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Modeling Sea Level Change Using the Coastal Modeling System

by Honghai Li and Mitchell E. Brown

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes procedures to incorporate a sea level change (SLC) curve within the Coastal Modeling System (CMS) operated in the Surface-water Modeling System (SMS), version 13.0 (Aquaveo 2010). The defined procedures are demonstrated in a long-term modeling simulation configured around an idealized inlet.

INTRODUCTION: Increasing atmospheric concentrations of greenhouse gases are warming the atmosphere and oceans. The global warming and the rise in ocean temperature may gradually increase ocean volume and change sea level (Figure 1) (IPCC 2014). Potential global sea level rise (SLR) combined with coastal storms can drastically change the depth of navigation channels and introduce sediment into navigation channels through adjacent shore erosion. Recognizing the impacts of global climate change with potential SLR on coastal and estuarine waterways, measures need to be taken to assess risk and vulnerability of navigation projects, to conduct research and development that support a reduction of future operation and maintenance costs, and to develop adaptation strategies and management plans to support operations and maintenance practice (USACE 2011).

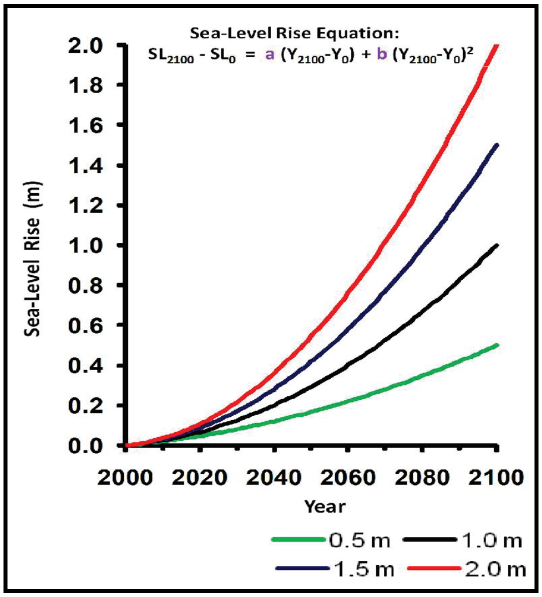


Figure 1. Projected 0.5, 1.0, 1.5, and 2.0 m SLR scenarios by the year 2100 (USACE 2011).

COASTAL MODELING SYSTEM (CMS): Numerical modeling is a powerful tool to conduct short- to long-term simulations in inlet and navigation projects and to investigate the impact of SLR on channel design and maintenance under changes in tides, wave climate, and sediment transport.

CMS is widely used by U.S. Army Corps of Engineers (USACE) in planning, design, and scientific investigation of navigation projects. The CMS can simulate waves, hydrodynamics, sediment transport, and morphodynamics with SLR to address problems related to channel shoaling, dredging, placement of dredged material, and coastal structure modifications. However, the present CMS only allows users to specify a constant SLR value in the model domain. Alternatively, users can manually blend the SLR curve in the open boundary condition. This CHETN describes a new capability of the CMS to incorporate a given projected SLC curve (NOAA 2012; USACE 2017) in the model simulation.

The CMS calculates water levels, depth-averaged currents, and waves in a two-dimensional (2D) field through the coupling of a hydrodynamic model CMS-Flow (Sanchez et al. 2014) and a wave model CMS-Wave (Lin et al. 2008). CMS-Flow is a 2D finite-volume model that solves the mass conservation and momentum equations of shallow water motion. CMS-Flow is forced by water surface elevation (WSE) (e.g., from tide) and river discharge at model boundaries, wave radiation stress, and wind forcing over a model computational domain. Physical processes calculated by CMS-Flow include wave-current interaction, sediment transport, morphology change, and salinity transport. CMS-Wave is a 2D quasi-steady spectral wave transformation model. The model contains theoretically derived formulations of wave diffraction, reflection, and wave-current interactions for wave simulation at coastal inlets with jetties and breakwaters.

SEA LEVEL CHANGES IN THE CMS: CMS-Flow lateral open boundaries allow water exchanges along with model driving forcing, such as flux and water level variation. Along a flux boundary, freshwater inflows or mean currents can be specified. Water level boundaries can be obtained from the measurements at coastal tidal gauges or composed from tidal constituents.

In the CMS, the general formula for the boundary WSE is specified by

$$\overline{\eta}_B = \overline{\eta}_0 + \overline{\eta}_E + \Delta\overline{\eta} \tag{1}$$

where $\overline{\eta}_B$ is the boundary WSE, $\overline{\eta}_0$ is the initial boundary WSE, $\overline{\eta}_E$ is the specified external boundary WSE, and $\Delta\overline{\eta}$ is the WSE offset. The unit of the variables in Equation (1) is meter.

The external WSE ($\overline{\eta}_E$) may be specified as a time series, either spatially constant or varying, or may be calculated from tidal/harmonic constituents. When a time series is specified, the values at each time-step are interpolated using piecewise Lagrangian polynomials. If tidal constituents are specified, then $\overline{\eta}_E$ is calculated as

$$\overline{\eta}_E(t) = \sum A_i \cos(\omega_i t - \kappa_i) \tag{2}$$

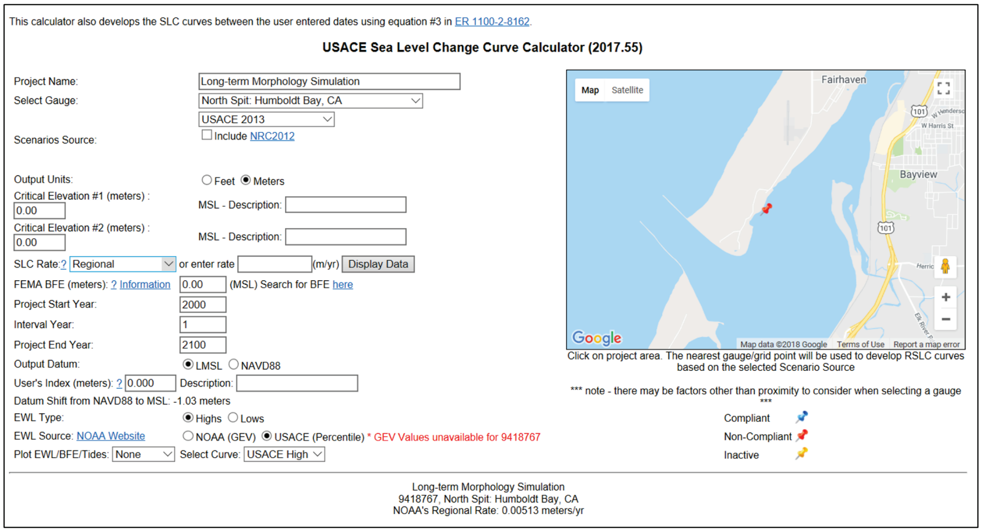
where i is the subscript indicating a tidal constituent, A_i is the mean amplitude (m), ω_i is the frequency (deg/hr), t is the elapsed time from the midnight of a starting year (hours), and κ_i is the phase lag (degrees).

The WSE offset ($\Delta\bar{\eta}$) represents a water level adjustment that can be a spatially and temporally constant value (vertical datum correction and SLC) or a time-varying curve (e.g., SLR).

CMS SIMULATION WITH SLC: To set up a CMS simulation with SLC scenario, users first need to select a predefined SLC curve.

The Intergovernmental Panel on Climate Change (IPCC) conducted review and assessment of scientific information in climate change and provides serial assessment reports on global greenhouse emission and SLC (IPCC 2014). Along with the IPCC evaluation of global SLC, the U.S. National Research Council (NRC) issues and updates SLR guidance documents for the U.S. coast. On the basis of the most recent IPCC and NRC SLR projections and considering the local land subsidence, USACE and the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic and Products and Services developed a web-based tool, USACE Sea Level Change Curve Calculator, to calculate projected rates of SLC for any location along the U.S. coast (USACE 2017).

Figure 2 shows the web tool to access an SLR curve at North Spit: Humboldt Bay, California, from 2000 to 2100. On this SLC Curve Calculator page, once a gauge location and a NOAA or USACE curve is selected, the corresponding Low, Intermediate, and High Curves will be shown, and the data at the site will be tabulated. The curves and data may be adjusted by specifying SLC Project Start Year and Project End Year, Output Unit (feet or meter), and Output Datum (Local Mean Sea Level or North American Vertical Datum of 1988). Figure 3 displays projected USACE Low, Intermediate, and High SLR curves. Figure 4 shows tabulated values of three SLR curves. Click “Print Table” at the bottom of the table or highlight and copy/paste the table for the CMS to use as the WSE offset, $\Delta\bar{\eta}$, at water level boundaries.



This calculator also develops the SLC curves between the user entered dates using equation #3 in ER 1100-2-8162.

USACE Sea Level Change Curve Calculator (2017.55)

Project Name: Long-term Morphology Simulation
Select Gauge: North Spit: Humboldt Bay, CA
Scenarios Source: USACE 2013
☐ Include NRC2012
Output Units: ○ Feet ● Meters
Critical Elevation #1 (meters) : 0.00 MSL - Description:
Critical Elevation #2 (meters) : 0.00 MSL - Description:
SLC Rate:? Regional or enter rate (m/yr)
FEMA BFE (meters): ? Information 0.00 (MSL) Search for BFE here
Project Start Year: 2000
Interval Year: 1
Project End Year: 2100
Output Datum: ● LMSL ○ NAVD88
User's Index (meters): ? 0.000 Description:
Datum Shift from NAVD88 to MSL: -1.03 meters
EWL Type: ● Highs ○ Lows
EWL Source: NOAA Website ○ NOAA (GEV) ● USACE (Percentile) * GEV Values unavailable for 9418767
Plot EWL/BFE/Tides: None Select Curve: USACE High

Click on project area. The nearest gauge/grid point will be used to develop RSLC curves based on the selected Scenario Source

*** note - there may be factors other than proximity to consider when selecting a gauge ***

Compliant 📌
Non-Compliant 📌
Inactive 📌

Long-term Morphology Simulation
9418767, North Spit: Humboldt Bay, CA
NOAA's Regional Rate: 0.00513 meters/yr

Figure 2. Selected location and period over which a projected SLR curve will be generated.

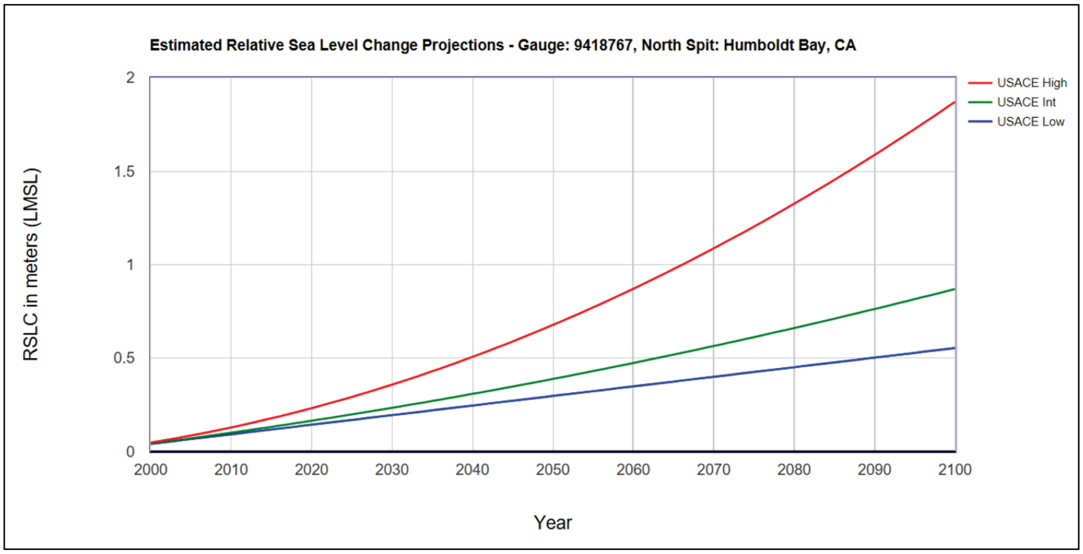
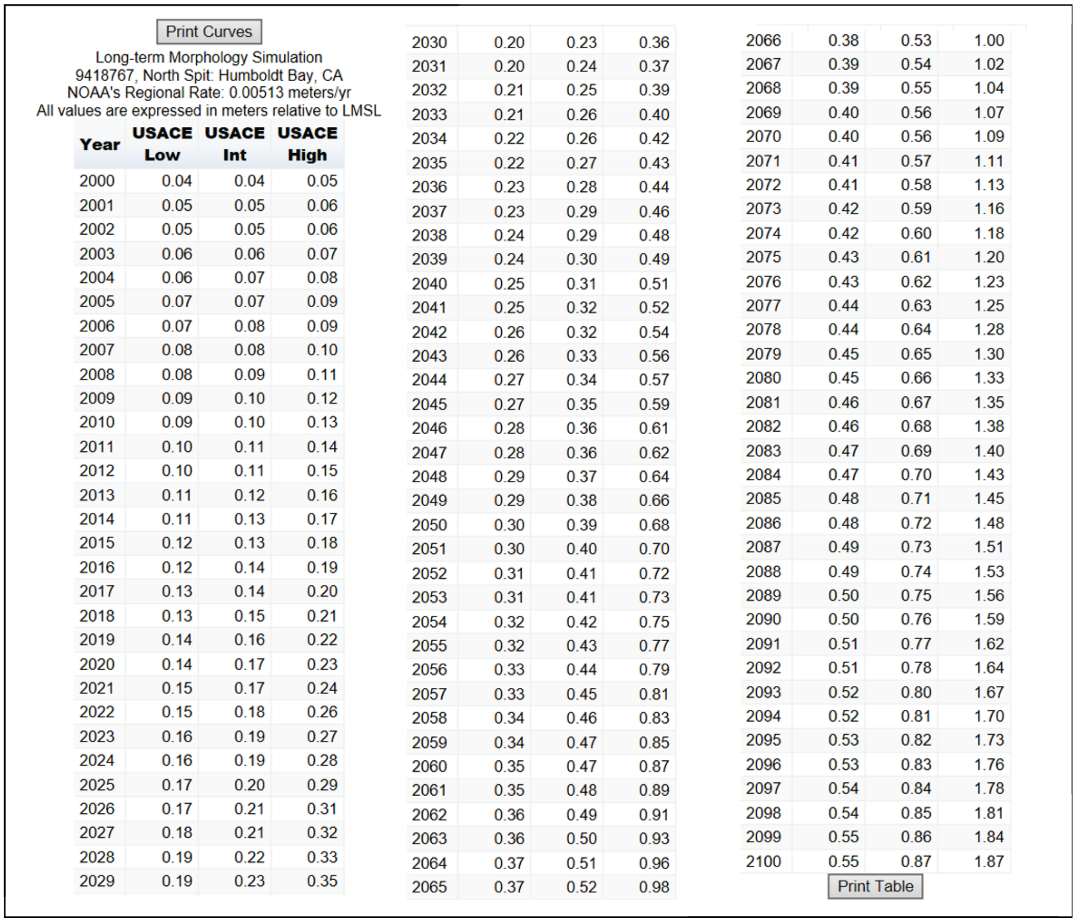


Figure 3. Projected low, intermediate, and high SLR curves at North Spit: Humboldt, California, from 2000 to 2100.



Long-term Morphology Simulation
9418767, North Spit: Humboldt Bay, CA
NOAA's Regional Rate: 0.00513 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low	USACE Int	USACE High
2000	0.04	0.04	0.05
2001	0.05	0.05	0.06
2002	0.05	0.05	0.06
2003	0.06	0.06	0.07
2004	0.06	0.07	0.08
2005	0.07	0.07	0.09
2006	0.07	0.08	0.09
2007	0.08	0.08	0.10
2008	0.08	0.09	0.11
2009	0.09	0.10	0.12
2010	0.09	0.10	0.13
2011	0.10	0.11	0.14
2012	0.10	0.11	0.15
2013	0.11	0.12	0.16
2014	0.11	0.13	0.17
2015	0.12	0.13	0.18
2016	0.12	0.14	0.19
2017	0.13	0.14	0.20
2018	0.13	0.15	0.21
2019	0.14	0.16	0.22
2020	0.14	0.17	0.23
2021	0.15	0.17	0.24
2022	0.15	0.18	0.26
2023	0.16	0.19	0.27
2024	0.16	0.19	0.28
2025	0.17	0.20	0.29
2026	0.17	0.21	0.31
2027	0.18	0.21	0.32
2028	0.19	0.22	0.33
2029	0.19	0.23	0.35
2030	0.20	0.23	0.36
2031	0.20	0.24	0.37
2032	0.21	0.25	0.39
2033	0.21	0.26	0.40
2034	0.22	0.26	0.42
2035	0.22	0.27	0.43
2036	0.23	0.28	0.44
2037	0.23	0.29	0.46
2038	0.24	0.29	0.48
2039	0.24	0.30	0.49
2040	0.25	0.31	0.51
2041	0.25	0.32	0.52
2042	0.26	0.32	0.54
2043	0.26	0.33	0.56
2044	0.27	0.34	0.57
2045	0.27	0.35	0.59
2046	0.28	0.36	0.61
2047	0.28	0.36	0.62
2048	0.29	0.37	0.64
2049	0.29	0.38	0.66
2050	0.30	0.39	0.68
2051	0.30	0.40	0.70
2052	0.31	0.41	0.72
2053	0.31	0.41	0.73
2054	0.32	0.42	0.75
2055	0.32	0.43	0.77
2056	0.33	0.44	0.79
2057	0.33	0.45	0.81
2058	0.34	0.46	0.83
2059	0.34	0.47	0.85
2060	0.35	0.47	0.87
2061	0.35	0.48	0.89
2062	0.36	0.49	0.91
2063	0.36	0.50	0.93
2064	0.37	0.51	0.96
2065	0.37	0.52	0.98
2066	0.38	0.53	1.00
2067	0.39	0.54	1.02
2068	0.39	0.55	1.04
2069	0.40	0.56	1.07
2070	0.40	0.56	1.09
2071	0.41	0.57	1.11
2072	0.41	0.58	1.13
2073	0.42	0.59	1.16
2074	0.42	0.60	1.18
2075	0.43	0.61	1.20
2076	0.43	0.62	1.23
2077	0.44	0.63	1.25
2078	0.44	0.64	1.28
2079	0.45	0.65	1.30
2080	0.45	0.66	1.33
2081	0.46	0.67	1.35
2082	0.46	0.68	1.38
2083	0.47	0.69	1.40
2084	0.47	0.70	1.43
2085	0.48	0.71	1.45
2086	0.48	0.72	1.48
2087	0.49	0.73	1.51
2088	0.49	0.74	1.53
2089	0.50	0.75	1.56
2090	0.50	0.76	1.59
2091	0.51	0.77	1.62
2092	0.51	0.78	1.64
2093	0.52	0.80	1.67
2094	0.52	0.81	1.70
2095	0.53	0.82	1.73
2096	0.53	0.83	1.76
2097	0.54	0.84	1.78
2098	0.54	0.85	1.81
2099	0.55	0.86	1.84
2100	0.55	0.87	1.87

Figure 4. Projected low, intermediate and high SLR values at North Spit: Humboldt, California, from 2000 to 2100.

LONG-TERM MORPHOLOGY MODELING FOR AN IDEALIZED TIDAL INLET: Motivated by the need to evaluate the effects of SLR on the USACE navigation projects, the CMS was developed to predict the morphological evolution of barrier islands and tidal inlets on climatological time scales (Styles et al. 2018). One hundred years of morphology change were calculated by using a morphological acceleration factor. In this section, an example of long-term morphology modeling is used to demonstrate the CMS setup with the incorporation of an SLR curve within an idealized tidal inlet system. Model calculations with and without SLR are compared.

Background for Idealized Case Study. The idealized bay and inlet system resembles the basin dimension of the Humboldt Bay inlet, California. Figure 5 shows the model domain. The initial bathymetry is uniform within the bay and inlet throat and deepens offshore following an equilibrium beach profile. A single sediment grain size (D_{50} = 0.2 millimeters) is used in the model.

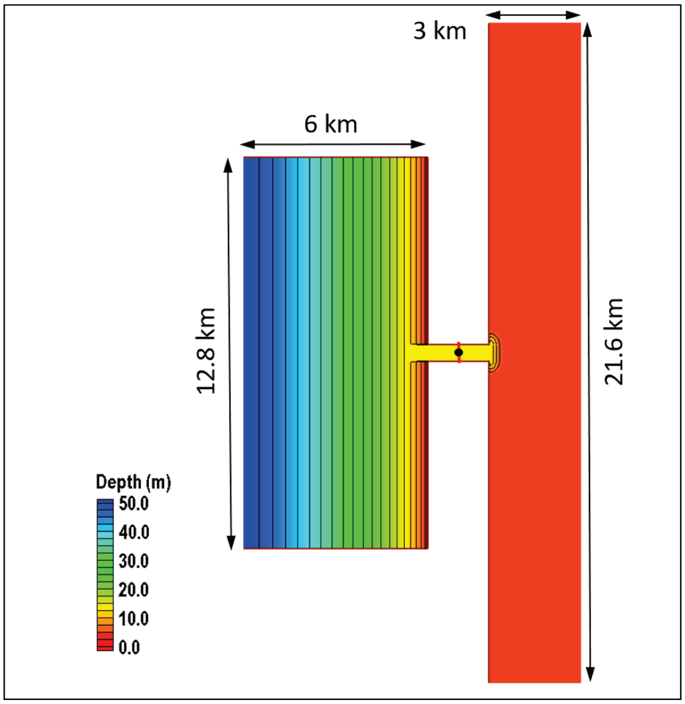
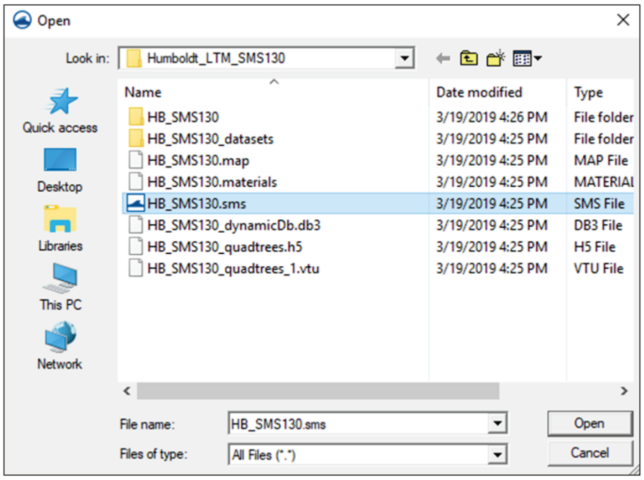


Figure 5. Idealized model domain and bathymetry. The red line is the selected transect across the inlet channel where mass and sediment fluxes were calculated, and the black dot is the selected location where time series results were analyzed.

The inlet system has simplified boundary conditions. The amplitude and phase of tidal constituents are extracted from the NOAA North Spit tide gauge for the Humboldt Bay model. A total of 13 tidal constituents are used to construct the WSE time series for the boundary condition. The mean tidal range is 1.5 meters (m) as dominated by the M2 (semi-diurnal) tide.

Wave data are derived from the Wave Information Studies database (Station #83047; 40.83°N, 124.42°W), which includes estimates of the directional spectra, significant wave height, peak period, average period, and direction (*http://wis.usace.army.mil/*). Humboldt Bay inlet has high average wave conditions and large waves approach from the west and northwest with maximum height exceeding 6 m. The wave spectra characteristics are prescribed at the offshore boundary and generate a wave field across the entire offshore boundary (Styles et al. 2018). Wind waves inside the bay are not included in the model.

CMS Setup for SLR Scenario. The CMS hydrodynamic and wave input files for Humboldt Bay were prepared using the SMS13.0 (Figure 6). Instructions for setting up a CMS simulation with an SLR curve are described below.



Look in: Humboldt_LTM_SMS130

Name	Date modified	Type
HB_SMS130	3/19/2019 4:26 PM	File folder
HB_SMS130_datasets	3/19/2019 4:25 PM	File folder
HB_SMS130.map	3/19/2019 4:25 PM	MAP File
HB_SMS130.materials	3/19/2019 4:25 PM	MATERIAL
HB_SMS130.sms	3/19/2019 4:25 PM	SMS File
HB_SMS130_dynamicDb.db3	3/19/2019 4:25 PM	DB3 File
HB_SMS130_quadtrees.h5	3/19/2019 4:25 PM	H5 File
HB_SMS130_quadtrees_1.vtu	3/19/2019 4:25 PM	VTU File

File name: HB_SMS130.sms
Files of type: All Files (*.*)

Figure 6. Files for the CMS simulation.

After opening “HB_SMS130.sms” in SMS 13.0, select *Boundary Conditions* tab under *Map* (*Map Data*) module in the SMS Data Tree. To specify WSE at the open boundary, click *Select Feature Arc* tool, highlight and right-click the WSE-forcing boundary string and then select *Assign Boundary Conditions…* (Figure 7). In the following pop-up window, the top portion shows the open boundary type. For *WSE-forcing*, users define the data source (*WSE Source*). The middle portion of the window is where users assign SLC information to the WSE-forcing boundary. The SLC value can be a constant or a predefined curve to represent temporal varying SLC (Figure 8).

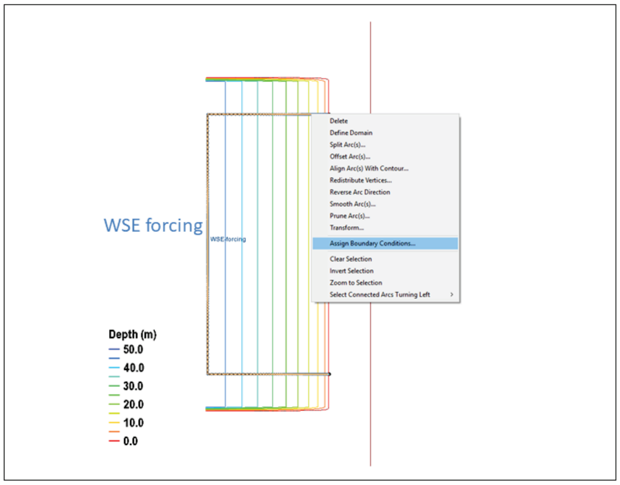
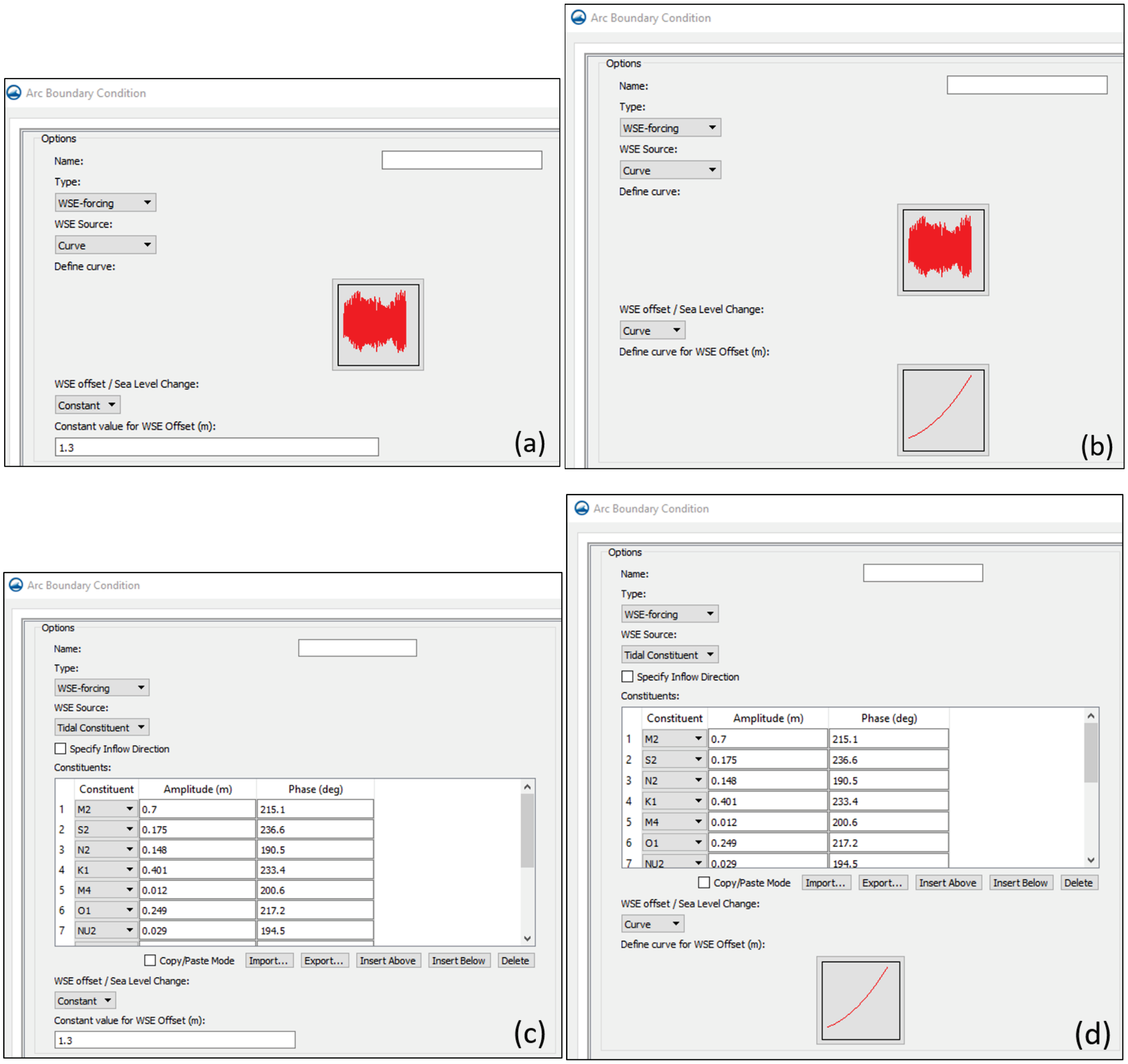


Figure 7. The WSE-forcing boundary setup.



(a) Arc Boundary Condition

Options

Name:

Type: WSE-forcing

WSE Source: Curve

Define curve:

WSE offset / Sea Level Change: Constant

Constant value for WSE Offset (m): 1.3

(b) Arc Boundary Condition

Options

Name:

Type: WSE-forcing

WSE Source: Curve

Define curve:

WSE offset / Sea Level Change: Curve

Define curve for WSE Offset (m):

(c) Arc Boundary Condition

Options

Name:

Type: WSE-forcing

WSE Source: Tidal Constituent

☐ Specify Inflow Direction

Constituents:

	Constituent	Amplitude (m)	Phase (deg)
1	M2	0.7	215.1
2	S2	0.175	236.6
3	N2	0.148	190.5
4	K1	0.401	233.4
5	M4	0.012	200.6
6	O1	0.249	217.2
7	NU2	0.029	194.5

☐ Copy/Paste Mode

WSE offset / Sea Level Change: Constant

Constant value for WSE Offset (m): 1.3

(d) Arc Boundary Condition

Options

Name:

Type: WSE-forcing

WSE Source: Tidal Constituent

☐ Specify Inflow Direction

Constituents:

	Constituent	Amplitude (m)	Phase (deg)
1	M2	0.7	215.1
2	S2	0.175	236.6
3	N2	0.148	190.5
4	K1	0.401	233.4
5	M4	0.012	200.6
6	O1	0.249	217.2
7	NU2	0.029	194.5

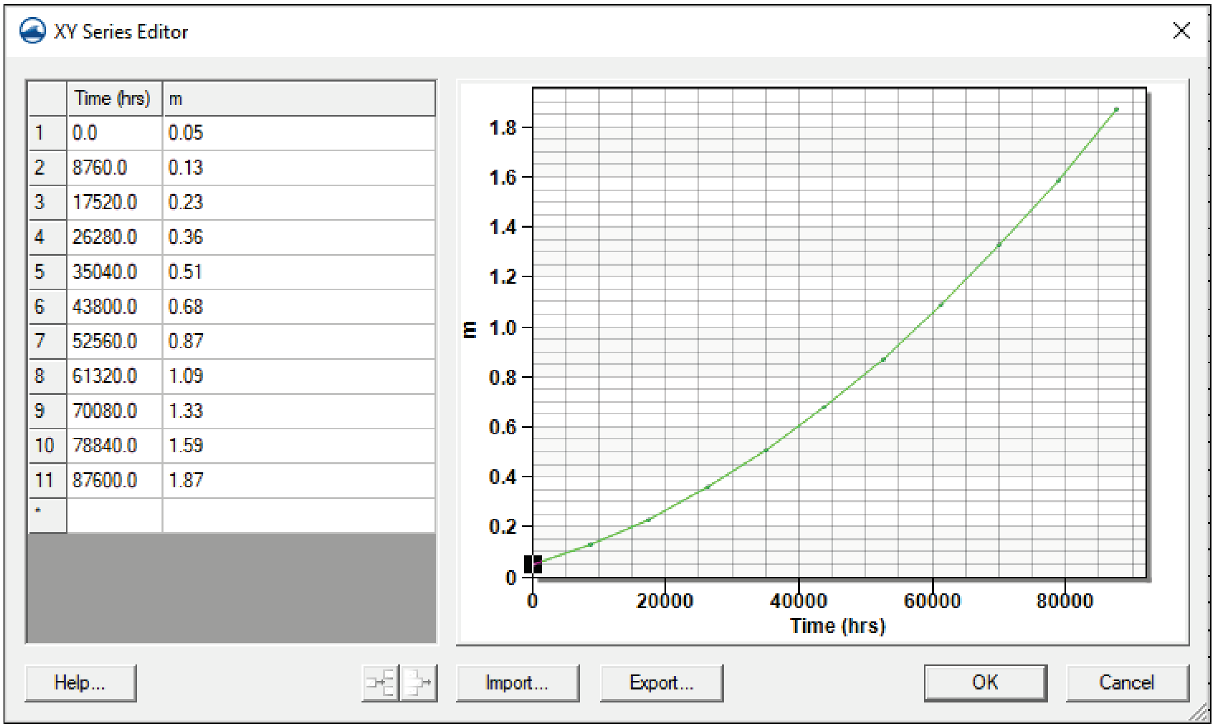
☐ Copy/Paste Mode

WSE offset / Sea Level Change: Curve

Define curve for WSE Offset (m):

Figure 8. Define SLC scenarios with different WSE-forcing sources: (a) constant SLC with a single time series of WSE-forcing, (b) SLC time series with a single time series of WSE-forcing, (c) constant SLC with WSE-forcing computed by selected tidal constituents, and (d) SLC time series with WSE-forcing computed by selected tidal constituents.

Users have the option to read an SLC time series into the CMS, either by clicking the Import button, or by entering SLC values manually in two separate data columns or by copying/pasting data from an opened Excel file. As shown in Figure 9, the 100-year SLR curve is obtained for Humboldt Bay and specified in the *Assign Boundary Conditions* section of the SMS interface based on the values listed in Figure 4 at a 10-year interval. Note that the total simulation time in Figure 9 is given for a 10-year period, which is equivalent to a 100-year condition as a morphological acceleration factor of 10 was specified in the CMS setup (Styles et al. 2018).



	Time (hrs)	m
1	0.0	0.05
2	8760.0	0.13
3	17520.0	0.23
4	26280.0	0.36
5	35040.0	0.51
6	43800.0	0.68
7	52560.0	0.87
8	61320.0	1.09
9	70080.0	1.33
10	78840.0	1.59
11	87600.0	1.87
*		

Figure 9. SLR values obtained for Humlboldt Bay in the SMS interface.

SIMULATION RESULTS: The CMS simulations were conducted for a 10-year period from 2001 to 2010. Calculated WSE and current velocities were saved and analyzed at the inlet channel output location (Figure 5). Figure 10 shows the time series WSEs and along-channel current speeds obtained with boundary forcing composed of 13 tidal constituents without (Figures 10(a) and 10(c), respectively) and with (Figures 10(b) and 10(d), respectively) 100-year SLR scenarios.

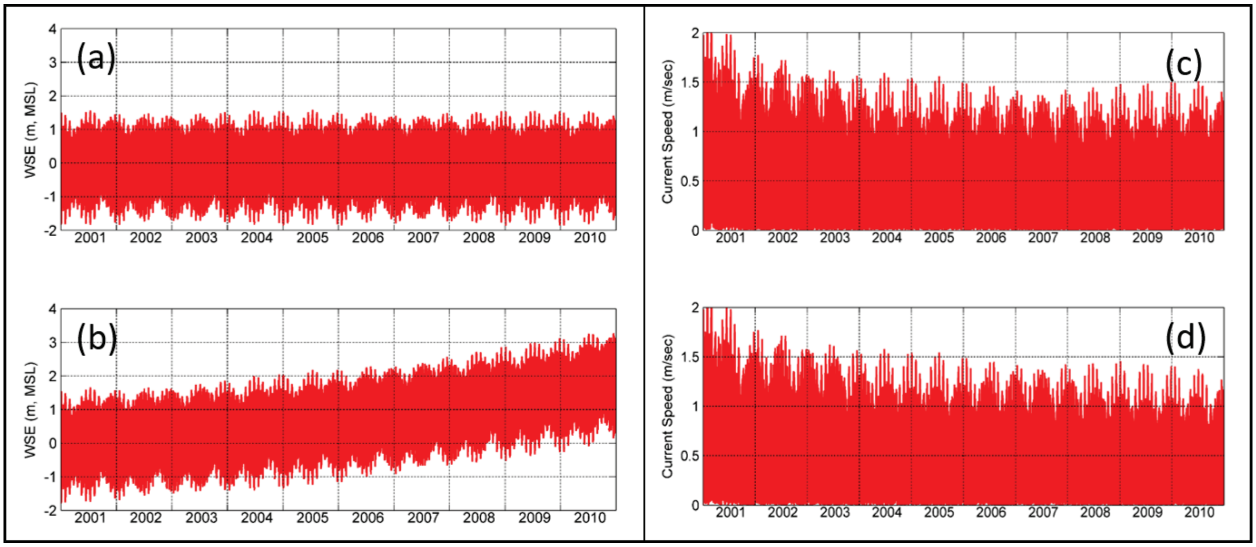


Figure 10. Calculated WSEs (left panel) and along-channel current speeds (right panel) at the inlet channel output location (see Figure 5). Model results were obtained with boundary forcing (a) and (c) composed of 13 tidal constituents without and (b) and (d) with 100-year SLR scenarios.

Calculated water volume flow and sediment flux rates across the transect in the inlet (Figure 5) are shown in Figures 11. By comparing simulation results with and without SLR projection, calculated along-channel current speeds and sediment fluxes decreased (Figures 10(d) and 11(d)) but water volume flow rates increased (Figures 11(a) and 11(b)) with SLR in the inlet.

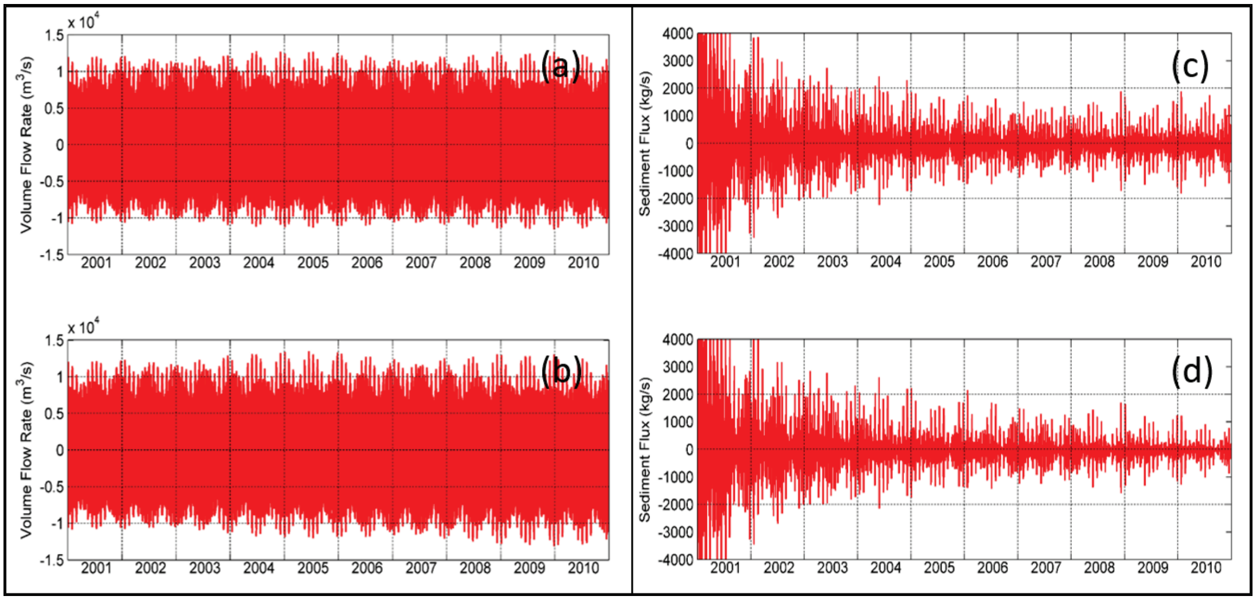


Figure 11. Calculated water volume flow rates (left panel) and sediment fluxes (right panel) across the transect in the middle of the inlet (see Figure 5) with boundary forcing composed of 13 tidal constituents. Simulation results in (a) and (c) were obtained without SLR, and in (b) and (d) with 100-year SLR scenarios.

CONCLUSIONS: SLC may be incorporated in the CMS through application of a constant value or a time-series curve within the SMS framework. Using a long-term modeling application for an idealized inlet system, implementation of the new feature and resultant long-term effects on hydrodynamic conditions and sediment transport related to SLR were demonstrated. Presently, this model capability is applicable to the *WSE-forcing* open boundary type specified as a WSE *Curve* or by *Tidal Constituents* in the CMS. Further improvement to the CMS can be made by adding the *WSE-forcing* for other boundary types (*Harmonic, Tidal Database,* et al.). For most of coastal model domains, spatially constant values can be a reasonable specification of SLR scenarios. However, SLC is location specific, and larger coastal domains may require spatially varying SLC values for future applications.

ADDITIONAL INFORMATION: This CHETN was prepared and funded under the Coastal Inlet Research Program (CIRP) and was written by Dr. Honghai Li (*Honghai.Li@usace.army.mil*, voice: 601-634-2840; fax: 601-634-3080), and Mr. Mitchell Brown (*Mitchell.E.Brown@usace.army.mil*) of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). The CIRP Program Manager, Ms. Tanya Beck (*Tanya.M.Beck@usace.army.mil*), reviewed this CHETN. Files for the example may be obtained by contacting the authors. This CHETN should be cited as follows:

Li, H., and M. E. Brown. 2019. *Modeling Sea Level Change Using the Coastal Modeling System*. ERDC/CHL CHETN-IV-119. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/33204.

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USACE. 2017. *USACE Sea Level Change Curve Calculator*. http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html