ERDC/CHL SR-25-DRAFT

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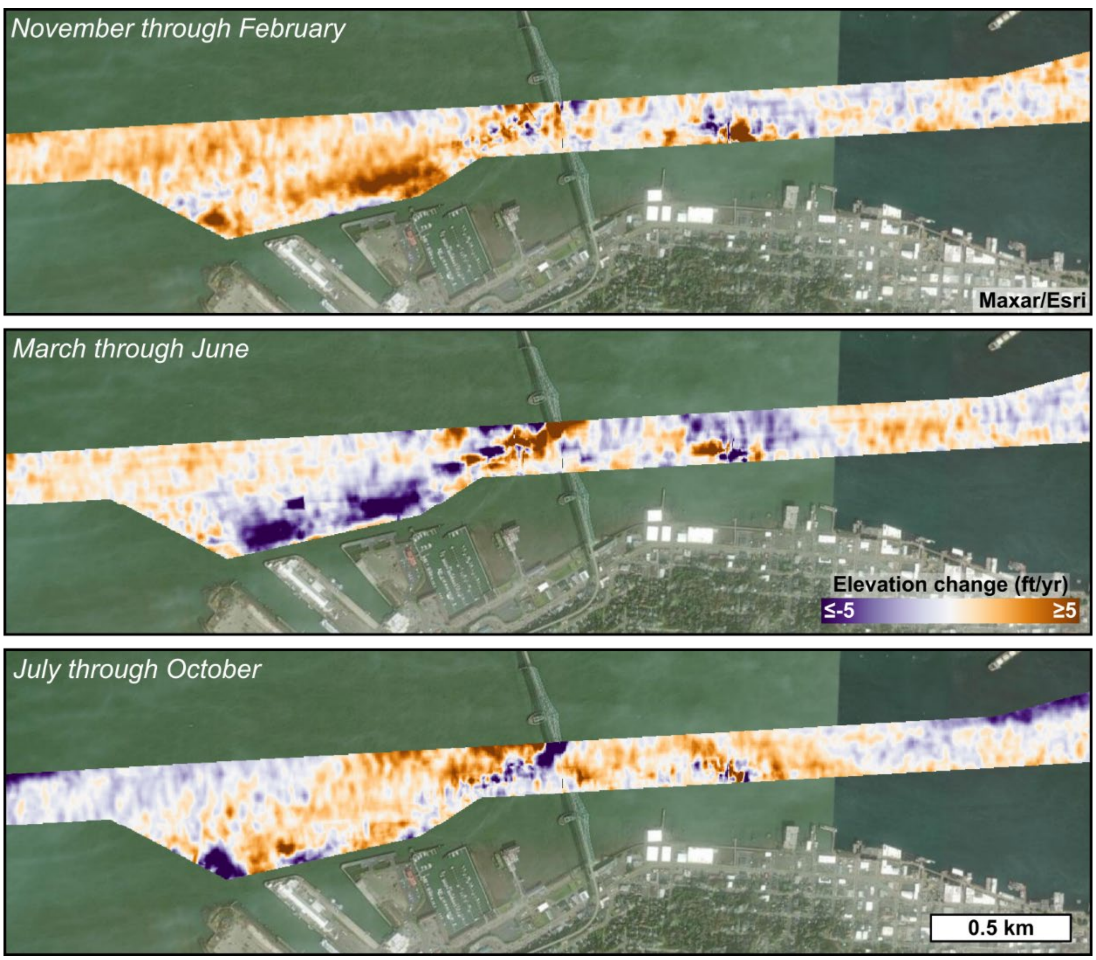
Coastal Inlets Research Program (CIRP) and Dredging Innovations Group (DIG)

Corps Shoaling Analysis Tool (CSAT) User Guide

Rachel Bain, Michael Hartman, Anna Dominique Godfrey, Charlene Sylvester, and Kathryn Smith

January 2025



Cover photo credit: Shoaling rate maps of the Columbia River navigation channel near Astoria, OR, created by the authors using CSAT. Satellite imagery provided by Maxar/Esri; used under license.

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Draft Special Report (SR)

Prepared for US Army Corps of Engineers
Washington, DC 20314-1000

Under Funding Account Code U4391284, AMSCO Code 060000 “Corps Shoaling Analysis Tool (CSAT) User Guide.”

Abstract

The Corps Shoaling Analysis Tool (CSAT) is a suite of computational routines for evaluating shoaling rates in navigation channels maintained by the US Army Corps of Engineers (USACE). This is achieved using survey data from the eHydro enterprise hydrographic survey database. At the local scale, CSAT's outputs are useful for understanding historical shoaling trends and identifying shoaling hotspots, while enterprise-level shoaling forecasts support Operations and Maintenance (O&M) planning over a 5-year time horizon. This user guide provides practical, step-by-step instructions for new CSAT users who wish to download, install, and run the tool. Later sections provide insight into CSAT's advanced features while also describing the methods and assumptions that underlie the calculations.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE) under Funding Account Code U4391284, AMSCO Code 060000 "Corps Shoaling Analysis Tool (CSAT) User Guide."

The work was performed by the Coastal Engineering Branch of the Navigation Division, US Army Engineer Research and Development Center–Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Ms. Lauren Dunkin was chief of the Coastal Engineering Branch, and Ms. Ashley Frey was chief of the Navigation Division. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty V. Wamsley.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

1.1 Background

The US Army Corps of Engineers (USACE) maintains hundreds of deep-draft coastal ports and waterways as part of its navigation mission, which is vital for sustaining maritime commerce and national security. Recurring hydrographic surveys are a fundamental component of navigation channel maintenance. USACE uses the hydrographic survey processing tool eHydro to efficiently standardize output files across the enterprise and provide storage of the bathymetric datasets. Hydrographic survey data for USACE-maintained navigation channels are then used to quantify shoaling and the volume of material to be removed at various depth increments.

The Corps Shoaling Analysis Tool (CSAT) is a hindcast algorithm that relies on the historical eHydro survey data to determine shoaling conditions. Based on the timing of pre- and post-dredging surveys, CSAT determines the dates of dredging events and then calculates shoaling rates for periods of time that were undisturbed by dredging. The calculated shoaling rates are then combined with the most recent eHydro survey elevations to forecast the volume of sediment exceeding various depth increments over a five-year forecasting horizon. These shoaling forecasts support objective decision making by USACE districts to optimize allocation of limited dredging dollars.

Prior documentation of CSAT development begins with the conference paper by Dunkin and Mitchell (2015), who reported on a legacy version of CSAT coded in the proprietary MATLAB programming language. The CSAT routines were later converted to open-source Python, and more detailed documentation of the algorithm was published by Dunkin et al. (2018). The 2018 report provides information about enterprise-level hydrographic survey procedures along with a high-level overview of CSAT's methodology for shoaling calculation. However, neither of these publications include step-by-step instructions for running CSAT, nor do they provide a detailed description of the quantitative methods within the CSAT source code. Six additional years of software development have occurred since the publication of the Dunkin et al. (2018) report, and there is growing interest from USACE districts to use CSAT as a practical tool for Operations and Maintenance (O&M) planning. Consequently, updated CSAT documentation is required.

CSAT's practical implementation has also been illustrated by several recent studies. For example, Wood et al. (2017) quantified shoaling rates in the Matagorda Ship Channel using CSAT, while Hamilton et al. (2018) quantified shoaling rates along the Gulf Intracoastal Waterway near Corpus Christi. Similarly, Perkey et al. (2022) used CSAT to calculate shoaling rates in the Calcasieu Ship Channel in the context of a broader sediment budget study, while Hartman et al. (2022) used the CSAT algorithm to quantify sediment accumulation rates along the Mississippi River's Southwest Pass. The Southwest Pass results were subsequently used by Copeland et al. (2023) while evaluating structural modifications to reduce navigation channel shoaling. Beyond these local case studies, Loney et al. (2019) describe how CSAT-derived shoaling analyses can be used for enterprise-level planning and budgeting. In broader application, papers by Scully and Young (2021), Bain et al. (2023), and Young et al. (2024) describe how the CSAT bathymetry products have been incorporated into a workflow for quantifying the underkeel clearance of commercial vessels transiting USACE navigation channels.

1.2 Objectives

There are two primary objectives of this user guide. First, this document was designed to serve as an instruction manual for new CSAT users who require a basic overview of how to use the software. Second, this guide was written as an extension of earlier documentation by Dunkin et al. (2018), providing additional documentation of CSAT's implicit assumptions and underlying calculations.

1.3 Approach

The contents of this user guide progress from simple, practical implementation to advanced analytical methods, with the sections arranged as follows. Section 2 serves as a "Quick Start Guide" for new CSAT users who wish to install and run CSAT but do not require a deeper understanding of the underlying theory and calculations. Section 3 provides a detailed description of the CSAT input files and begins to explain how the user can alter the input parameters for enhanced project suitability. The contents of the CSAT output files are detailed in Section 4. Section 5 elaborates on the assumptions and calculation methods on which CSAT is built and continues the explanation of various input parameters that can optionally be modified by the user.

2 Quick Start Guide

This section provides a checklist of steps for installing and running CSAT using the default parameters. For simplicity, a description of the underlying theory and calculations is omitted here; these are instead detailed in Section 5. Within this section, action items are shown as **blue, boldface text**. The remaining text is explanatory.

2.1 Downloading Python Distribution

CSAT runs in an environment with a particular set of Python packages. This environment can be created using either the Anaconda or the Miniconda distribution (collectively hereafter referred to as Conda distributions). The steps for downloading a Python distribution are provided in the following sections.

2.1.1 Check for Existing Conda Distributions

The first installation step involves checking whether Conda is already installed on the user's computer:

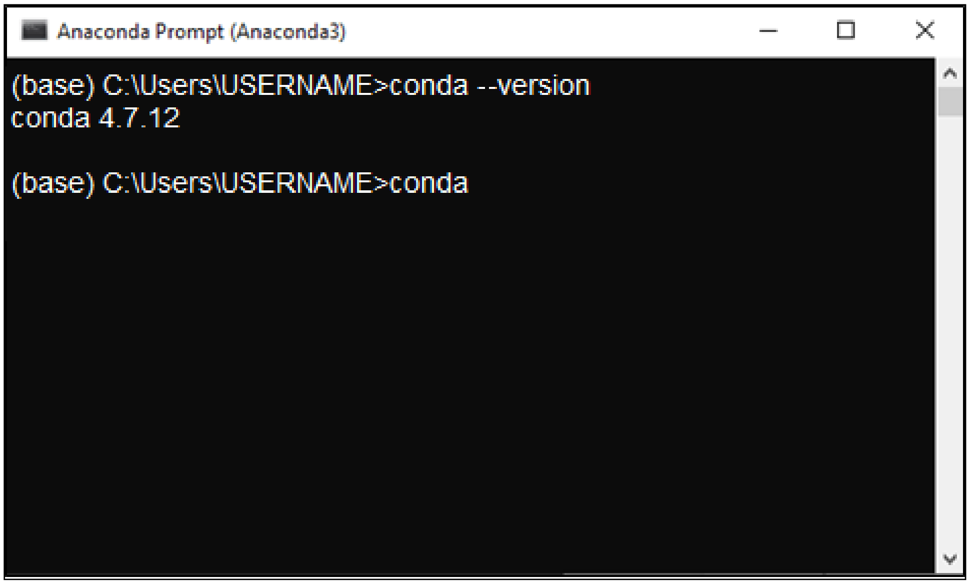
- **Open the `Start` menu and search for an `Anaconda3` directory.** If the `Anaconda3` directory is found, open an Anaconda prompt from within this directory. If the `Anaconda3` directory is not found, skip to Section 2.1.2.

- **In the Anaconda prompt, type the following command and hit `Enter`:**

```
conda --version
```

- **Verify the Conda version number within the Anaconda prompt.** If Conda is already installed on the computer, the previous command will return a version number, as shown in Figure 1. Note that the actual version number may differ from what appears in Figure 1, but the key idea is that some version number should be listed. This means that Anaconda is already installed, and the user should skip to Section 2.2.

Figure 1. Example output from the tasks in Section 2.1.1. In this example, Anaconda is already installed on the user's computer, and the version number is 4.7.12. The actual version number may vary depending on the installation date.



If Conda is *not* already installed, the user will receive the following error message:

```
'conda' is not recognized as an internal or external
command, operable program, or batch file.
```

On receiving this error message, the user should proceed to Section 2.1.2 to install Anaconda.

2.1.2 Download and Install Anaconda (or Miniconda)

The following tasks should only be completed if the `Anaconda3` folder was missing or if an error message was returned during the tasks in Section 2.1.1. Both issues indicate that Anaconda is not preinstalled on the user's computer and must be installed now. The process for installing Anaconda varies depending on whether the user has a Corpsnet computer, with the procedures described separately below.

2.1.2.1 On a Corpsnet Computer

These instructions are specific to USACE employees working on a Corpsnet computer, which is defined as a computer connected to the main USACE network domain and which has limited program installation capability. Users without a Corpsnet computer should skip to Section 2.1.2.2.

- **Go to the USACE App Portal and search for Anaconda**. Several versions of Anaconda have been approved and are available for installation, but installation of the most recent version (version 2022.05 at the time of publication) is recommended for use with CSAT.

At the time of publication, the software request does not require any manager approval or additional licensing. However, the time required for completing the installation is variable. Users have reported installation times between 10 minutes and 48 hours following the installation request.

- **After receipt of Anaconda from the Enterprise Service Desk, open a command prompt, type the following command, and hit `Enter`**:

```
conda --version
```

If a version number similar to Figure 1 is returned by this command, Anaconda is now successfully installed, and the user may proceed to Section 2.2. If installation issues with the Anaconda software are encountered, please contact the Enterprise Service Desk.

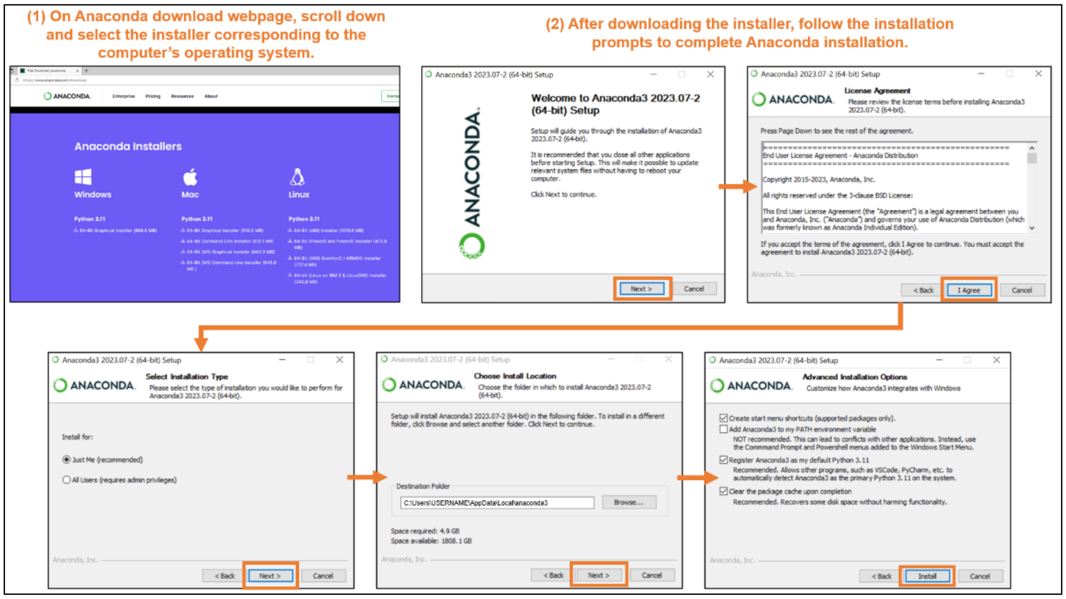
2.1.2.2 On a Non-Corpsnet Computer

These instructions are for members of the public and for USACE employees who are not using a Corpsnet computer. These users may choose from either the full Anaconda distribution or the smaller Miniconda distribution. CSAT performance and output will be identical regardless of which option is selected. Note that only one of the following two options should be completed.

- **Option 1—Install the full Anaconda distribution** by visiting the Anaconda website and downloading the installer corresponding to the computer's operating system.[1] (At the time of publication, the installers were located near the bottom of the Anaconda webpage.) After the download is complete, the user should run the installer and follow the installation prompts, as shown in Figure 2.

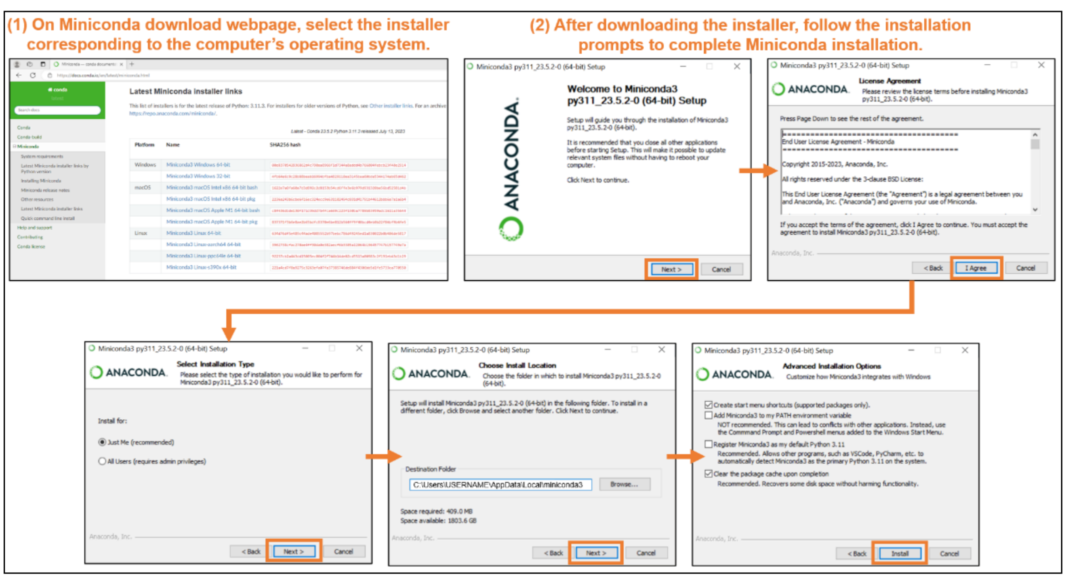
1. https://www.anaconda.com/download.

Figure 2. A workflow for downloading and installing Anaconda on a non-Corpsnet computer.



- **Option 2—Install the smaller Miniconda distribution** by visiting the Miniconda website and downloading the installer corresponding to the computer's operating system.[2] After the download is complete, the user should run the installer and follow the remaining installation prompts, as shown in Figure 3.

Figure 3. A workflow for downloading and installing Miniconda on a non-Corpsnet computer.



2. https://docs.conda.io/en/latest/miniconda.html.

- **After completing Option 1 or Option 2, open a command prompt, type the following command, and hit `Enter`**:

```
conda --version
```

If a version number similar to Figure 1 is returned by this command, Anaconda is now successfully installed. (Note that the actual version number may differ from what appears in Figure 1, but some version number should be listed.)

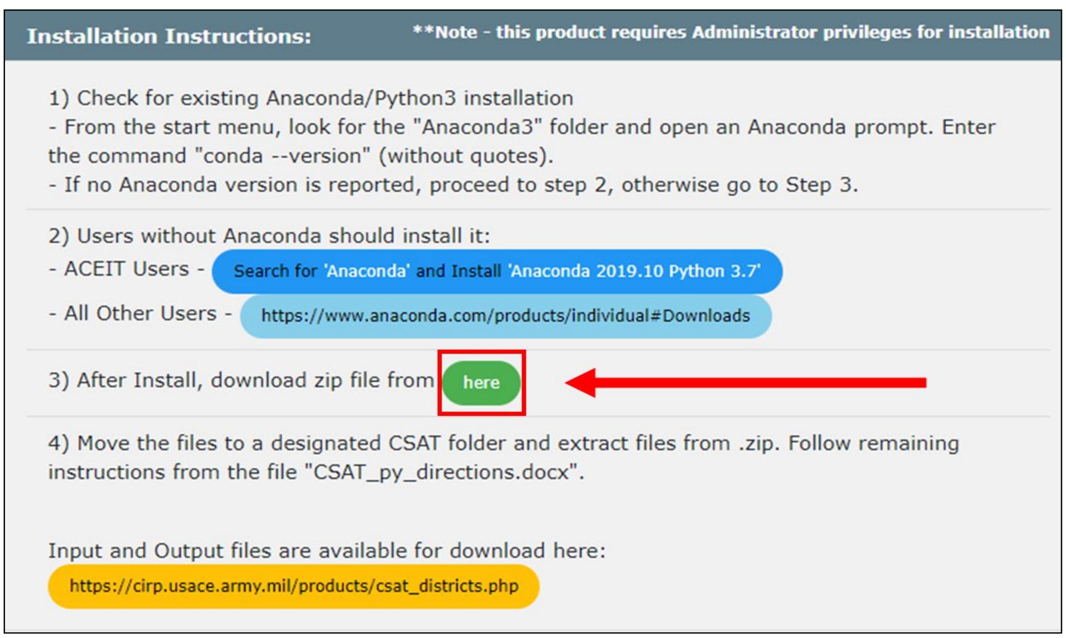
2.2 Downloading the Corps Shoaling Analysis Tool (CSAT)

The current version of CSAT (version 2.6.4 at the time of publication) is available on the CIRP website. The following section provides instructions for downloading and extracting CSAT.

- **Navigate to the CSAT information page on the CIRP website.**[3]

- **Scroll to the `Installation Instructions` and click the green button**, as shown in Figure 4. This will initiate the download of a .zip file containing the CSAT executable.

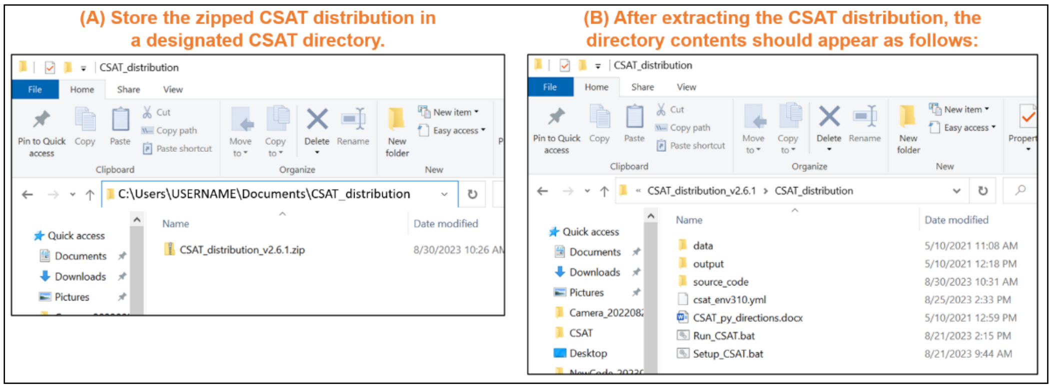
Figure 4. Screenshot illustrating the location of the download link for the Corps Shoaling Analysis Tool (CSAT) on the Coastal Inlets Research Program (CIRP) website.



3. https://cirp.usace.army.mil/products/csat.php.

- **Save the .zip file to an easily accessed directory location**. For example, it may be convenient to place the CSAT download in a designated subdirectory of the `Documents` folder, as shown in Figure 5*A*.

Figure 5. An example directory structure containing zipped CSAT executable (*A*) and contents of CSAT distribution after extracting the zipped files (*B*).



- **Extract the contents of the .zip file to the designated `CSAT` directory**.

- **Enter the `CSAT_distribution` subdirectory and examine the contents**, which should look similar to Figure 5*B*. Specifically, the directory should contain three subfolders:

1. `data`
2. `output`
3. `source_code`

There should also be four files:

1. `csat_env310.yml`
2. `CSAT_py_directions.docx`
3. `Run_CSAT.bat`
4. `Setup_CSAT.bat`

The purpose of each file is described in Sections 2.3 through 2.5.

2.3 Setting up the CSAT Environment

The next step involves setting up a designated Conda environment containing the Python packages required by CSAT without interfering with any Python packages that have already been installed for other applications. Environment setup only needs to be completed once, after which it will remain accessible to CSAT as long as Anaconda remains installed on the computer.

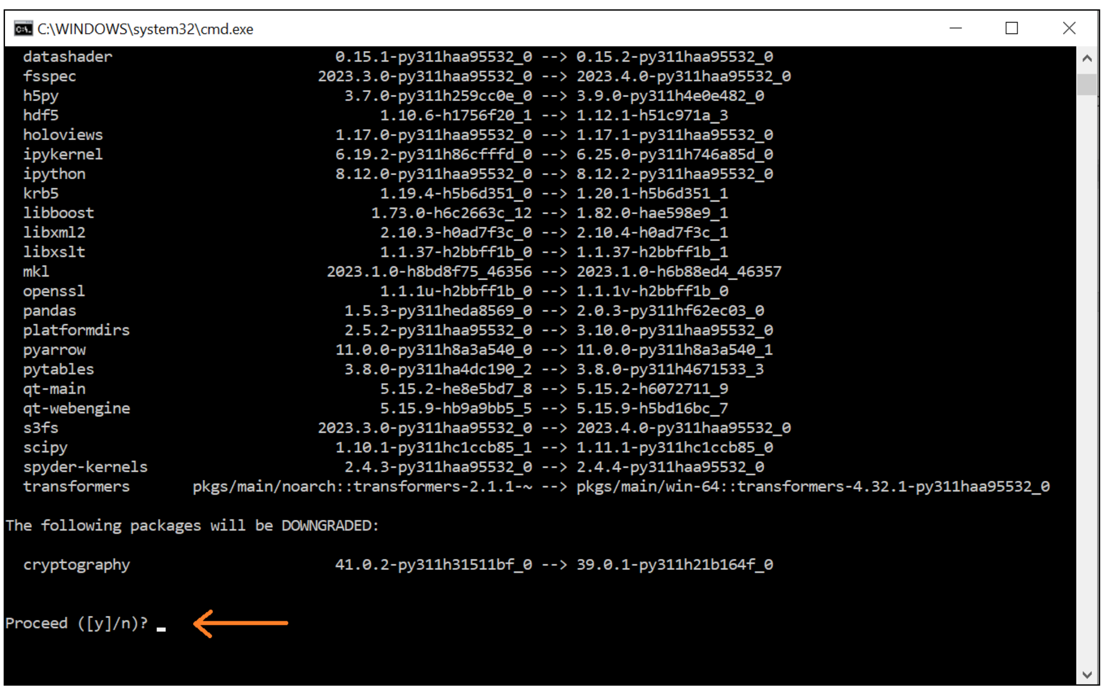
- **Double-click on `Setup_CSAT.bat`**, which should be located inside the `CSAT_distribution` subdirectory created in Section 2.2 (see Figure 5*B*). A console window will open to show the installation progress.

- After several minutes, user input will be required to continue the environment setup (see Figure 6). **When the screen displays**

```
Proceed ([y]/n)?
```

the user should type `y` and hit `Enter`. After this, the environment creation will proceed without any additional input from the user. Note that 3 to 15 minutes may elapse before the CSAT environment is fully installed.

Figure 6. An example of a request for a user input during CSAT environment setup (Section 2.3). When asked whether to proceed, the user should type y and hit Enter.



- After 3 to 15 minutes, Conda will finish creating the CSAT environment. The user will see:

```
(base) C:\Users\USERNAME\...\CSAT_distribution>echo off
Press any key to continue . . .
```

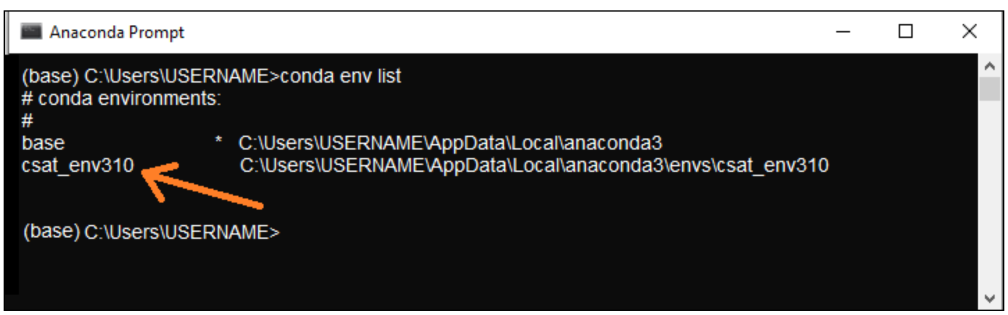
When this prompt appears, **press any key to complete the installation**.

- **Open the `Start` menu, enter the `Anaconda3` folder, and open the Anaconda Prompt. To verify that the environment was installed correctly, type the following command within the Anaconda Prompt and hit `Enter`**:

```
conda env list
```

The Anaconda Prompt should display a list of environments similar to Figure 7. Confirm that an environment named `csat_env310` is present, indicating that the environment has installed successfully. The user can now proceed to Section 2.4.

Figure 7. A list of Conda environments installed on the user's computer, including the **`csat_env310`** environment created in Section 2.3.



Important note for Corpsnet users: when trying to run `Setup_CSAT.bat`, users on Corpsnet may encounter a dialog window which indicates that the batch script was unable to run because it was downloaded from the internet. If this occurs, the following steps may correct the issue.

- **Right-click `Setup_CSAT.bat` and select `Properties`**.

- **At the bottom of the `Properties` window, check the box indicating that the batch script comes from a trusted source**.

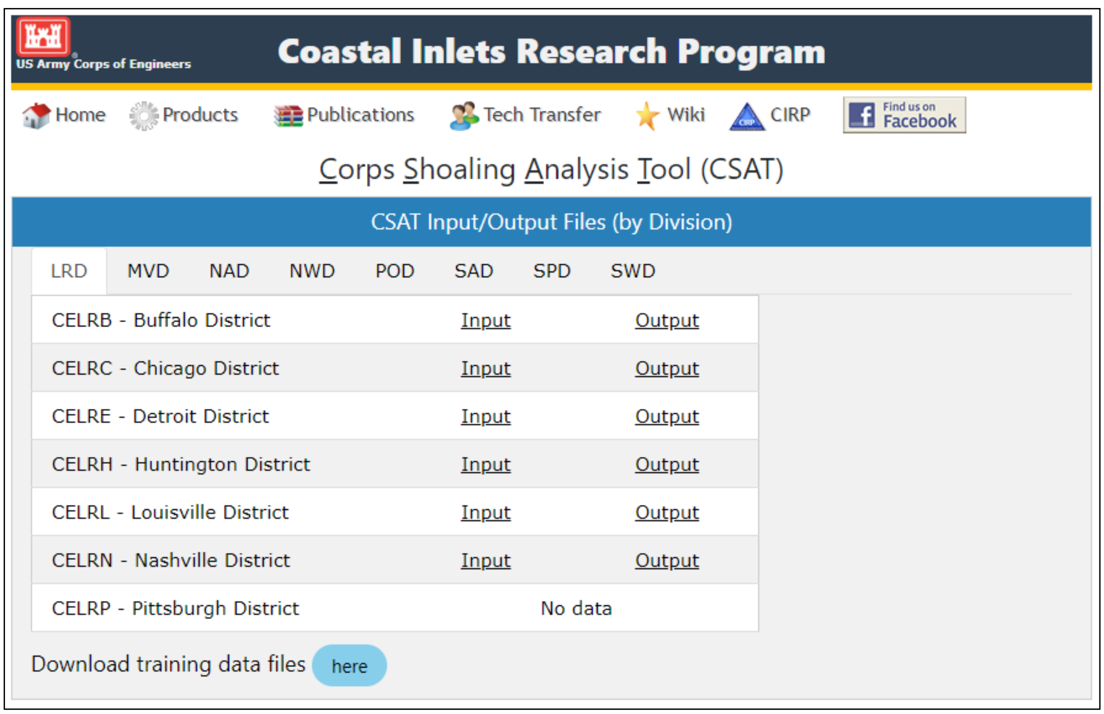
- **Return to Section 2.3 and reattempt the environment installation**.

2.4 Obtaining Input Data

CSAT generates shoaling rate estimates from repeat surveys of the study area. These surveys are uploaded by the districts into eHydro (see Section 5.1 for details) and preprocessed into a specific format (Section 5.2) to facilitate use within CSAT. These preprocessed bathymetric datasets are available for download from the CIRP website, as described in the following section.

- **Navigate to the CSAT input/output page on the CIRP website**, which has links to downloadable survey data for each USACE district (Figure 8).[4] Note that each division can be accessed via its three-letter identifier using the tabs below the blue banner.

Figure 8. The CSAT input files for each district are available for download from the CIRP website.



- **Click the `Input` link next to the district of interest to begin the data download**.

4. https://cirp.usace.army.mil/products/csat_districts.php.

- **Follow the download prompts to save the zipped bathymetry file to the `CSAT_distribution\data` subdirectory**, which was created during Section 2.2. Note that the download may take several minutes or more depending on internet speed and file size.

- After the download is complete, **extract the contents of the zipped bathymetry to the `CSAT_distribution\data` subdirectory**.

- Because CSAT searches for a specific directory structure, it is necessary to ensure that unzipping the bathymetry file did not result in nested directories. **Using File Explorer, ensure that the directory structure exactly matches**:

`…\CSAT_distribution\data\CEXYZ` **(CORRECT)**

where `CEXYZ` is the district symbol. Depending on how the files were extracted, an extra directory layer may be present:

`…\CSAT_distribution\data\CSAT_NCF_CEXYZ\CEXYZ` **(INCORRECT)**

In this situation, the user should **cut-and-paste the `CEXYZ` directory directly into the `data` directory to eliminate the nesting** before proceeding to Section 2.5.

For a detailed description of the data directory contents, see Section 3.1.

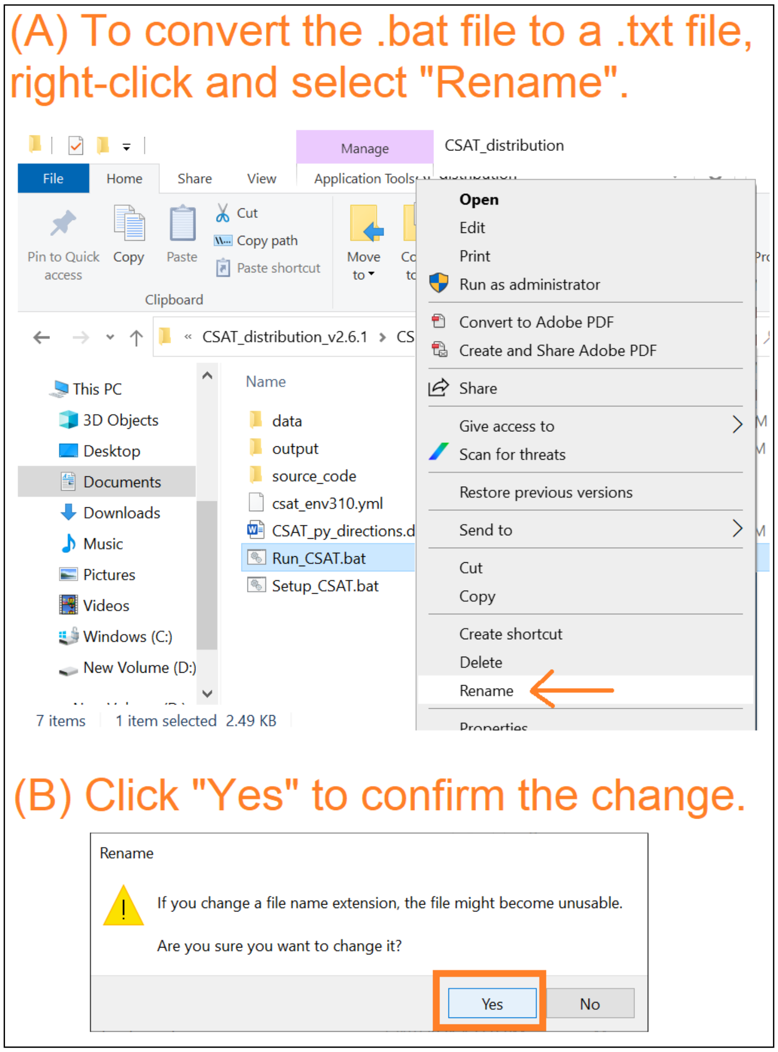
2.5 Running CSAT

CSAT is run using the batch script `Run_CSAT.bat`, which was downloaded during Section 2.2. The following section contains instructions for configuring the batch script and then running CSAT.

- **Right-click `Run_CSAT.bat` and select `Edit` to open the batch script in a text editor (e.g., Notepad or Notepad++)**.

- (Optional) If security settings prevent the batch script from opening, **right-click the file and select `Rename`, and then change the name from `Run_CSAT.bat` to `Run_CSAT.txt`. Select `Yes` to confirm that you want to change the file extension.** An example is shown in Figure 9. Double-clicking `Run_CSAT.txt` should now open the script in a text editor.

Figure 9. Example showing how to convert the batch script into a text file prior to further editing in a text editor.



- **From within the text editor, find the following lines of `Run_CSAT.bat`:**

```
rem CHANGE DISTRICT NAME BELOW
CALL set DISTRICT=CESAS
echo DISTRICT=%DISTRICT%
```

At the time of publication, this block of code began at Line 35; however, it may shift up or down in future CSAT versions.

- The default district is Savannah District (CESAS). **This is updated by replacing `CESAS` with the desired district symbol in `Run_CSAT.bat`**:

```
rem CHANGE DISTRICT NAME BELOW
CALL set DISTRICT=CEXYZ          ← CHANGE
echo DISTRICT=%DISTRICT%
```

  where `CEXYZ` indicates the district of interest. It is important to ensure that there are no spaces before or after the equal sign, as spaces will cause the script to fail.

- (Optional) Additional modifications can be made to `Run_CSAT.bat` which will limit shoaling analysis to specific periods of time, enable or disable raster file output generation, or adjust other input parameters. These optional features are described in Section 3.

- After updating the district symbol and making any optional changes to the parameters, **save the batch file**.

- If the batch script was converted to a text file due to security restrictions, **rename `Run_CSAT.txt` to `Run_CSAT.bat` using the steps shown in Figure 9**.

- **Double-click `Run_CSAT.bat` to run CSAT**. A console window will appear and display progress updates, but no further input is required from the user. The progress updates are automatically saved to a file named `CSAT_distribution\logging_output.log` for debugging purposes.

The total runtime for CSAT depends on several factors. A large quantity of reaches, reaches with many surveys, and reaches with large spatial extents will all contribute to longer runtimes. In general, computing the shoaling results for a single reach will take between 10 seconds and 2 minutes.

3 CSAT Input Files and Optional Inputs

3.1 Description of CSAT Input Files

As described in Section 2.4, the downloaded CSAT input files should be stored in a directory named:

```
…\CSAT_distribution\data\CEXYZ
```

where `CEXYZ` is the district symbol. The contents of the `data` directory are detailed in this section.

3.1.1 NetCDF Files Containing Bathymetry

Each reach surveyed by the district should have a bathymetry file with the following naming convention:

```
…\CSAT_distribution\data\CEXYZ\<reach_name>.nc
```

where <reach_name> is the name of the reach within the National Channel Framework (USACE 2023). Although CSAT users do not need to open or interact with the bathymetry files, information about the file contents is provided here for advanced users who desire to perform additional analyses beyond CSAT's built-in capabilities. The bathymetry is stored within NetCDF4 files as described by Unidata (2018), and each file contains the following variables:

- **time**—timestamps of the bathymetric surveys, formatted as YYYYMMDD strings. The dimensions are *nTime* × 1, where *nTime* is the number of bathymetric surveys stored in the file. (*Note*: "time" may also be called "Time" in legacy file versions.)

- **points**—integer indices of the points within the reach. The dimensions are *nPoints* × 1, where *nPoints* is the number of survey points.

- **latitudes**—the Northing (in feet, local State Plane) of each bathymetric survey point indexed in points.[5] The dimensions are *nPoints* × 1.

- **longitudes**—the Easting (in feet, local State Plane) of each bathymetric survey point indexed in points. The dimensions are *nPoints* × 1.

- **elevations**—the depth of water at each survey point indexed in points during each bathymetric survey. The dimensions are *nPoints* × *nTime*. If the point lacks survey data, this is represented by a fill value of 9999. Note that the value for elevations is positive down, so a point which is 40 ft below the survey datum will have a value of +40 ft in the elevations variable.[6,7]

- **surveyID**—strings indicating the district-generated eHydro survey ID for each bathymetric survey. The dimensions are 50 × *nTime*. Survey IDs which are less than 50 characters are padded with spaces to be exactly 50 characters long.

- **crsSTPL**—a placeholder integer object used to report Coordinate Reference System attributes.

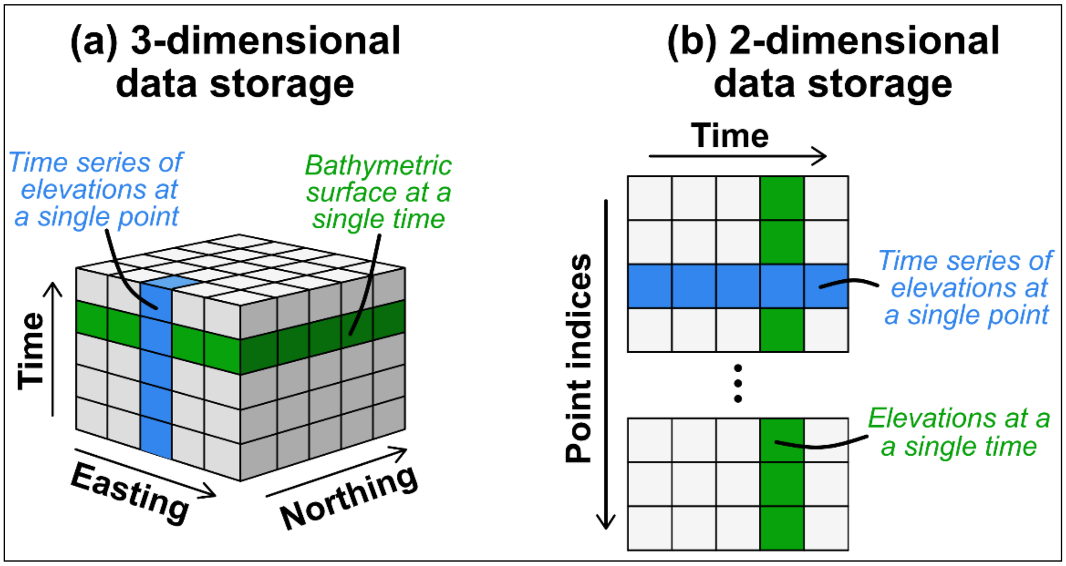
For clarity, the user should note that although the CSAT bathymetry may be conceptualized as a three-dimensional time stack of data (Figure 10*a*), in practice CSAT reduces the bathymetry to a two-dimensional dataset by assigning a unique index (the "points" variable) to each survey point (Figure 10*b*). The geographic coordinates corresponding to each point are stored as separate variables ("longitudes" and "latitudes") which have the same dimensions as "points."

5 Note that the variable names "latitudes" and "longitudes" are remnants of a legacy file version in which the geographic coordinates of the survey points were stored as degrees latitude and degrees longitude. In the modern file versions, the geographic coordinates are in projected feet, although the variable name has not been changed.

6 Note that the fill value representing missing data may be different in legacy file versions.

7. For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 10. An illustration of the data storage format within the CSAT input NetCDF files. In subplot (*a*), each of the small cubes in the stack contains an elevation measurement for a single longitude, latitude, and timestamp. This allows the data to be conceptualized as a three-dimensional bathymetric time stack. However, in practice CSAT reduces the input data to two dimensions (subplot *b*) by assigning a unique index to each survey point within the reach.



3.1.2 Uniform Points Table

Within the downloaded data directory, there should also be a text file named

```
…\CSAT_distribution\data\CEXYZ\uniform_pts_table.txt
```

where `CEXYZ` is the district symbol. This file, which contains information about all bathymetric surveys for all reaches surveyed by the district, is a comma-separated table which can be viewed in Microsoft Excel or an equivalent spreadsheet editor. The table contains the following eight columns:

- **SurveyDateStamp** (Column A)—the date of the bathymetric survey in YYYYMMDD format.
- **SurveyType** (Column B)—indicates whether the survey is a condition survey (CS label), before-dredge survey (BD label), or after-dredge survey (AD label). Immediately after data download, this column will be empty, which tells CSAT to automatically determine the survey type using the methodology described in Section 5.4. The user may also manually define the survey type by entering labels into Column B; see Section 5.4 for detailed instructions.

- **SurveyID** (Column C)—the district-assigned name of the bathymetric survey from eHydro.
- **Reach_Name** (Column D)—the name of the reach containing the survey data.
- **Reach_ID** (Column E)—the identifier of the reach within the National Channel Framework (USACE 2023).
- **Cell_Size** (Column F)—the length of one side of the square bathymetric survey cell, in feet.
- **Use** (Column G)—Boolean (1 = yes, 0 = no) indicating whether CSAT should use the survey when calculating shoaling rates. Immediately after download, all surveys will have a 1 in this column. The user may optionally choose to discard surveys by inserting a 0 in this column; see Section 5.6 for detailed instructions.
- **pctCoverage** (Column H)—the percentage of total reach area which the bathymetric survey covers. Values near 0% indicate minimal coverage, whereas values near 100% indicate that a large portion of the reach was surveyed.

3.1.3 Reach Table

The last file included with the downloaded data is a second text file named:

```
…\CSAT_distribution\data\CEXYZ\reach_table.txt
```

where `CEXYZ` is the district symbol. This file contains information about each reach in the district and is stored as a comma-delimited table which can be opened with Microsoft Excel or an equivalent spreadsheet editor. The table contains the following eleven variables:

- **Reach_ID** (Column A)—the name of the reach within the National Channel Framework (USACE 2023).
- **Sheet_Name** (Column B)—the name of the plot sheet which includes the reach.
- **Reach_Name** (Column C)—the name of the reach.

- **Depth** (Column D)—the authorized depth of the reach, in feet relative to the local survey datum.

- **Depth_Proj** (Column E)—the maintained depth of the reach, in feet relative to the local survey datum.

- **Name** (Column F)—the name of the project.

- **Projection** (Column G)—the name of the local State Plane, which corresponds to the "latitude" (i.e., Northing) and "longitude" (i.e., Easting) variables from the bathymetry NetCDF files.

- **CCR_group** (Column H)—Channel Condition Report group.

- **CCR_line_1** (Column I)—Channel Condition Report comment line 1.

- **CCR_line_2** (Column J)—Channel Condition Report comment line 2.

- **raster_cel** (Column K)—the length of one side of the square bathymetric survey cell, in feet.

Although CSAT will run without any modification of `reach_table.txt`, the user can optionally add columns to `reach_table.txt` to designate reach-by-reach volume loss thresholds for identifying dredging events. Detailed instructions are provided in Section 5.4.2.

3.2 Optional Inputs

The quick-start instructions in Section 2 will run CSAT using default parameters and all available bathymetric data, but individual project needs may necessitate altering one or more optional parameters. Instructions for updating these parameters appear throughout the remainder of this document, as shown in Table 2.

3.2.1 Start and End Dates for Analysis

By default, the CSAT shoaling rate analysis will begin with the earliest available eHydro survey and end with the latest available eHydro survey. However, in certain scenarios it may be desirable to limit the analysis to a user-defined window of time. For example, research suggests that shoaling rates may increase after new work dredging because the wider, deeper channel is a more efficient sediment trap (Rosati 2005; Wise and Mouraenko 2007). As a result, a more accurate forecast may be obtained by limiting the analysis to a period when the maintained depth and channel width were constant.

To update the start date or the end date for analysis, open `Run_CSAT.bat` in a text editor (see Section 2.5) and find the lines which read

```
rem CHANGE THE DATE BELOW IF DESIRED: YYYYMMDD FORMAT MUST
      BE 8 CHARACTERS
rem REMOVE 'rem' and then modify number. There should be
      no spaces between =.
REM set start_date=20090101
REM set end_date=20151231
IF NOT DEFINED start_date (SET start_date=_)
IF NOT DEFINED end_date (SET end_date=_)
```

In the code block above, the first two lines of code (beginning with `rem`) are instructions for the user and should not be altered. The third and fourth lines (beginning with `REM`) will manually set the start and/or end date if the comment designator `REM` is deleted. The fifth and sixth lines (beginning with `IF NOT DEFINED`) should not be altered, as these tell CSAT to use the default eHydro dates if the user did not make changes to Line 3 or Line 4.

To manually set the start date, which is stored as the `start_date` parameter, delete `REM` from the third line of code and enter the desired date as follows:

```
rem CHANGE THE DATE BELOW IF DESIRED: YYYYMMDD FORMAT MUST
      BE 8 CHARACTERS
rem REMOVE 'rem' and then modify number. There should be
      no spaces between =.
set start_date=YYYYMMDD1                          ← CHANGE
REM set end_date=20151231
IF NOT DEFINED start_date (SET start_date=_)
IF NOT DEFINED end_date (SET end_date=_)
```

where `YYYYMMDD1` is the desired analysis start date. Similarly, to manually set the end date via the `end_date` parameter, delete `REM` from the fourth line of code and edit the code to read:

```
rem CHANGE THE DATE BELOW IF DESIRED: YYYYMMDD FORMAT MUST
     BE 8 CHARACTERS
rem REMOVE 'rem' and then modify number. There should be
     no spaces between =.
REM set start_date=20090101
set end_date=YYYYMMDD2                          ← CHANGE
IF NOT DEFINED start_date (SET start_date=_)
IF NOT DEFINED end_date (SET end_date=_)
```

where `YYYYMMDD2` is the desired analysis end date. When making these edits, it is necessary to ensure that there are no spaces before or after the equals sign, as extra spaces will cause CSAT to fail. In addition, if both the start date and the end date are set manually, the user should ensure that `end_date` is later in time than `start_date`. Reversing the values will result in no analysis being performed.

3.2.2 Shoaling Rate Averaging Method

CSAT generates a representative shoaling rate for each bathymetric survey cell by averaging measured shoaling rates from all possible combinations of elevation measurements. At the time of publication, four possible averaging methods are available in CSAT, as summarized in Table 1. Additional details on the underlying mathematical calculations are provided in Section 5.7.

Table 1. Summary of averaging methods available for generating representative shoaling rates in CSAT.

Averaging Method Designator	Description	For Further Information, See:
AvgRate_ftPerYr	Unweighted arithmetic mean of all shoaling measurements for a given pixel, in feet per year.	Section 5.7.1
WeightedAvgRate_ ftPerYr	Weighted arithmetic mean of all shoaling measurements for a given pixel, in feet per year. The measurements are weighted using the time elapsed between the corresponding survey pair, so rates based on longer observation intervals will carry more weight in the average. This is the default method.	Section 5.7.2
EndpointAvgRate_ First_Last_ftPerYr	Arithmetic mean of shoaling rates derived from the first and last surveys in each dredging interval, in feet per year.	Section 5.7.3
WeightedAvgRate_ MedFilt_ftPerYr	Values of WeightedAvgRate_ftPerYr, which are then smoothed spatially using a 70 ft × 70 ft kernel.	Section 5.7.4

The default averaging method is a weighted average of all available shoaling rates for a given pixel. Within the average, the individual shoaling rates are weighted based on the time elapsed between the surveys corresponding to that rate. If the user desires to apply an alternate averaging method, this can be achieved by opening `Run_CSAT.bat` in a text editor (see Section 2.5) and locating the following lines of code:

```
rem RASTER - enable raster output creation. 1-Enable, 0-Disable
set RASTER=1
REM set RASTER_TYPE=WeightedAvgRate_ftPerYr
```

The third line of this code block contains the relevant code for updating the averaging method. (Note that the first and second lines, which enable or disable the creation of certain output files, are further discussed in Section 4.9.) To manually define the averaging method, delete the comment designator `REM` from Line 3 and replace `WeightedAvgRate_ftPerYr` with either `AvgRate_ftPerYr`, `EndpointAvgRate_First_Last_ftPerYr`, or `WeightedAvgRate_MedFilt_ftPerYr` (see Table 1). For example, to tell CSAT to substitute the endpoint average, update the third line as follows:

```
rem RASTER - enable raster output creation. 1-Enable, 0-Disable
set RASTER=1
set RASTER_TYPE= EndpointAvgRate_First_Last_ftPerYr    ← CHANGE
```

3.2.3 Other Optional Inputs

In addition to specifying start and end dates and changing the averaging method, several other optional inputs are also available within CSAT. For example, it is possible to alter the threshold volumes used for dredge event identification, discard individual bathymetric surveys, override the survey type, and disable the creation of certain output files to speed the runtime. The full list of optional CSAT inputs appears in Table 2 and Table 3. For detailed instructions on how to modify CSAT's behavior, refer to the section indicated in the last column of each table.

Table 2. Summary of optional CSAT inputs.

Parameter	Description	Default Value	For Further Instructions, See:
`date_merge_window`	Window of time in which surveys may be merged into a single survey if they meet specific criteria	10 days	Section 5.5
`end_date`	End date for CSAT analysis. Any bathymetric surveys after this date will be discarded by CSAT.	latest bathymetric survey in eHydro	Section 3.2.1
`PCTTHRESH`	Threshold percent change in volume. If the percent change in volume between consecutive surveys is negative and exceeds the magnitude of `PCTTHRESH`, then CSAT assumes that the later survey is an AD survey.	2.5%	Section 5.4.2
`RASTER`	Boolean to enable or disable creation of images displaying the final eHydro survey and a map of shoaling rates for each reach.	True	Section 3.1.1
`RASTER_TYPE`	Averaging method used for calculating the representative shoaling rate at each bathymetric survey point in the reach.	weighted average	Section 3.2.2
`start_date`	Start date for CSAT analysis. Any bathymetric surveys before this date will be discarded by CSAT.	earliest bathymetric survey in eHydro	Section 3.2.1
`VOLTHRESH`	Threshold change in volume. If the loss of volume between consecutive surveys exceeds the magnitude of `VOLTHRESH`, then CSAT assumes that the later survey is an AD survey	-10^{10} cy	Section 5.4.2

Table 3. Additional options to customize the CSAT output which are not controlled by the parameters from Table 2.

Description	Default Behavior	For Further Instructions, See:
Omit user-specified hydrographic surveys from the shoaling analysis.	All surveys between `start_date` and `end_date` are used.	Section 5.6
Manually designate specific surveys as after-dredge (AD) events.	CSAT automatically assigns survey type.	Section 5.4.1

3.2.4 Important Note about Overwriting Output

By default, the CSAT output is stored in a directory named:

```
…\CSAT_distribution\output\CEXYZ\YYYYMMDD1__to__YYYYMMDD2
```

where CEXYZ is the district symbol, YYYYMMDD1 is the analysis start date, and YYYYMMDD2 is the analysis end date. If the user runs CSAT multiple times with the same start and end dates but different input parameters, the most recent CSAT results will overwrite any earlier output with the same analysis dates. It is highly recommended to manually rename any earlier output directories with a more descriptive name before rerunning CSAT. For example, if the merging window was manually changed from 10 days to 5 days (see Section 5.5), the output directory for the 5-day merging might be renamed to

```
…\CSAT_distribution\output\CEXYZ\YYYYMMDD1__to__YYYYMMDD2_5day
```

by right-clicking on the original output directory and clicking Rename. This will ensure that the original output is not overwritten during subsequent CSAT runs.

4 Output File Contents

The tabular output data and raster files generated by CSAT are saved in the `CSAT_distribution\output` subdirectory.

4.1 Table of Average, Minimum, and Maximum Shoaling Rates (by Pixel)

For each reach, the average, minimum, and maximum shoaling rates at each pixel are stored in CSV (comma-separated values) files named `<reach name>_avg_max_min.csv`. An example of the file contents appears in Figure 11. The number of rows in the CSV files corresponds to the number of 10 ft × 10 ft bathymetric survey cells in the reach. Each CSV file contains 8 columns with the following data:

- **`X`** (Column A)–contains the *x*-coordinate of the bathymetric survey cell in feet. The measurements are in the same coordinate system as the original eHydro data, which may be the Easting from the local State Plane projected coordinate system or Universal Transverse Mercator (UTM) feet.

- **`Y`** (Column B)–contains the *y*-coordinate of the bathymetric survey cell in feet, using the same coordinate system as Column A.

- **`WeightedAvgRate_ftPerYr`** (Column C)–contains the weighted average shoaling rate calculated for this survey cell using Equation (16a). The values are given in vertical feet per year, with positive rates indicating shoaling and negative rates indicating scouring. For the green-highlighted row in Figure 11, the bathymetric survey cell has a weighted average shoaling rate of 0.109 ft/yr.

- **`MaxRate_ftPerYr`** (Column D)–the maximum observed shoaling rate for this survey cell. The values are given in vertical feet per year, with positive rates indicating shoaling and negative rates indicating scouring. For the green-highlighted row in Figure 11, the maximum observed shoaling rate is 0.262 ft/yr.

- `MinRate_ftPerYr` (Column E)–the minimum observed shoaling rate for this survey cell. The values are given in vertical feet per year, with positive rates indicating shoaling and negative rates indicating scouring. For the green-highlighted row in Figure 11, the minimum observed shoaling rate is 0.045 ft/yr.

- `LastZ_ft` (Column F)—the elevation of the survey cell relative to the survey datum at the timestamp of the most recent survey. The values are given in feet and are positive up (such that negative numbers indicate an elevation below the datum). For the green-highlighted row in Figure 11, the bathymetric survey cell had an elevation of −3.273 ft Mean Lower Low Water (MLLW) during the most recent survey.

- `Num_Svys` (Column G)—the number of bathymetric surveys containing an elevation measurement at this pixel. The values in this column may vary from pixel to pixel if incomplete or partial surveys were present in the bathymetric dataset. For the green-highlighted row in Figure 11, eleven bathymetric surveys contained a measured elevation at this location.

- `Num_Svy_Pairs` (Column H)—the number of paired surveys that were used to calculate the average (Column C), maximum (Column D), and minimum (Column E) shoaling rates at this location. Column H may be as large as

$$\max(Column\ H) = \frac{(Column\ G)!}{2! \cdot (Column\ G - 2)!} \quad (1)$$

if no dredging events occurred between surveys. (Note that the ! symbol in Equation 1 indicates a factorial.) In practice, the value in Column H will be smaller than the maximum value given by Equation (1) because surveys separated by dredging events cannot be paired to calculate a shoaling rate. For additional details on the survey pairing methodology, see Section 5.6.

Figure 11. Example contents of the output file `<reach name>_avg_max_min.csv`.

	A	B	C	D	E	F	G	H
1	X	Y	WeightedAvgRate_ftPerYr	MaxRate_ftPerYr	MinRate_ftPerYr	LastZ_ft	Num_Svys	Num_Svy_Pairs
2	3324212.536	13830425.39	0.137	0.359	0.043	-3.256	11	2
3	3324212.536	13830415.39	0.109	0.262	0.045	-3.273	11	2
4	3324222.536	13830415.39	0.112	0.219	0.067	-3.259	11	2
5	3324202.536	13830405.39	0.096	0.297	0.012	-3.284	11	2

4.2 Table of Volume Differences between Surveys (by Reach)

For each reach, the total volume difference between pairs of surveys is stored in a CSV file named `<reach name>_SurveyPairVolumeDifference.csv`. The number of rows in the CSV file corresponds to the number of possible bathymetric survey pairs that are not separated by a dredging event (see Section 5.6 for details on the pairing methodology). Each CSV file contains the following five columns:

- **`SurveyDateBefore`** (Column A)—the timestamp of the earlier survey within the survey pair. The dates are formatted as YYYYMMDD. For the green-highlighted row in Figure 12, the earlier survey in the pair is timestamped 26 June 2015.

- **`SurveyDateAfter`** (Column B)—the timestamp of the later survey within the survey pair. The dates are formatted as YYYYMMDD. For the green-highlighted row in Figure 12, the later survey in the pair is timestamped 28 July 2015.

- **`ElevDiff_CY`** (Column C)—the difference in sediment volume between the two surveys, with positive numbers indicating an accumulation of sediment and negative numbers indicating a loss of sediment. These values are given in cubic yards. For the green-highlighted row in Figure 12, Column C shows that 8,817 cy of sediment accumulated in the reach between 26 June 2015 and 28 July 2015.

- **`AnnualShoalingRate_ftperyr`** (Column D)—the spatially averaged annual shoaling rate, calculated from the survey timestamps indicated in Column A and Column B. The values are given in feet per year. For the green-highlighted row in Figure 12, the pixels in the reach shoaled at an average rate of 19.9 ft/yr between 26 June 2015 and 28 July 2015.

- **`AnnualShoalingVolume_CYperyr`** (Column E)—the annual shoaling rate for the reach (in cubic yards) based on the pair of surveys indicated in Column A and Column B. This is the volume of sediment that would accumulate in one year if the shoaling rates in Column D persisted for the full year. For the green-highlighted row in Figure 12, Column E shows a calculated annual shoaling rate of 100,570 cy/yr.

Figure 12. Example contents of the output file `<reach name>_SurveyPairVolumeDifference.csv`.

	A	B	C	D	E
1	SurveyDateBefore	SurveyDateAfter	ElevDiff_CY	AnnualShoalingRate_ftperyr	AnnualShoalingVolume_CYperyr
2	20141030	20150429	166.19	0.068	335.134
3	20141030	20150529	-1500.257	-0.507	-2595.231
4	20150429	20150529	-1607.183	-3.908	-19554.059
5	20150626	20150728	8817.066	19.937	100569.66
6	20150626	20150828	8423.565	9.746	48803.194

4.3 Table of Forecast Dredging Volumes (by Reach)

For each reach, the forecast dredging volumes for various cut depths at 6-month increments are stored in a CSV file named `<reach name>_volumes.csv`. Each row of the CSV file corresponds to a different cut depth, while the columns store the forecast volume of sediment above that cut depth. An example appears in Figure 13. Specific column descriptions are as follows:

- **`dredge_cut_ft`** (Column A)—the cut depth in feet, relative to the local survey datum.
- **`Now`** (Column B)—the volume of sediment above a given cut depth **at the timestamp of the most recent bathymetric survey**.[8] The volume is for the entire reach and is given in cubic yards. For the green-highlighted row in Figure 13, the most recent bathymetric survey showed 1,712,898 cy of sediment above the −48 ft MLLW cut depth. This is the volume of sediment that would need to be removed to achieve a 48 ft cut depth if the channel were dredged immediately after the most recent bathymetric survey.
- **`N_months`**, where *N* is a number between 6 and 60 (Columns *C* through *L*)—the volume of sediment which is forecast to be present above a given cut depth *N* months after the most recent bathymetric survey. The volume is for the entire reach and is given in cubic yards. For the green-highlighted row in Figure 13, CSAT predicts that if dredging occurred 36 months (Column H) after the most recent bathymetric survey, 1,812,184 cy of sediment would need to be removed from the reach to achieve a 48 ft cut depth.

8 Important note: the variable name “Now” **does not** refer to today’s date.

Figure 13. Example contents of the output file `<reach name>_volumes.csv`.

	A	B	C	D	E	F	G	H	I	J	K	L
1	dredge_cut_ft	Now	6_months	12_months	18_months	24_months	30_months	36_months	42_months	48_months	54_months	60_months
57	-50	2108335	2124882	2141430	2157978	2174526	2191073	2207621	2224169	2240716	2257264	2273812
58	-49	1910616	1927164	1943712	1960259	1976807	1993355	2009902	2026450	2042998	2059546	2076093
59	-48	1712898	1729445	1745993	1762541	1779088	1795636	1812184	1828732	1845279	1861827	1878375
60	-47	1515179	1531727	1548275	1564822	1581370	1597918	1614465	1631013	1647561	1664108	1680656
61	-46	1317496	1334040	1350584	1367129	1383674	1400219	1416764	1433310	1449856	1466402	1482948
62	-45	1120079	1136605	1153132	1169662	1186193	1202725	1219258	1235792	1252327	1268863	1285400
63	-44	924623	941085	957553	974026	990502	1006983	1023466	1039953	1056444	1072940	1089439

4.4 List of Surveys Omitted from CSAT Calculations (by Reach)

A list of surveys omitted from CSAT's calculations is stored in the CSV files named `<reach name>_SurveysNotUsed.csv`. Surveys may be omitted according to user specification (Section 5.6; Figure 29) or if they are timestamped outside the designated analysis window (Section 3.2.1).

4.5 List of Surveys Skipped during CSAT Calculations (District-Wide)

A list of surveys skipped during CSAT's calculations is stored in the CSV file named `Surveys_skipped.csv`. In addition to the survey ID, this file also reports the reason that the survey was not used. If two or more surveys close in time were merged, only the earliest date is retained within the CSAT calculations. In this situation, the date(s) of the later merged surveys will be reported within `Surveys_skipped.csv`. Note that the surveyed elevations from these later surveys are still incorporated into the shoaling calculations, but the observed bed elevation is shifted to the timestamp of the earliest survey in the merged set.

4.6 List of After-Dredge (AD) Surveys and Volume Dredged (by Reach)

For each reach, a list of after-dredge surveys and volumes is stored in the CSV files named `<district symbol>_<reach name>_dredged_date_vol.csv`. Each CSV file contains the following two columns:

- **`SurveyDate`** (Column A)—the date of the after-dredge survey. This includes surveys which are explicitly flagged as after-dredge surveys in eHydro via the use of `AD` in the file name, along with surveys that the CSAT user manually designated as after-dredge surveys. It additionally may include surveys which CSAT automatically identified as after-dredge surveys due to a loss in volume exceeding some threshold value. For additional details on how CSAT automatically identifies dredging events, see Section 5.4.

- **`Volume Change (cy)`** (Column B)—the volume reduction between the indicated after-dredge survey (Column A) and the survey immediately preceding the after-dredge survey. This is assumed to be the dredging volume for the dredging event.

Figure 14. Example contents of a comma-separated values (CSV) file named **`<district symbol>_<reach name>_dredged_date_vol.csv`**.

	A	B
1	SurveyDate	Volume Change (cy)
2	1/31/2018 0:00	113300
3	7/11/2019 0:00	28100
4	1/10/2023 0:00	36500

4.7 District-Wide Shoaling Rate Summary

A summary of the average, maximum, and minimum shoaling rates for each of a district's reaches is stored in the file named `stats_shoal3D.csv`. An example appears in Figure 15. The file contains four columns, as follows:

- **`Reach_ID`** (Column A)—the name of the reach.

- **`AverageRate_FtPerYr`** (Column B)—this is the average of the average shoaling rates for each pixel, converted to vertical feet per year. The values are constrained to be ≥0 (corresponding to shoaling), so Column B will automatically display a value of 0 if the reach is scouring. For example, if the representative average volumetric shoaling rate at the i^{th} pixel is given by $\overline{R^i}$ (in cubic yards per year), then the value in Column B is given by

$$\text{Column B} = \max\left[\left(\frac{0.27\text{ft}}{\text{cy}}\right)\frac{1}{N}\sum_{i=1}^{N}\overline{R^i}\ ,\ 0\right], \qquad (2)$$

where N is the total number of pixels and 0.27 ft/cy is the conversion from cubic yards to vertical feet assuming a bathymetric grid with $\Delta x = \Delta y = 10$ ft. Note that the alternative averaging methods (i.e., $\left(\overline{R^i}\right)_{EP}$,

$\left(\overline{R^i}\right)_W$, or $\left(\overline{R^i}\right)_{W,f}$; see Section 5.7) may be substituted for $\overline{R^i}$ in Equation (2) depending on the user-determined CSAT inputs.

- **`MaxAverageRate_FtPerYr`** (Column C)—this is the average of the maximum shoaling rates observed at each pixel, converted to vertical feet per year. The values are constrained to be ≥0 (corresponding to shoaling). In symbols, this is calculated as

$$\text{Column C} = \max\left[\left(\frac{0.27\text{ ft}}{\text{cy}}\right)\frac{1}{N}\left[\max\left(\left\{R^1_{j,k}\right\}\right)+\max\left(\left\{R^2_{j,k}\right\}\right)+\cdots + \max\left(\left\{R^N_{j,k}\right\}\right)\right] \;,\; 0\right] \quad (3)$$

where $\left\{R^i_{j,k}\right\}$ is the set of all volumetric shoaling rates at pixel i calculated from surveys timestamped t_j and t_k (see Section 5.6 for details). The conversion factor of 0.27 ft/cy again assumes a bathymetric survey grid with $\Delta x = \Delta y = 10$ ft. For the green-highlighted row in Figure 15, Column C contains a value of 7.412 ft/yr. This indicates that if all pixels simultaneously display their maximum measured shoaling rate, the reach will shoal at approximately 7.4 ft/yr.

- **`MinAverageRate_FtPerYr`** (Column D)—this is the average of the minimum shoaling rates observed at each pixel, converted to vertical feet per year. In symbols, this is calculated as

$$\text{Column D} = \left(\frac{0.27\text{ft}}{\text{cy}}\right)\frac{1}{N}\left[\min\left(\left\{R^1_{j,k}\right\}\right)+\min\left(\left\{R^2_{j,k}\right\}\right)+\ \ldots + \min\left(\left\{R^N_{j,k}\right\}\right)\right] \quad (4)$$

with all variables as defined for Equation (3). The values in Column D are allowed to be positive (indicating shoaling) or negative (indicating scouring). For the green-highlighted row in Figure 15, Column D contains a value of −5.055 ft/yr. This indicates that if all pixels simultaneously display their minimum measured shoaling rate, the reach will scour at approximately 5.0 ft/yr.

Figure 15. Example contents of `stats_shoal3D.csv`.

	A	B	C	D
1	Reach_ID	AverageRate_FtPerYr	MaxAverageRate_FtPerYr	MinAverageRate_FtPerYr
5	CENAP_AI_02_CCC_2	0.101	0.474	-1.078
6	CENAP_BI_01_BIE_1	0.546	11.485	-15
7	CENAP_BI_01_BIE_2	0.049	7.412	-5.055
8	CENAP_BI_02_OCC_1	0.218	16.938	-13.094
9	CENAP_CD_01_POI_1	0.123	0.653	-0.203
10	CENAP_CD_01_POI_2	0.553	2.477	-0.545

4.8 District-Wide Dredge Volume Tabulation

A Summary Planning Quantity (SPQ) table for the district is stored in the CSV file named `SPQ_<district symbol>.csv`. In the file, each reach corresponds to a block of 11 rows, corresponding to various times elapsed between the most recent bathymetric survey and the next dredging event. For example, Figure 16 shows a portion of the SPQ table for Philadelphia District. In this example, the results for Absecon Inlet reach AI_01_AIE_1 are in Rows 2 through 12, while the results for Absecon Inlet reach AI_01_AIE_2 are in Rows 13 through 23. The files contain 42 columns, as follows:

- **`TimeToDredge`** (Column A)—the elapsed time, in months, between the most recent bathymetric survey and a hypothetical future dredging event.
- **`Sheet_Name`** (Column B)—the name of the bathymetric plotsheet.
- **`Channel_Area_ID_FK`** (Column C)—the `ChannelArea_ID` associated with the reach. These values come from the National Channel Framework.
- **`R_Q_NAME`** (Column D)—the name of the reach.
- **`Depth`** (Column E)—the maintained depth of the reach, in feet relative to the local datum.
- **`PotentialDredgeDate`** (Column F)—the calendar date of hypothetical dredging, corresponding to the elapsed time in Column A. For rows with a value of 0 months in Column A, Column F contains the date of the most recent bathymetric survey.

- **VA_p##** (Columns G through AP)—these columns report the volume of material above target cut depths relative to the reach's authorized depth. Using this nomenclature, VA_p0 is equivalent to authorized depth. VA_p2 is the volume above a cut depth of authorized depth plus 2 ft of overdepth.

Figure 16. Example of `SPQ_<district symbol>.csv`.

	A	B	C	D	E	F	G	H	I
1	TimeToDredge	Sheet_Name	Channel_Area_ID_FK	R_Q_NAME	Depth	PotentialDredgeDate	VA_p16	VA_p15	VA_p14
2	0	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2021	418371	372083	327284
3	6	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	9/10/2021	419630	373342	328544
4	12	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2022	420889	374602	329803
5	18	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	9/10/2022	422149	375861	331062
6	24	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2023	423408	377120	332321
7	30	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	9/10/2023	424667	378379	333580
8	36	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2024	425926	379638	334840
9	42	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	9/10/2024	427185	380898	336099
10	48	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2025	428445	382157	337358
11	54	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	9/10/2025	429704	383416	338617
12	60	Absecon Inlet	AI_01_AIE	AI_01_AIE_1	20	3/10/2026	430963	384675	339876
13	0	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2021	56437	34925	20842
14	6	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	9/10/2021	61739	39631	24781
15	12	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2022	67267	44538	29032
16	18	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	9/10/2022	73016	49634	33516
17	24	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2023	78914	54902	38197
18	30	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	9/10/2023	84899	60325	43060
19	36	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2024	90956	65914	48102
20	42	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	9/10/2024	97076	71656	53274
21	48	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2025	103257	77511	58589
22	54	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	9/10/2025	109524	83451	64035
23	60	Absecon Inlet	AI_01_AIE	AI_01_AIE_2	20	3/10/2026	115879	89455	69620
24	0	Absecon Inlet	AI_02_CCC	AI_02_CCC_1	15	6/22/2022	298934	280491	262374
25	6	Absecon Inlet	AI_02_CCC	AI_02_CCC_1	15	12/22/2022	301519	283074	264952

4.9 Last Survey Images

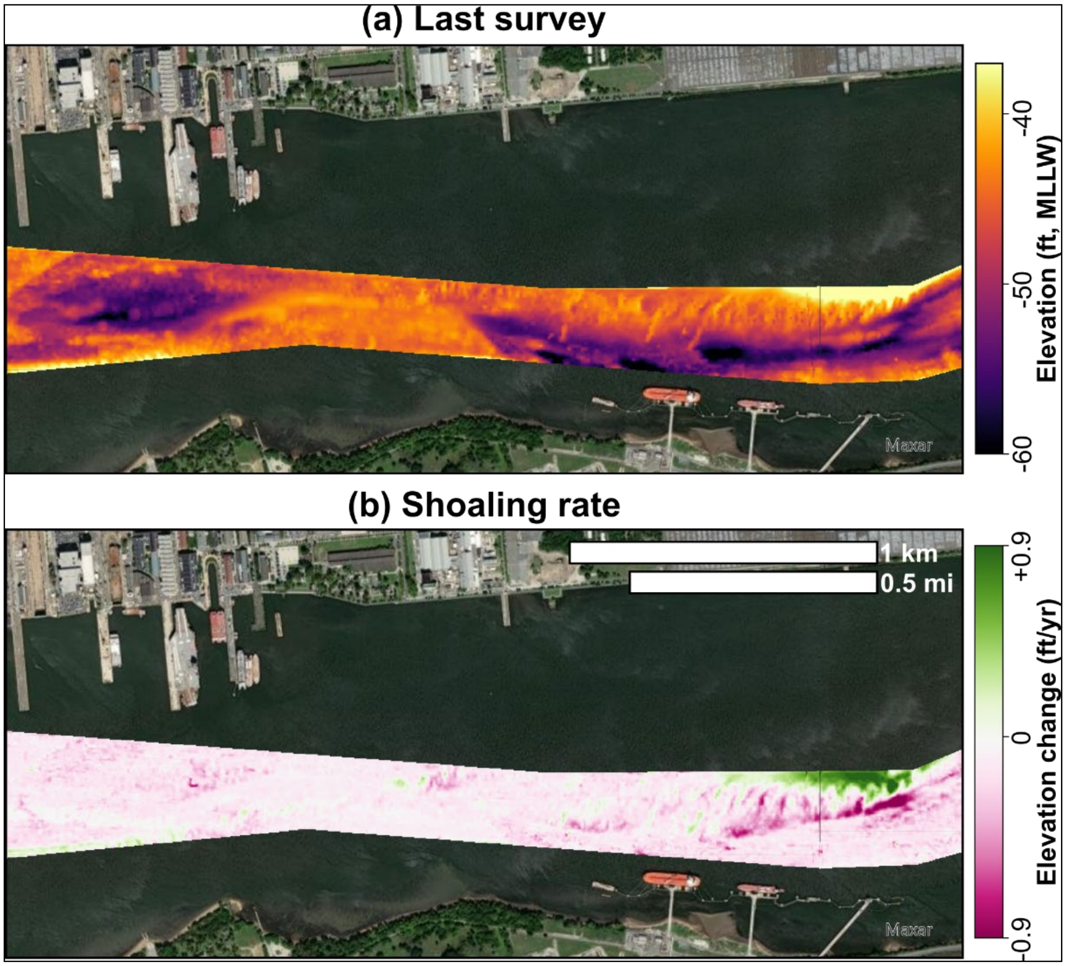
The CSAT output also includes images of the last survey for each reach. These are stored in a subdirectory of the output folder named:

```
…/output/CEXYZ/YYYYMMDD__to__YYYYMMDD/Last Surveys
```

where `CEXYZ` is the district symbol. The name of each image matches the reach name. All output is formatted as spatially referenced GeoTIFFs which can be dragged-and-dropped into GIS software for easy visualization. An example is shown in Figure 17*a*.

If the last bathymetric survey for the reach was incomplete, the missing pixels in the *Last Survey* image will be forward-filled with the most recent bathymetric measurement available. This ensures that the entire reach has bathymetric coverage in these images. For additional details on the forward-filling methodology, see Section 5.7.5.

Figure 17. Example of last survey GeoTIFF (*a*) and shoaling rate GeoTIFF (*b*) for a reach in the Philadelphia navigation channel. In subplot (*b*), *green* indicates shoaling, and *pink* indicates scouring. (Powered by Esri.)



Generating the final survey images may lead to a significant increase in the CSAT runtime. For users who do not wish to visualize the final surveys and only require tabular output (Sections 4.1 through 4.8), image creation can be disabled via the `RASTER` parameter in `Run_CSAT.bat`. To disable raster creation, open `Run_CSAT.bat` (see Section 2.5) and locate the lines which read

```
rem RASTER - enable raster output creation. 1-Enable, 0-Disable
set RASTER=1
```

In this code block, the first line (beginning with `rem`) is a comment containing instructions for the user and should not be modified. The second line sets the value of the Boolean `RASTER`. Raster creation can be disabled by setting this parameter to zero, as follows:

```
rem RASTER – enable raster output creation. 1-Enable, 0-Disable
set RASTER=0                                            ← CHANGE
```

Note that setting RASTER to zero will disable creation of both the final survey images and the shoaling rate images discussed in Section 4.10.

4.10 Shoaling Rate Images

The final component of the CSAT output is a set of images showing the representative shoaling rate (i.e., values of $\overline{R^i}$, $\left(\overline{R^i}\right)_{EP}$, $\left(\overline{R^i}\right)_{W}$, or $\left(\overline{R^i}\right)_{W,f}$, as described in Section 5.7) for each reach. The specific variable which is displayed in the image depends on the method selected by the user (Section 3.2.2). If no method is selected by the user, then the representative shoaling rate displayed in these images will default to $\left(\overline{R^i}\right)_{W}$. The images are stored in a subdirectory of the output folder named

```
…/output/CEXYZ/YYYYMMDD__to__YYYYMMDD/Shoaling Rates
```

where CEXYZ is the district symbol. All file names match the name of the reach. The images are spatially referenced GeoTIFFs which can be dragged-and-dropped into GIS software for easy visualization (e.g., Figure 17*b*). The user should note that the rates in the images have been pre-converted from volumetric shoaling rates (cubic yards per year) to a rate of elevation change (feet per year) to facilitate interpretation.

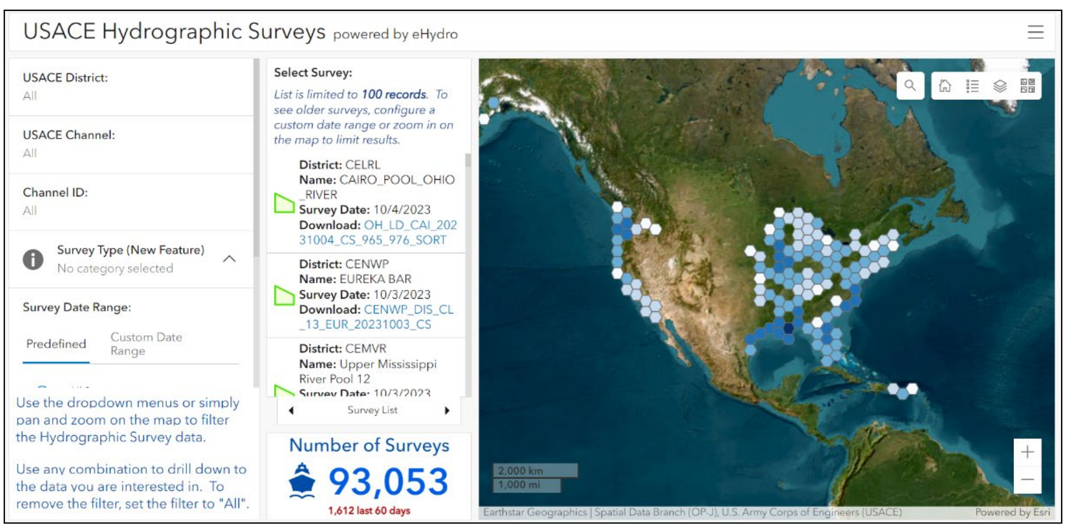
Generating the final survey images may lead to a significant increase in the CSAT runtime. For users who do not wish to visualize the shoaling rates and only require tabular output (Sections 4.1 through 4.8), image creation can be disabled via the RASTER parameter in Run_CSAT.bat following the instructions in Section 4.9. Note that setting RASTER to zero will disable creation of both the shoaling rate images and the final survey images (Section 4.9).

5 Methods and Assumptions

5.1 Source of Survey Data

The primary source of bathymetric data for the CSAT calculations is the USACE eHydro database, which is an enterprise-level platform for storing and disseminating hydrographic survey data in a standardized format among all USACE districts with a navigation mission.[9] Uploading survey data to eHydro was mandated for coastal districts in 2016 and for inland districts in 2019 (USACE 2019), including surveys predating the mandate by five years. Consequently, comprehensive coastal survey coverage is available from 2011 to the present for coastal districts and 2014 to the present for inland districts. New surveys must now be uploaded to the eHydro system within fifteen business days, generating a rapidly growing, publicly accessible database of bathymetric conditions across the United States (Figure 18). Beyond internal usage by USACE to determine channel maintenance requirements, the eHydro data are used externally by NOAA (as mandated under 33 CFR § 209.325; Code of Federal Regulations 1978), the US Coast Guard, and local stakeholders.

Figure 18. The eHydro dashboard.[10] As of 5 October 2023, there were 93,053 bathymetric surveys available in the eHydro database. CSAT automatically downloads and reprocesses all eHydro survey data before making the reprocessed data available on the CIRP website (see Section 2.4).



9. Ongoing CSAT development is incorporating lidar datasets from the channel margins to supplement the eHydro survey data (Sylvester et al. 2023; Sylvester and Hartman, in press).

10. https://www.arcgis.com/apps/dashboards/4b8f2ba307684cf597617bf1b6d2f85d

The files uploaded to eHydro include raw survey data in XYZ format and several processed hydrographic survey products. The XYZ data are stored in ASCII files with columns for Easting, Northing, and depth at irregularly spaced survey points. These XYZ files are thinned relative to the original survey density; districts may optionally upload a second XYZ file at the full density. The processed products include a survey condition report, a PDF plotsheet displaying depths within the reach during the survey, and a geodatabase containing shoal polygons, elevation contours, and a triangulated irregular network (TIN) object for interpolating the scattered XYZ points. Of these products, the TIN is the most critical element for the subsequent CSAT calculations (see Section 5.2).

Hydrographic mapping procedures, including data collection and postprocessing, are not standardized at the national level. Because each district has its own surveying methodology, expounding on the technical details is beyond the scope of this document. However, Section 5.3 describes several common issues with the eHydro products which, if present, will propagate forward into the CSAT results.

5.2 Survey Post-Processing for CSAT

After obtaining the hydrographic survey data from eHydro, CSAT performs several postprocessing steps before the shoaling calculations. The postprocessing routine is described in the following paragraphs.

5.2.1 Data Gridding

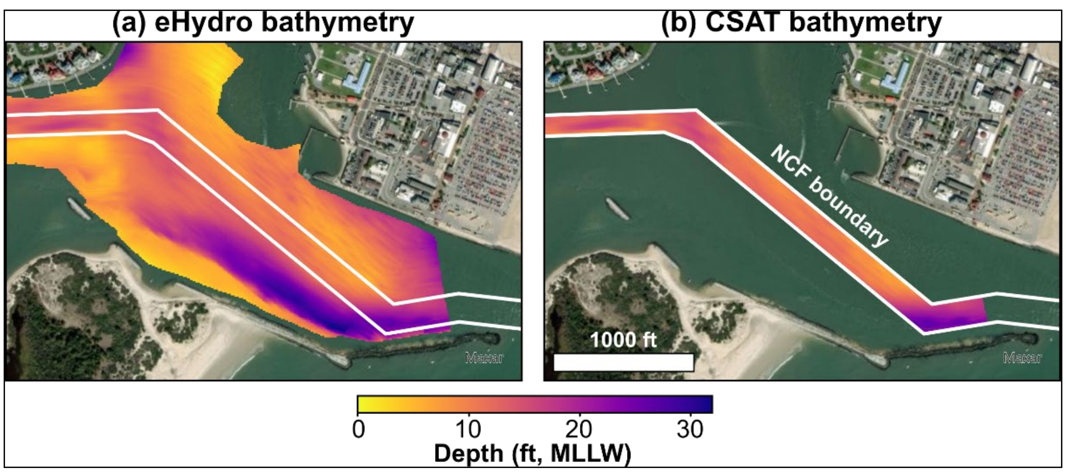
CSAT performs its shoaling calculations on a regular grid of points with $\Delta x = \Delta y = 10$ ft. Because the hydrographic survey data uploaded to eHydro by the districts are not gridded, additional postprocessing is necessary to generate the CSAT bathymetric inputs. This is achieved by resampling the district-provided eHydro TIN to produce an interpolated surface with the required regular spacing. TIN methods were first developed by Peucker et al. (1976; 1978) and have become a widely used technique for bathymetric surface generation (e.g., see review by Andes and Cox 2017), with native implementation in many geospatial software packages. CSAT performs the gridding using the TIN construction tools available in ArcGIS Pro. The TIN is constrained to limit the maximum triangular element edge length, preventing interpolating across larger spans than desired. The edge length is determined by a parameter from the National Channel Framework.

Once the TIN has been constructed, the bathymetric surface is converted into a regular grid and appended to the respective NetCDF file for each reach overlapped by the survey.

5.2.2 Clipping to National Channel Framework

Although the eHydro survey data may extend beyond the navigation channel boundaries, CSAT clips the survey data to the limits of the National Channel Framework (NCF; see USACE 2023) during postprocessing. An example from Ocean City Inlet, Maryland, is shown in Figure 19. In Figure 19*a*, notice that the eHydro survey data extend from bank-to-bank, whereas the NCF reach (white polygon) spans only a portion of the total inlet width. CSAT uses the NCF polygon as a clipping template and retains only the bathymetric data falling within the federally authorized navigation channel (Figure 19*b*). Consequently, the shoaling rates generated by CSAT are specific to the portion of the inlet which USACE is mandated to maintain.

Figure 19. Clipping the eHydro bathymetry using the National Channel Framework (NCF) polygons to produce the CSAT input files. Example shows bathymetric conditions from Ocean City Inlet, Maryland, on 15 December 2020. (Powered by Esri.)

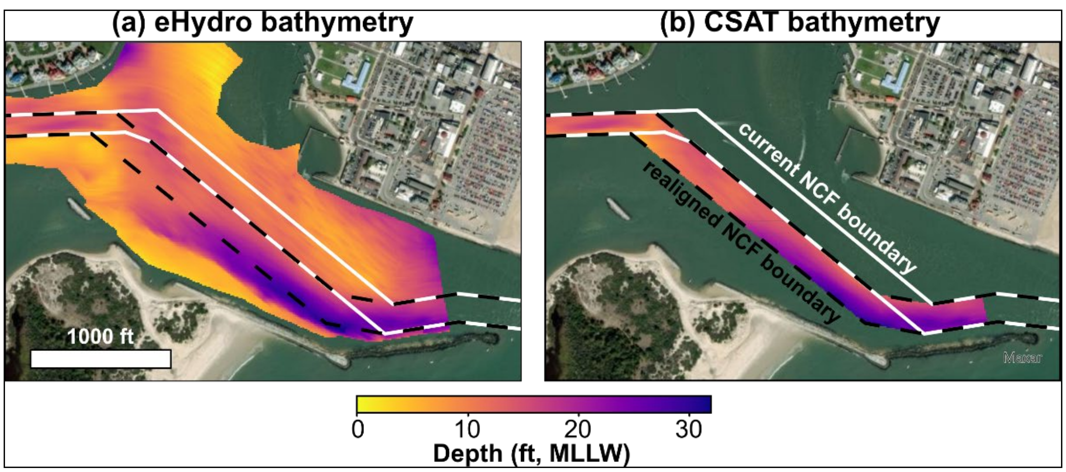


The NCF polygons outline the navigable width of the channel and do not encompass the channel side slopes (USACE 2013). As a result, the side slopes are not represented by the clipped CSAT input bathymetry, and CSAT's forecast shoaling volumes do not account for additional dredging that may be required outside the channel toe. However, enhanced CSAT capabilities which evaluate shoaling rates beyond the navigation channel boundaries are in active development (Sylvester et al. 2023; Sylvester and Hartman, in press) and will become available in future CSAT versions.

5.2.3 Channel Realignment Handling

In regions with high shoaling rates, the district may attempt to reduce the channel maintenance requirements by shifting the authorized channel to a naturally deeper location. This channel realignment is accompanied by a redrawing of the associated NCF polygon. Continuing the example from Figure 19, Baltimore District (NAB) has proposed realigning the authorized navigation channel to take advantage of deeper water in Ocean City Inlet (USACE-NAB 2022). The position of the realigned navigation channel is shown by the dashed black polygon in Figure 20*a*. When the NCF is altered, CSAT automatically reprocesses the eHydro bathymetry by clipping all survey data to the updated channel position, as shown in Figure 20*b*. Bathymetric data corresponding to the old channel position (e.g., Figure 19*b*) are not retained within the CSAT input files.

Figure 20. Continuation of the example in Figure 19, showing proposed channel realignment at Ocean City Inlet, Maryland (USACE-NAB 2022). The current channel position is shown as the *solid white polygon*, and the realigned channel position is shown by the *dashed black polygon*. When a district realigns a navigation channel, CSAT reprocesses the survey data based on the new channel position. Bathymetry corresponding to the old channel position is discarded by CSAT. (Powered by Esri.)



It should be emphasized that the CSAT input NetCDF files (Section 3.1.1) only contain bathymetric data for the active channel position (as defined by the NCF polygons), regardless of the channel position on the survey date. Surveys of the pre-realignment channel will always be clipped to the new channel position after the channel is realigned. The implication of this postprocessing step is that CSAT is unable to compare shoaling rates in the pre- and post-realignment channels, except in areas where the old and new NCF polygons overlap.

5.2.4 Datum Shift Handling

CSAT assumes that all surveys are referenced to a consistent vertical datum and are suitable for comparison. However, several districts (including New Orleans District, MVN, and Galveston District, SWG) have used multiple datums between the inception of eHydro and the present. CSAT users can identify these surveys by looking for datum designators like Mean Low Tide (MLT) or MLLW in the input file named `uniform_pts_table.txt` (Section 3.1.2) and. If multiple datums are present for the same reach, all surveys with the secondary datum should be manually disabled by setting values in the `Use` column to 0 (zero) in `uniform_pts_table.txt` (Figure 29). For example, in SWG, it is common to have surveys referenced to both Mean Low Water (MLW) and MLLW. To avoid errors due to inconsistent vertical datums, disabling all MLW surveys and retaining only the MLLW surveys is recommended when running CSAT.

To accommodate specific project needs and remove the need for manually discarding surveys, datum corrections are preprogrammed into CSAT for two USACE navigation channels—Southwest Pass and the Calcasieu Ship Channel, both maintained by MVN. In Southwest Pass, bathymetric data collected before 26 January 2017 were reported relative to Mean Low Gulf (MLG), while bathymetric data collected after 26 January 2017 are reported relative to MLLW. CSAT automatically corrects for the Southwest Pass datum shift by increasing the depth by 3.5 ft for surveys predating 26 January 2017. In symbols, this is represented as

$$z_{\text{MLLW}} = z_{\text{MLG}} - 3.5\text{ ft} \quad \text{(in Southwest Pass, Louisiana)}, \qquad (5)$$

where z is positive up (see USACE-MVN 2021). In the Calcasieu Ship Channel, bathymetric data collected before 1 May 2018 were reported relative to MLG, while bathymetric data collected after 1 May 2018 are reported relative to MLLW. CSAT automatically corrects for the Calcasieu datum shift by increasing the depth by 1 ft for surveys predating 1 May 2018. In symbols,

$$z_{\text{MLLW}} = z_{\text{MLG}} - 1.0\text{ ft} \quad \text{(in Calcasieu Ship Channel, Louisiana)}, \qquad (6)$$

where z is positive up (see USACE-MVN 2018).

These datum shifts are hard coded into the CSAT source code and cannot be changed using `Run_CSAT.bat`. If district users require datum corrections for channels other than Southwest Pass and Calcasieu, these should be reported to the CSAT point of contact listed on the CIRP website.[11]

5.3 Common Errors in the Bathymetric Data

Hydrographic surveying practices vary among the districts, and survey errors are likely to be site-specific depending on local conditions. However, the CSAT development team has identified several errors which frequently appear in the eHydro products and which directly affect the CSAT results. Understanding these issues will enable the CSAT user to quality control the CSAT output and identify regions of the channel where the calculated shoaling rate may be inaccurate due to poor quality eHydro data.

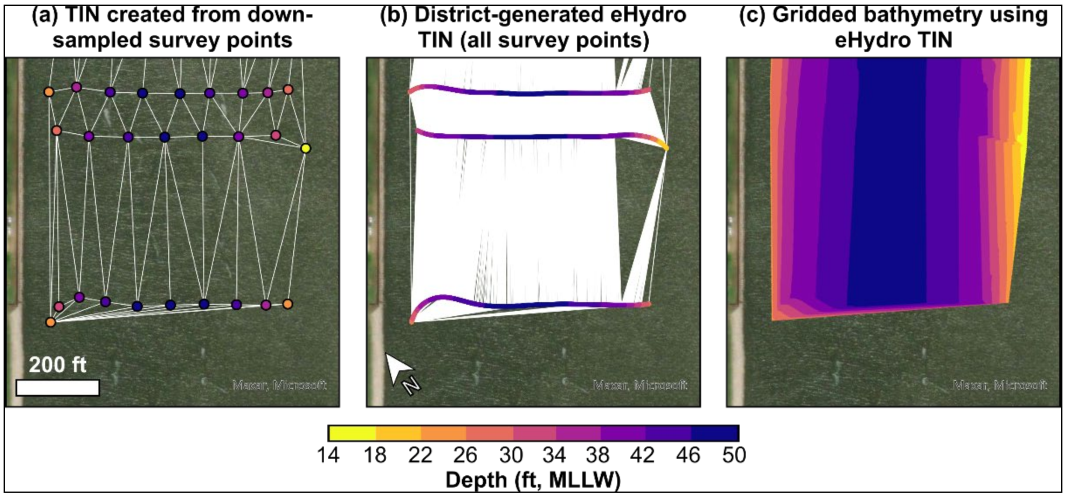
5.3.1 Apparent Shoaling Because of Survey Line Concavity

Under optimal conditions, survey vessels are directed to cross the channel in a straight line perpendicular to the channel centerline (USACE 2013). However, real-world navigation conditions rarely allow for perfectly straight survey transects. Although curved transects in the center of a reach do not pose a major challenge for postprocessing, a concave transect at the end of a reach may result in the appearance of an artificial shoal when the data are gridded.

An illustration of this phenomenon appears in Figure 21, which shows survey data from the Sabine-Neches Waterway, Texas. Notice that the outermost transect curves inwards towards the interior of the reach. When the irregular survey points are triangulated (Figure 21*b*; a downsampled TIN is shown in Figure 21*a* for improved visualization of the triangles), the concavity of the outermost transect results in triangles being drawn between the shoal on the left bank and the shoal on the right bank. Gridding the bathymetry using this TIN creates the appearance of a shoal spanning the entire width of the channel (Figure 21*c*). Including this survey in the CSAT analysis will result in an artificially high shoaling rate near the end of the reach due to the poor quality interpolation.

11. https://cirp.usace.army.mil/products/csat.php.

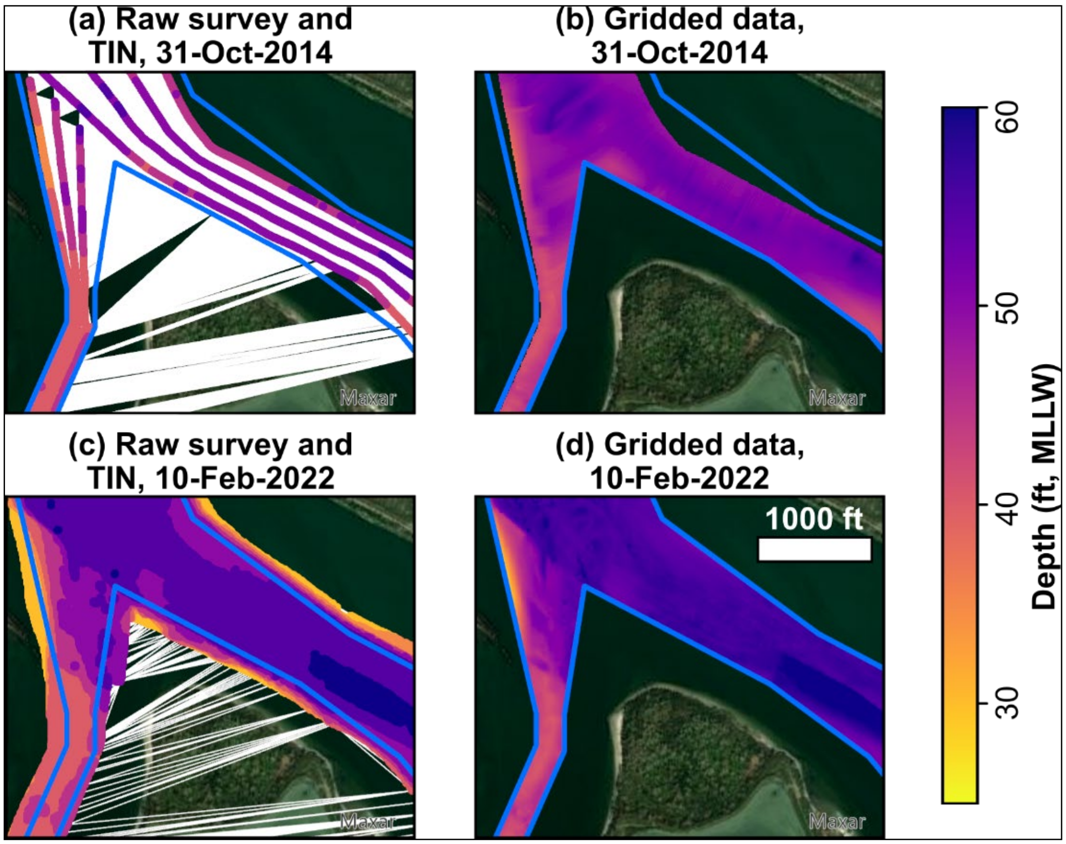
Figure 21. Example of TIN creation and bathymetric gridding for a concave survey transect from the Sabine-Neches Waterway, Texas. Subplot (*a*) shows an illustrative example of a TIN created from a subset of the eHydro survey points to facilitate visualization of the TIN triangles, while subplot (*b*) shows an actual eHydro TIN uploaded to eHydro by Galveston District (SWG). Each *white* line is the edge of a triangle. Subplot (*c*) shows the results after converting the eHydro TIN to gridded bathymetry. Because the transect concavity allowed for triangulation between the left and right banks, an artificial shoal extends across the entire width of the channel at the survey boundary. (Powered by Esri.)



5.3.2 Erroneous Interpolation across Land

Errors in the gridded bathymetry (and consequently in the calculated shoaling rates) may also occur near bifurcations in the NCF, such as in the vicinity of an island or a channel confluence. This is a consequence of the TIN interpolating across non-channel areas when a bathymetric survey extends down both branches of the bifurcation. An example of this behavior appears in Figure 22, which displays the navigation channel near Drum Island in Charleston Harbor, South Carolina. Figure 22*a* shows the raw survey points and associated TIN from a hydrographic survey in October 2014. Because the survey covered both sides of Drum Island, the TIN triangles cross Drum Island and connect the two branches of the navigation channel. Relatively sparse survey coverage results in bathymetric information from the western channel being used to create gridded bathymetry along the margin of the eastern channel (Figure 22*b*).

Figure 22. Example of TIN creation at a NCF bifurcation in Charleston Harbor, South Carolina. The *white lines* are TIN triangle edges, while the *thick blue lines* are the NCF polygon boundaries. Subplot (*a*) shows an example of a survey which is fully contained within the NCF polygon. When the raster is created from the TIN (*b*), bathymetric data propagates across the bifurcation and may affect the CSAT output. Subplot (*c*) shows the contrasting example of a survey which extends outside the NCF polygon. Although the TIN crosses over the island, clipping by the NCF polygon (*d*) eliminates potential errors in the bathymetry. (Powered by Esri.)



For clarity, it should be noted that the presence of a bifurcation in the NCF does not guarantee that the gridded CSAT bathymetry will contain interpolation errors. An example of nonproblematic interpolation is shown in Figure 22*c* and Figure 22*d*. In February 2022, the raw survey points extend outside the boundaries of the NCF (Figure 22*c*). Even though the TIN triangles still cross Drum Island, any errors resulting from interpolation across land are eliminated when the gridded data are clipped to the NCF boundaries (Figure 22*d*). Consequently, quality checks of CSAT results near channel bifurcations should examine the original eHydro data to determine whether the coverage was adequate to prevent interpolation errors within the navigation channel.

5.4 Dredge Event Identification

CSAT calculates shoaling rates by differencing the time series of elevations at each pixel. To obtain an accurate representation of natural sediment transport rates, it is critical to avoid differencing elevations which are separated by one or more dredging events since the elevation change during the associated time intervals reflects an artificial removal of sediment from the channel. Although after-dredge surveys are often specified by the districts when uploading to eHydro, inconsistent survey naming conventions may result in after-dredge surveys lacking the AD indicator. CSAT determines when dredging occurred using three methods:

1. **Method 1 (direct input from the CSAT user):** the user may optionally designate specific bathymetric surveys as after-dredge surveys.
2. **Method 2 (information from the district):** eHydro file names which include AD are automatically treated as after-dredge surveys during the CSAT calculations.
3. **Method 3 (built-in checks for loss of volume within CSAT):** if the loss of sediment volume between consecutive surveys exceeds a threshold magnitude, the later survey is automatically treated as an after-dredge survey.

These three methods are listed in order of precedence; that is, if a CSAT user explicitly designates the survey type, this input will always override the second and third methods. If the CSAT user does not designate the survey type, but the district labeled the survey as AD, then the survey will automatically be treated as an after-dredge survey regardless of the outcome of the third method.

Because the second method requires input from the district rather than the user, it is not discussed further here. Details on the first and third methods are provided below.

5.4.1 User-Flagged After-Dredge Surveys

In the first method, the user can flag specific surveys as after-dredge surveys before running CSAT. There are several scenarios in which this may be desirable. For example, a district user may realize that an eHydro survey has been mislabeled based on known dredging activity. Other CSAT users may likewise wish to override the survey type based on visual examination of the bathymetry files and the appearance of dredge cuts in surveys which are not labeled AD in eHydro.

Manual designation of the survey type requires editing the file named

```
…/CSAT_distribution/data/CEXYZ/uniform_pts_table.txt
```

which will automatically be included with the data download (Section 2.4). To avoid altering the original file, first make a copy of `uniform_pts_table.txt` in the same directory and rename the copy `SurveyUpdate.txt`. Then, edit the file by opening `SurveyUpdate.txt` as a comma-delimited table in Microsoft Excel or an equivalent spreadsheet editor. Each row of the table corresponds to one survey. Immediately after data download, the `SurveyType` in Column B will be empty, which indicates that CSAT should automatically assign the survey type using the methodology from Section 5.4.2.

Figure 23. Example of **`SurveyUpdate.txt`**. In this hypothetical example, the user has manually designated Row 4 as an after-dredge (AD) survey by typing **`AD`** in the **`SurveyType`** column (Column B).

	A	B	C	D	E
1	SurveyDateStamp	SurveyType	SurveyID	Reach_Name	Reach_ID
2	20130821		BR_01_BRH_20130821_BD_4041_30X	REACH A	BR_01_BRH_1
3	20170308		BR_01_BRH_20170308_CS_4577_40X	REACH A	BR_01_BRH_1
4	20150106	AD	NY_02_ANC_20150106_CS_4240_45X	REACH A	BR_01_BRH_1
5	20180124		BR_01_BRH_20180124_CS_4658_40X	REACH A	BR_01_BRH_1
6	20230124		NY_05_RHF_20230124_OT_5254_45	REACH A	BR_01_BRH_1

To manually force a specific survey type, the user can populate the `SurveyType` column (Column B) with the after-dredge survey designator `AD`. In the hypothetical example of Figure 23, the user has typed `AD` in Cell B4, which will force CSAT to treat the survey in Row 4 as an after-dredge survey. In rows where the `SurveyType` is left blank, CSAT will proceed to Method 2 (checking for `AD` in the district-provided survey ID) and then to Method 3, which is described below.

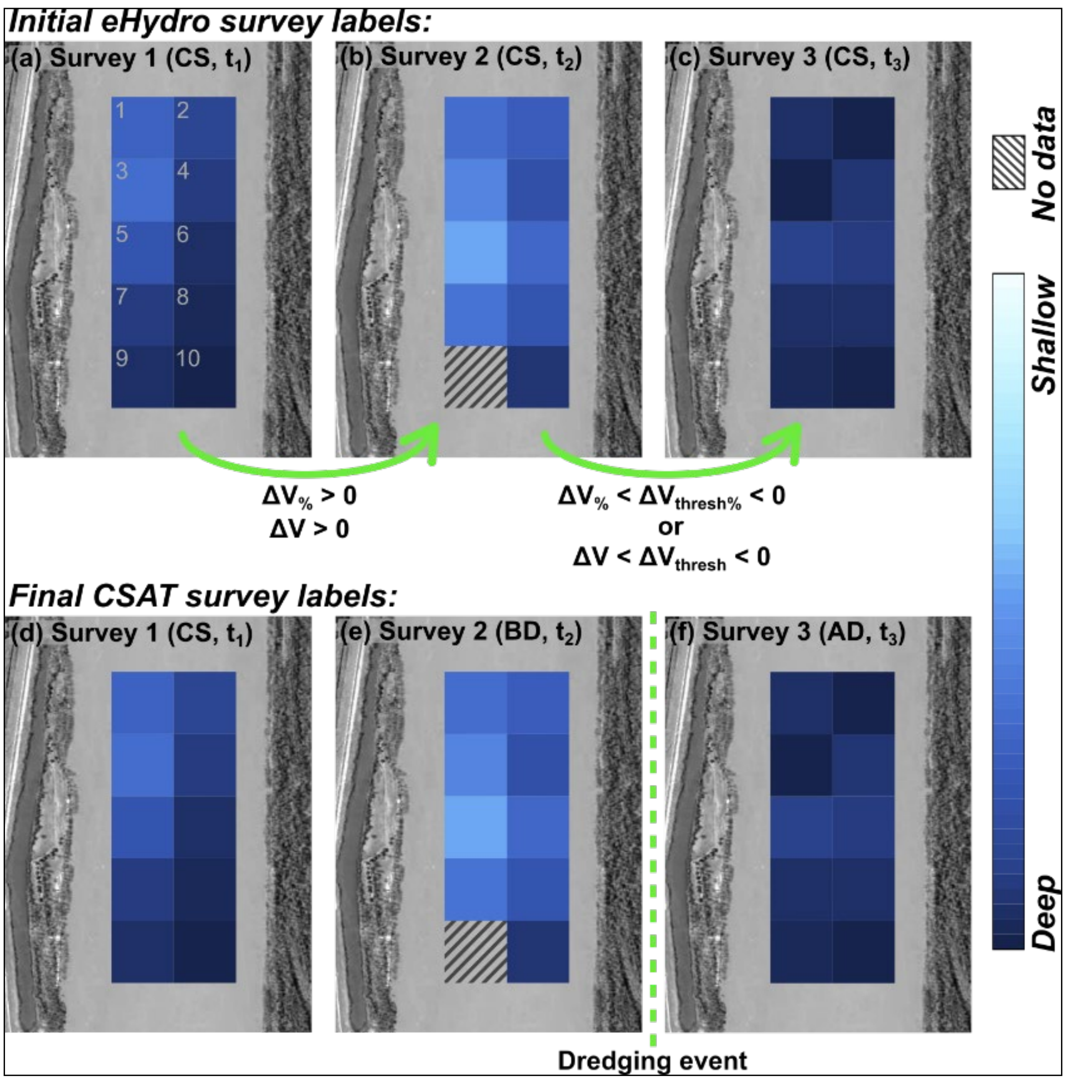
5.4.2 Automatic Volume Loss Checking

The third method is automatic and requires no interaction from the CSAT user, although the user may optionally specify threshold volume loss magnitudes. As an initial step in the calculations, CSAT differences all consecutive surveys and calculates the gain or loss of sediment volume within the reach. If the percent change in volume

$$\Delta V_{\%} = \frac{V\left(t_{j+1}\right) - V\left(t_j\right)}{V\left(t_j\right)} \cdot 100\%, \tag{7}$$

between consecutive surveys is positive (Figure 24*a* and Figure 24*b*), then CSAT assumes that no dredging occurred between t_j and t_{j+1}. However, if $\Delta V_{\%} < \Delta V_{\text{thresh}\%}$ for some prespecified threshold $\Delta V_{\text{thresh}\%} < 0$ (Figure 24*b* and Figure 24*c*), then CSAT assumes that the loss in volume was caused by dredging. In this situation, the later survey is reassigned an AD label (Figure 24*f*).

Figure 24. Example of dredging event identification based on volume changes between surveys. Note exaggeration in survey cell size for illustrative purposes.



The default value of $\Delta V_{\text{thresh\%}}$ is −2.5%. The user may also optionally specify a value of $\Delta V_{\text{thresh\%}}$ within the CSAT batch script using the input parameter `PCTTHRESH`. To set `PCTTHRESH` manually, open `Run_CSAT.bat` in a text editor (see Section 2.5) and locate the following lines:

```
REM Volume change thresholds for dredge event detection
REM set VOLTHRESH=-5000
REM set PCTTHRESH=2.5
```

Deleting the comment designator `REM` from the third line of this code block will replace the default value of `PCTTHRESH` with a user-specified value. Edit the batch script to read

```
REM Volume change thresholds for dredge event detection
REM set VOLTHRESH=-5000
set PCTTHRESH=XYZ                                    ← CHANGE
```

where `XYZ` is the desired percent change threshold. The user should take care to avoid extra spaces before or after the equal sign, as extra spaces will cause CSAT to fail.

Note that the optional, user-supplied value of `PCTTHRESH` within `Run_CSAT.bat` is the *absolute value* of $\Delta V_{\text{thresh\%}}$; that is,

$$\texttt{PCTTHRESH} = \left| \Delta V_{\text{thresh\%}} \right| > 0 \tag{8}$$

Therefore, the user should always input a positive number when editing the batch script. CSAT will handle the sign convention internally.

In addition to checking the percent change in sediment volume, CSAT also searches for dredging events by checking the magnitude of dimensional volume change. If the volume difference between consecutive surveys

$$\Delta V = V\left(t_{j+1}\right) - V\left(t_j\right), \tag{9}$$

is positive (Figure 24*a* and Figure 24*b*), then CSAT assumes that no dredging occurred between t_j and t_{j+1}. However, if $\Delta V < \Delta V_{\text{thresh}}$ for some prespecified threshold $\Delta V_{\text{thresh}} < 0$ (Figure 24*b* and Figure 24*c*), then CSAT assumes that the loss in volume was caused by dredging. In this situation, the later survey is reassigned an AD label (Figure 24*f*), regardless of how the district labeled the survey in eHydro.

The default value of ΔV_{thresh} is -10^{10} cy. The user may optionally specify a different value of ΔV_{thresh} using the `VOLTHRESH` parameter in `Run_CSAT.bat`. To set `VOLTHRESH`, open `Run_CSAT.bat` in a text editor (see Section 2.5) and locate the following lines:

```
REM Volume change thresholds for dredge event detection
REM set VOLTHRESH=-5000
```

In this block of code, the first line is a header, while the second line will set the value of `VOLTHRESH` if the comment designator `REM` is deleted. Edit the batch script to read

```
REM Volume change thresholds for dredge event detection
set VOLTHRESH=-XYZ                                  ← CHANGE
```

where `-XYZ` is the desired volume threshold in cubic yards. The user should take care to avoid any spaces before or after the equal sign, as extra spaces will cause CSAT to fail. Because dredging results in a loss of volume, the volume threshold in the batch script should always be a negative number; that is,

$$\texttt{VOLTHRESH} = \Delta V_{\text{thresh}} < 0 . \tag{10}$$

The values of `PCTTHRESH` and `VOLTHRESH` set within `Run_CSAT.bat` (or the default values, if `PCTTHRESH` and `VOLTHRESH` are not set by the user) are applied uniformly to all reaches within a district. This may result in missed or erroneously flagged after-dredge events if there are significant differences in the reaches' horizontal footprints. For example, if ΔV_{thresh} is set to a large-magnitude value representative of typical dredging volumes in large-footprint reaches, dredging events in small-footprint reaches may be missed by the CSAT algorithm. Meanwhile, if ΔV_{thresh} is set to a small-magnitude value representative of typical dredging volumes in small-footprint reaches, natural scour events may be erroneously flagged as after-dredge surveys in large-footprint reaches.

To compensate for these potential issues, the user has the option of specifying PCTTHRESH or VOLTHRESH on a reach-by-reach basis within the file named

```
…/CSAT_distribution/data/CEXYZ/reach_table.txt
```

which will automatically be included with the data download (Section 2.4). To edit the file, open reach_table.txt as a comma-delimited table in Microsoft Excel or an equivalent spreadsheet editor. Prior to editing, this file contains eleven columns (Column A through Column K) storing information about each reach, including the reach ID, maintained depth, and geographic projection (see Section 3.1.3 for column descriptions). To set unique values of PCTTHRESH for each reach, add a column labeled VolPercent in the first empty column of reach_table.txt and populate it with the desired threshold percentages. Similarly, to set unique values of VOLTHRESH for each reach, add a column labeled VolElevChange in the first empty column of reach_table.txt and populate it with the desired threshold volumes. An example is shown in Figure 25.

Figure 25. Example of **reach_table.txt** with columns named **VolPercent** and **VolElevChange** added to store unique values of **PCTTHRESH** and **VOLTHRESH** for individual reaches. Note that Columns *C* through I are not shown to facilitate visualization.

	A	B	J	K	L	M
1	Reach_ID	Sheet_Name	CCR_line_2	raster_cel	VolPercent	VolElevChange
2	BR_01_BRH_1	BAY RIDGE AND RED HOOK CHANNELS	REACH A	10	5	-15000
3	BR_01_BRH_2	BAY RIDGE AND RED HOOK CHANNELS	REACH B	10	2.5	-20000
4	BR_01_BRH_3	BAY RIDGE AND RED HOOK CHANNELS	REACH C	10	5	-12000
5	BR_01_BRH_4	BAY RIDGE AND RED HOOK CHANNELS	REACH D	10	5	-14000
6	BR_01_CRK_1	Browns Creek	Reach_1	10	2.5	-8000
7	BR_01_CRK_2	Browns Creek	Reach_2	10	2.5	-5000
8	BR_01_CRK_3	Browns Creek	Reach_3	10	10	-10000
9	BT_01_BUT_1	BUTTERMILK CHANNEL	REACH A	10	5	-13000

5.5 Merging Surveys

Depending on district-specific surveying practices, a district may upload multiple surveys in close succession, with each survey only covering a portion of the channel reach. Often, this is due to the large size of reaches being managed by the district. In such cases, CSAT can merge these partial surveys into a single composite survey represented by a single timestamp (i.e., the earliest date of the partial surveys).

CSAT merges surveys by identifying pairs of consecutive surveys which fulfill three criteria. First, the survey timestamps must be separated by less than some predefined threshold, that is,

$$t_{N+1} - t_N < \Delta t_{\text{thresh}} . \tag{11}$$

The default value of Δt_{thresh} is 10 days. Second, all overlapping measurements at timestamps t_N and t_{N+1} must be identical

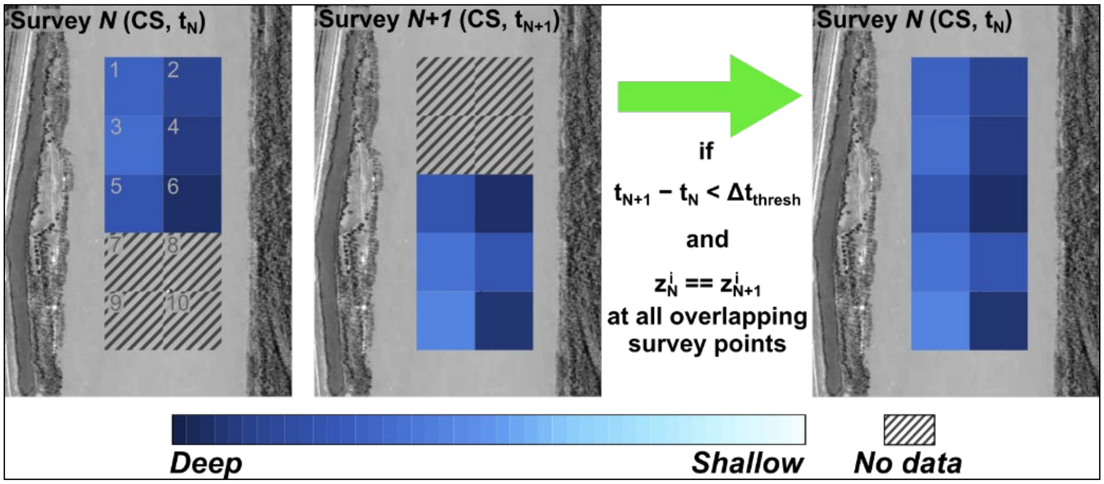
$$z_N^i == z_{N+1}^i , \tag{12}$$

for all values of i in the reach, unless z_N^i was not surveyed or z_{N+1}^i was not surveyed. Finally, the survey types must not cross a dredging event, which is determined using the cases in Table 4. If Equation (11) and Equation (12) are both satisfied and the survey types are acceptable for merging, then the two surveys are merged into a single survey with a timestamp of t_N. An example of survey merging is shown in Figure 26. This process is repeated iteratively until all temporally proximate surveys meeting the three criteria have been merged.

Table 4. Summary of scenarios in which consecutive surveys can and cannot be merged into a single survey.

t_N survey type	t_{N+1} survey type	OK to merge?
AD	AD	True
AD	BD	False
AD	CS	False
BD	AD	False
BD	BD	True
BD	CS	False
CS	AD	False
CS	BD	True
CS	CS	True

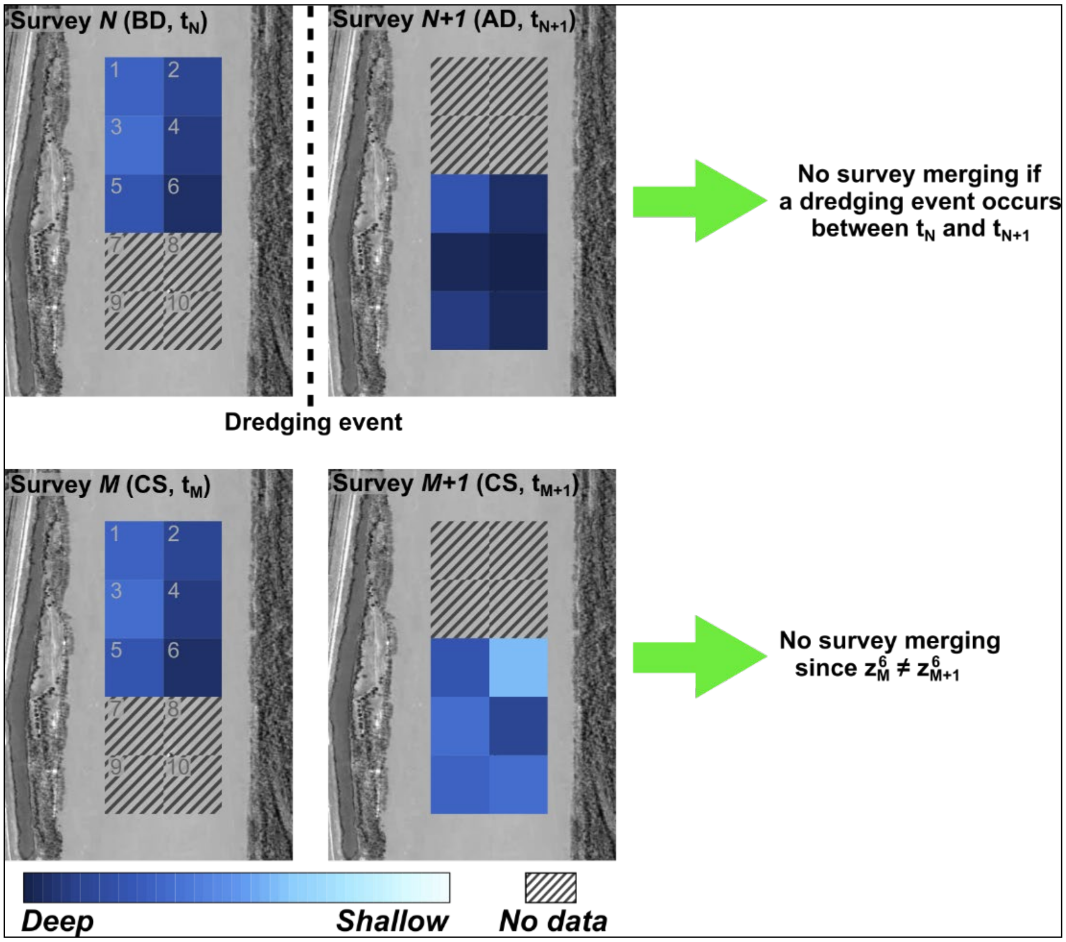
Figure 26. Example of a scenario in which two surveys are merged into a single survey within CSAT. Note that the two overlapping survey cells (5 and 6) have identical depths for both surveys.



As a further illustration, two example scenarios in which surveys would *not* be merged are shown in Figure 27. In the upper row of the figure, a before-dredge survey occurs at the north end of the reach at time t_N. The south end of the reach is then dredged, and an after-dredge survey of this southern portion occurs at t_{N+1}. Even though Equation (11) and Equation (12) are both satisfied (note that the two overlapping survey cells, labeled Cells 5 and 6, have identical depths in both surveys), the occurrence of a dredging event automatically means that the surveys will not be merged. The lower row of Figure 27 illustrates a scenario in which Equation (11) is satisfied, and the survey types (both CS) are acceptable to merge. However, because the depth has changed at one of the overlapping survey cells, no merging is performed on these two surveys.

Although the default window for survey merging is Δt_{thresh} = 10 days, CSAT users can optionally alter the acceptable window length by setting the `date_merge_window` parameter in the batch script to an integer of their choosing. Setting `date_merge_window` to a value of 0 will limit CSAT to only merge surveys that have the same date. The merging rules in Table 4 will still be applied regardless of the `date_merge_window` value.

Figure 27. Examples of scenarios in which consecutive surveys are *not* merged into a single survey. In the *upper row*, the two surveys are separated by a dredging event and cannot be merged. In the *lower row*, the elevation of Cell 6 differs between timestamps t_M and t_{M+1}, so CSAT does not merge the surveys.



5.6 Initial Survey Pair Rate Calculations

CSAT's forecasting algorithm predicts future dredging volumes using a representative historical shoaling rate at each pixel. This representative shoaling rate is determined by averaging the measured shoaling rates from all usable survey pairs in the eHydro bathymetry. The methodology for identifying survey pairs is described in this section.

For a reach with N bathymetric surveys, the total number of possible survey pairs is given by

$$\text{total survey pairs} = \frac{N!}{2! \cdot (N-2)!}, \qquad (13)$$

where the ! symbol indicates a factorial. However, as described in Section 5.4, shoaling rates from surveys separated by one or more dredging events do not represent natural sediment transport processes and must be omitted to avoid artificially lowering the representative shoaling rate. Consequently, if any dredging events occurred over the duration of the bathymetric timestack, the number of usable survey pairs will be smaller than the value given by Equation (13).

To determine the final set of survey pairs used for analysis, CSAT creates a list of all possible survey combinations and then discards any pairs which are separated by one or more dredging events. An example is shown in Figure 28 and Table 5. For the initial set of 6 bathymetric surveys in Figure 28, there are 15 possible survey pairs (Equation 13). However, the presence of dredging events between t_2 and t_3 and between t_5 and t_6 dictates that not all 15 pairs will generate usable shoaling rates. For example, pairing Survey 2 and Survey 4 is not physically reasonable because sediment was artificially removed from the channel between these two timestamps. After discarding all survey pairs which cross a dredging event, only four survey pairs remain (Table 5): Surveys 1 and 2, Surveys 3 and 4, Surveys 3 and 5, and Surveys 4 and 5. Note that due to missing data at the 9th survey cell, the number of survey pairs is further reduced at this particular location; only a single survey pair (Surveys 3 and 4) yields a usable shoaling rate (Table 5).

Figure 28. Example of the 6 bathymetric surveys for identifying candidate survey pairs. Dredging events occur at the *dashed vertical lines*. The survey cell indices appear in the *leftmost* frame.

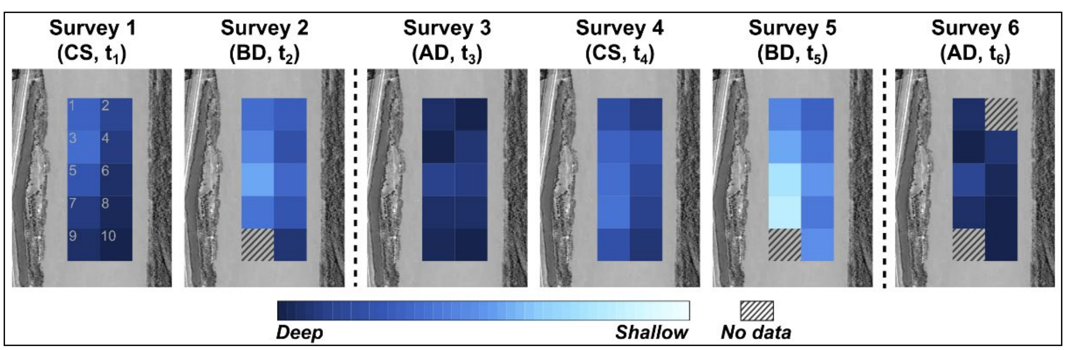


Table 5. Pairs of surveys with valid shoaling rates for the example in Figure 28.

Survey cell in Figure 28	Candidate survey pairs and associated shoaling rates
i = 1, 2, 3, 4, 5, 6, 7, 8, 10	$(t_1, t_2) \rightarrow R^i_{1,2}$ $(t_3, t_4) \rightarrow R^i_{3,4}$ $(t_3, t_5) \rightarrow R^i_{3,5}$ $(t_4, t_5) \rightarrow R^i_{4,5}$
i = 9	$(t_3, t_4) \rightarrow R^9_{3,4}$

Beyond CSAT's automatic routine for eliminating pairs of surveys which span dredging events, users can manually designate surveys which should not be used to calculate shoaling. Any survey pairs which contain one of the user-indicated survey indices will also be discarded. This manual survey omission is achieved by editing the file named

```
…/CSAT_distribution/data/CEXYZ/SurveyUpdate.txt
```

which is created by copying and renaming `uniform_pts_table.txt` (see Section 5.4.1). To edit the file, open `SurveyUpdate.txt` as a comma-delimited table in Microsoft Excel or an equivalent spreadsheet editor. Each row of the table corresponds to one survey. Changing values in the column labeled `Use` (Column G) from one (1) to zero (0) will tell CSAT that the survey should not be used. An example is shown in Figure 29.

Figure 29. Example of `SurveyUpdate.txt`. In Rows 3 and 4, Values in the `Use` column (Column G) have been set to zero (0), which tells CSAT to omit these surveys when calculating shoaling rates.

	A	B	C	D	E	F	G	H	I
1	SurveyDateStamp	SurveyType	SurveyID	Reach_Name	Reach_ID	Cell_Size	Use	pctCoverage	reach_name
2	20130821		BR_01_BRH_20130821_BD_4041_30X	REACH A	BR_01_BRH_1	10	1	3.92	BR_01_BRH
3	20170308		BR_01_BRH_20170308_CS_4577_40X	REACH A	BR_01_BRH_1	10	0	100	BR_01_BRH
4	20150106		NY_02_ANC_20150106_CS_4240_45X	REACH A	BR_01_BRH_1	10	0	5.28	BR_01_BRH
5	20180124		BR_01_BRH_20180124_CS_4658_40X	REACH A	BR_01_BRH_1	10	1	100	BR_01_BRH
6	20230124		NY_05_RHF_20230124_OT_5254_45	REACH A	BR_01_BRH_1	10	1	20.66	BR_01_BRH

Finally, for each candidate survey pair and each survey cell (e.g., Table 5), the volumetric shoaling rate (in cubic yards per year) is calculated as

$$R^i_{j,k} = \frac{z^i_k - z^i_j}{t_k - t_j} \cdot \Delta x \cdot \Delta y \,, \tag{14}$$

where t_j and t_k are the survey timestamps ($j < k$), z^i is the elevation of the i^{th} survey cell at the time indicated by the subscript, and Δx and Δy are the horizontal dimensions of a single survey cell. Following standard USACE survey conventions, CSAT always assumes that $\Delta x = \Delta y = 10$ ft. Applying Equation (14) for all candidate survey pairs yields a set of shoaling rates $\{R^i_{j,k}\}$ with cardinality M.

5.7 Representative Shoaling Rates

The CSAT forecasting algorithm requires the set of shoaling rates to be reduced to a single representative shoaling rate for each survey cell. CSAT users may choose between four methods for generating these representative values, which are described in the following sections.

5.7.1 Simple Averaging

The first available forecasting method involves the use of a simple average shoaling rate. This is selected in `Run_CSAT.bat` by setting `RASTER_TYPE` to `AvgRate_ftPerYr` (see Section 3.2.2). For the general case, the simple average at survey cell *i* is calculated as

$$\overline{R^i} = \frac{1}{M} \sum R^i_{j,k} \ , \qquad (15a)$$

where the sum includes all M members of $\{R^i_{j,k}\}$. Continuing the example from Figure 28, the simple average shoaling rate for the first row of Table 5 is given by

$$\overline{R^i} = \frac{1}{4}\left(R^i_{1,2} + R^i_{3,4} + R^i_{3,5} + R^i_{4,5}\right). \qquad (15b)$$

Because only one candidate survey pair is available for the ninth survey cell, its simple average shoaling rate is equal to $R^9_{3,4}$.

5.7.2 Weighted Averaging

The second forecasting method is a weighted arithmetic mean, which is calculated such that longer observation intervals carry greater weight. This is selected in `Run_CSAT.bat` by setting `RASTER_TYPE` to `WeightedAvgRate_ftPerYr` (see Section 3.2.2) For the i^{th} survey cell, the calculation is written symbolically as

$$\left(\overline{R^i}\right)_W = \frac{\sum\left(R^i_{j,k} \cdot \Delta t_{j,k}\right)}{\sum \Delta t_{j,k}}, \tag{16a}$$

where $\Delta t_{j,k} = t_k - t_j$. As in the simple average (Section 5.7.1), the sums in Equation (16a) include all combinations of *j* and *k* in $\left\{R^i_{j,k}\right\}$. Applying Equation (16a) to the first row of Table 5 yields

$$\left(\overline{R^i}\right)_W = \frac{R^i_{1,2} \cdot \Delta t_{1,2} + R^i_{3,4} \cdot \Delta t_{3,4} + R^i_{3,5} \cdot \Delta t_{3,5} + R^i_{4,5} \cdot \Delta t_{4,5}}{\Delta t_{1,2} + \Delta t_{3,4} + \Delta t_{3,5} + \Delta t_{4,5}}. \tag{16b}$$

Assuming the surveys in Figure 28 are evenly spaced in time, $\left(\overline{R^i}\right)_W$ will be more heavily weighted towards $R^i_{3,5}$ due to measurement over a longer time interval. Because only one candidate survey pair is available for the ninth survey cell, the weighted average shoaling rate at this cell becomes $\left(\overline{R^9}\right)_W = R^9_{3,4}$.

5.7.3 Endpoint Averaging

The third method involves forecasting using an end point average, which is selected in `Run_CSAT.bat` by setting `RASTER_TYPE` to `EndpointAvgRate_First_Last_ftPerYr` (see Section 3.2.2). This involves separating the bathymetric data into blocks of surveys separated by dredging events. For the example of Figure 28, notice that there are three dredge-separated survey blocks: one block from t_1 to t_2, a second block from t_4 to t_5, and a final block containing the survey at t_6. Calculating the end point average for the first row of Table 5 involves averaging the shoaling rates corresponding to the first and last data-containing surveys in each block:

$$\left(\overline{R^i}\right)_{EP} = \frac{R^i_{1,2} + R^i_{3,5}}{2}, \; i \neq 9. \tag{17a}$$

Notice that the third survey block (i.e., the t_6 survey) has been omitted from Equation (17a) due to the absence of candidate survey pairs. For Cell 9, the end point rate for the second survey block is $R^9_{3,4}$ due to the lack of survey data at t_5. After accounting for the absent shoaling rate for the first survey block (Table 5), the endpoint average for Cell 9 reduces to:

$$\left(\overline{R^9}\right)_{EP} = R^9_{3,4} \ . \tag{17b}$$

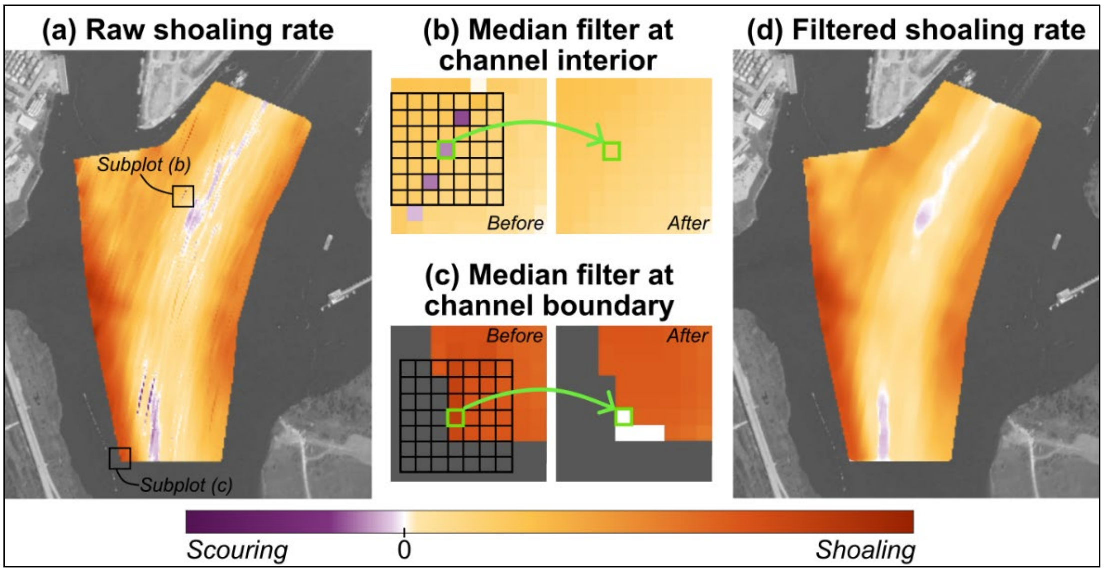
For the general case containing an arbitrary number of dredging events Q, the numerator of Equation (17a) may contain as many as $Q + 1$ values, which correspond to the end point shoaling rates of each dredge-separated survey block. However, the number of included shoaling rates may be lower than $Q + 1$ if a survey block contains no candidate survey pairs (e.g., if the survey block contains only one survey, such as the last frame of Figure 28). The denominator of Equation (17a) will always equal the number of dredge-separated survey blocks containing at least one usable survey pair.

5.7.4 Weighted Average with Spatial Filtering

The final CSAT forecasting method is a spatially filtered weighted average. This is selected in `Run_CSAT.bat` by setting `RASTER_TYPE` to `WeightedAvgRate_MedFilt_ftPerYr` (see Section 3.2.2). The method begins with precalculated values of $\left(\overline{R^i}\right)_W$ from Equation (16a) for all survey cells. The values of $\left(\overline{R^i}\right)_W$ are then smoothed using the following median filtering algorithm. First, a 7 × 7 square kernel is defined (Figure 30*b*). This kernel is centered on the *i*th point in space, and the median value for the set of 49 survey points intersecting the kernel is calculated and assigned to the central point as $\left(\overline{R^i}\right)_{W,f}$.

At the time of user guide publication, the native Python functions used for spatial filtering defaulted to zero-padding the data at any locations where the kernel extended outside the bounds of the reach grid (Figure 30*c*, *left frame*). Consequently, values of $\left(\overline{R^i}\right)_{W,f}$ were artificially set to zero if more than half of kernel cells were outside the channel boundary (Figure 30*c*, *right frame*). Although the filter provided the desired smoothing in the channel interior, pixels near reach corners are often erroneously assigned a shoaling rate of zero. This is a known error which may be corrected in future versions of CSAT, provided that the native Python functions are corrected.

Figure 30. Example of spatial filtering the CSAT shoaling rates, as described in Section 5.7.4. Subplot (*a*) shows precalculated values of $\left(\overline{R^i}\right)_W$, with noise visible. The data are spatially filtered by substituting the median value of a 7 × 7 kernel centered on the survey cell of interest (subplot *b*). If the kernel extends beyond the channel boundary (subplot *c*), any survey cells with no data are treated as having a shoaling rate of zero for purposes of calculating the median. When more than half of kernel cells are outside the channel boundary, as shown in the example, the filtered shoaling rate will be set to zero. Subplot (*d*) shows the final values of $\left(\overline{R^i}\right)_{W,f}$. (Map data: Google Earth.)



5.7.5 Automatically Enforced Upper and Lower Shoaling Rate Limits

For each of the averaging methods described in Sections 5.7.1 through 5.7.4, CSAT automatically bounds the representative shoaling rates to fall within predefined upper and lower limits. Specifically, if the calculated value of $\overline{R^i}$, $\left(\overline{R^i}\right)_W$, $\left(\overline{R^i}\right)_{EP}$, or $\left(\overline{R^i}\right)_{W,f}$ exceeds +30 vertical ft/yr, then the rate is automatically reset to 30 ft/yr. Similarly, if the pixel is calculated to scour at an average rate which is more negative than −15 vertical ft/yr, then the rate is automatically reset to −15 ft/yr. This follows from the assumption that shoaling rates more than 30 ft/yr and scouring rates in excess of −15 ft/yr are physically unreasonable, and the large magnitude values must be the result of poor-quality bathymetric measurements or unidentified dredging events.

The automatic upper and lower bounds on $\overline{R^i}$, $\left(\overline{R^i}\right)_W$, $\left(\overline{R^i}\right)_{EP}$, and $\left(\overline{R^i}\right)_{W,f}$ are hard coded into CSAT and cannot be changed using `Run_CSAT.bat`.

Altering these values requires the user to edit the underlying source code `CSAT.py`, which is not recommended for new CSAT users.

5.8 Pixelwise Forecasting

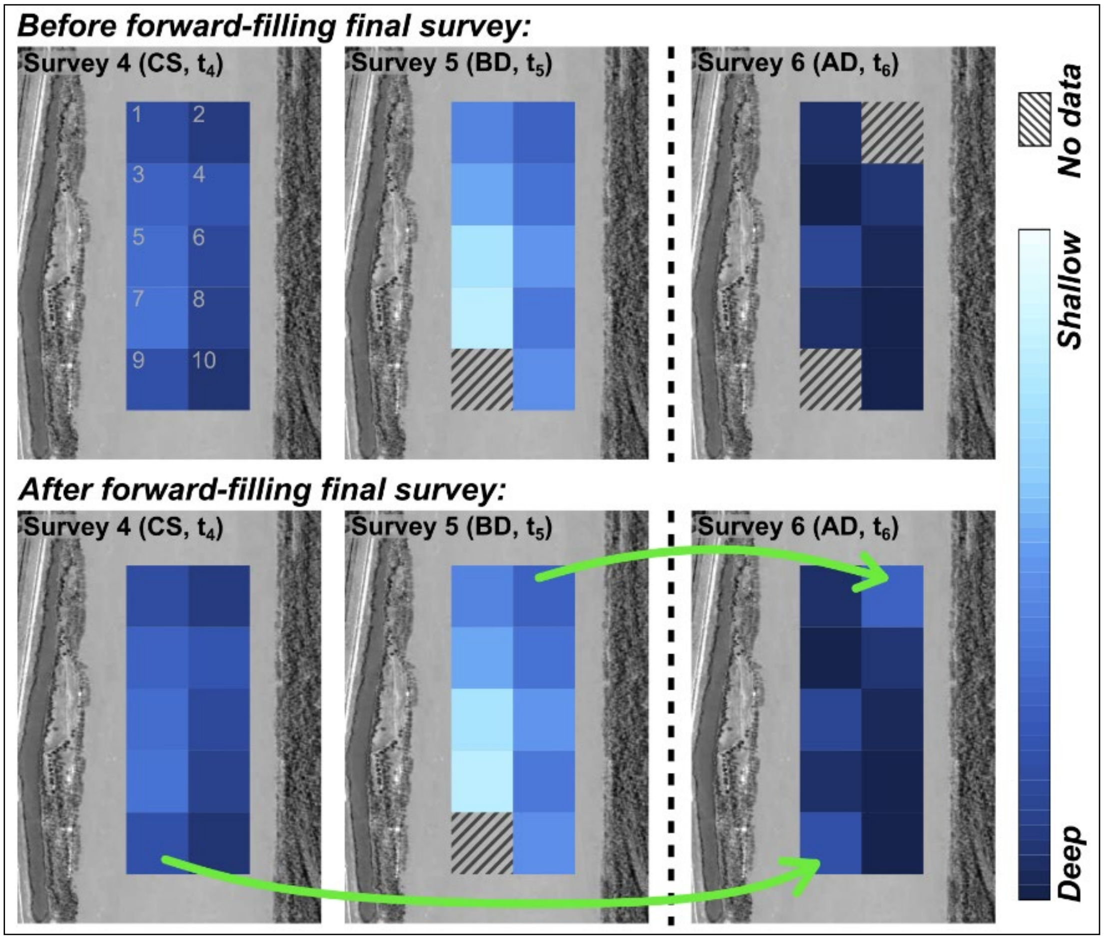
After calculating a representative shoaling rate for each pixel, the last step in the CSAT algorithm is to forecast future sediment volumes in the channel. This forecasting is achieved by forward-filling the final survey and then linearly projecting the elevation to future dates. The details are discussed in the following sections.

5.8.1 Forward-Filling the Last Survey

The “initial conditions” for the CSAT forecast correspond to the timestamp of the last bathymetric survey in eHydro (or the last bathymetric survey in the analysis window if the user designated a specific end date; see Section 3.2.1). However, if the last bathymetric survey had incomplete spatial coverage, it is necessary to fill in the missing bathymetric survey cells before proceeding with the forecast. This is achieved by forward-filling gaps in the last survey using information from the previous surveys.

The procedure for forward-filling is illustrated in Figure 31, which shows the last three timestamps from Figure 28. Notice that a dredging event occurs at the dashed black line between t_5 and t_6. In this example, Survey 6 is the last survey in the bathymetric dataset and will be used as the initial condition for the CSAT forecast. However, Survey 6 contains no data for the second and ninth survey cells, which makes it impossible to predict future elevations at these locations. To compensate for this issue, CSAT sets $z_6^2 = z_5^2$ since Survey 5 is the most recent survey containing a measurement at Cell 2. The most recent measurement at Cell 9 occurs during Survey 4, so CSAT sets $z_6^9 = z_4^9$. This yields a complete bathymetric surface which can be input into the forecasting algorithm. Images of the forward-filled final surveys are included in the CSAT output; see Section 4.9.

Figure 31. Example of forward-filling the final survey prior to forecasting. If any pixels from the final survey lack data, the most recent elevation measurement is substituted. This forward projection is allowed to cross dredging events.



For clarity, it is emphasized that the forward-filling routine is the only step in the CSAT algorithm in which information is allowed to cross a dredging event (shown by the dashed black line in Figure 31). The underlying assumption is that the district omitted these cells from the after-dredge survey because it was known *a priori* that dredging did not occur at these locations. For example, if the dredging contract did not include Cells 2 and 9 in Figure 31, then the district would have no reason to survey these regions during the after-dredge survey, and the forward propagation of the pre-dredging elevation is reasonable. For all other steps in the CSAT algorithm, including survey pairing for shoaling rate calculation (Section 5.6), the analysis is not allowed to cross dredging events.

5.8.2 Generating the Forecast

Although many studies suggest that shoaling should decelerate as the channel infills with sediment (Galvin 1982; Vicente and Uva 1984; Babcock 1989; Kraus and Larson 2001; Larson and Kraus 2001; Kraus and Larson 2003; Rosati and Kraus 2009), CSAT simplifies the forecasting calculations by assuming that the shoaling rate at any given pixel is constant through time. The only exception is if additional shoaling would cause the pixel to become subaerially exposed, in which case the elevation of the pixel is set to zero (relative to the local datum). Consequently, after applying the forward-filling routine to generate an initial elevation surface, the elevation at the i^{th} survey cell is simply calculated as

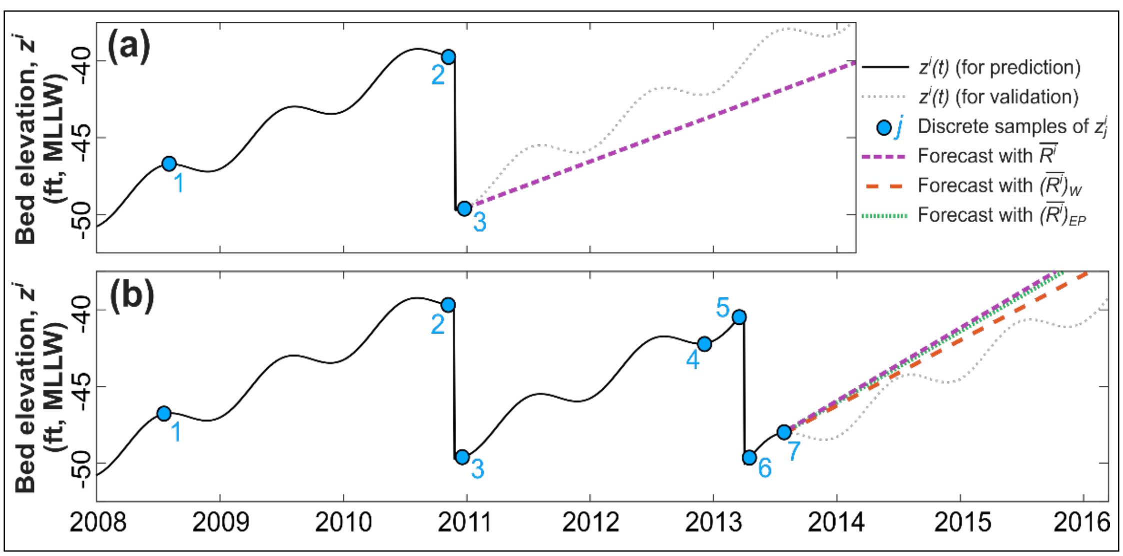
$$z^i\left(t_{final}+\Delta t\right)= \min\left[z^i\left(t_{final}\right)+\overline{R^i}\cdot\Delta t\cdot\left(\frac{0.27\,\text{ft}}{\text{cy}}\right)\ ,\ 0\right], \tag{18}$$

with z^i measured in feet relative to the survey datum, t_{final} and Δt measured in years, and $\overline{R^i}$ measured in cubic yards per year as defined in Equation (18). The conversion factor of 0.27 ft/cy assumes a standard bathymetric grid with $\Delta x = \Delta y = 10$ ft. In Equation (18), the simple average shoaling rate $\overline{R^i}$ may be replaced with the weighted average $\left(\overline{R^i}\right)_W$, the endpoint average $\left(\overline{R^i}\right)_{EP}$, or the spatially filtered weighted average $\left(\overline{R^i}\right)_{W,f}$ (see Sections 5.7.1 to 5.7.4) depending on the method specified by the user in `Run_CSAT.bat`.

In many coastal systems, shoaling rates vary seasonally due to summer versus winter meteorological conditions (e.g., Ranasinghe and Pattiaratchi 2003; Tidwell and Wang 2004; Williams and Kraus 2011; Fortunato et al. 2021) or the effect of freshwater discharge on the strength and position of the turbidity maximum (e.g., Allen et al. 1977; Bale et al. 1985; Kostaschuk and Atwood 1990; Uncles et al. 2006; Toublanc et al. 2016). However, CSAT's linear forecasting is not designed to capture these seasonal variations due to its dependence on a time-averaged shoaling rate for each pixel. Depending on the timing and quantity of previous bathymetric surveys, an oscillatory sediment deposition rate may result in either under- or overprediction of shoaling, and care should be taken when interpreting the CSAT output in channels which are known to display a strong seasonality.

An illustration of CSAT's linear forecasting for a hypothetical channel with seasonal variations in the natural shoaling rate appears in Figure 32. For the example in Figure 32*a*, the survey data are comprised of a condition survey during a peak in sediment deposition (j = 1), a before-dredge survey during period of scour (j = 2), and an after-dredge survey shortly thereafter (j = 3). Because of the survey timing, the only shoaling rate that can be calculated is the crest-to-trough rate $R^i_{1,2}$; note that in this situation, $\overline{R^i} = \left(\overline{R^i}\right)_W = \left(\overline{R^i}\right)_{EP} = R^i_{1,2}$. Since $R^i_{1,2}$ is lower than the long-term average shoaling rate and the initial condition for the forecast (j = 3) falls within a seasonal trough, the forecast consistently underpredicts the future bed elevation. Additionally, the error in prediction is magnified when the forecasting interval $\Delta t = N + 5$ years for integer values of N because CSAT's linear forecast cannot represent the midyear peaks in deposition.

Figure 32. Illustration of potential errors associated with a linear shoaling forecast at a pixel with strong seasonality. Subplot (a) is an example in which future bed elevations are underpredicted; note that $\overline{R^i}$, $\left(\overline{R^i}\right)_W$, and $\left(\overline{R^i}\right)_{EP}$ are identical due to the configuration of the samples. In subplot (b), the results accurately predict bed elevation for a forecasting interval of exactly Δt= 1 year, but performance is poor at intervals of Δt= 6 months.



In certain forecasting scenarios, the issues illustrated by Figure 32*a* may be improved by increasing the number of surveys, varying the timing of surveys throughout the year, or selecting an appropriate averaging method. Figure 32*b* continues the example of Figure 32*a* by adding four additional surveys to the dataset, with the representative shoaling rate now calculated from the set of rates $\left\{R^i_{1,2}, R^i_{3,4}, R^i_{3,5}, R^i_{4,5}, R^i_{6,7}\right\}$. Although each of $\overline{R^i}$, $\left(\overline{R^i}\right)_W$, and $\left(\overline{R^i}\right)_{EP}$ overpredict the known bed elevation, the weighted average can produce forecasts with comparatively small error at forecasting intervals of Δt = 1 year and Δt = 2 years. However, forecasting at the intervening 6-month intervals is still inaccurate regardless of which averaging method is selected, suggesting that CSAT's most appropriate usage in systems with strongly seasonal behavior may be for annual forecasting.

6 Conclusions and Recommendations

6.1 Conclusions

The CSAT calculates channel shoaling volumes using historical channel surveys and uses the shoaling rates to predict future dredging volumes. The tool leverages ongoing efforts by the USACE to standardize the way hydrographic surveys are uploaded and processed through its eHydro program. The CSAT algorithm estimates future localized shoaling rates through a hindcasting algorithm based on historic shoal volumes, and it is designed to incorporate new hydrographic surveys as they become available. The addition of hydrographic surveys ensures that the shoaling rate predictions are continually updated. Consequently, trends from seasons or other dredging maintenance changes are incorporated into the shoaling analysis.

The CSAT output files provide valuable data needed for various applications, which are listed below:

- Shoaling rate grids can be used to identify hot spots or areas of increased sedimentation.
- Constraining the time period to align with a specific event more closely (extratropical storm, rainfall or drought periods, dredge schedule change or dredge type change) may lend insight into the impacts that these events caused to the sedimentation within the channel.
- Volume tables with five-year predictions at incrementing depths provide information within the Channel Portfolio Tool (CPT) to support prioritization of maintenance dredging needs during dredge planning.

6.2 Recommendations

Since CSAT uses historical hydrographic surveys to predict future shoaling rates, it is recommended that management implement survey protocols to survey the full channel on a recurring basis. All surveys, including condition, before-dredge, and after-dredge surveys, should then be uploaded to eHydro. Finally, although uploading pre-2012 surveys to eHydro is not required under USACE regulations, districts may experience improvements in CSAT accuracy by adding older data to the eHydro system.

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Mathematical Notation

Abbreviation or Symbol	Meaning	Dimensions (if applicable)	CSAT units (if applicable)
i	spatial index	–	–
j,k	time indices	--	–
M	cardinality (size) of a set of values	--	–
nPoints	the number of bathymetric survey points contained within a CSAT input file.	[-]	–
nTime	the number of bathymetric survey timestamps represented within a CSAT input file.	[-]	–
R	general symbol for shoaling rate	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
$R^i_{j,k}$	volumetric shoaling rate at point i, calculated from the surveys timestamped t_j and t_k (with $j < k$)	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
$\overline{R^i}$	representative shoaling rate at point i, which is calculated using a simple average of all candidate survey pairs (see Section 5.7.1)	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
$\left(\overline{R^i}\right)_{EP}$	representative shoaling rate at point i, which is calculated by averaging the endpoint rates (see Section 5.7.3)	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
$\left(\overline{R^i}\right)_{W}$	representative shoaling rate at point i, which is calculated using a time-weighted average of all candidate survey pairs (see Section 5.7.2)	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
$\left(\overline{R^i}\right)_{W,f}$	representative shoaling rate at point i, which is calculated using a weighted average with spatial filtering (see Section 5.7.4)	$[L^3T^{-1}]$ or $[LT^{-1}]$	cy/yr or ft/yr (specified in text)*
t	time	[T]	date (when referring to individual survey) or days (when referring to time elapsed between surveys)
Δt	a time interval	[T]	days, months, or years, as required to maintain dimensional homogeneity
Δt_{thresh}	a threshold time interval used to determine whether two temporally proximal surveys can be merged into a single survey.	[T]	days
V	volume	$[L^3]$	cubic yards (cy)
ΔV	change in volume between consecutive surveys	$[L^3]$	cubic yards (cy)
$\Delta V_{\%}$	percent change in volume between consecutive surveys	[-]	percentage
ΔV_{thresh}	a threshold change in volume used for identifying unlabeled dredging events	$[L^3]$	cubic yards (cy)
$\Delta V_{\text{thresh\%}}$	a threshold percent change in volume used for identifying unlabeled dredging events	[-]	percentage
Δx	survey cell size measured east-west (assumed to be 10 ft following standard USACE survey conventions)	[L]	feet
Δy	survey cell size measured north-south (assumed to be 10 ft following standard USACE survey conventions)	[L]	feet
z^i_j	elevation at point i and time j	[L]	feet
$\{\,\}$	denotes a mathematical set of one or more values	–	–
!	factorial	–	–

* For a standard 10 ft-by-10 ft bathymetric grid, a per-pixel volumetric shoaling rate in cy/yr can be converted to a vertical shoaling rate in ft/yr using the conversion factor 1 cy/yr = 0.27 ft/yr.

Abbreviations

AD	After-dredge survey
BD	Before-dredge survey
CS	Condition survey
CPT	Channel Portfolio Tool
CSAT	Corps Shoaling Analysis Tool
CSV	Comma-separated values
ERDC	Engineer Research and Development Center
i	Spatial index
j,k	Time indices
M	Cardinality (size) of a set of values
MLG	Mean Low Gulf
MLLW	Mean Lower Low Water
MLT	Mean Low Tide
MLW	Mean Low Water
MVN	New Orleans District
NAB	Baltimore District
NCF	National Channel Framework
O&M	Operations & Maintenance
R	Shoaling rate
SPQ	Summary Planning Quantity
SWG	Galveston District
TIN	Triangulated irregular network

USACE	US Army Corps of Engineers
UTM	Universal Transverse Mercator

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED: START DATE	3. DATES COVERED: END DATE
January 2025	Draft Special Report (SR)	FY 2024	FY 2025

4. TITLE AND SUBTITLE
Corps Shoaling Analysis Tool (CSAT) User Guide

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT

5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CHL SR-25-DRAFT

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES
Funding Account Code U4391284, AMSCO Code 060000 "Corps Shoaling Analysis Tool (CSAT) User Guide."

14. ABSTRACT
The Corps Shoaling Analysis Tool (CSAT) is a suite of computational routines for evaluating shoaling rates in navigation channels maintained by the US Army Corps of Engineers (USACE). This is achieved using survey data from the eHydro enterprise hydrographic survey database. At the local scale, CSAT's outputs are useful for understanding historical shoaling trends and identifying shoaling hotspots, while enterprise-level shoaling forecasts support Operations and Maintenance (O&M) planning over a 5-year time horizon. This user guide provides practical, step-by-step instructions for new CSAT users who wish to download, install, and run the tool. Later sections provide insight into CSAT's advanced features while also describing the methods and assumptions that underlie the calculations.

15. SUBJECT TERMS
Navigation channels; Shoaling; Sediment transport; Bathymetry; Hydrographic surveying

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	SAR	84

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