Sea Level Analysis Tool (SLAT)

Technical Documentation

The Sea Level Analysis Tool (SLAT) is a user-friendly web application that enables users to visualize observed sea level data, compare observations to projected sea level change, and estimate when tidal and extreme water levels will intersect with elevation thresholds related to local infrastructure (e.g., roads, power generating facilities, dunes). SLAT facilitates the application of United States Army Corps of Engineers (USACE) Engineer Regulation (ER) 1100-2-8162 and Engineering Pamphlet (EP) 1100-2-1, which provide guidance for incorporating sea level change into USACE projects.

This document provides more detailed technical information on the key components of the tool. The document begins by covering information for each of the input tabs and then for tool output.

If you are looking for general guidance on using the tool, consider using the help pop-ups designated by the "?" symbol within the tool itself.

Project Location

The Project Location tab allows users to select NOAA tide gauges, USACE tide gauges, and gridpoints from the NOAA et al. (2022) and NOAA et al. (2017) projections. Specifically, the tab includes:

- The 143 NOAA gauges for which NOAA-NOS has published a sea level change rate
- The 31 USACE gauges featured in the 2022 Louisiana Tide Gage Atlas
- The 1,461 gridpoints that are accessible through the NOAA CO-OPS Derived Product API (DAPI)

Several of the NOAA gauges have quality flags that represent data irregularities that may be worth considering before pursuing analysis. The definitions for these flags are offered below:

- **Short record**: The distance between the first and last monthly MSL recorded for the gauge is less than 40 years.
- **Missing data**: There is a gap in the gauge's data that exceeds five years.
- **Inactive**: The gauge is not included in CO-OPS register of water level stations and may not have data for recent years.
- **Local event**: The gauge includes a trend annotation on Tides & Currents indicating that a local event (e.g., an earthquake or datum issue) may have impacted sea level.

Datum and Units

The Datum and Units tab allows users to (1) align sea level data, projections, and critical elevations to datums or start years and (2) select measurement units.

Users can choose between two different reference frames around which to orient the data and projections in the tool:

- **Datums** are established vertical reference frames that can be used to represent observational records, sea level change projections, and physical infrastructure heights.
- **The start year reference frame** focuses exclusively on sea level projections, showing the amount of sea level change projected since the selected start date.

The following tidal datums are offered (if available):

- Mean Higher High Water (MHHW)
- Mean High Water (MHW)
- Mean Sea Level (MSL)
- Mean Tide Level (MTL)
- Mean Low Water (MLW)
- Mean Lower Low Water (MLLW)

SLAT also offers several geodetic datums, as available:

- North American Vertical Datum of 1988 (NAVD88)
- Puerto Rico Vertical Datum of 2002 (PRVD02)
- Virgin Islands Vertical Datum of 2009 (VIVD09)
- Guam Vertical Datum of 2004 (GUVD04)

Given local vertical land movement, the height of the tide gauge station relative to geodetic datums may change over time. For instance, if the gauge is subsiding, its height relative to NAVD88 may decrease. These dynamics are not represented in SLAT. Instead, projections are based on the *current* relationship between the gauge and the geodetic datum. More specifically, NOAA tide gauges are re-surveyed with respect to their geodetic datums every year. If the new survey shows a significant difference from the published relationship, a new value will be published with a new "accepted date." Conversely, if the survey shows the relationship is still true within survey tolerance, then the station height and accepted date stay unchanged. SLAT shows the accepted date for each tide gauge.

More information on these and other datums is available at the NOAA Tidal Datums page.

In addition to datums, SLAT allows users to represent projections with respect to a start year. If this option is selected, plots and tables represent cumulative sea level *change* since the base year (rather than projected sea *level*). Currently, SLAT does not offer datums for USACE tide gauges and NOAA gridpoints. Accordingly, only the start year reference frame is available for scenario development at these locations.

As described below, the datum or start year alignment process depends on the available data and projections.

- **Monthly sea level data** is downloaded with respect to the STND datum and then adjusted to the user-selected datum using the values provided by NOAA for the selected gauge. Monthly sea level data is not available if the start year reference frame is selected instead of a datum.
- **Equation-based projections** (i.e., USACE 2019, CARSWG 2016, and NOAA et al. 2012) are set to start at 0 feet above the MSL datum at the midpoint of the datum epoch. They are adjusted to the user-selected datum using the values provided by NOAA. Under the start year reference frame, projections are set to start at 0 in the start year.
- **NOAA interagency and local projections** (i.e., NOAA et al. 2022, NOAA et al. 2017, and all the local projections) are defined with respect to a baseline year or baseline range, as summarized in Table 1 below.

Table 1. Baseline years for NOAA interagency and local projections

Source	Baseline year
NOAA et al. 2022	2005
NOAA et al. 2017	2000
Maryland 2018	2000
Maryland 2013	2000
Massachusetts 2022	2008
New Jersey 2025	1995-2014
New Jersey 2020	2000
New York 2024	1995-2008
New York 2017	2000-2004
NPCC 2024	1995-2008
NPCC 2019	2000-2004
NPCC 2015	2000-2004
NRC 2012	2000

These projections are adjusted to the MSL datum by adding the estimated amount of sea level rise that occurred between (1) the center of the datum epoch and (2) the baseline year of the projections (or the center of the baseline range). As described in Appendix A of the Application Guide for the 2022 Sea Level Rise Technical Report, multiple models can be used to estimate this number, including (1) a local, non-linear trend, (2) a regional, non-linear trend, and (3) a local, linear trend. SLAT uses:

- A local, non-linear trend for the 102 gauges for which the trend is available
- A regional, non-linear trend for the 19 gauges for which the local, non-linear trend is not available

Both the local and regional non-linear trends are accessed through the NASA Interagency Sea Level Rise Scenario Tool. Note that this adjustment is not necessary for gridpoints (which are not aligned to datums) or the 22 gauges without NOAA interagency or local projections.

The same process is used to connect NOAA interagency projections to start years that fall before the baseline year. For start years after the baseline year, SLAT subtracts the sea level change projected for the start year from each projection so that each curve begins at 0 in the start year. Local projections are typically too sparse to support this adjustment. Accordingly, local projections are not available for the start year reference frame.

The Datum and Units tab also allows the user to select the units for the analysis (i.e., meters or feet). User-entered critical elevations are automatically adjusted following a change in units. Note that sea level trends are always presented in mm/year (regardless of the selected units) for consistency with NOAA's practice.

Coastal Water Levels

The Coastal Water Levels tab allows users to (1) select the tidal, extreme, and custom water levels that are relevant to their project and (2) construct moving averages for the selected water levels.

Water levels

The following tidal water levels are offered to users, where available:

- Mean Higher High Water (MHHW)
- Mean High Water (MHW)
- Mean Sea Level (MSL)
- Mean Low Water (MLW)
- Mean Lower Low Water (MLLW)

Additionally, the following extreme water levels (EWLs) are offered, where available:

- Monthly maxima and minima (projections are not available)
- 1% Annual Exceedance Probability (AEP), high and low water
- 10% Annual Exceedance Probability (AEP), high and low water
- 50% Annual Exceedance Probability (AEP), high and low water
- 99% Annual Exceedance Probability (AEP), high and low water

Users can also add custom water levels for NOAA tide gauges. Similar to EWLs, custom water levels are defined with respect to the selected datum at the local tide gauge.

For gridpoints and USACE tide gauges, MSL is the only supported water level.

Averages

Users can select monthly realizations and 5- and 19-year moving averages of the tidal water levels and monthly minima and maxima. Moving averages are centered (e.g., 1992 represents the average of all values from 1983 through 2001). Monthly realizations and moving averages are not available for the other EWLs, which are derived rather than directly measured.

Additionally, users can select an epoch average visualization that shows the average water level for NOAA's historical, current, and forthcoming epochs. Note that SLAT calculates the epoch averages from monthly values, whereas official NOAA datums are derived from hourly data. Accordingly, the epoch averages in SLAT diverge slightly from the official datums published by NOAA.

Scenario Projections

The Scenario Projections tab allows users to estimate trends and select sea level change projections.

Trends are estimated using a linear regression model that controls for the seasonal cycle. At a high level, the trend *b* is estimated as:

$$y_i = bt_i + m_i + \varepsilon_i \quad (1)$$

where y_i is the water level at time *i*, t_i is the fractional year at time *i*, m_i is the month at time *i* (as a factor variable), and ε_i is the residual at time *i*. By default, SLAT uses an autoregressive integrated moving average (ARIMA) model of order 1. This model, which is also used by NOAA-NOS, is described in more detail in Zervas (2009, pp. 15-18). SLAT also allows users to estimate trends with a simple linear regression model. The simple linear model produces an unbiased estimate of the trend but may underestimate the standard error due to the autocorrelation between consecutive monthly values.

SLAT includes three types of projections:

- **Equation-based projections** are constructed using a quadratic function based on the estimated linear sea level change rate plus an acceleration constant that differentiates each scenario. Projected sea level is calculated at a monthly time scale.
- **NOAA interagency projections** come from the two federal interagency sea level reports released in 2017 and 2022. Projections are available at a decadal time scale.

- **Local projections** come from a variety of research institutions and state and local governments. The time scale for projections varies from source to source.

Each source (such as USACE 2019) has multiple scenarios (e.g., Low, Intermediate, and High). In some cases, the scenarios also include ranges representing the uncertainty *within* each scenario (e.g., 17th, 50th, and 83rd percentiles).

All the sources in SLAT are designed principally to project Mean Sea Level (MSL). However, for many engineering applications, alternative water levels (e.g., MHHW, MLLW, or EWLs) are more relevant for decision-making. SLAT allows users to extend the MSL projections to other water levels using linear superposition. This method applies the current distance between MSL and the target water level to projected values, such that rough projections can be created for the target water level. Notably, this method assumes that the offsetting distance is constant over time. This assumption may not hold, for example, if the location is experiencing tidal amplification. Accordingly, users may want to assess the stability of these relationships when projecting non-MSL water levels or, at a minimum, keep this assumption in mind and take non-MSL projections with a grain of salt.

The projection sources are described in more detail below.

Equation-based projections

SLAT offers equation-based projections from the following sources:

- **USACE 2019**: The projections defined in ER 1100-2-8162 and cited in EP 1100-2-1
- **CARSWG 2016**: The projections used in the Department of Defense Regional Sea Level (DRSL) Database
- **NOAA et al. 2012**: The projections defined in the 2012 NOAA et al. interagency report

Note that these projections are available for all the gauges in SLAT but not for the gridpoints.

Equation-based projections are constructed using the following formula:

$$p = \alpha\,(t_2 - t_1) + \beta\,(t_2^2 - t_1^2) \quad (2)$$

- p is the projected mean sea level relative to the MSL datum (e.g., 1983-2001 MSL for gauges on the National Tidal Datum Epoch).
- α is the linear rate of sea level change at the selected gauge.
- t_2 is the number of years between the projection and July 1992.
- t_1 is the number of years between the datum epoch midpoint or the projection start year and July 1992.
- β is the acceleration of sea level change for the given scenario.

β is the only term that differentiates the projections from one another. The following β values are used in the tool:

Table 2. Acceleration constants for equation-based scenarios

Global sea level rise (1992 to 2100, m)	**β value** (mm/year^2)	**USACE 2019**	**NOAA et al. 2012**	**CARSWG 2016**
0.2	0	Low	Lowest	Lowest
0.5	0.0271	Intermediate	Intermediate-Low	Low
1.0	0.0700			Medium
1.2	0.0871		Intermediate-High	
1.5	0.113	High		High
2.0	0.156		Highest	Highest

The equation-based projections can be customized by selecting the linear sea level change rate used as α across all equation-based projections. Multiple options are offered because each choice presents tradeoffs:

- **The bias-variance tradeoff** arises in choosing the start point to use in estimating the current sea level change rate. Using a longer record increases estimation precision (by virtue of leveraging additional data) but also increases bias (as older data is less relevant to current conditions). Conversely, using a shorter record reduces bias but also reduces precision.
- **The consistency-recency tradeoff** arises in choosing the end point to use in estimating the current sea level change rate. Using the most recent end point leverages the maximum amount of recent data but may introduce minor inconsistencies with previous analysis, given that new observations are recorded each month. Conversely, using a fixed rate (such as the rates previously published by NOAA in a report or on Tides & Currents) can promote consistency but ignores the most recent data.

By default, SLAT suggests the NOAA-NOS trend estimate published on Tides & Currents. This rate is discussed in section B-2 of EP 1100-2-1 (pp. 89-95). The NOAA-NOS estimate includes the entire tidal record (starting at the first available observation) through the previous calendar year, hence prioritizing reduced variance and increased consistency.

An alternative to the NOAA-NOS estimate is the 40-year record rate. This trend is estimated with all the monthly data within 40 years of the last available observation. This estimate attempts to minimize bias while aligning with guidance in EP 1100-2-1, which recommends a minimum record length of 40 years.

NOAA interagency projections

SLAT offers two sets of NOAA interagency projections that represent the NOAA et al. 2017 and 2022 technical reports. The 2022 report also includes an Application Guide that supports interpretation and use of the report.

There are a few key differences between these projections:

- **The 2022 report removes the Extreme (2.5m) scenario** given scientific advancements suggesting this rate of sea level rise is very unlikely.
- **The 2022 scenarios reflect slower acceleration before 2050 and greater acceleration thereafter**, producing the same estimated sea level rise by 2100 (see Figure 10 in the Application Guide).
- **Projections are made available for different gridpoints.** For NOAA et al. 2022, the gridpoints appear at integer latitude-longitude pairs (e.g., 26, –82). The NOAA et al. 2017 gridpoints are centered in between those pairs (e.g., 26.5, –82.5).

The 2022 report was released as an update to the 2017 report, and the more recent version should generally be used going forward.

Both reports include two representations of uncertainty (see Figure 4 in the Application Guide):

- **The scenarios** (e.g., Low, Intermediate) reflect emissions uncertainty and uncertainty in low confidence processes.
- **The likely ranges** (e.g., the shading around each scenario) provided for each scenario represent uncertainty in the physical processes that produce sea level change.

Unlike the equation-based projections (which produce projected values at any time interval), the NOAA interagency projections are generally only available at a decadal time scale. Since some use cases require annual values, projections are linearly interpolated for each year.

Local projections

SLAT includes several local projections that are available for discrete regions, as summarized in Table 3 below.

Table 3. Sources for local projections

Source	Locations
Maryland 2018	All Maryland gauges
Maryland 2013	All Maryland gauges
Massachusetts 2022	All Massachusetts gauges
New Jersey 2025	All New Jersey gauges

Source	Locations
New Jersey 2020	All New Jersey gauges
New York 2024	All New York gauges
New York 2017	All New York gauges
NPCC 2024	The Battery, NY
NPCC 2019	The Battery, NY
NPCC 2015	The Battery, NY
NRC 2012	Select West Coast gauges

Similar to the NOAA interagency projections, some of these projections include likely ranges in addition to central tendencies for each scenario. However, local projections are generally available at a less frequent time scale. This increases the uncertainty for the annual values between projections, and accordingly, local projections are not interpolated.

Critical Thresholds

The Critical Thresholds tab allows users to identify local elevations relevant to their project (e.g., the height of a sea wall or critical access road) and estimate when various water levels might intersect with those thresholds. Intersections can occur when water levels exceed the threshold or, in the case of gauges with negative relative sea level change, when water levels fall below the threshold.