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Miscellaneous Publication 176

2024
STATE OF ALASKA
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DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

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Suggested citation:
Horen, K.C., 2024, Still water inundation modeling with hydrological connectivity: Alaska Division of Geological & Geophysical Surveys Miscellaneous Publication 176, 34 p. https://doi.org/10.14509/31154

STILL WATER INUNDATION MODELING WITH HYDROLOGICAL CONNECTIVITY

Keith C. Horen[1]

ABSTRACT

This publication details a hydrologically connected inundation modeling method developed by the Alaska Division of Geological & Geophysical Surveys (DGGS) using geographic information system (GIS) processing tools. This method improves upon a widely used, GIS-based inundation modeling method commonly called a bathtub model (BTM; Poulter and Halpin, 2008). DGGS's method considers hydrological barriers and connections during the modeling process to map the extent of inundation more accurately (fig. 1). Leveraging Esri's ArcGIS Pro Raster Function tools, DGGS takes advantage of in-memory processing to improve the speed and efficiency of our models. This method specifically models still water inundation at a community-specific level and is not comparable with coastal total water level models, nor is it appropriate for regional or larger areas. With the increasing prevalence of high-resolution digital elevation models (DEM), DGGS's still water inundation model (SWIM) method is an effective, locally replicable alternative to larger, more complex modeling methods, making our approach accessible to municipal and community analysts.

Figure 1. Comparison of a simple bathtub inundation model (left) and a hydrologically connected bathtub model (right) in Teller, Alaska. The area in blue is hydrologically connected to the inundation source, whereas the areas in red are protected by barriers and incorrectly depicted as inundated in the simple bathtub model.

INTRODUCTION

Inundation modeling is an invaluable tool for public safety, and accurately modeling inundation extents is a critical step for hazard assessment and forecasting. Various methods have been developed to model inundation extents, the most common and accessible of which is the GIS-

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based, simple BTM described by Poulter and Halpin (2008), which delineates inundation extent (Moorhead and Brinson, 1995; Titus and Richman, 2001) by identifying DEM raster cells with values below a given elevation representing the modeled still water height. The most significant drawback to using a simple BTM is that all areas below the water height input, even those that are disconnected from the flood source by physical barriers, will be shown as inundated, creating unrealistic inundation extents (fig. 1). In contrast, complex hydrodynamic models that rely on specialized software, large computational resources, and expert knowledge may account for hydrological connectivity, but these models are often inaccessible to the average GIS user, especially in Alaska, where necessary data coverage and resources are often lacking (Overbeck, 2017).

Multiple solutions have been suggested to address the hydrological connectivity issue presented by simple BTM. Li and others (2014) incorporated Esri's Cost Distance geoprocessing tool into their BTM method to limit modeled extents to only those raster cells that are connected to the flood source, informing the models of Sekovski and others (2015). Alternately, Poulter and Halpin (2008) applied raster cell connectivity definitions that are equivalent to those found in Esri's Region Group geoprocessing tool used by the National Oceanic and Atmospheric Administration (NOAA, 2017). Either of these geoprocessing tools can be used to assess raster surface connectivity, but the Cost Distance tool is needlessly computationally (and time) intensive unless a cost variable such as slope is incorporated, as demonstrated in the total water level inundation models produced by Perini and others (2016). The Region Group tool also identifies connections between raster cells but, crucially, does not eliminate unconnected groups of cells from the final output the way the Cost Distance tool does, instead categorizing each group of connected cells with a unique identifier. A user can then assess these categorized groups of cells to discriminate those that should be retained from those that should be removed from the final inundation extent. Using the Region Group tool allows users to identify areas blocked by hydrological barriers for removal while maintaining areas that are hydrologically connected by culverts and other subsurface avenues of connectivity that may not be represented within a DEM. As noted by NOAA, this step is necessary because most DEMs do not include "…detailed pipe network analysis or engineering-grade hydrologic [sic] analysis…" (NOAA, 2017).

The SWIM method developed by DGGS primarily differs from previous methods by taking advantage of the built-in, in-memory processing made possible by Esri's ArcGIS Pro Raster Function tools. While in-memory processing was possible in previous iterations of Esri software using Python scripting and utilized by the Cost Distance and Region Group methodologies, the previous GIS-based modeling methods investigated for this paper generated multiple intermediate datasets in excess of their final output (Li and others, 2014; NOAA, 2017; Perini and others, 2016; Sekovski and others, 2015). The SWIM method requires at most two input datasets, and while several temporary raster datasets are created in-memory, only one intermediate table is created as an output, significantly reducing permanent memory storage requirements. An additional, major point of difference between DGGS's modeling method and other GIS-based methods is that hydrological connectivity is addressed without the need for DEM editing, time-consuming visual selection of unconnected regions, or complex modeling software.

METHOD

DGGS developed the SWIM method in Esri's ArcGIS Pro version 3.2.0 software, though it is advisable to update to the most recent software version available to ensure the Raster Function tool performs as expected. Multiple steps require an ArcGIS Pro Spatial Analyst extension license. Additionally, a DEM in GeoTIFF format is required and, where available and necessary, a line or polygon feature class representing hydrological connections such as culverts. All data should be projected in the same coordinate system, using the same units. This method is compatible with both digital terrain model (DTM) and digital surface model (DSM) rasters, but it should be noted that man-made hydrological barriers may be absent from DTM, while DSM may include man-made features that could act as erroneous barriers, such as bridges. If a feature class of hydrological connections is needed but unavailable, modelers may create and populate one, provided these connective features are known or identifiable within imagery.

The following provides details on the processing steps required to generate a SWIM with hydrological connectivity using DGGS's method. A visual schematic of these steps is provided in figure 2. The location of the tools described in the following steps are provided in parentheticals for reference and unique user input values are denoted by brackets.

Processing Steps

1. Reclassify DEM cells below the modeled still water height using a simple BTM. This step outputs an integer raster with values of 1 for inundated and NoData for non-inundated cells, regardless of connectivity.
    - 1.1. Open the Remap tool (Raster Function pane > Reclass > Remap) and set the following:
        - 1.1.1. General
            - 1.1.1.1. Name = Extents
            - 1.1.1.2. Output Pixel Type = 8 Bit Unsigned
        - 1.1.2. Parameters
            - 1.1.2.1. Raster = [DEM]
            - 1.1.2.2. Remap Definition type = List
            - 1.1.2.3. Minimum = [minimum elevation of DEM]
            - 1.1.2.4. Maximum = [modeled still water height]
            - 1.1.2.5. Output = 1
            - 1.1.2.6. Change missing values to NoData = CHECKED
2. Group simple BTM cells by spatial connectivity. This step outputs an integer raster with values between 1 and 65,535, each unique value representing a contiguous region of cells. As discussed by Poulter and Halpin (2008), the number of neighboring cells included in a

connectivity assessment is critical to the final extent results. Using a four-cell neighborhood for this step only assesses cells that are orthogonal to the cell being evaluated, while an eight-cell neighborhood includes orthogonal and diagonal cells. An eight-cell neighborhood is recommended for this analysis.

2.1. Open the Region Group tool (Raster Function pane > Data Management > Region Group) and set the following:

  2.1.1. General

    2.1.1.1. Name = Regioned

    2.1.1.2. Output Pixel Type = 16 Bit Unsigned

  2.1.2. Parameters

    2.1.2.1. Zone Raster = Extents

    2.1.2.2. Number of Neighbor Cells = Eight

    2.1.2.3. Zone Connectivity = Within

    2.1.2.4. Add Link = No Link

    2.1.2.5. Exclude Value = 0

3. <u>Assess hydrological connectivity of grouped cells.</u> This step outputs either a single integer value representing a region that is connected to the inundation source or a table of features and corresponding integer values representing the regions those features connect.

3.1. If a feature class of hydrological connection features is NOT being used, use the Explore tool (Map tab > Navigate panel > Explore) and do the following:

  3.1.1. Click on the region(s) of cells that is connected to the inundation source.

  3.1.2. Note the Pixel Value provided in the Pop-up pane, then skip to Step 6.

3.2. If a feature class of hydrological connection features (line or polygon) is being used, open the Tabulate Area tool (Geoprocessing pane > Spatial Analyst > Zonal > Tabulate Area) and set the following:

  3.2.1. Parameters

    3.2.1.1. Input raster or feature zone data = [hydrological connections feature class]

    3.2.1.2. Zone field = [numeric attribute field containing unique values] (e.g. OBJECTID)

    3.2.1.3. Input raster or feature class data = Regioned_Extents

    3.2.1.4. Class field = Value

    3.2.1.5. Output table = Connections_Table

3.2.1.6. Classes as rows in output table = CHECKED

3.2.1.7. Processing cell size = [DEM resolution]

4. Remove duplicate region values from the hydrological connections table. Multiple features may provide connections to a single region. This step ensures only one instance of each region value is present within the hydrological connections table and is necessary for future steps to function correctly.
    - 4.1. Open the Delete Identical tool (Geoprocessing pane > Data Management > General > Delete Identical) and set the following:
        - 4.1.1. Parameters
            - 4.1.1.1. Input Dataset = Connections_Table
            - 4.1.1.2. Field(s) = Value
5. Add and populate a numeric attribute field in the hydrological connections table. This step assigns the modeled still water height as the output value for each of the connected regions and is necessary for future steps to function correctly. Value must use the same elevation units (e.g., feet, meters) as the input DEM.
    - 5.1. Open the Add Field tool (Geoprocessing pane > Data Management > Fields > Add Field) and set the following:
        - 5.1.1. Parameters
            - 5.1.1.1. Input Table = Connections_Table
            - 5.1.1.2. Field Name = Output
            - 5.1.1.3. Field Type = Double (64-bit floating point)
    - 5.2. Open the Calculate Field tool (Geoprocessing pane > Data Management > Fields > Calculate Field) and set the following:
        - 5.2.1. Parameters
            - 5.2.1.1. Input Table = Connections_Table
            - 5.2.1.2. Field Name = Output
            - 5.2.1.3. Expression Type = Python
            - 5.2.1.4. Output = [modeled still water height]
6. Reclassify only the hydrologically connected cells below the modeled still water height to create a single elevation surface. The output of this step is a floating-point raster depicting the modeled extents with cell values equal to the modeled still water height.
    - 6.1. Open the Remap tool (Raster Functions pane > Reclass > Remap) and set the following:

6.1.1. General

6.1.1.1. Name = Connected

6.1.1.2. Output Pixel Type = 32 Bit Float

6.1.2. Parameters

6.1.2.1. Raster = Regioned_Extents

6.1.2.2. If following from Step 3.1.2 (no hydrological connection feature class used), repeat sub-steps 6.1.2.2.2 and 6.1.2.2.3 to add a row for each value corresponding to all regions connected to the inundation source(s). Multiple region value inputs may be required if more than one inundation source is present or a single inundation source is functionally disconnected from itself due to a lack of coverage within the DEM. Skip to Step 7 after running the Remap tool with the following parameters:

6.1.2.2.1. Remap Definition = List

6.1.2.2.2. Minimum = [region value]

6.1.2.2.3. Maximum = [region value + 1]

6.1.2.2.4. Output = [modeled still water height]

6.1.2.3. If following from Step 5.2.1.4 (hydrological connection feature class used).

6.1.2.3.1. Remap Definition = Table

6.1.2.3.2. Remap Table = Connections_Table

6.1.2.3.3. Input Field = Value

6.1.2.3.4. Output Field = Output

6.1.2.3.5. Input Max Field = (leave blank)

6.1.2.3.6. Remap Table Type = Simple

6.1.2.3.7. Change missing values to NoData = CHECKED

7. <u>Generate inundation depth raster.</u> The output of this step is the final product of this model, a 32-bit floating point raster that depicts the inundation depth at the modeled still water height for all hydrologically connected extents.

7.1. Open the Calculator tool (Raster Functions pane > Math > Calculator) and set the following:

7.1.1. General

7.1.1.1. Name = Inundation_Depth

7.1.1.2. Output Pixel Type = 32 Bit Float

7.1.1.3. Match Variables = CHECKED

7.1.1.4. Union Dimensions = UNCHECKED

7.1.2. Parameters

7.1.2.1. Raster Variables

7.1.2.1.1. c = Connected_Regioned_Extents

7.1.2.1.2. d = [DEM]

7.1.2.2. Expression

7.1.2.2.1. Con(c – d > 0, c – d, 0)

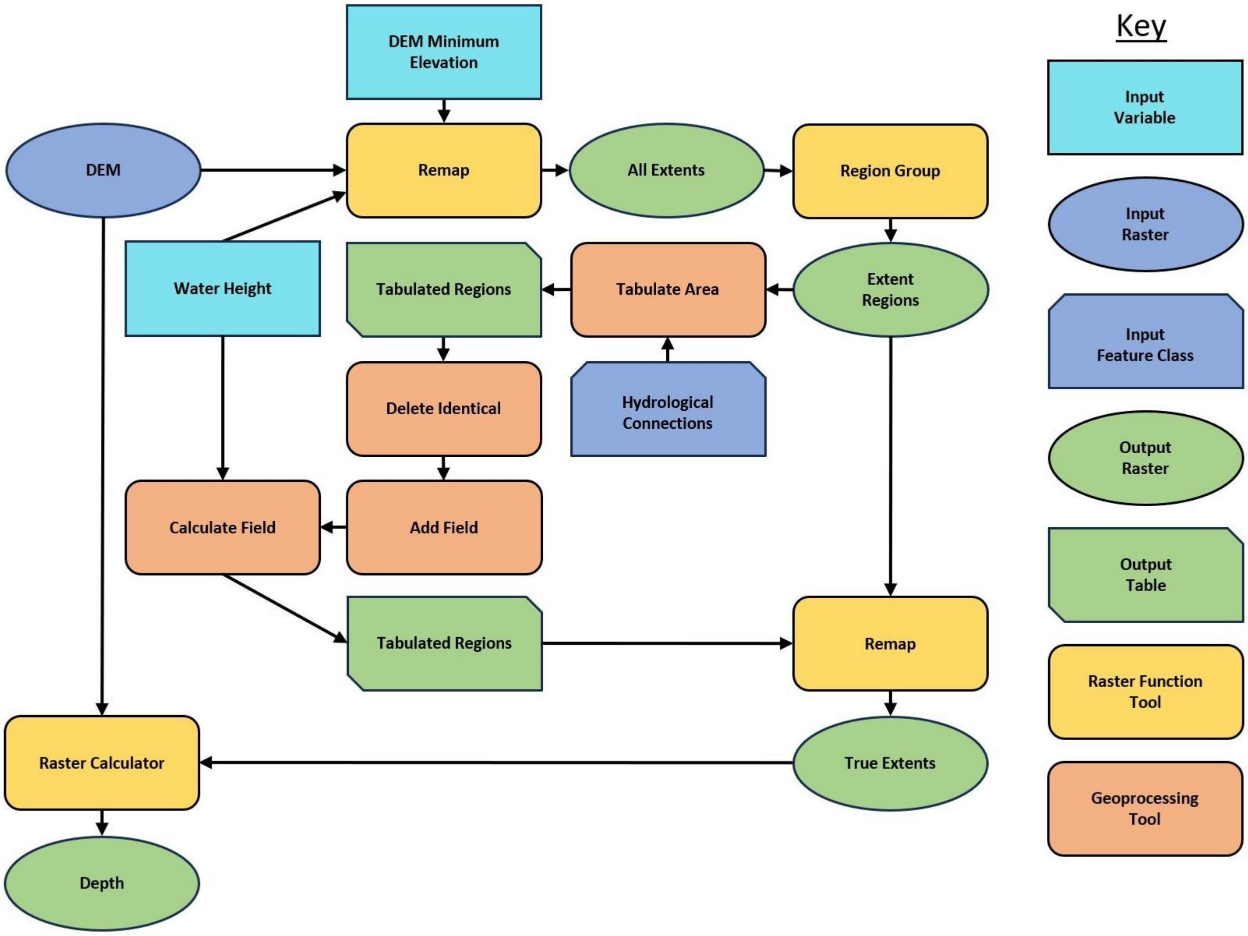

Figure 2. Schematic of still water inundation modeling with hydrological connectivity processing steps.

PROCESSING EXAMPLES

In September 2022, DGGS collected high-water marks (HWM) in several communities impacted by flooding caused by Extra-tropical Cyclone Merbok (Horen and others, 2022). We applied this modeling method to two locations: Hooper Bay, where the model could be applied without the use of a hydrological connection feature class (Christian and others, 2024), and Teller, where hydrological connection features were necessary. All data in the following examples are reported in meters in the NAVD88 (GEOID12B) vertical datum.

Hooper Bay

DGGS collected 121 high-quality HWM in Hooper Bay on September 20, 2022, using Global Navigation Satellite System (GNSS) equipment (Horen and others, 2022). We divided these HWM data into two subsets using a random number generator, with one subset (A) used to estimate the flood height and the other (B) used to evaluate that estimate. Subsets A and B consisted of 60 and 61 HWM observations, respectively (appendix A). Using the upper-lower bounds method of uncertainty propagation (University of North Carolina [UNC], 2018), the estimate derived from subset A was 4.899 ± 0.644 m. An individual comparison to this estimate was calculated for each HWM in subset B, resulting in an average agreement of +0.015 m and a root-mean-square error (RMSE) of 0.277 m.

DGGS produced both a simple BTM and a hydrologically connected SWIM using a 1-meter resolution lidar DTM collected in 2016 by the United States Geological Survey (USGS; OCM Partners, 2024). DGGS used the processing steps for applying our method without a hydrological connection feature class to create the SWIM and generated the simple BTM following the processing instructions detailed in Step 1 of the SWIM method. Screenshots of the tools and settings used during processing, as well as visualizations of the resultant outputs, are provided in appendix B.

To compare the extents of these two models, DGGS evaluated the total area of modeled inundation within a 4 km^2 region centered on the community of Hooper Bay (table 1; fig. B1). Within this region, the simple BTM method modeled an area of inundation covering 3.417 km^2, while the SWIM method modeled an area of inundation covering 3.370 km^2. This comparison demonstrates that within this study area the simple BTM produced a seven-percent overestimation of inundation extents in uninundated areas. Field observations corroborated the inundation extents modeled by the SWIM method (Christian and others, 2024; Horen and others, 2022).

Table 1. Simple BTM and SWIM method comparison results.

Method	Total Area (km^2)	Inundated Area (km^2)	Uninundated Area (km^2)
Simple BTM	4.000	3.417	0.583
SWIM	4.000	3.370	0.630

Teller

DGGS collected 79 high-quality HWM in Teller on September 21, 2022, using Global Navigation Satellite System (GNSS) equipment (Horen and others, 2022). We divided these HWM data into two subsets using a random number generator, with one subset (A) used to estimate the flood height and the other (B) used to evaluate that estimate. Subsets A and B consisted of 39 and 40 HWM observations, respectively (appendix C). Using the upper-lower bounds method of uncertainty propagation (UNC, 2018), the estimate derived from subset A was 2.813 ± 0.326 m. An individual comparison to this estimate was calculated for each HWM in subset B, resulting in an average agreement of +0.033 m and a root-mean-square error (RMSE) of 0.158 m.

DGGS produced two hydrologically connected models using the SWIM method and the Cost-Distance method. We applied each method to a 1-meter resolution topographic–bathymetric (topobathy) lidar DTM collected in 2019 by the U.S. Army Corps of Engineers (USACE; OCM Partners, 2023); this DEM was not edited to reflect hydrological connections. DGGS used the processing steps for applying our method with a hydrological connection feature class to create the SWIM and followed the steps described by Sekovski and others (2015) and Perini and others (2016) to create the Cost-Distance model. The attenuation artifice (Sekovski, 2015) applied during the Cost-Distance method was 0.004; this value acts "as a proxy for bed friction and infiltration over distance from the shoreline" (Perini, 2016) during modeling. Screenshots of the tools and settings used during processing, as well as visualizations of the resultant outputs, are provided in appendix D.

To compare the extents of these two models, DGGS evaluated the total area of modeled inundation within an 8-km^2 region centered on the community of Teller (table 2; fig. D1). Within this region, the Cost-Distance method modeled an area of inundation covering 5.155 km^2, while the SWIM method modeled an area of inundation covering 5.800 km^2. This comparison demonstrates that within this study area the Cost-Distance method produced an eight-percent underestimation of the total inundation extents. Field observations corroborated the inundation extents modeled by the SWIM method (Horen and other, 2022).

Table 2. Cost-Distance and SWIM method comparison results.

Method	Total Area (km^2)	Inundated Area (km^2)	Uninundated Area (km^2)
Cost-Distance	8.000	5.155	2.845
SWIM	8.000	5.800	2.700

DISCUSSION

DGGS's method is not unique in displaying hydrological connectivity, but it can more accurately depict inundation extents by not only accounting for barriers within a DEM but also connections that might otherwise be overlooked in other workflows. Furthermore, DGGS's method utilizes the built-in, in-memory processing made possible by Esri's ArcGIS Pro Raster Function tools, limiting extraneous file outputs and improving processing time. However, DGGS's hydrologically connected inundation modeling method does have limitations.

This method is intended to map the extent of still water height inundation, which does not include variable inundation associated with wave setup and runup. Total water level inundation models (tide + surge + wave setup + runup) require complex input data that are currently difficult to collect or absent from much of Alaska (Overbeck, 2017). Despite this, it may be possible to use proxy variables with other models to emulate total water level inundation. For example, classifying a DEM with Manning's roughness coefficients (Arcement and Schneider, 1989) could provide a cost surface for the Cost Distance tool to be used in conjunction with predicted tide and surge levels to estimate variable inundation extents. Additionally, the hydrological connectivity depicted using DGGS's method does not factor in the capacity and flow rates of connecting features. For the purposes of community-level modeling, it is reasonable to assume still water heights will achieve hydrostatic equilibrium on either side of connecting features, but it is worth noting that fluid dynamic variables may need to be incorporated for more complex pipe networks.

By developing this still water inundation model with hydrological connectivity, DGGS seeks to provide access to accurate inundation modeling at the community scale. Alaska's coastline is more than 75,000 km (46,600 miles) long, accounting for more than half of the coast of the continental U.S. (NOAA, 2022), yet national hydrodynamic models are not currently able to provide adequate coverage for most of the state (Overbeck, 2018). The method presented here is meant to fill this modeling gap with an easy-to-use, user-friendly approach for local officials and GIS users to assess inundation risk for their communities, a vital and necessary step for public safety and community planning.

ACKNOWLEDGMENTS

This work was made possible with U.S. Geological Survey, Coastal Marine Hazards Resources Program funding through an Alaska Climate Adaptation Science Center funding opportunity. The author extends special thanks to Richard Buzard and Alexander Nereson for improving this publication through thoughtful and informative review. The views and conclusions contained in this document are those of the author and should not be interpreted to represent the opinions or policies of the Alaska Division of Geological & Geophysical Surveys, the U.S. Geological Survey, or the U.S. Government. Mention of trade names or commercial products does not constitute endorsement by the Alaska Division of Geological & Geophysical Surveys, the U.S. Geological Survey, or the U.S. Government.

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APPENDIX A: HOOPER BAY HIGH-WATER MARK DATA SUBSETS

For a full description of these data, including coordinate, accuracy, and description information, reference DGGS Raw Data File 2022-14 (Horen and others, 2022). HWM data are listed by point identification number (PID).

SUBSET A		
PID		PID
3008		3059
3009		3060
3011		3074
3013		3076
3014		3077
3019		3078
3020		3079
3023		3083
3024		3086
3025		3088
3026		3091
3029		3092
3031		3093
3032		3096
3034		3097
3035		3098
3036		3106
3038		3107
3039		3109
3040		3111
3041		3113
3044		3114
3047		3115
3048		3116
3050		3119
3051		3120
3055		3121
3056		3122
3057		3125
3058		3001B

SUBSET B		
PID		PID
3002		3070
3003		3071
3004		3072
3005		3073
3006		3075
3007		3080
3010		3081
3012		3082
3018		3084
3021		3085
3022		3087
3027		3089
3028		3090
3030		3094
3033		3095
3037		3099
3042		3100
3043		3101
3045		3102
3046		3103
3049		3104
3052		3105
3053		3108
3054		3110
3061		3112
3062		3117
3063		3118
3064		3123
3065		3124
3066		3001A
3069		

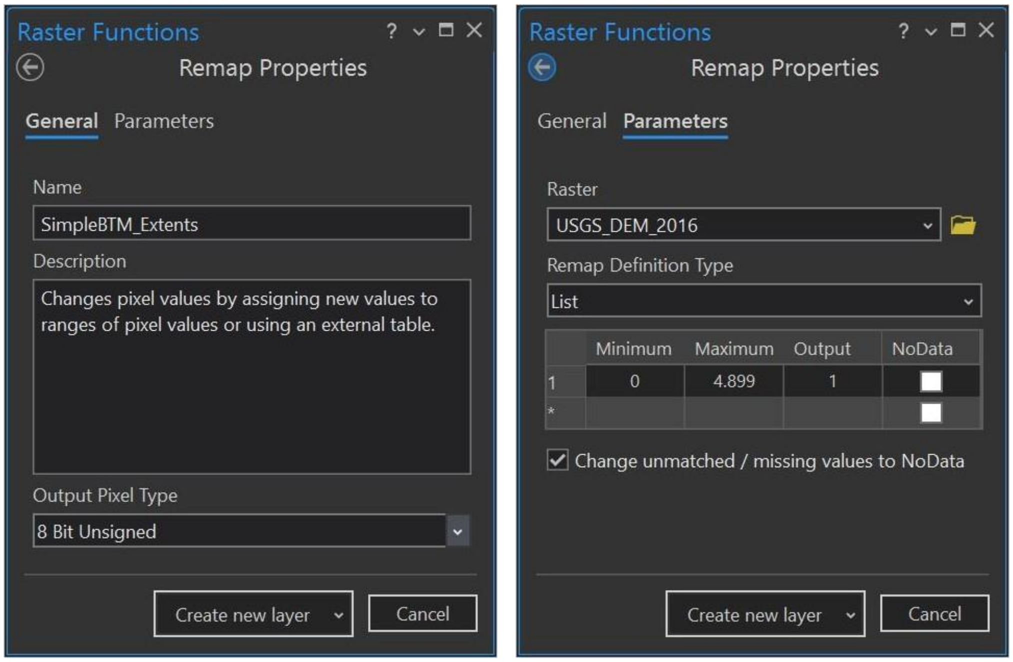
APPENDIX B: HOOPER BAY INUNDATION MODEL PROCESSING

The following is a step-by-step example of how DGGS modeled the still water inundation in Hooper Bay resulting from Extra-tropical Cyclone Merbok. We used HWM data (Horen and others, 2022) to estimate the flood height of this event as 4.899 ± 0.644 m NAVD88 (GEOID12B). Using this estimate, we applied both a simple BTM and SWIM to a 1-meter resolution DTM (fig. B1; OCM Partners, 2024).

Figure B1. Hooper Bay study area (red outline) with 2016 USGS lidar DTM hillshade basemap (OCM Partners, 2024).

Simple BTM Processing

DGGS followed the processing instructions detailed in Step 1 of the SWIM method (page 3) to produce the simple BTM.



Name: SimpleBTM_Extents

Description: Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type: 8 Bit Unsigned

Raster: USGS_DEM_2016

Remap Definition Type: List

	Minimum	Maximum	Output	NoData
1	0	4.899	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure B2. Screenshots of Remap Raster Function tool with settings used to create simple BTM.

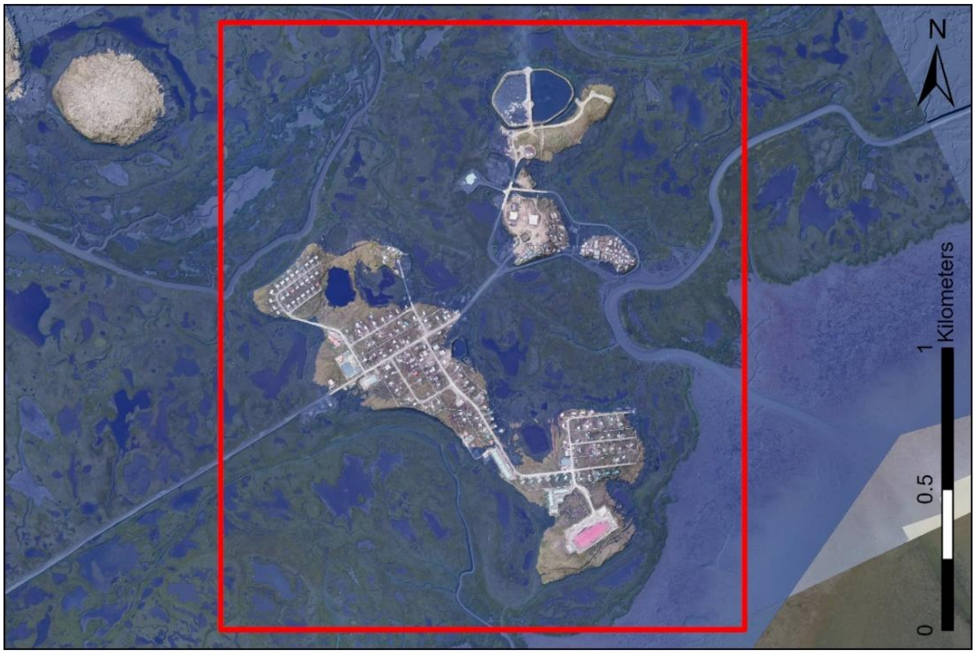
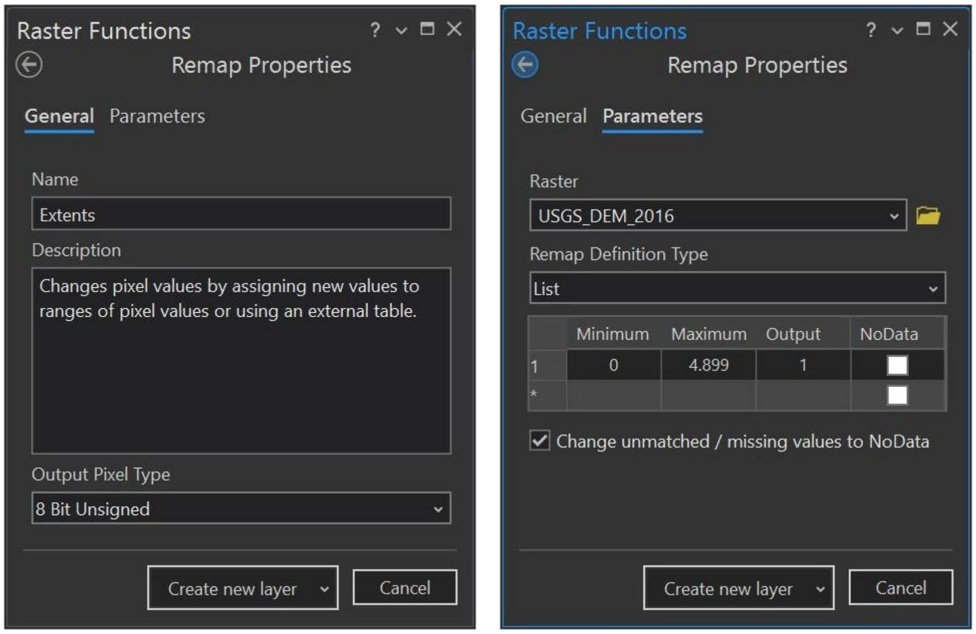


Figure B3. Simple BTM inundation extents (blue) at 4.899 m.

SWIM Processing

Step 1 (page 3). Reclassify DEM cells below the modeled still water height using a simple BTM.



Name

Extents

Description

Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type

8 Bit Unsigned

Raster

USGS_DEM_2016

Remap Definition Type

List

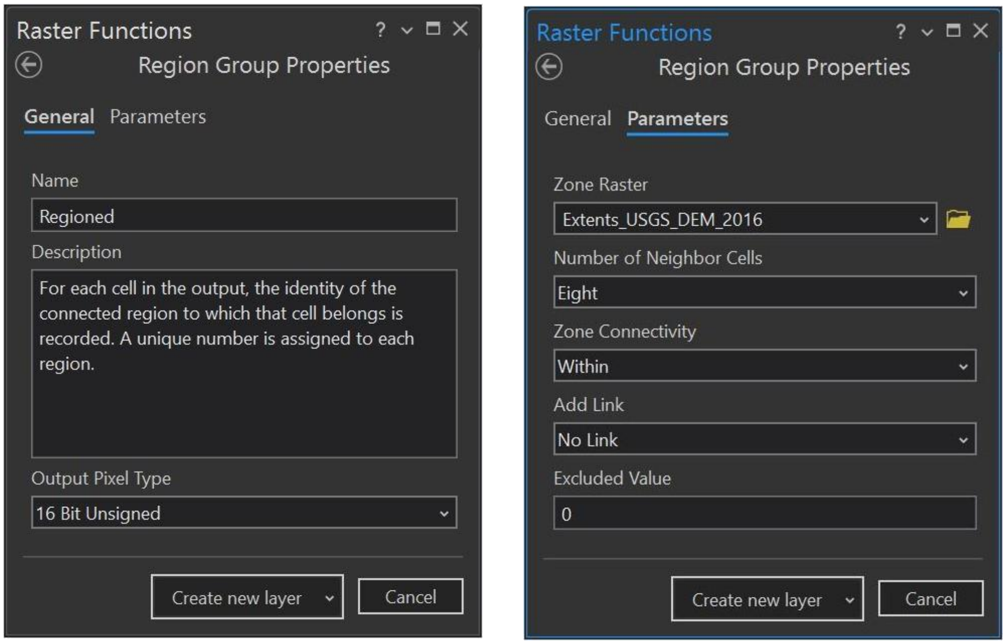
	Minimum	Maximum	Output	NoData
1	0	4.899	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure B4. Screenshots of Remap tool with settings used to create Step 1 output.

Figure B5. Step 1 output.

Step 2 (page 3). Group simple BTM cells by spatial connectivity.


Raster Functions

Region Group Properties

General | Parameters

Name: Regioned

Description: For each cell in the output, the identity of the connected region to which that cell belongs is recorded. A unique number is assigned to each region.

Output Pixel Type: 16 Bit Unsigned

Raster Functions

Region Group Properties

General | Parameters

Zone Raster: Extents_USGS_DEM_2016

Number of Neighbor Cells: Eight

Zone Connectivity: Within

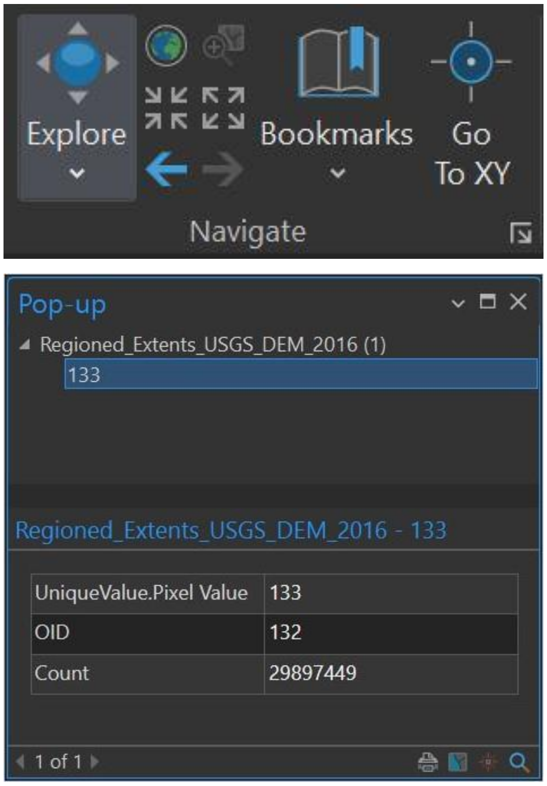
Add Link: No Link

Excluded Value: 0

Figure B6. Screenshots of Region Group tool with settings used to create Step 2 output.

Figure B7. Step 2 output.

Step 3 (page 4). Assess hydrological connectivity of grouped cells. Since a hydrological connection feature class was not used, we followed the instructions of Step 3.1., skipping to Step 6 after noting the Pixel Value of the selected region.

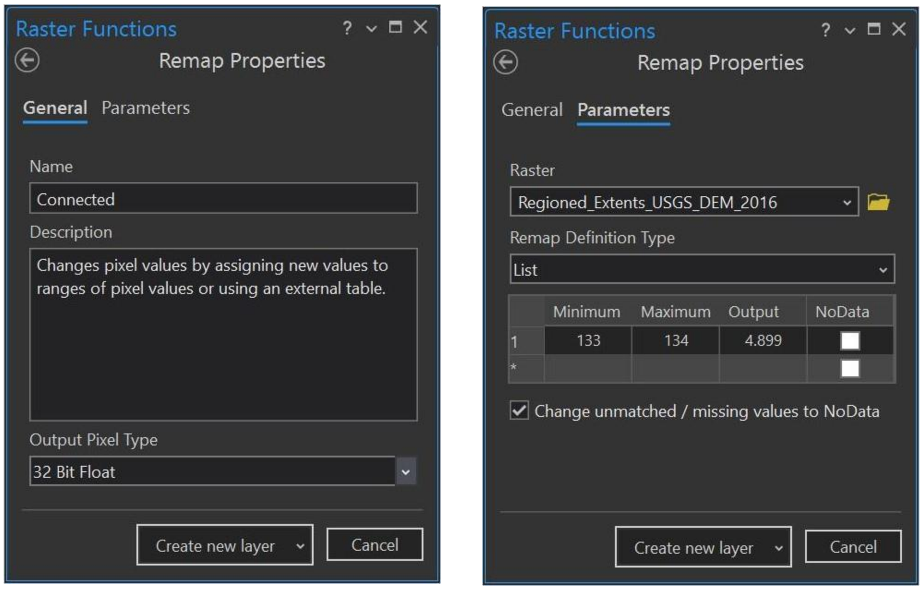


Regioned_Extents_USGS_DEM_2016 - 133

UniqueValue.Pixel Value	133
OID	132
Count	29897449

Figure B8. Step 3 Explore tool (top) and Pop-up results (bottom).

Step 6 (page 5). Reclassify only the hydrologically connected cells below the modeled still water height to create a single elevation surface. Since a hydrological connection feature class was not used, we followed the instructions of Step 6.1.2.2.



Name: Connected

Description: Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type: 32 Bit Float

Raster: Regioned_Extents_USGS_DEM_2016

Remap Definition Type: List

	Minimum	Maximum	Output	NoData
1	133	134	4.899	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure B9. Screenshots of Remap tool with settings used to create Step 6 output.

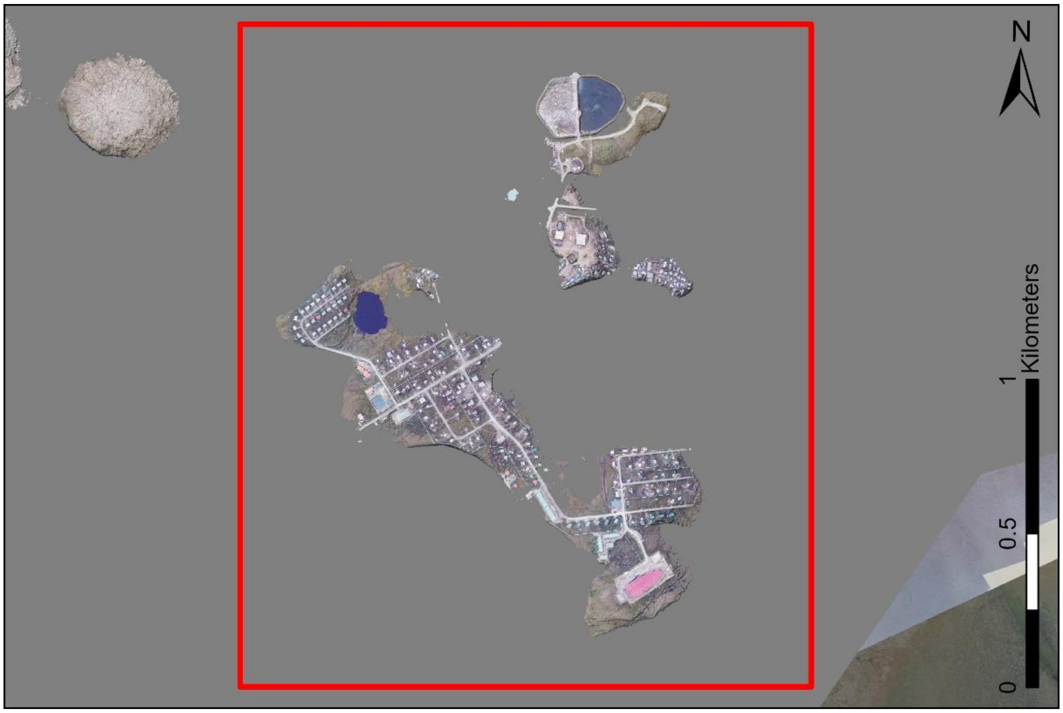
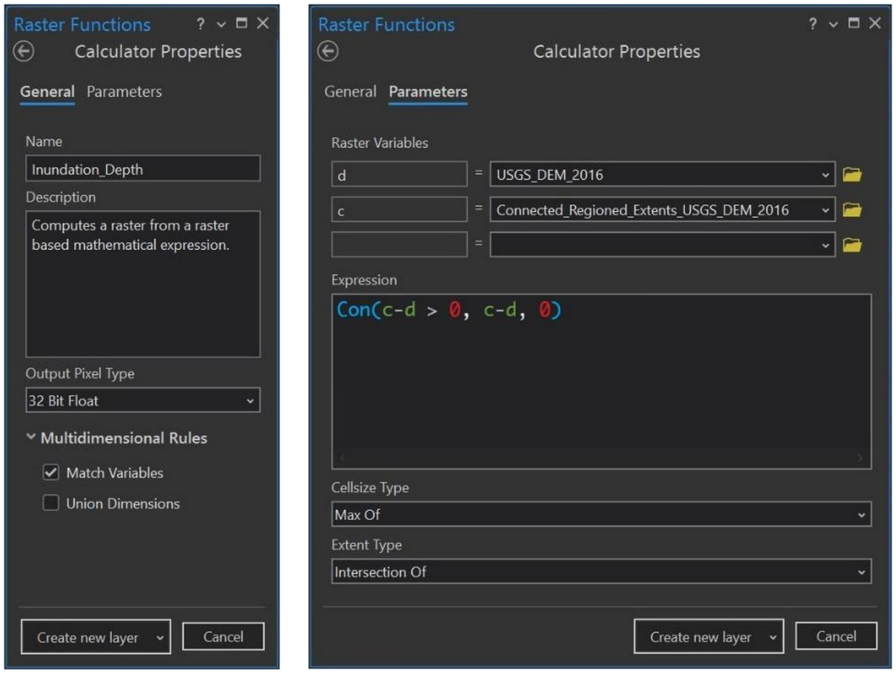


Figure B10. Step 6 output.

Step 7 (page 6). Generate inundation depth raster.



Name
Inundation_Depth

Description
Computes a raster from a raster based mathematical expression.

Output Pixel Type
32 Bit Float

Multidimensional Rules
☑ Match Variables
☐ Union Dimensions

Raster Variables
d = USGS_DEM_2016
c = Connected_Regioned_Extents_USGS_DEM_2016

Expression
```
Con(c-d > 0, c-d, 0)
```

Cellsize Type
Max Of

Extent Type
Intersection Of

Figure B11. Screenshots of Calculator tool with settings used to create Step 7 output.

Figure B12. Step 7 output.

APPENDIX C: TELLER HIGH-WATER MARK DATA SUBSETS

For a full description of these data, including coordinate, accuracy, and description information, reference DGGS Raw Data File 2022-14 (Horen and others, 2022). HWM data are listed by point identification number (PID).

SUBSET A	
PID	**PID**
2000	2042
2002	2044
2003	2045
2005	2050
2006	2052
2011	2054
2015	2055
2018	2057
2019	2059
2021	2060
2023	2061
2024	2062
2025	2066
2030	2067
2031	2068
2033	2079
2036	2082
2037	2083
2038	2084
2039	

SUBSET B	
PID	**PID**
2001	2040
2004	2041
2007	2043
2008	2046
2009	2047
2010	2048
2012	2049
2013	2051
2014	2053
2016	2056
2017	2058
2020	2063
2022	2064
2026	2065
2027	2069
2028	2070
2029	2071
2032	2072
2034	2080
2035	2081

APPENDIX D: TELLER INUNDATION MODEL PROCESSING

The following is a step-by-step example of how DGGS modeled the still water inundation in Teller resulting from Extra-tropical Cyclone Merbok. We used HWM data to estimate the flood height of this event as 2.813 ± 0.326 m NAVD88 (GEOID12B). Using this estimate, we applied both a Cost-Distance model and SWIM to a 1-meter resolution DTM (fig. D1; OCM Partners, 2023).

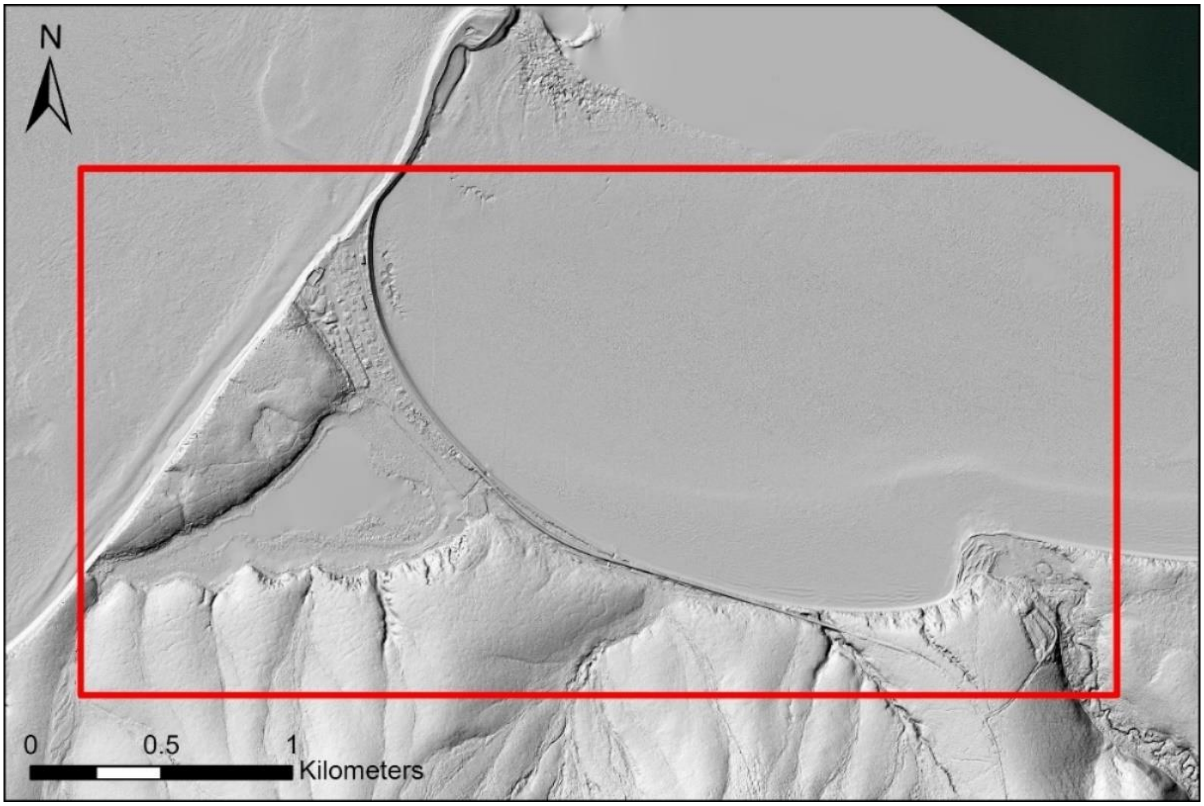
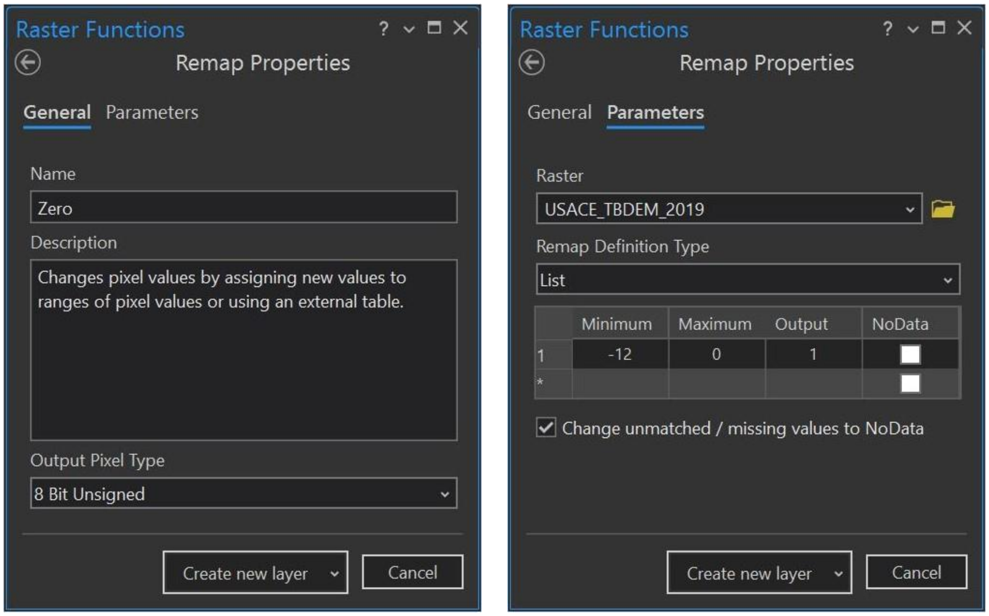


Figure D1. Teller study area (red outline) with USACE 2019 topobathy lidar DTM hillshade basemap (OCM Partners, 2023).

Cost-Distance Model Processing

DGGS followed the processing instructions detailed by Sekovski and others (2015) to produce the Cost-Distance method model.

Step 0. <u>Create a source raster.</u> DGGS used the Remap tool to generate a source raster consisting of cells from the DTM with values less than 0 m NAVD88 (GEOID12B).



Name: Zero

Description: Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type: 8 Bit Unsigned

Raster: USACE_TBDEM_2019

Remap Definition Type: List

	Minimum	Maximum	Output	NoData
1	-12	0	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure D2. Screenshots of Remap tool with settings used to create Step 0 output.

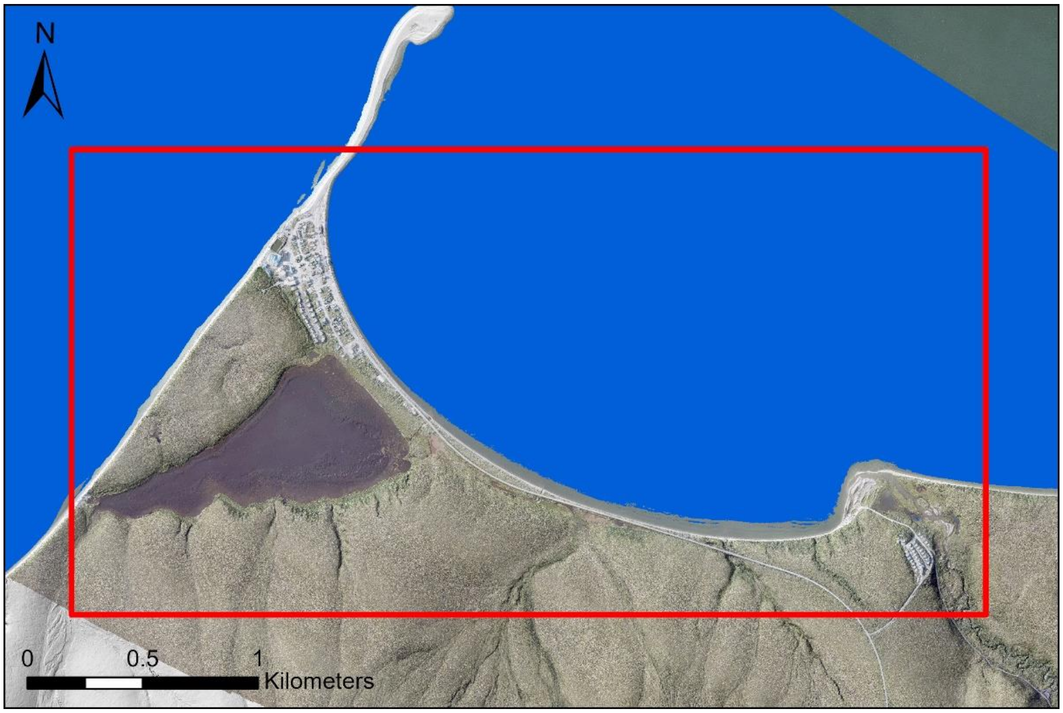
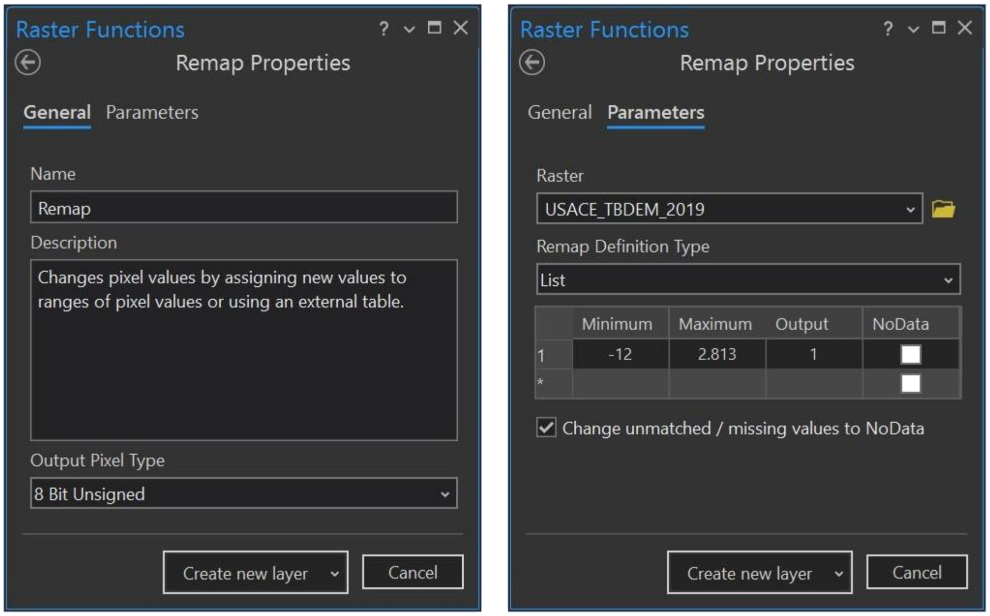


Figure D3. Step 0 output.

Step 1. Reclassify to exclude all elements that have an elevation greater than the modeled water level.



Name
Remap

Description
Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type
8 Bit Unsigned

Raster
USACE_TBDEM_2019

Remap Definition Type
List

	Minimum	Maximum	Output	NoData
1	-12	2.813	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure D4. Screenshots of Remap tool with settings used to create Step 1 output.

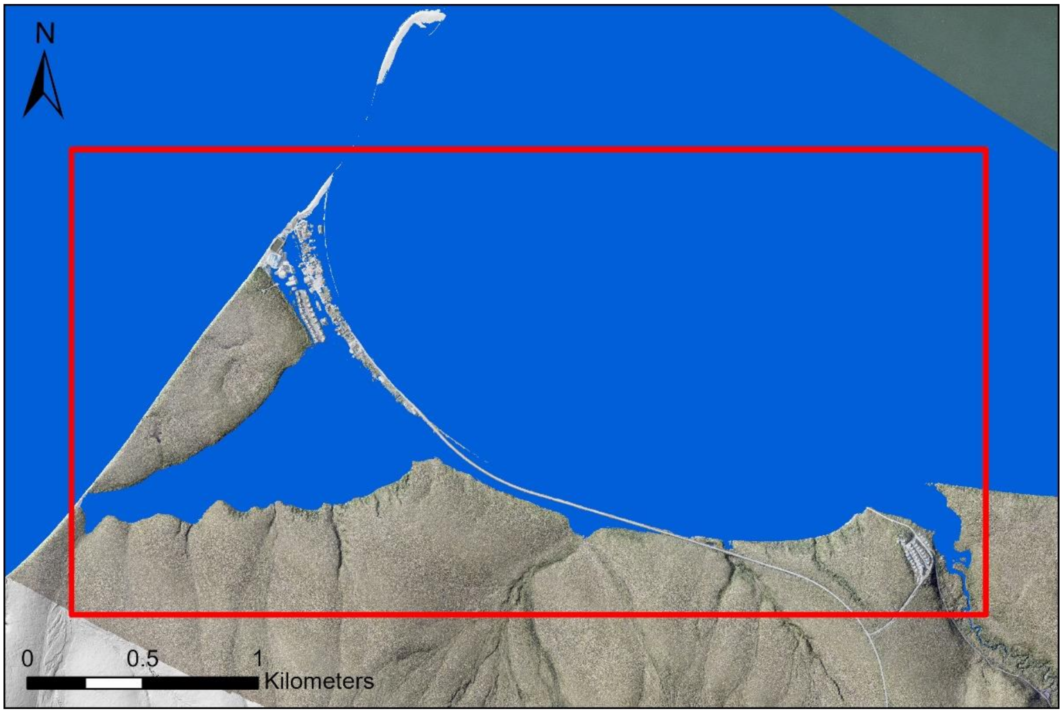
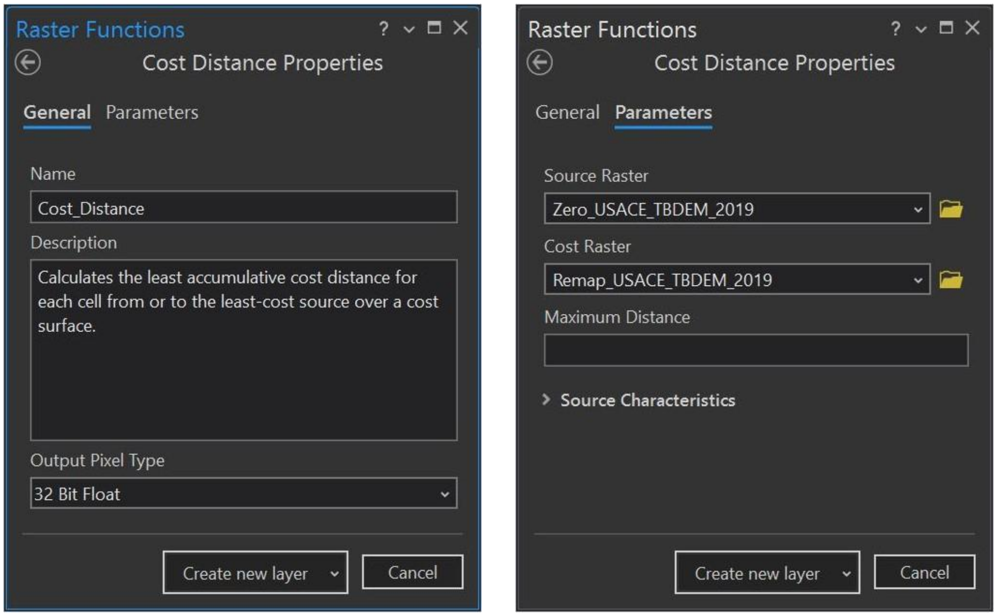


Figure D5. Step 1 output.

Step 2. Apply Cost-Distance tool to generate cost value raster.



Name: Cost_Distance

Description: Calculates the least accumulative cost distance for each cell from or to the least-cost source over a cost surface.

Output Pixel Type: 32 Bit Float

Source Raster: Zero_USACE_TBDEM_2019

Cost Raster: Remap_USACE_TBDEM_2019

Maximum Distance:

Figure D6. Screenshots of Cost-Distance tool with settings used to create Step 2 output.

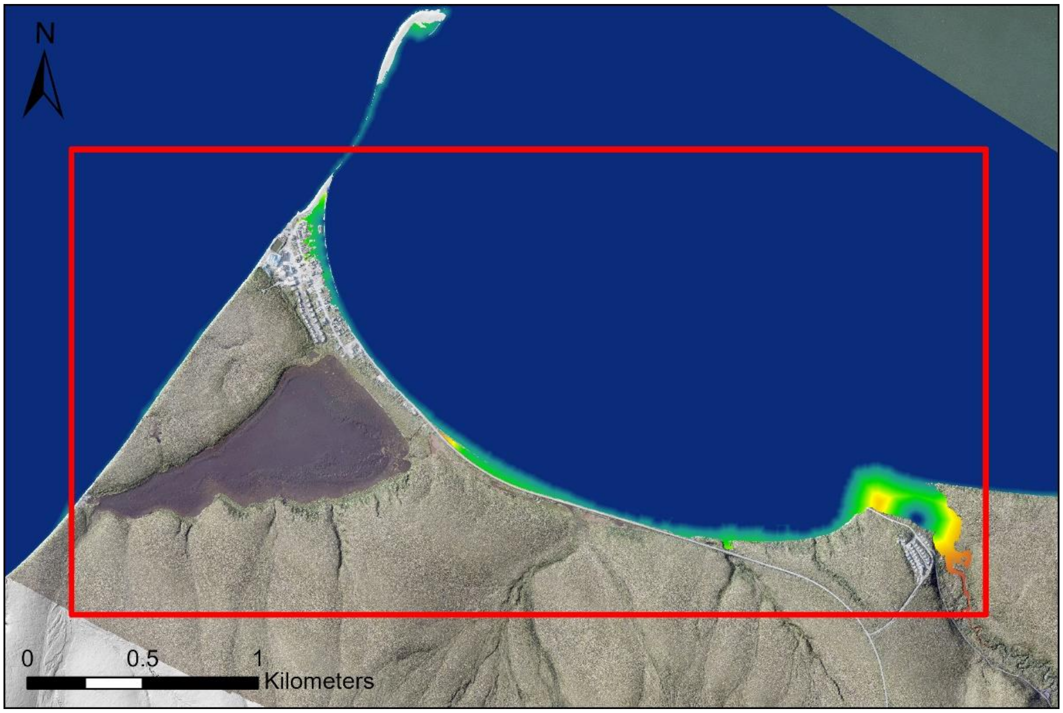
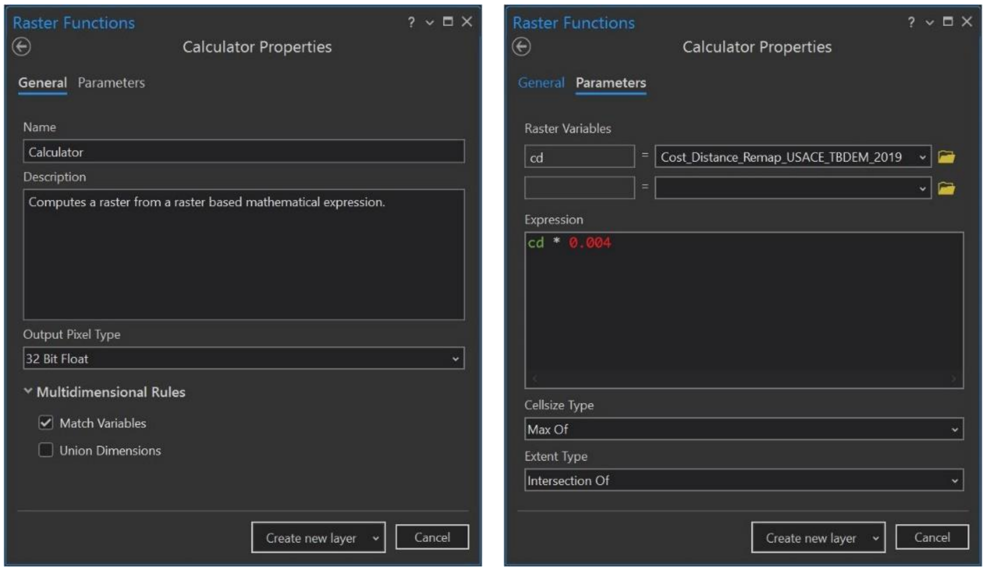


Figure D7. Step 2 output.

Step 3. <u>Multiply the cost value raster by the attenuation artifice to generate a proxy elevation raster.</u>



Name: Calculator

Description: Computes a raster from a raster based mathematical expression.

Output Pixel Type: 32 Bit Float

☑ Match Variables

☐ Union Dimensions

Raster Variables: cd = Cost_Distance_Remap_USACE_TBDEM_2019

Expression:

```
cd * 0.004
```

Cellsize Type: Max Of

Extent Type: Intersection Of

Figure D8. Screenshots of Calculator tool with settings used to create Step 3 output.

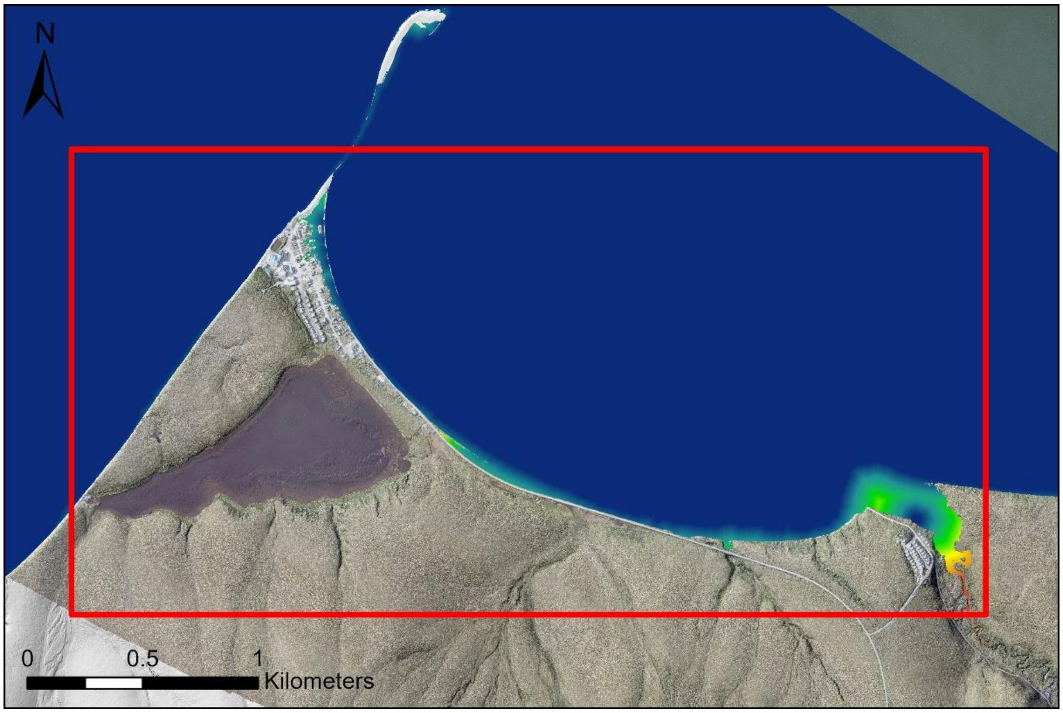
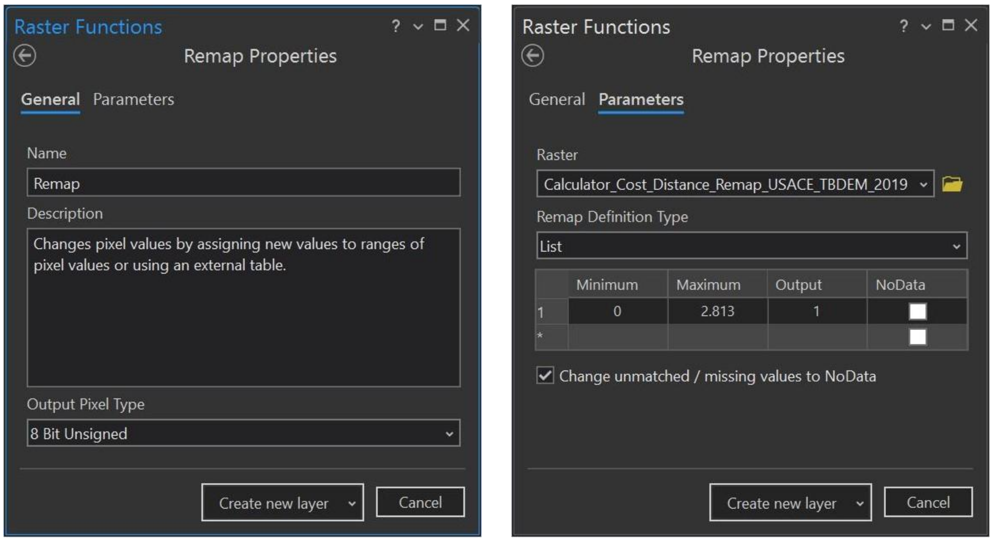


Figure D9. Step 3 output.

Step 4. Reclassify proxy elevation raster to exclude all elements that have an elevation greater than the modeled water level.



Name: Remap

Description: Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type: 8 Bit Unsigned

Raster: Calculator_Cost_Distance_Remap_USACE_TBDEM_2019

Remap Definition Type: List

	Minimum	Maximum	Output	NoData
1	0	2.813	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure D10. Screenshots of Calculator tool with settings used to create Step 4 output.

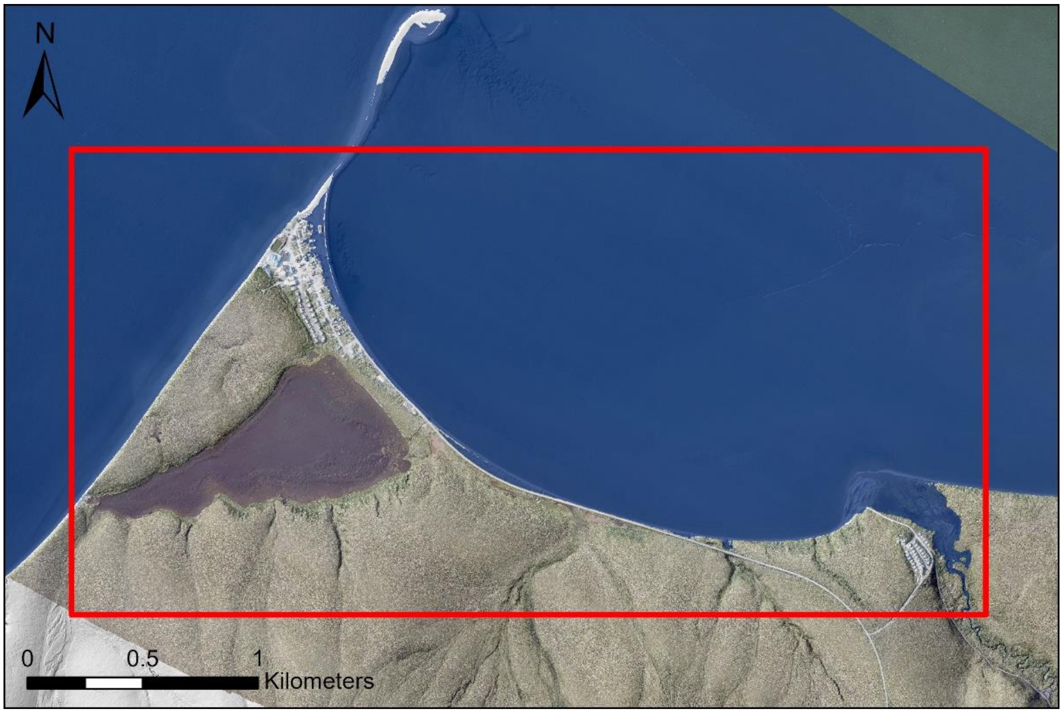
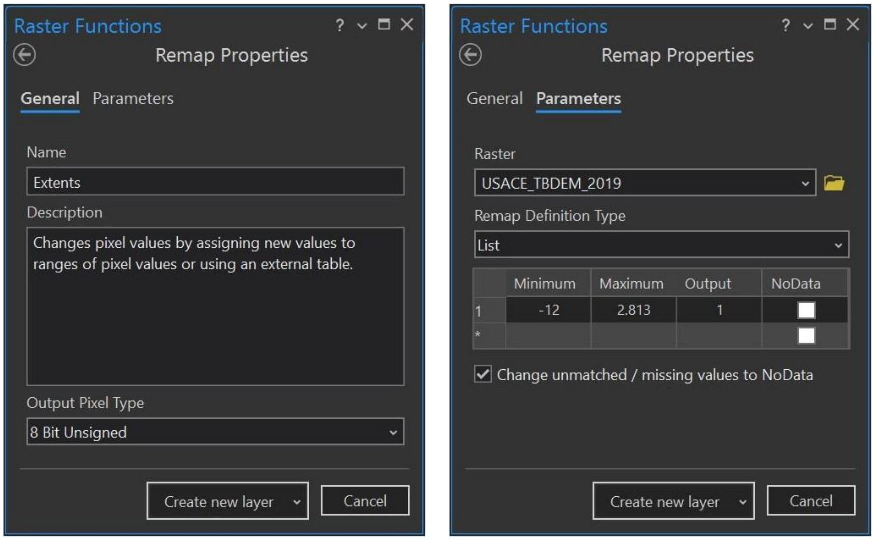


Figure D11. Step 4 output.

SWIM Processing

Step 1 (page 3). Reclassify DEM cells below the modeled still water height using a simple BTM.



Name

Extents

Description

Changes pixel values by assigning new values to ranges of pixel values or using an external table.

Output Pixel Type

8 Bit Unsigned

Raster

USACE_TBDEM_2019

Remap Definition Type

List

	Minimum	Maximum	Output	NoData
1	-12	2.813	1	☐
*				☐

☑ Change unmatched / missing values to NoData

Figure D12. Screenshots of Calculator tool with settings used to create Step 4 output.

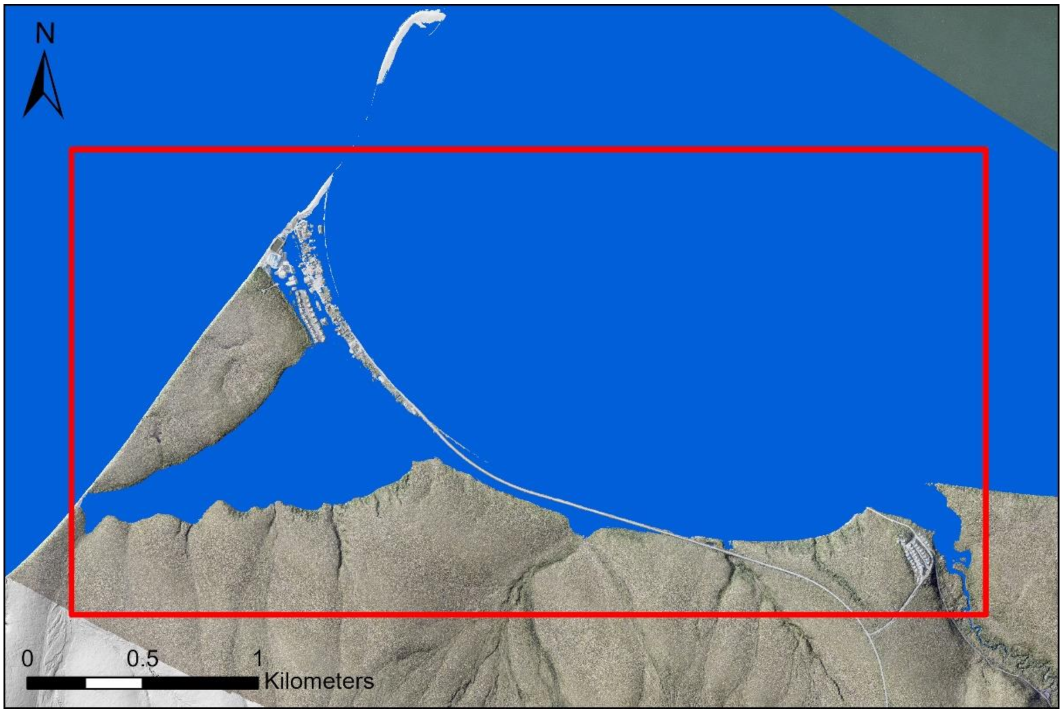
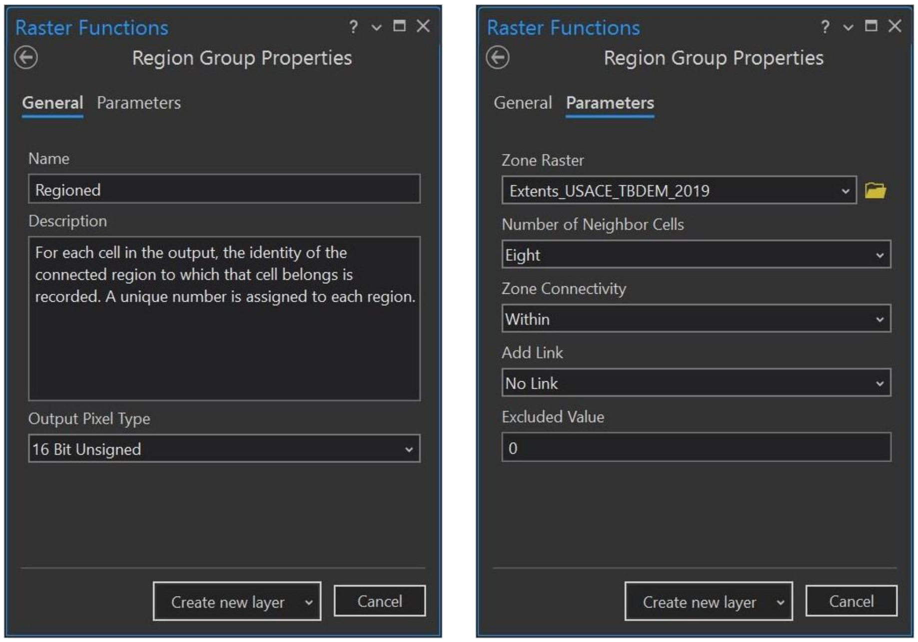


Figure D13. Step 4 output.

Step 2 (page 3). Group simple BTM cells by spatial connectivity.



Name: Regioned

Description: For each cell in the output, the identity of the connected region to which that cell belongs is recorded. A unique number is assigned to each region.

Output Pixel Type: 16 Bit Unsigned

Zone Raster: Extents_USACE_TBDEM_2019

Number of Neighbor Cells: Eight

Zone Connectivity: Within

Add Link: No Link

Excluded Value: 0

Figure D14. Screenshots of Region Group tool with settings used to create Step 2 output.

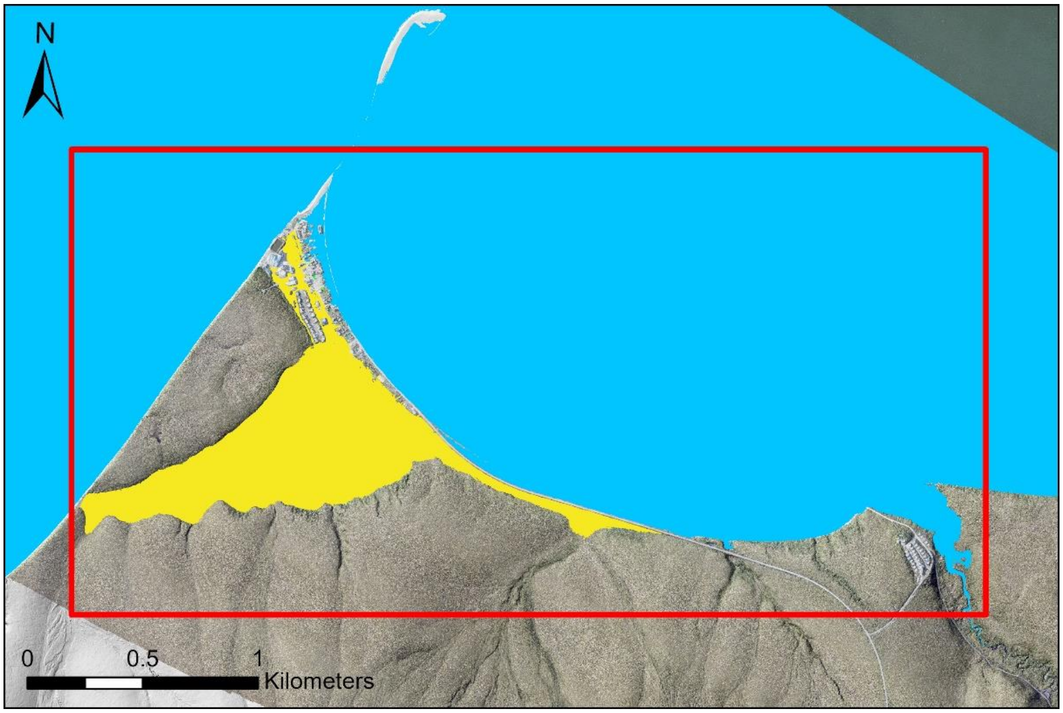
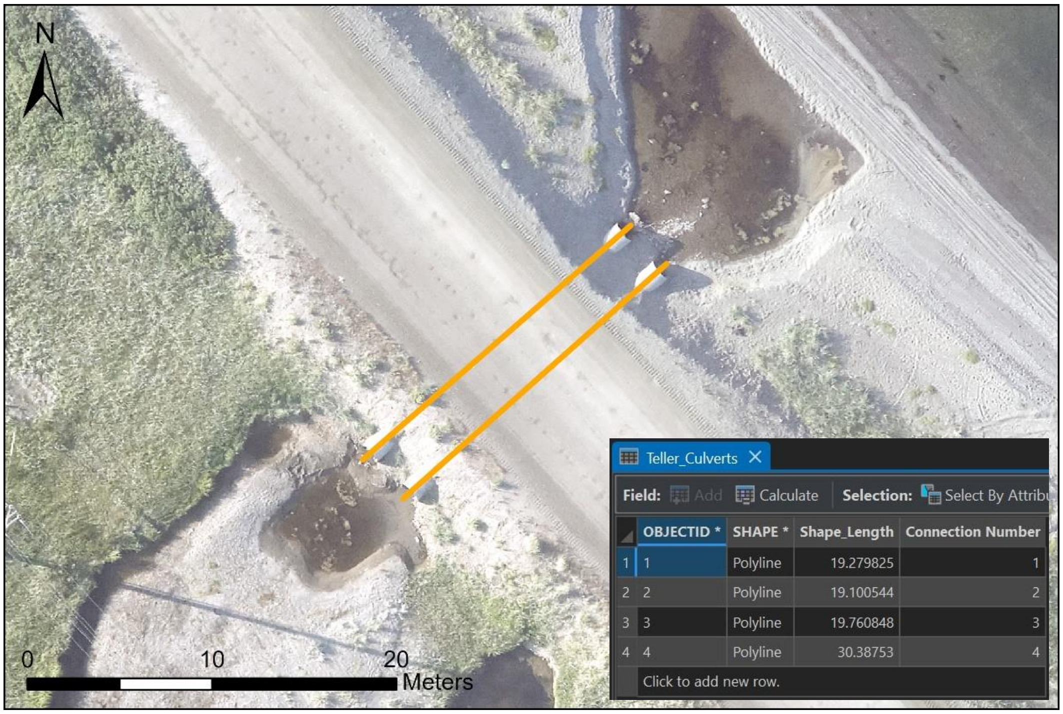


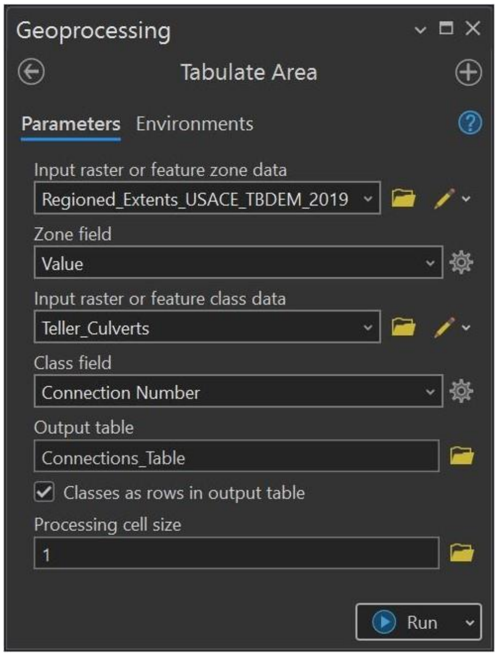
Figure D15. Step 2 output.

Step 3 (page 4). Assess hydrological connectivity of grouped cells. Since we applied a hydrological connection feature class, we followed the instructions of Step 3.2.



	OBJECTID *	SHAPE *	Shape_Length	Connection Number
1	1	Polyline	19.279825	1
2	2	Polyline	19.100544	2
3	3	Polyline	19.760848	3
4	4	Polyline	30.38753	4
	Click to add new row.			

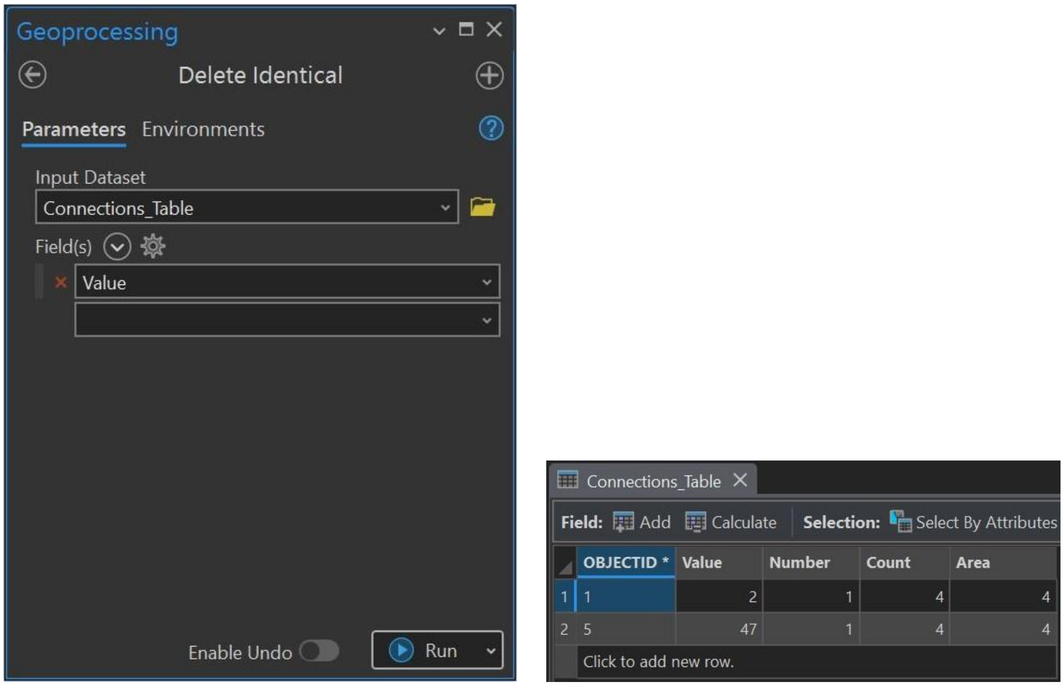
Figure D16. Example of connectivity features (culverts) used in Step 3 and feature class attribute table.



Input raster or feature zone data: Regioned_Extents_USACE_TBDEM_2019
Zone field: Value
Input raster or feature class data: Teller_Culverts
Class field: Connection Number
Output table: Connections_Table
☑ Classes as rows in output table
Processing cell size: 1

Figure D17. Screenshot of Tabulate Area tool with settings used.

Step 4 (page 5). Remove duplicate region values from the hydrological connections table.



Input Dataset: Connections_Table

Field(s): Value

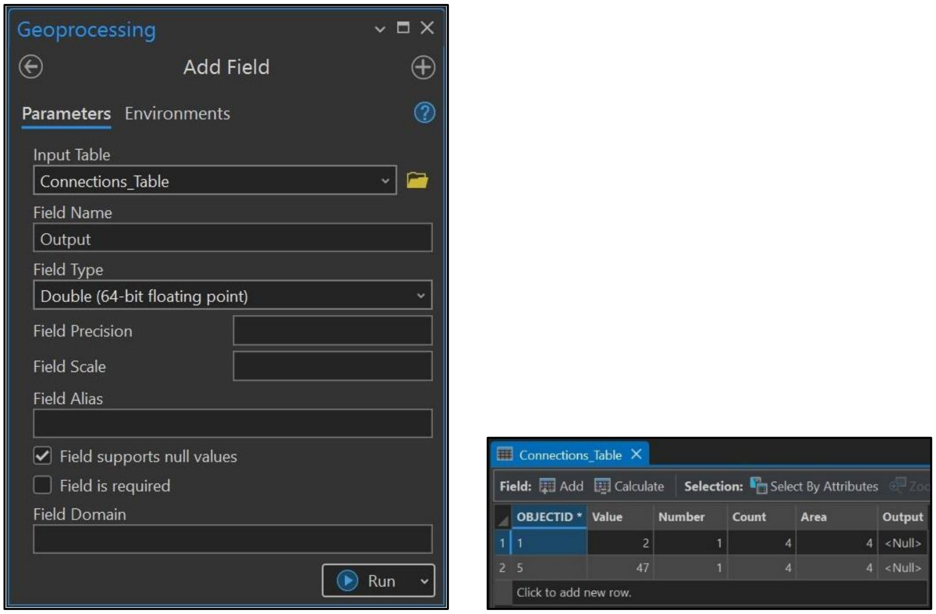
Connections_Table

	OBJECTID *	Value	Number	Count	Area
1	1	2	1	4	4
2	5	47	1	4	4

Click to add new row.

Figure D18. Screenshots of Delete Identical tool with settings used and Step 4 output.

Step 5 (page 5). Add and populate a numeric attribute field in the hydrological connections table.



Input Table: Connections_Table

Field Name: Output

Field Type: Double (64-bit floating point)

Field Precision:

Field Scale:

Field Alias:

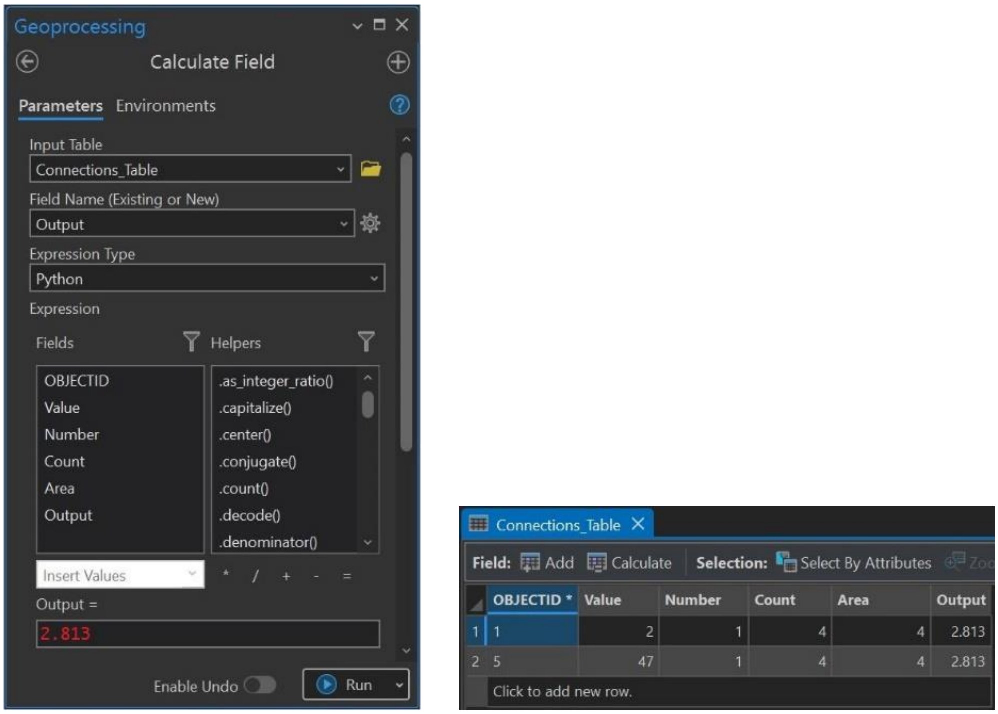
☑ Field supports null values

☐ Field is required

Field Domain:

	OBJECTID *	Value	Number	Count	Area	Output
1	1	2	1	4	4	<Null>
2	5	47	1	4	4	<Null>

Figure D19. Screenshots of Add Field tool with settings used and Step 5.1. output.



Input Table: Connections_Table

Field Name (Existing or New): Output

Expression Type: Python

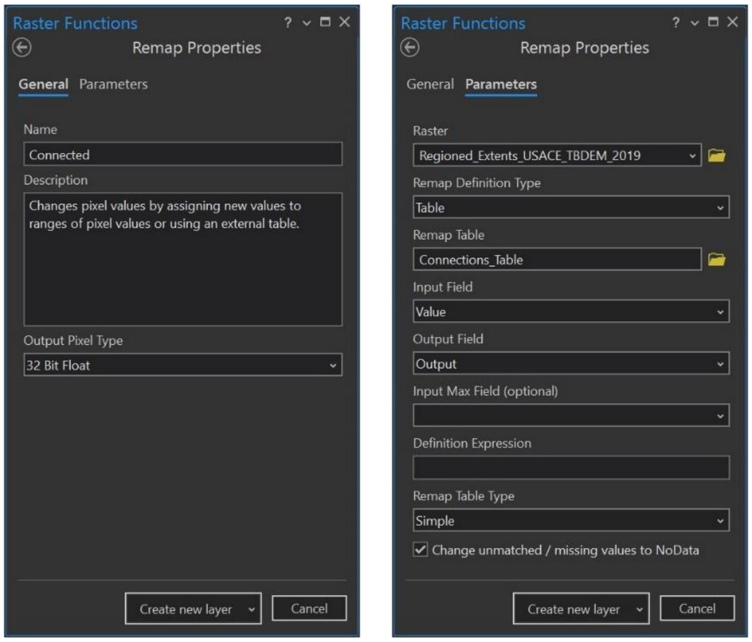
Expression

Output = 2.813

	OBJECTID *	Value	Number	Count	Area	Output
1	1	2	1	4	4	2.813
2	5	47	1	4	4	2.813

Figure D20. Screenshots of Calculate Field tool with settings used and Step 5.2. output.

Step 6 (page 5). Reclassify only the hydrologically connected cells below the modeled still water height to create a single elevation surface. Since we used a hydrological connection feature class, we followed the instructions of Step 6.1.2.3.



Name
Connected
Description
Changes pixel values by assigning new values to ranges of pixel values or using an external table.
Output Pixel Type
32 Bit Float

Raster
Regioned_Extents_USACE_TBDEM_2019
Remap Definition Type
Table
Remap Table
Connections_Table
Input Field
Value
Output Field
Output
Input Max Field (optional)
Definition Expression
Remap Table Type
Simple
☑ Change unmatched / missing values to NoData

Figure D21. Screenshots of Remap tool with settings used to create Step 6 output.

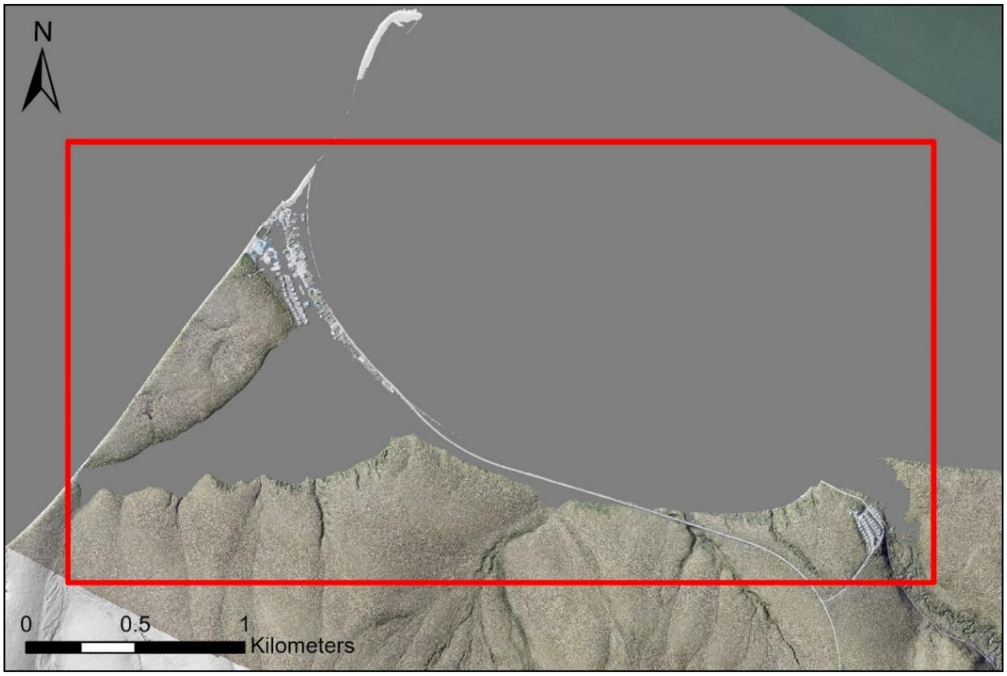
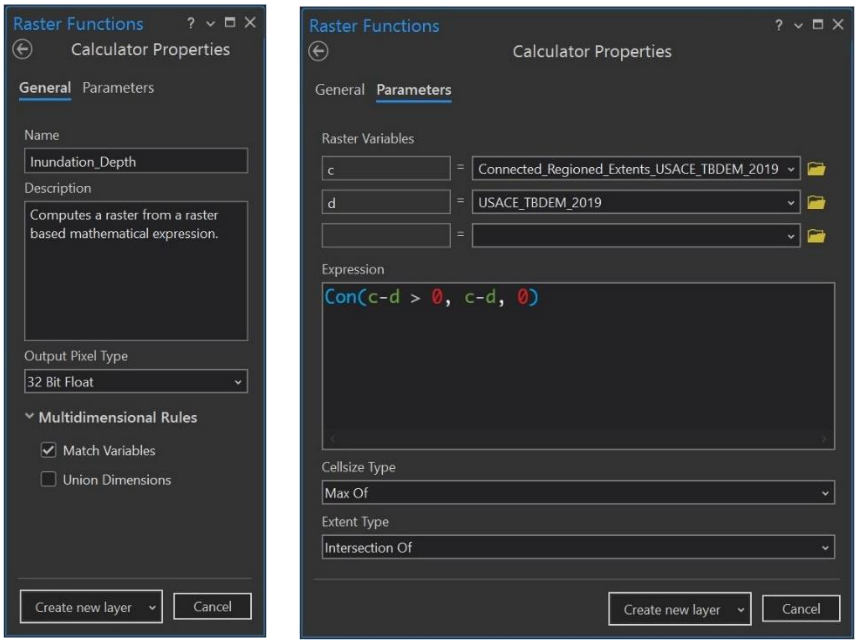


Figure D22. Step 6 output.

Step 7 (page 6). Generate inundation depth raster.


Raster Functions

Calculator Properties

General

Name: Inundation_Depth

Description: Computes a raster from a raster based mathematical expression.

Output Pixel Type: 32 Bit Float

Multidimensional Rules

☑ Match Variables

☐ Union Dimensions

Parameters

Raster Variables

c = Connected_Regioned_Extents_USACE_TBDEM_2019

d = USACE_TBDEM_2019

Expression:

```
Con(c-d > 0, c-d, 0)
```

Cellsize Type: Max Of

Extent Type: Intersection Of

Figure D23. Screenshots of Calculator tool with settings used to create Step 7 output.

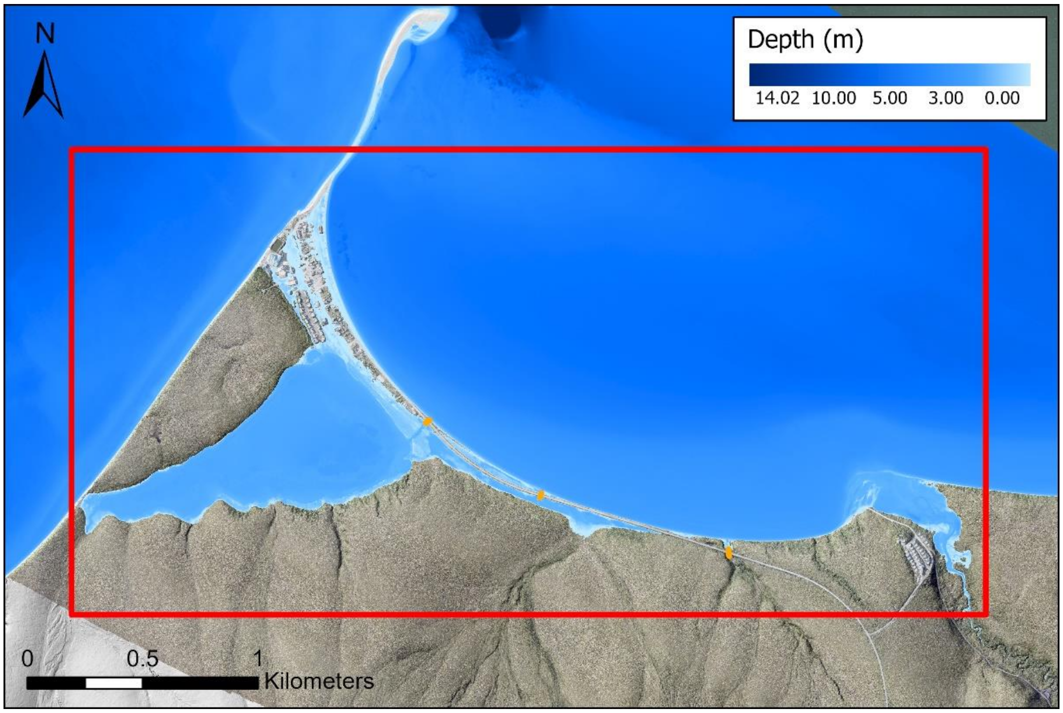


Figure D24. Step 7 output.