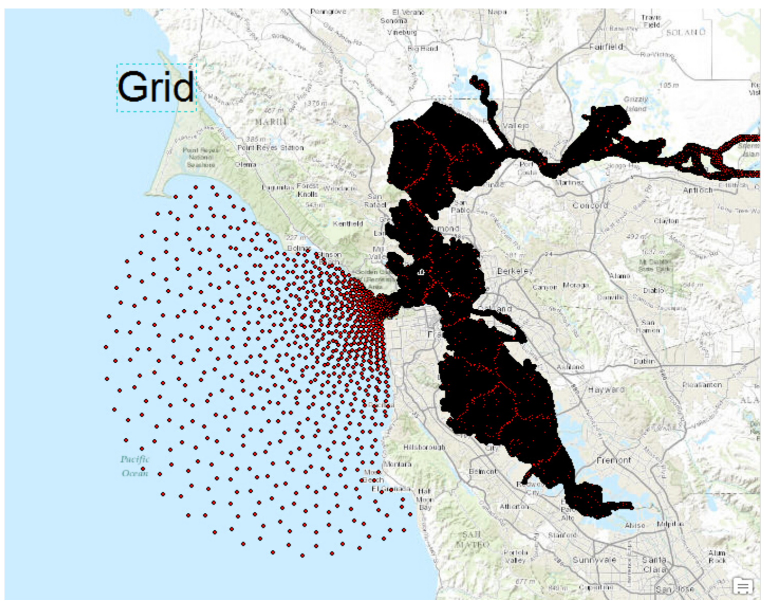

Figure 2: Model grid

gives an overall view of the study area at the scale of full domain. It is seen that the grids have a much lower resolution in the far coastal area than inside the bay.

Once the gird is generated, the next requirement is to specify the depth at each grid point. As illustrated by Stacey et al. [3], the bathymetry data is collected from several different sources, including USGS soundings (2005), USGS lidar (2005) and USGS coarse grid (ca 1995). The depth is stored in a file called depth.dat. In SUNTANS, the developers use the interpolation method of inverse distance weighting to attain the bathymetry file. However, after comparing every spatial interpolation method in ArcGIS, the Natural Neighbor method that can fit the bathymetry best is chosen. The defect of this method is that it has included the values in the land. This happens during the interpolation process and is because the computational area is not a polygon. However, the powerful ability of presenting data in ArcGIS can neglect the unnecessary parts due to interpolation by adding additional layers. Here in this analysis, a bathymetry layer (COMMISSION FOR ENVIRONMENTAL COOPERATION) is added to the map representing the land parts. The Suisun Bay, which is considered as fresh water, is replaced by adding a layer representing rivers and lakes. This treatment helps analyze the effect of river discharge on salinity distribution.

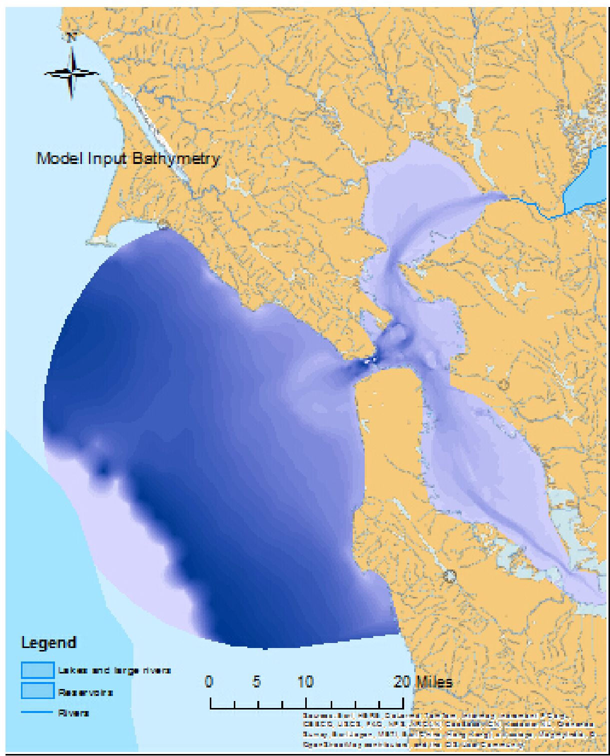

Figure 3: Model input bathymetry

In figure 3, the model input bathymetry plotted by ArcGIS is given. The deeper blue indicates larger depth, while light blue denotes shallower area. The depth tends to decrease as it approaches inland. The mouth of the estuary and the ship channel inside the bay area have larger depth. Whether or not this input bathymetry represents the real topography can be checked via its comparison with the existing data. The existing bathymetry data is collected from San Francisco Bay Area Regional Database (USGS). Here, only the data inside the bay area is available. In figure 4, the bathymetry based on the USGS data is presented. Slight difference occurs between model input and downloaded bathymetry data but the model input file preserves the key

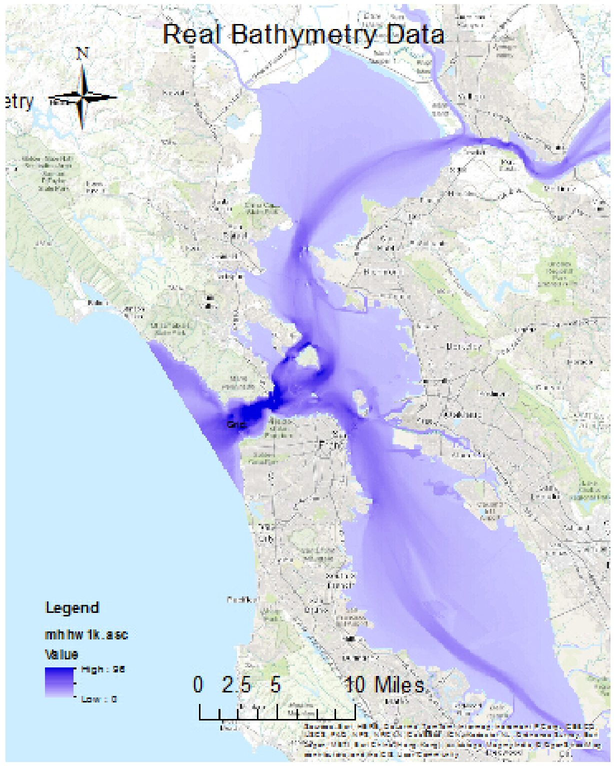

Figure 4: Real bathymetry data (USGS)

features of San Francisco Bay. Better results should be obtained if finer grid is used. The difference may result from interpolation method. In figure 3, since two methods (idw and Natural Neighbor) are used to interpolate the depth, the discontinuity may occur. Since the Natural Neighbor method presents a better result in ArcGIS, this method may be used to create the bathymetry file in the future.

In this section, ArcGIS plays an important role of presenting the grid file, providing a simple and direct way of viewing the resolution of the grid. In the comparison between the two bathymetry datasets, the data from USGS is used, which validates the model input bathymetry.

4 Visualization of the Output Data

In this section, several model output files are visualized using ArcGIS. By adding different datasets to the map, it becomes more convenient to capture the key features of the output data. Lakes and Rivers data collected from USGS and NHDPlus stream data are created as two different layers and are put on the top of the output data layer. This treatment provides a direct look into the fresh water discharge, which can affect the distribution of salinity. Note that the velocity, free surface elevation and temperature are the results of the last time step. The salinity data is presented at both the initial state and the steady state.

In figure 5, the model output velocity profile is presented. Yellow denotes negative values of approximately $-1.12\ m/s \sim -0.08\ m/s$. These negative values indicate fresh water going into the sea. Ching represents small values that fall between $-0.08\ m/s \sim -0.33\ m/s$. It is seen that Ching occupies a large percentage in San Pablo Bay and South Bay. These values can be considered as fluctuations and may result from the mixing between fresh water and salty water. Deep blue denotes larger positive velocities ($0.43\ m/s \sim 0.85$), which is saltier sea water coming into the bay. Note that a small percentage of deep blue occurs at the mouth of Suisun Bay, which is due to the suddenly decreased channel width. This example case is a two-dimensional run, the velocity values are considered at the water surface. In the classical estuarine analysis, exchange flow occurs at the mouth of the estuary with fresh water going out at the shallower part of the water column and sea water coming in at the deeper part. The dominating negative values of velocity at the mouth proves this theory. However, unexpected values exist in South Bay. A small percentage of negative velocities are close to the mouth of San Lorenzo Creek in South Bay, while the rivers with much larger fresh water discharges in San Pablo Bay don't have similar features. This phenomenon needs a further study in a smaller scale as was done by M. Stacy (2012), who used the same model but focus on the South Bay alone.

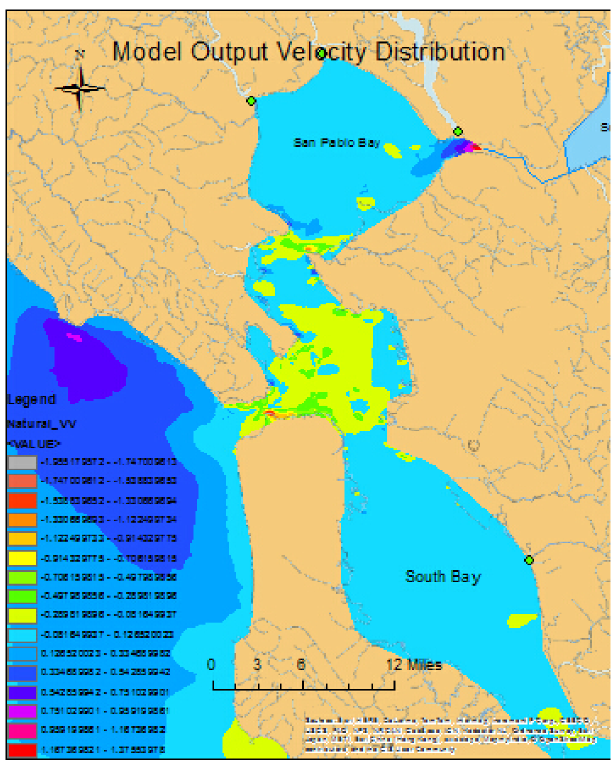

Figure 5: Model output velocity

In figure 6, the model output free surface elevation is shown. Dark green that occupies San Pablo Bay and South Bay indicates small surface elevation with values approximate to 4.23 $cm \sim 5.34$ cm. The warm color, yellow and red, denote larger values of 5.65 $cm \sim 7.74$ cm. The largest free surface elevation is at the mouth of San Francisco Bay, which results from the narrow channel at the mouth. And it is seen that as sea water is shoaling, the elevation is gradually increasing. However the large river discharge of Napa River, Sonoma Creek and Petaluma River in San Pablo Bay don't seem to play an important role in the distribution of surface elevation. Since no large scale data is available in San Francisco Bay, proper observational sites near the mouth of these rivers should be chosen. And the time series of the observational data should be utilized to compare with the model result.

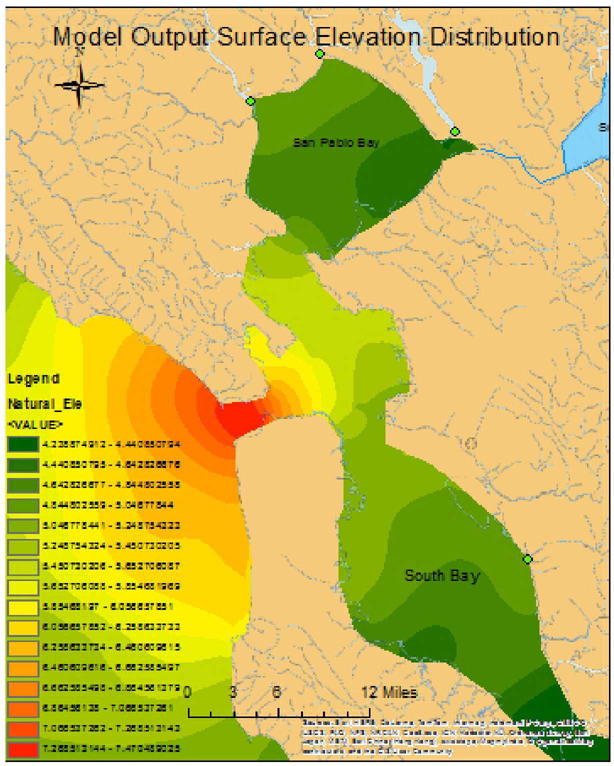

Figure 6: Model output free surface elevation

In figure 7, the SUNTANS output salinity distribution at the initial state is presented. The values of salinity fall between $0 \sim 32psu$ and 0 indicates fresh water. In this figure, yellow represents fresher water with small values, while red is saltier water with high values. However, as it is shown, salty water with high salinity occupies most part of San Francisco Bay, and only a small amount of fresh water occurs at the mouth of Suisun Bay. This figure, however, is not able to present the features in Suisun Bay, as it has been considered as a fresh water resource in the upper layer. In the model setup, two rivers (Sacramento River and San Joaquin River), which are inside Suisun Bay are considered. The initial salinity values at the mouth of these river (type 2 boundary) are assumed to be zero. Although the result of Suisun Bay is not shown in this report, the water in Suisun is occupied by fresh water with salinity values approximate to $0psu$. Hence, the neglect of the effect of Suisun Bay is reasonable. The salty water dominated condition result from the initial background salinity, which is set to be 32 psu.

Figure 8 presents the model output salinity of a more steady state, which is 24 hours later. The green bracket indicates a fresh water discharge and a mixing between fresh water and salty water. More obvious result of the fresh water discharge may be obtained from longer period of model run. However, after comparing the results of 12 hours later and 24 hours later, no obvious difference is found, which indicates that the assumed initial background salinity is not set properly, and the fresh water is not able to make enough effect on the salinity distribution even in San Pablo Bay under this condition. This example case only considered two fresh water resources (the initial salinity is set to be 0 at the mouth of two river). And the river fluxes are set to be 0 at the mouths, which is not able to provide enough force to drive fresh water towards the sea. With these limitations in mind, the effect of fresh water discharge may be weakened compared with real condition.

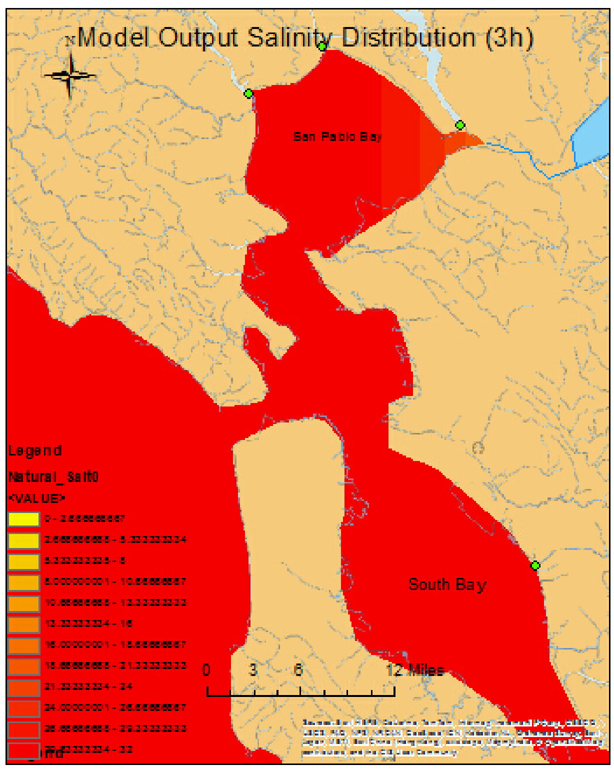

Figure 7: Model output salinity at initial state

The temperature distribution at the last time step is shown in figure 9. The result of temperature is consistent with that of salinity. In the figure, the white indicates the warmer sea water dominating in most parts of San Francisco Bay, while the pink in San Pablo Bay means cold fresh water brought by the river discharge.

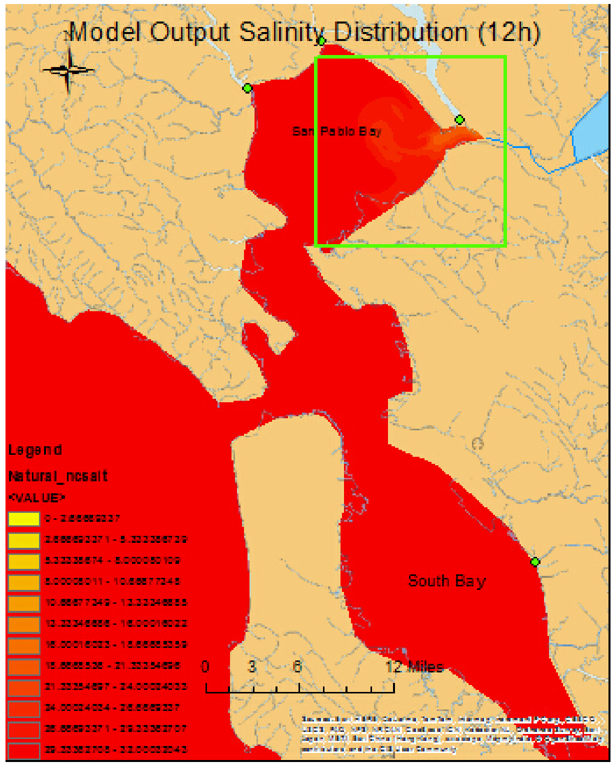

Figure 8: Model output salinity at steady state

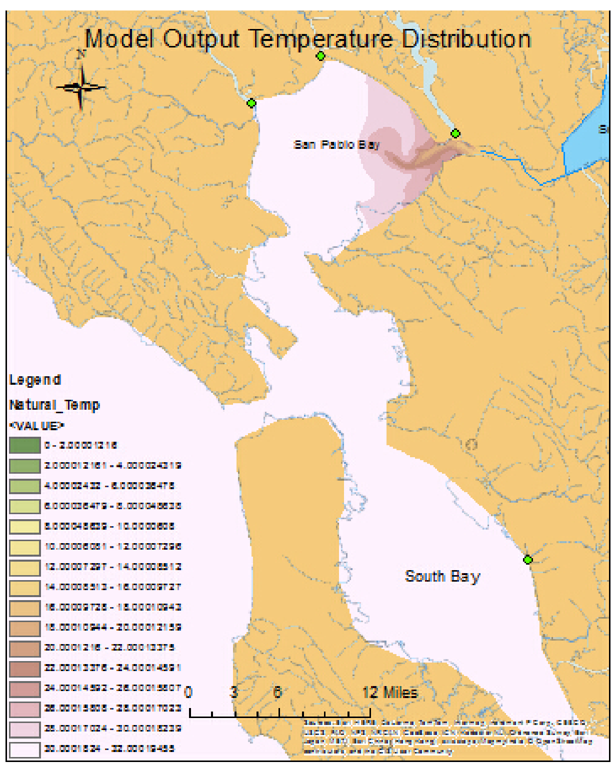

Figure 9: Model output temperature

5 Discussion

The data of salinity collected from USGS is presented in figure 10, where darker yellow represents fresher water and lighter yellow denotes saltier water. This salinity distribution is compatible with common sense. The water close to the shore where river discharge exists is fresher, while saltier water intrudes into the bay and dissipates. The distribution of observational data is different with that of model output. Although the salinity distribution is related to several effects in estuaries and varies with time. For example, there is obvious difference of salinity distribution between flood and ebb, spring tide and neap tide. The salinity data collected from USGS lack the time information and the SUNTANS output data is based simply on the assumptions of the initial condition. Depending upon this condition, it is reasonable to have different distribution profiles.

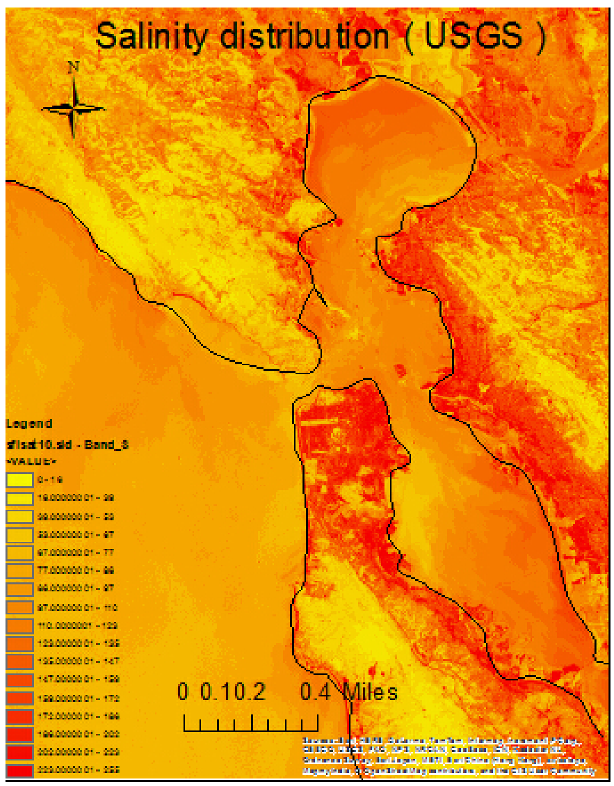

Figure 10: Salinity distribution (USGS data)

NHDPlus data provides an convenient method of pinpointing river mouth and examining freshwater discharge of each river. It's important to check the freshwater source before further discussion. In figure 11 and 12, the main annual freshwater flows in San Pablo Bay and South Bay are presented. The mean annual flows in Sacramento River and San Joaquin River are 24719.65 ft^3/s and 5966.199 ft^3/s, respectively. The effects of river discharge in Suisun Bay is dominating compared with other effects, such as exchange flow, diffusive flux and tidal effects. In San Pablo Bay, there are three main freshwater sources, which are Petuluma River, Sonoma Creek and Napa River. The mean annual flows are 133.762 ft^3/s, 172.6 ft^3/s and 311.214 ft^3/s. Compared with those in Suisun Bay, the freshwater discharges in San Pablo Bay are small but may not be neglected to obtain reasonable results. In South Bay, no significant freshwater sources can be found in South Bay. The largest two indicated in figure 12 are San Lorenzo Creek and San Francisquito Creek with the annual mean flow of each being 21.676 ft^3/s and 25.794 ft^3/s. No gaged watershed is considered. Therefore, the effects of river discharge should play a more important role in San Pablo Bay in the salinity distribution than South Bay. The neglect of these freshwater resources decrease the accuracy of the result. In the study of Stacey et al. [3], More freshwater sources, including major and minor rivers, small ungaged watersheds and wastewater returns are considered. And their running period is 15 days. Due to the limited computational resources and errors that come from MPI computing, I am not able to accomplish a multiple-processors run. So longer period is not tested in this review.

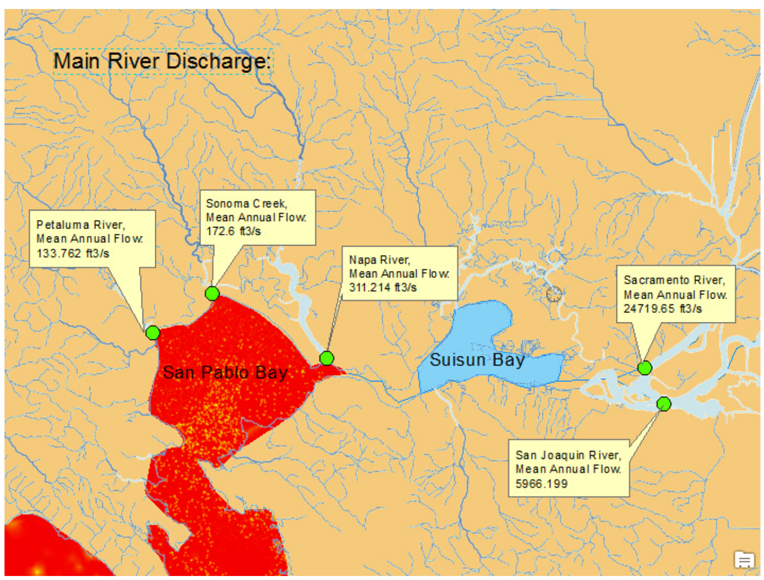

Figure 11: Freshwater source in San Pablo Bay

To compare the characteristics of salinity in San Pablo Bay and South Bay, several representative markers are chosen. By discussing the salinity variation with time at each marker, the effect of river discharge will be shown. In San Pablo Bay, I choose seven markers with the 1st starting at the mouth of Suisun Bay and the others extending towards the sea. The time variation of salinity at each marker is given in figure 13. As we can see, the variation of salinity near the mouth is more clear and becomes dumped towards the sea. At the 1st marker, the variation has a range from 28 psu to 20 psu, while the range of variation of the four marker far from the mouth falls between 32 psu and 30 psu. This figure is compatible with figure 8. As the effect of river discharge

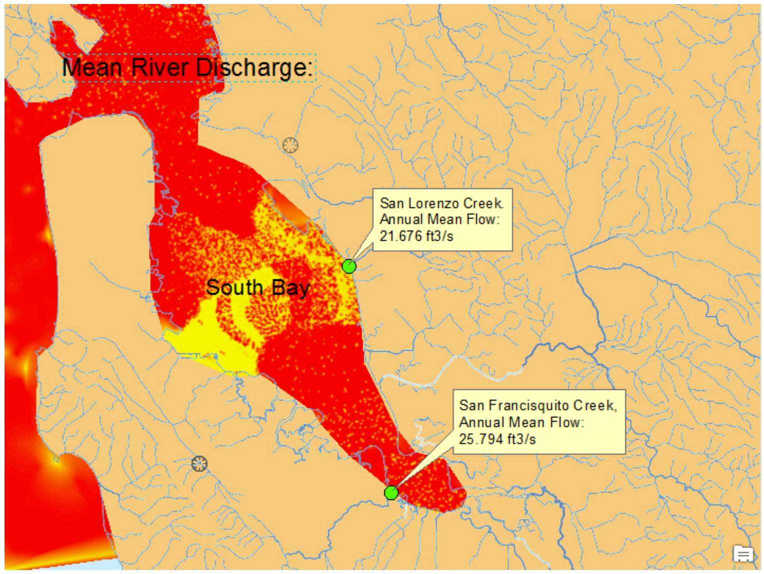

Figure 12: Freshwater source in South Bay

decreases, the time variation of salinity becomes small. As the marker is closer to the ocean, the salinity is close to the background salinity, which is 32 *psu*. Basically, the variation of salinity is periodic with the period of 12 hours. In the initial condition, the harmonic analysis rather than observational data is used to simulate the tide. The component of tide is semidiurnal component, M_2 that only considers the effect of earth rotation with respect to the Moon. The period of M_2 component is 12 hours, which is consistent with the period of salinity variation. This consistency indicates the tidal effects on the distribution of salinity. And this result agrees well with that of Stacey et al. [3]. In South Bay, I choose five marker starting from that close to the shore and extending towards the ocean. The time variation of salinity at these markers is shown in figure 14. There is only slight variation of salinity in South Bay. The range is between 31.999835 *psu* and 31.999810 *psu*. These variations may be neglected. The salinity is fluctuating over 24 hours and no trend can be found. No periodic variation indicates that tide is not affecting the salinity in South Bay strongly. This may be because the initial background salinity is not chosen properly. The South Bay is fulfilled with 32 *psu* salinity at the moment that the run starts. No freshwater source is another reason that no freshwater mechanisms exist in South Bay to adjust salinity. In the former study, tidal oscillation is dominating mechanism in the South Bay. However, the setup of unrealistic initial and boundary conditions, and the incomplete consideration of tide ($M2$ tide only) make it difficult to conclude the tidal effect in South Bay.

By comparing the salinity distribution and time variation in San Pablo Bay and South Bay, we may have such conclusion that the river discharge play a significant role in salinity compared with other effects, which are wind, dispersion and exchange flow. Tidal effect is seen in San Pablo Bay but not in South Bay. This may be because of the improper boundary and initial conditions. However, in order to obtain more accurate and persuasive result, more freshwater sources should be added to the boundary conditions and longer run should be implemented. Plus, since this model run is a proof-of-concept exercise to establish the ability of ArcGIS to visualize the result of a numerical model. No specific sites are chosen and no related observational data is provided. There is no comparison between the time series of salinity and measurements. With this defect, it may be improper to assert that the model result is correct. (Chua et al. [4] tested the model performance in the northern reach and Stacey et al. [3] tested the model in South Bay under more realistic conditions). Further studies need to be done to validate the ability of SUNTANS to resolve dynamics in San Pablo Bay and even Central Bay.

In addition, the running period of SUNTANS in this project is not long enough to consider comprehensive effects made by tide. The period of 24 hours is not able to present the salinity variation between flood and ebb tide, or spring and neap tide.

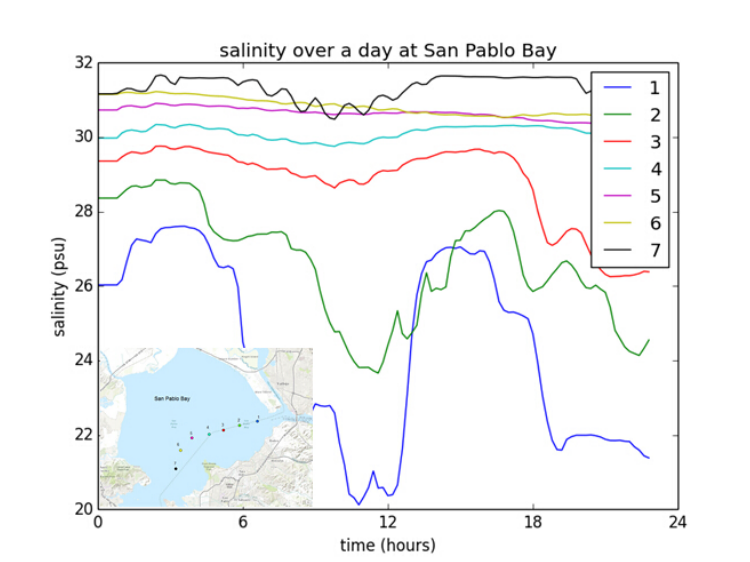

Figure 13: Freshwater source in San Pablo Bay

6 Summary

In this study, ArcGIS is proved to be a powerful tool in assisting the analysis of the result of a numerical model (SUNTANS). In the section of model setup, ArcGIS provides an efficient method of checking the model bathymetry and boundary conditions. By adding proper layers, such as NHDPlus, Lakes and Rivers (USGS), the freshwater sources can be found. In the section of visualizing the model output data, the interpolation tool, Natural Neighbor, is implemented, which results in the figures that can present different features

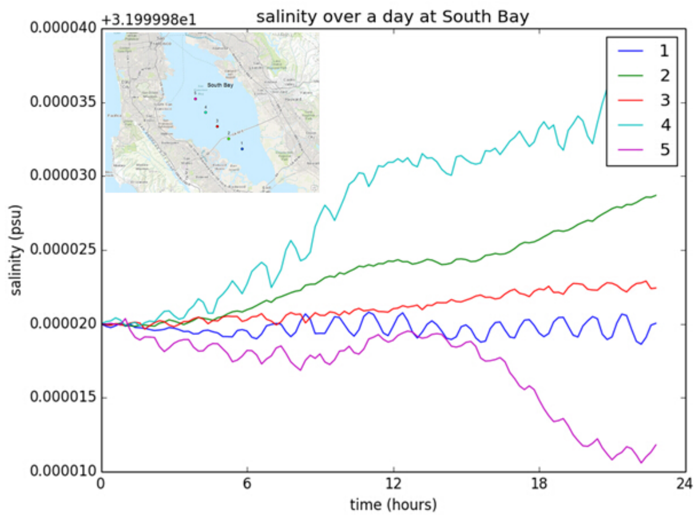

Figure 14: Freshwater source in South Bay

well. This well-performed interpolation method provides an alternative to the model developers in interpolating the depth. With the assistance of ArcGIS, the results in San Pablo Bay and South Bay indicate that river discharge plays an important role in salinity distribution and variation. The tidal effects that greatly affect the salinity variation in San Pablo Bay fail to make similar effects in South Bay, which suggests that more freshwater sources should be considered and more realistic initial conditions (background salinity) should be applied.

In the further study, the same method (SUNTANS and ArcGIS) will be applied to my project, which is associated with Galveston Bay in Texas. The data of freshwater source and wind are more abundant and accessible in my research. The real-time tidal data can be obtained using the output of a Regional Ocean Model (ROMS) [6]. Hence, a more realistic study can be accomplished and animations should be made using ArcGIS as well.

Acknowledgement

Thanks to Dr. Madiment for the inspiration and guidance in this project. Thanks to Dr. Maidment, Dr. Tarboton, Dr. Castronova, and Dr. Band for the wonderful lectures throughout this semester. Thanks to Dr. Hodges and Dr. Rayson for the guide in running SUNTANS model.

References

[1] R. A. Walters, R. T. Cheng, T. J. Conomos, Time scales of circulation and mixing processes of san francisco bay waters, Hydrobiologia 129 (1985)

13–36.

[2] O. Fringer, M. Gerrisen, R. Street, An unstructured grid, finite volume, nonhydrostatic, parallel coastal ocean simulator, Ocean Modeling 14 (2006) 139–173.

[3] M. Stacey, R. Holleman, E. S. Gross, Test applications of high resolution 3- dimensional hydrodynamic model (suntans) to san francisco bay, Contribution No. 638. San Francisco Estuary Institute, Oakland, California (2011).

[4] V. P. Chua, O. B. Fringer, T. J. Conomos, Sensitivity analysis of three-dimensional salinity simulations in north san francisco bay using the unstructured-grid suntans model, Ocean Modelling 39(3-4) (2011) 332–350.

[5] S. Baston, R. E. Harris, Modelling the hydrodynamic characteristics of tidal flow in the pentland firth (2014).

[6] D. B. Haidvogel, H. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, A. Shchepetkin, Model evaluation experiments in the north atlantic basin: Simulations in nonlinear terrain-following coordinates, Dyn. Atmos. Oceans 32 (2000) 239–281.