Seabed Landforms Classification Toolset

User Manual

Overview

The Seabed Landforms Classification Toolset provides a series of classified products derived from input bathymetry data (Figure 1). Input bathymetry data is first classified into 'surface elements', which break up the seascape into components based on slope (ArcGIS Spatial Analyst), ruggedness (VRM, Benthic Terrain Modeler, BTM, Walbridge et al. 2018), and bathymetric position index 'BPI' (Slope Position, Geomorphometry and Gradients Metric Toolbox, GGMT, Evans et al. 2014). The foundation of this framework was presented in Linklater et al. (2019), and this framework has been further developed into an ArcGIS toolset whereby users can perform a semi-automated classification to define seabed landforms (Linklater et al. 2023, in press).

A series of procedures are implemented to classify the surface elements into seabed landforms, which represent key features of the seascape, including peaks, reefs/banks, scarps, depressions and channels, and plains. Users may perform an optional plain classification and can perform additional manual editing on the landform layer to generate a classification to suit their individual needs. Data preparation tools are provided to prepare the bathymetry dataset for surface element and landform analysis if required.

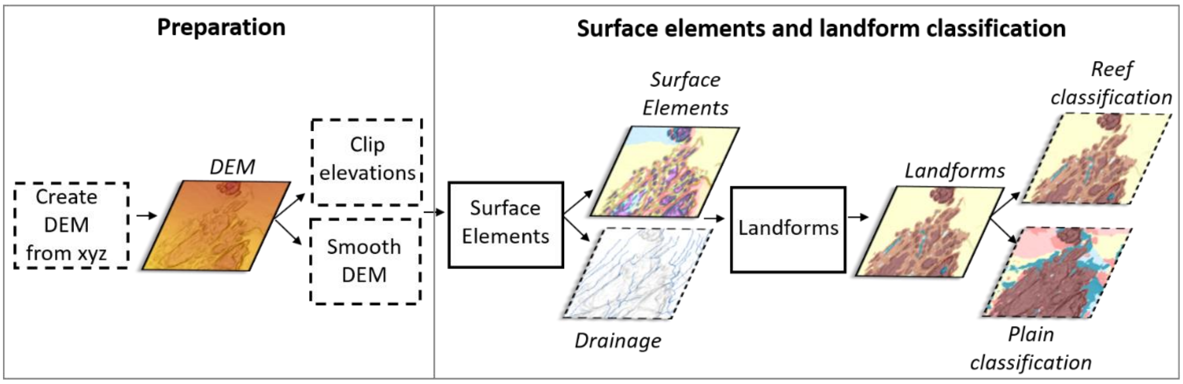

Figure 1 Workflow diagram representing overview of datasets and processes of the Seabed Landforms Classification Toolset. Dashed outline indicates optional processing steps and outputs.

This toolset was developed using ArcGIS 10.8 and requires an Advanced licence and Spatial Analyst extension.
For additional resources on how to use tools, please see this web explainer which provides additional background: https://arcg.is/1Tqmv50

Set up workspace

- Open Arc Map (Advanced licence) and check out Spatial Analyst extension
- Save the MXD to your working directory [Note: all outputs from the classification will be written to the location where your MXD is saved]
- 'Scratch' and 'Working' geodatabases containing all the outputs from the Seabed Landforms Classification toolbox will be created in the directory where the MXD is saved
- Load the 'Seabed Landforms Classification' toolbox into Arc Map. Note: The toolbox can be saved anywhere

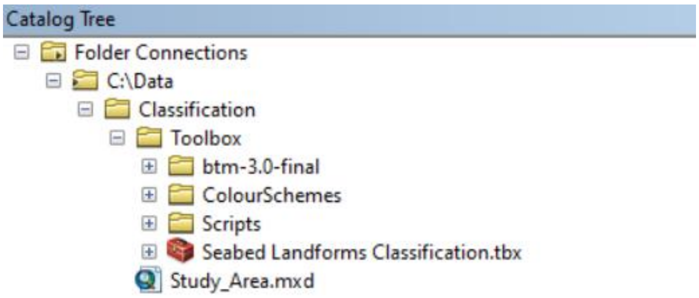

Figure 2: Example working directory. 'Seabed Landforms Classification' tool outputs will be saved in same directory as Arc Map Document (.mxd).

Preparation: Digital Elevation Model (DEM) preparation

Tools within the Preparation Toolset are Optional, as the user may or may not require the functionality outlined below.

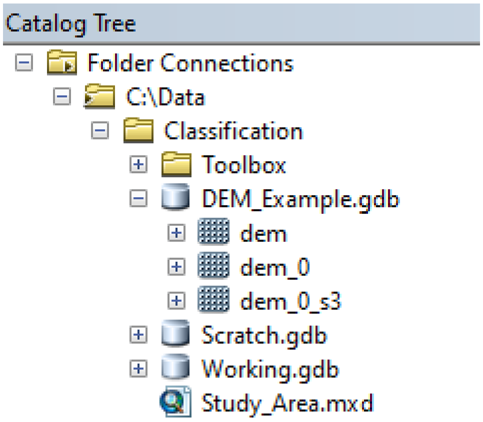

Figure 3: Example outputs based on an input dem ('dem') which has been clipped to 0 m elevation ('dem_0') and then smoothed three times ('dem_0_s3').

Create DEM from XYZ (Optional)

If the user has the elevation data in an XYZ format, this tool can grid the XYZ data into an ArcGIS raster format. A co-ordinate system is required to be specified, which should match the known co-originate system of the input XYZ.

Clip elevations (Optional)

An upper and lower elevation value can be set by the user to clip the DEM. The values used to clip the dataset will be added as a suffix to the output dataset, e.g. dem_10 if the dataset was clipped at -10 m elevation (Figure 3). Input values must be negative. The Seabed Landforms Toolset has been developed for open coast, shelf settings and is not designed for land or estuarine environments. It is recommended all DEMs be clipped to 0 m elevation for the upper extent of data to represent bathymetry only, and estuarine environments be excluded unless determined by the user as appropriate (Figure 4).

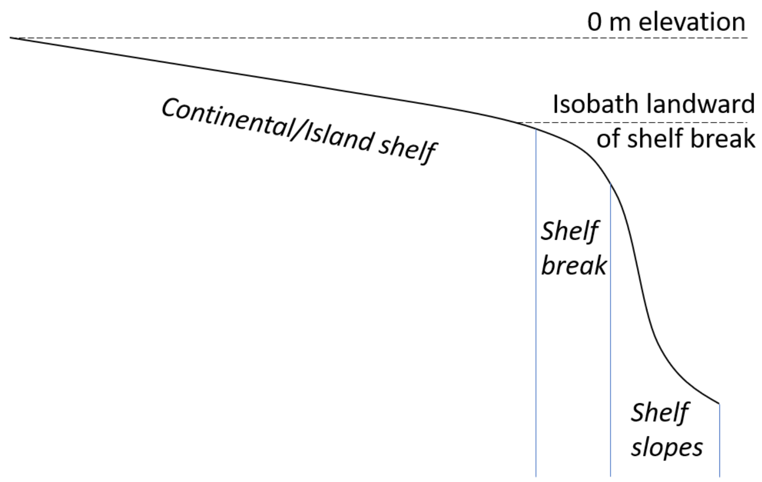

Figure 4: Recommended to clip elevations to within continental/island shelf extent – excluding land areas and steep-gradient changes in elevation that can occur at the shelf break.

Furthermore, the lower depth extent of the dataset should be considered where there is a large variation in elevation. If the dataset extends beyond the continental or island shelf to include the shelf break, shelf slope and/or abyssal plain, it is strongly recommended the lower extent of elevation be clipped to a depth landward of the shelf break (Figure 4). This is due to the nature of the Bathymetry Position Index (BPI) calculation, which calculates relative height across the DEM (based on user-defined windows). Where a steep change in gradient occurs, such as the drop-off of a shelf break, this will 'flatten' the remaining features on the shelf, and they may appear much smaller in relief relative to the prominent drop-off feature. For optimal performance of the classification toolset, it is recommended the user select a depth threshold landward of the shelf break.

Smooth DEM (Optional)

Smoothing can be performed to reduce noise artefacts in the dataset. This is particularly effective with noise within marine lidar or bathymetry datasets derived from satellite imagery which are more likely to have speckled noise.

The smoothing function performs a 'Median' filter using the Focal Statistics tool within ArcGIS. Median filters were determined to be most effective as they do not include the extremities of data values as would occur with a 'Mean' calculation. Users can input a smoothing iteration. The number of smoothing iterations is added as a suffix to the output dataset e.g. dem_s3 if the DEM was smoothed with three iterations (Figure 3).

Case study data has been provided for a sample area of multibeam echosounder data collected at Shellharbour, NSW Australia by the New South Wales Department of Planning, Industry and Environment in 2017 (Figure 5). The full survey data is available for download via the Australian Oceanographic Data Portal (https://portal.aodn.org.au/).

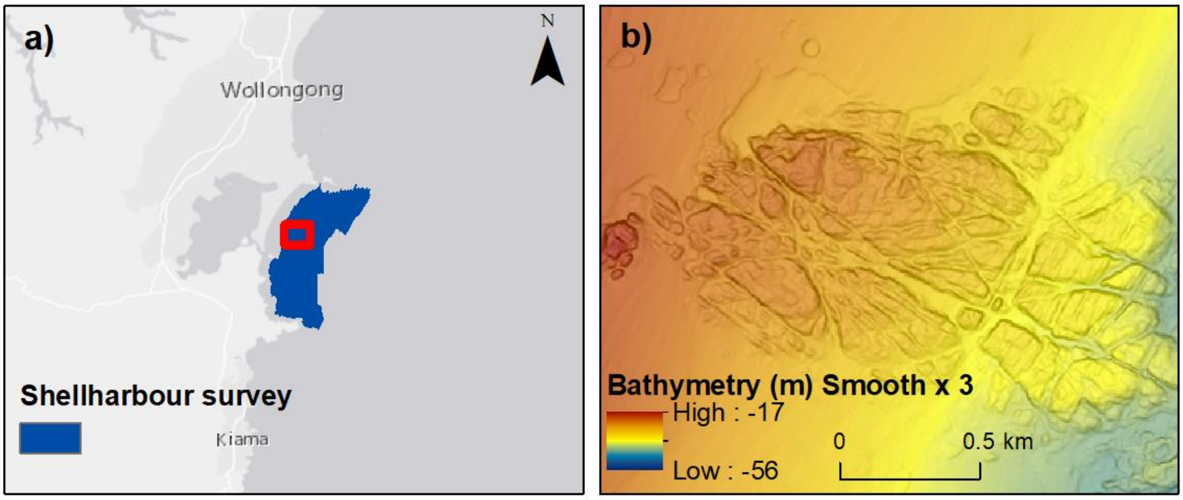

Figure 5 Case study bathymetry data provided for Shellharbour, NSW a) Location of Shellharbour multibeam echosounder data; b) sample data extent, bathymetry DEM smoothed with three iterations [See case study data: 'shellh05_s3' for DEM input].

Surface Elements and Landforms Classifications

Step 1: Derive terrain variables

The first step of the classification derives the four terrain variables needed for the surface elements and landforms classification: slope, ruggedness (vrm), finescale and broadscale bathymetric position index (BPI) (Figure 7, Table 1).

Slope calculates the gradient change of the surface in degrees. Slope is calculated using the ArcGIS 'Slope' Spatial Analyst tool and uses a 3 x 3 cell window.

Ruggedness (vrm) calculates the variation of a surface as a representation of roughness, with output values ranging from 0 (no variation) to 1 (complete variation) (Figure 12, see user guide for BTM toolbox). Ruggedness is calculated using the 'Ruggedness (vrm)' tool in Benthic Terrain Modeler v3.0 toolbox (Walbridge et al., 2018) and uses a 3 x 3 window. See BTM tool and documentation for further information.

Bathymetric Position Index (BPI) calculates relative elevation across a seascape, where large positive values represent higher elevation areas of the dataset, large negative values represent area of lower elevation, and values around zero represent flatter areas (Figure 6, Figure 12, see user guides for GGMT toolbox, 'Slope Position' tool, for further information). BPI is calculated at a broad scale, to capture larger seabed features, and a finescale, to capture smaller seabed features (Figure 12).

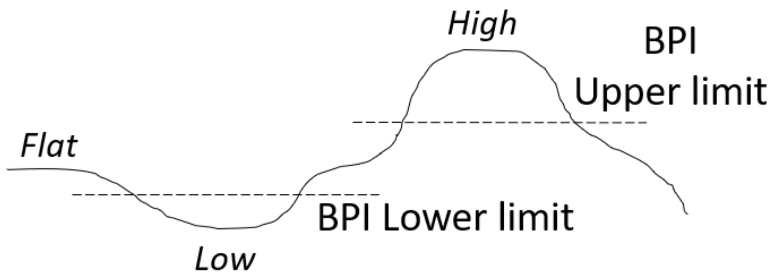

Figure 6 Upper and lower limits of BPI thresholds for finescale and broadscale BPI determine areas classed as highs, lows and flats in the surface elements classification.

The tool specifies the window size (distance in cells) that is used to calculate broadscale and finescale BPI surfaces based on a user-defined distance. For example, a threshold of 150 cells will use a 150 cell-radius (750 m for a 5 m cell DEM) from an individual cell to calculate relative elevation. This 150-cell window will be run across the entire dataset to calculate the relative high, flat and low areas of the dataset at a broad scale.

BPI is calculated using the 'Slope Position' tool in the Geomorphometry and Gradient Metrics v2.0 toolbox (Evans et al., 2014). The 'Slope Position' function from GGMT has been integrated into the Seabed Landforms Classification Toolset. See GGMT tool and documentation for further information.

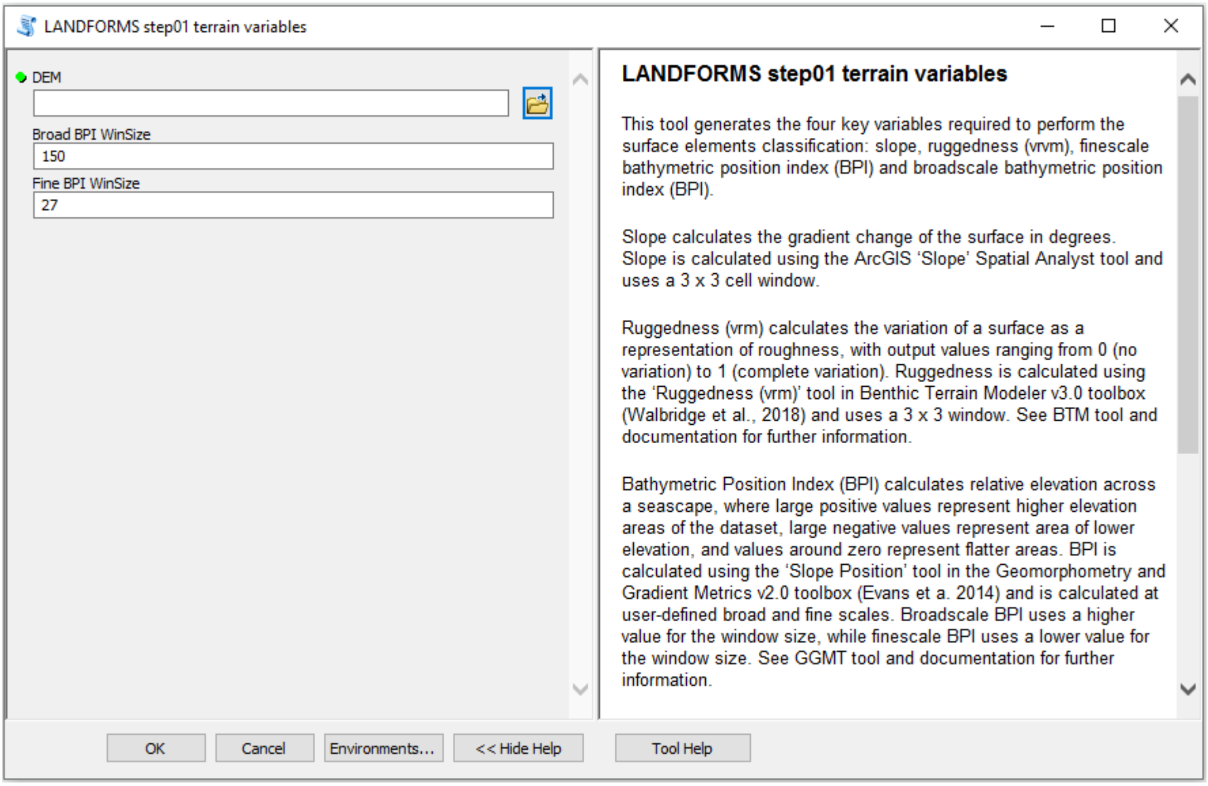

Figure 7 Screengrab of 'LANDFORMS Step 01 terrain variables' interface, with default settings.

Table 1: Input terrain variables for surface elements classification, default settings, key tools and associated Seabed Landforms script.

Terrain variable	Default (based on 5 m cell size with smoothing)	Tool	Seabed Landforms script
Slope	10 degrees	ArcGIS Spatial Analyst	SURFEL-slope
Ruggedness	0.00005 (unitless)	Ruggedness (VRM) – BTM	SURFEL-ruggedness
Finescale BPI	Window 27 cell; -10; +10 (unitless)	Slope Position – GGMT	SURFEL-finebpi
Broadscale BPI	Window 150 cell; -10; +10 (unitless)	Slope Position – GGMT	SURFEL-broadbpi

Step 2: Classify surface elements

The surface elements classification breaks up the seascape into components based on slope (ArcGIS Spatial Analyst), ruggedness (VRM, Benthic Terrain Modeler, BTM, Walbridge et al., 2018), and bathymetric position index 'BPI' (Slope Position, Geomorphometry and Gradients Metric Toolbox, GGMT, Evans et al. 2014). The user is required to enter classification thresholds for each variable, which forms the resultant surface elements. The approach has been developed to target shelf reef features, which are captured effectively by the ruggedness (VRM) variable.

Terrain variables, default thresholds and the associated tools and scripts are outlined in Table 1. The default settings have been determined based on a 5 m cell size raster input with smoothing (3 iterations). Settings should be modified by the user based on the resolution and features of interest within each dataset. The settings applied are recorded as a text file prefixed with 'Current Session'.

The surface elements classification characterises the surface into 11 detailed classes of surface texture which may combine one or two reclassified terrain variables. For example, “Broadscale high Rugose” surface element class combines the user-defined ‘high’ broadscale BPI class and ‘rugose’ ruggedness class. The “surface element” labels are defined in the output “SURF_EL” field. These 11 surface element classes are aggregated into 7 classes to create a “summarised surface elements” layer, which offers a simplified layer for users to interpret features. For example, the “Broadscale high Rugose” would be aggregated with other rugose ‘high’ classes to form “Rugose outcrops”. The “summarised surface element” labels are defined in the output “SUM_SE” field.

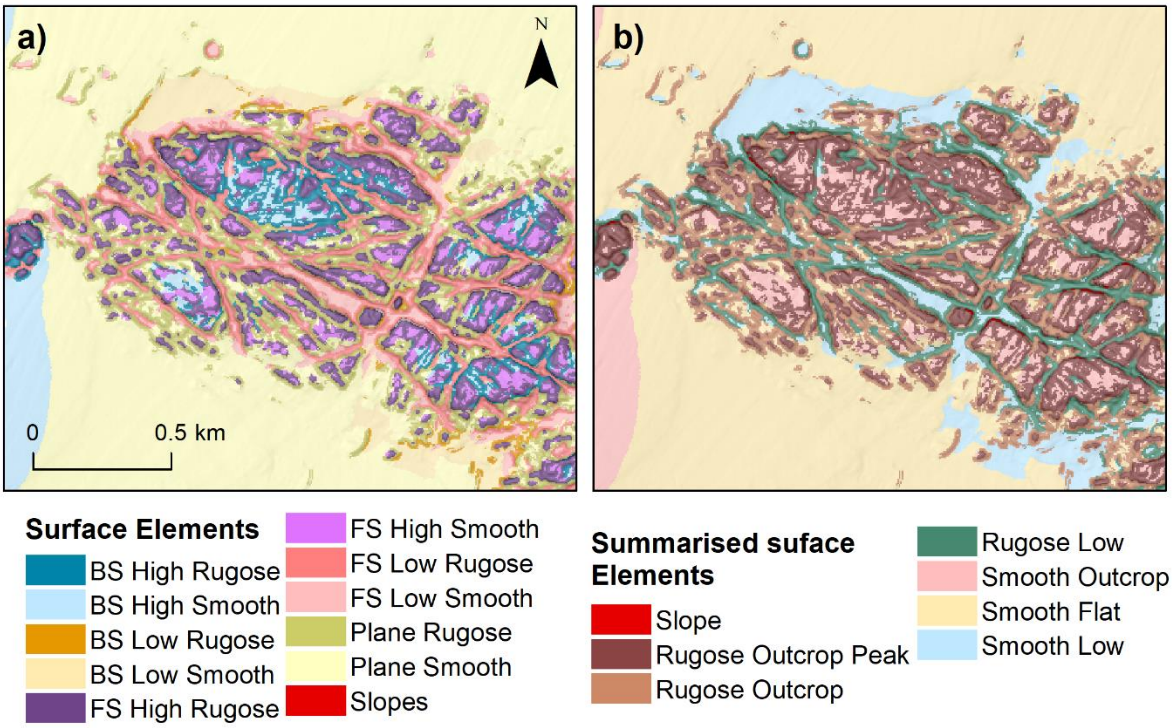

Figure 8 a) Classified surface elements; and b) summarised surface elements [See 'Shellh05_surf_elem' output file and associated colour schemes].

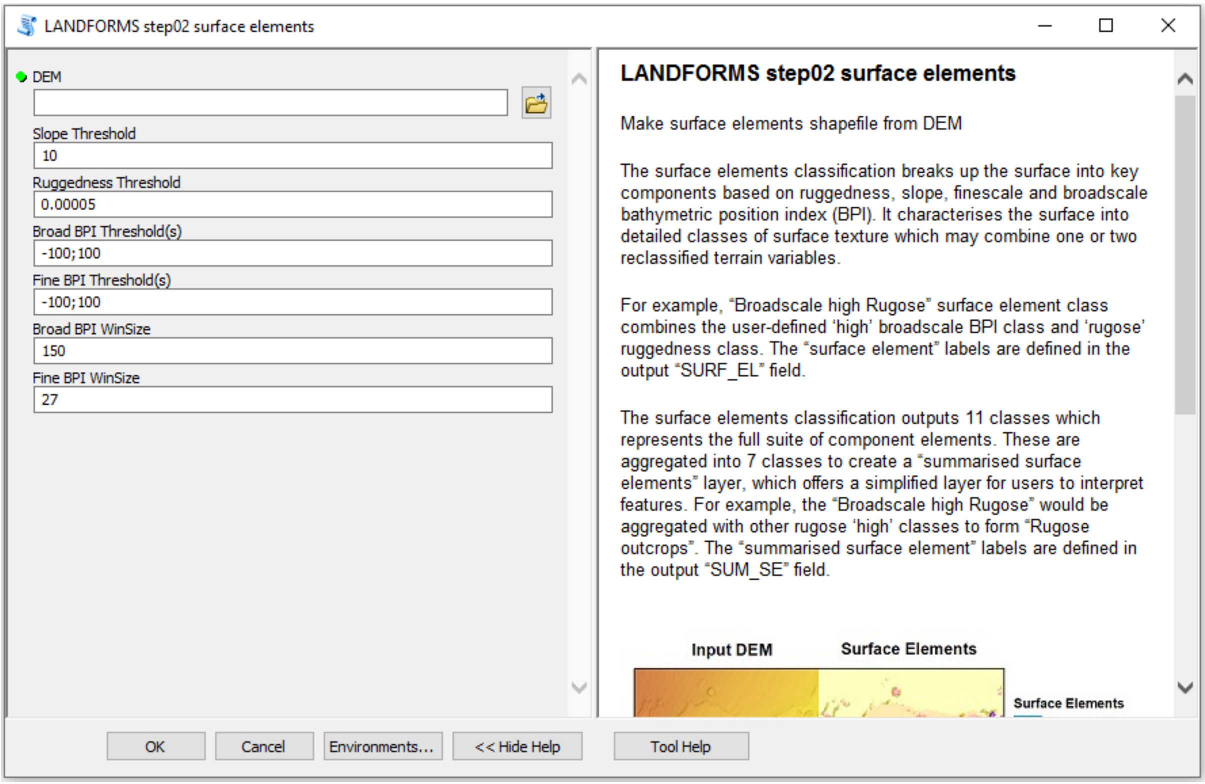

Figure 9: Screengrab of 'LANDFORMS Step 2 Surface Elements' tool interface, with default settings.

Determining suitable threshold values

Default values are provided for the surface elements classification, based on a 5 m input DEM smoothed with 3 iterations of smoothing (using 'PREP smooth DEM'). Users are required to explore suitable threshold values for their individual dataset to ensure the classification captures their features of interest. A guide showing example settings with varied scenarios of input DEM resolutions and levels of smoothing are provided in Supplementary Table 1, Supplementary Figure 1 and Supplementary Figure 2.

Tip: Users may explore different threshold settings using the 'Classified' menu within the layer's Symbology settings (Layer Properties – Symbology tab – Classified menu). This will allow the user to readily test different threshold settings before deciding on a suitable threshold.

Slope

The user-defined threshold value will be used to classify higher slope areas, which will be classed as "Slopes" in the surface elements classification. These classes will ultimately be defined as "Scarps" in the landform classification.

User-defined thresholds will reclassify the data into "slope" (higher slope) classes. For example, a slope threshold of 10 degrees will reclassify: 1) all values >= 10 as "slope" surface element classes; and 2) all values < 10 degrees as lower slope areas, not defined in the surface elements and landform classifications. All values <10 degrees are instead defined by other surface element classes (ruggedness, finescale BPI, broadscale BPI).

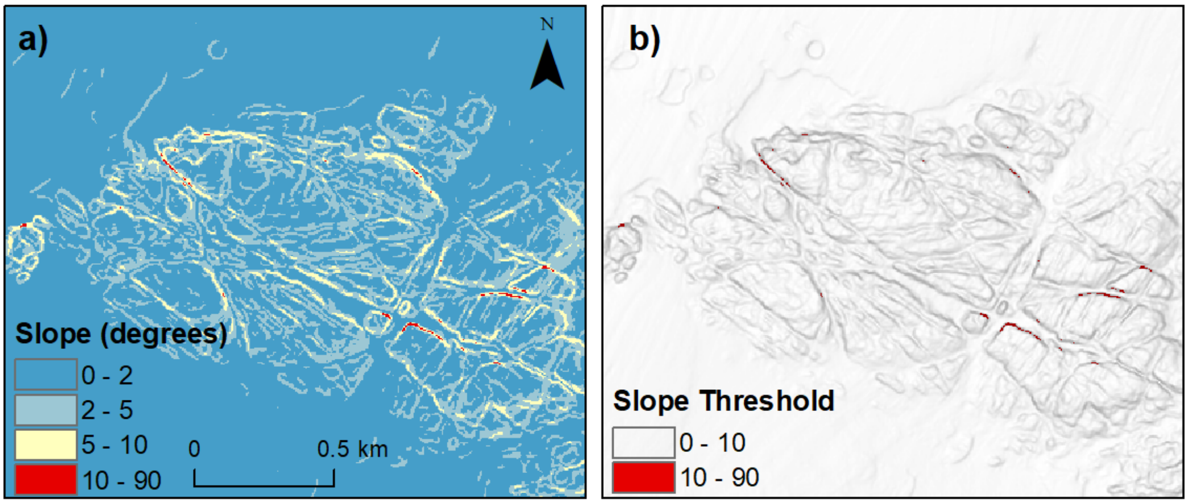

Figure 10: a) Slope variable; and b) Slope threshold showing values ≥ 10 degrees. Input DEM 5 m cell size Shellarbour multibeam data smoothed with three iterations [See case study data: 'shellh05_s3' for DEM input, and 'Shellh05_slp' for slope output].

A suitable slope threshold can be determined by the user, specific to the study area (Figure 10). Default values are based on a 5 m DEM smoothed with three iterations and are intended as a guide. Individual datasets should be interrogated to determine the most suitable threshold settings.

Ruggedness

The user-defined threshold value will be used to define the extent of rugose outcrops, which will be carried through to the surface elements classification as “Rugose” classes and, for example, may become a “Reef/Bank” class in the landform classification. Areas below the selected ruggedness value for rugose features will be carried through as “Smooth” classes in the surface elements classification and, for example, may become a “Plain” class in the landform classification.

A user-defined threshold will reclassify the data into “rugose” (higher ruggedness) and “smooth” (lower ruggedness) classes. For example, a ruggedness threshold of 0.00005 will reclassify: 1) all values >= 0.00005 as “rugose” surface element classes; and 2) values <0.00005 as “smooth” surface element classes.

The ruggedness threshold will vary based on the cell size of the input DEM and iterations of smoothing. Examples of settings applied to selected public DEM datasets with varying resolutions, with and without smoothing, are provided in Supplementary Table 1, Supplementary Figure 1 and Supplementary Figure 2.

When determining the ruggedness threshold, it is important to note that subsequent steps in the classification methodology will identify polygons within a rugose outcrop. If the rugose outcrop edge is adequately captured by the ruggedness threshold, 'gaps' within the outcrop will be identified in later steps as polygons within the outcrop surface. To select a suitable ruggedness threshold, the extent of rugose outcrops captured needs to be balanced with the amount of noise captured, and in turn, manual editing required. Noise correction steps applied in later steps of the landform classification reduce noise within the dataset. See the 'preliminary landforms' section for further information on the noise correction procedure.

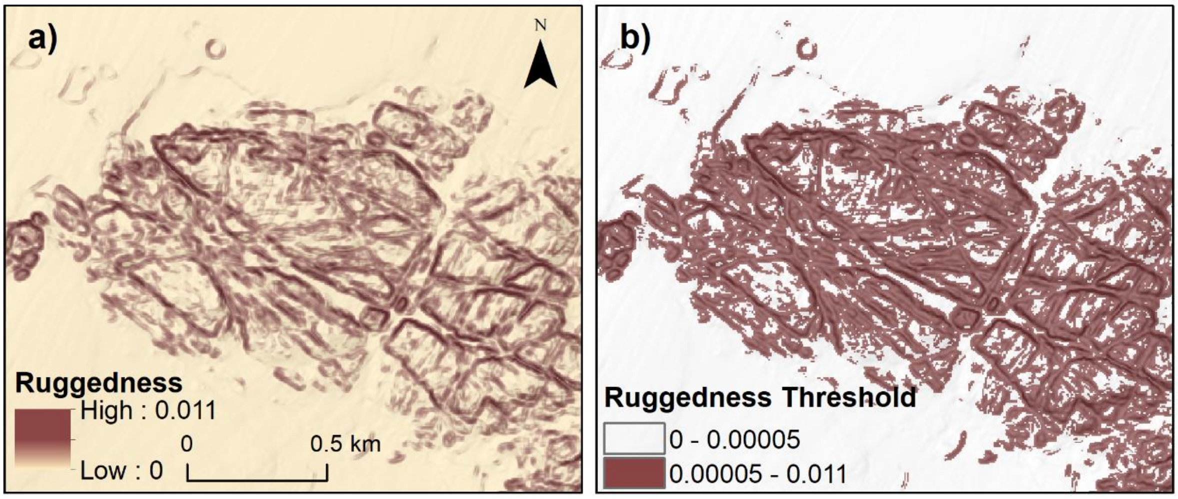

Figure 11 a) Ruggedness (VRM) variable; and b) Ruggedness (VRM) threshold ≥ 0.00005 (unitless) [See case study data 'shellh05_s3' for input, and 'Shellh05_vrm' for ruggedness output].

Default values for ruggedness are based on a 5 m DEM smoothed with three iterations and are intended as a guide. Input DEM resolution and smoothing alters the output ruggedness, and threshold values should be adjusted accordingly. Individual datasets should be interrogated to determine the most suitable threshold settings, taking into account level of smoothing and DEM cell size (See Supplementary Table 1, Supplementary Figure 1 and Supplementary Figure 2 for example datasets and settings).

Bathymetric Position Index

Users will select two threshold values for each of the finescale and broadscale datasets which will define the high, low and flat areas (Figure 6). For example, in the case of the broadscale BPI dataset: two user-defined thresholds will be used to reclassify the data into “Broadscale Low” (negative BPI values), “Flat” (BPI values around zero), and “Broadscale High” (positive BPI values) classes. For example, a threshold of -100; 100 will create a reclassified polygon separated into three classes: 1) the lower extent of data values (dataset-dependent) to -100. These larger, negative BPI values as classed as “Broadscale Low”; 2) -100 to 100. These data values around zero are classed as “Flat”; 3) 100 to the upper extent of data values (dataset-dependent). These larger, positive BPI values are classed as “Broadscale High”. “Broadscale High” surface elements, for example, may become “Peak” classes in the landform classification, and “Broadscale Low” classes, for example, may become “Depressions and channels” in the landform classification.

Default values are based on a broadscale BPI window size of 150 cells with 5 m DEM smoothed with three iterations, and are intended as a guide. Individual datasets should be interrogated to determine the most suitable threshold settings.

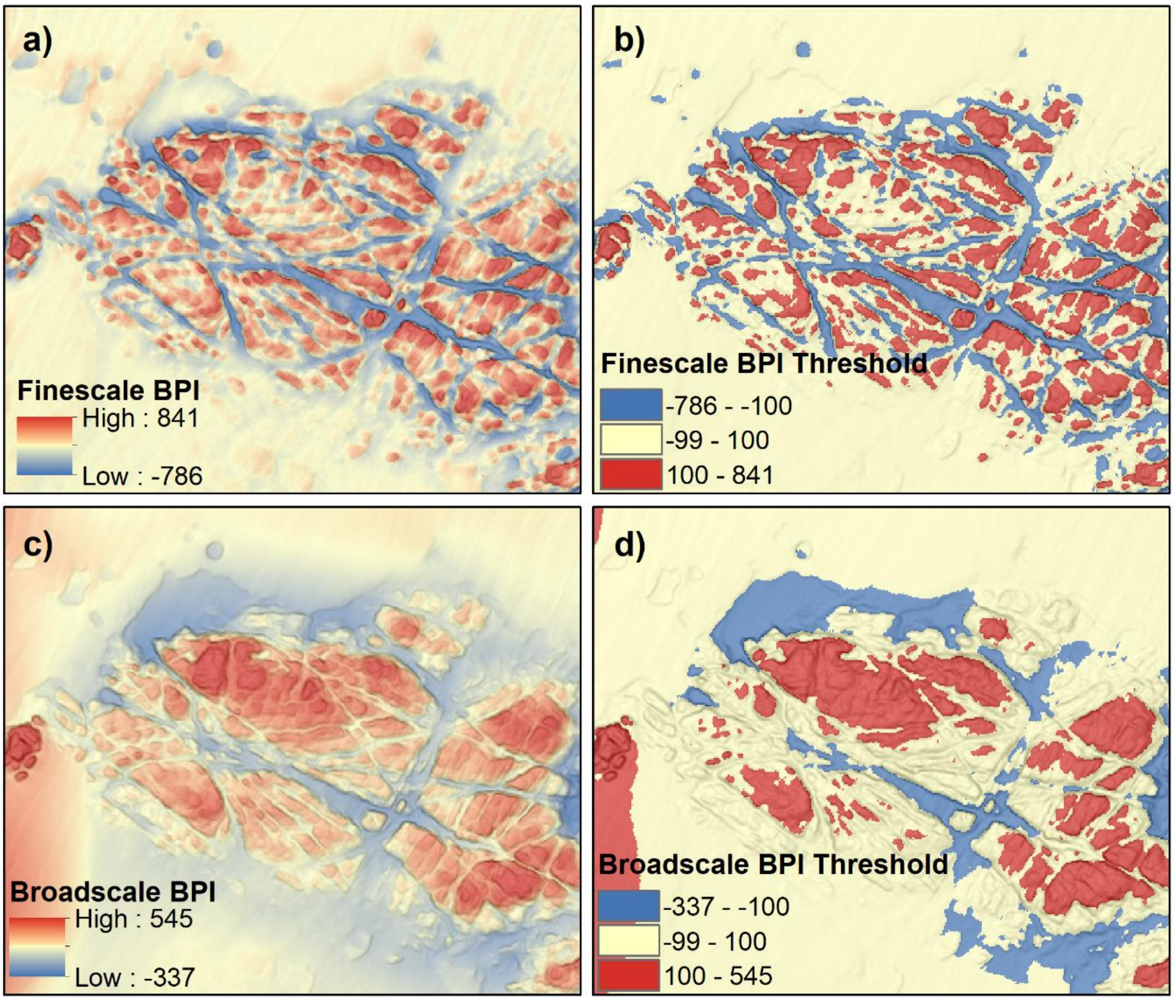

Figure 12: a) Finescale BPI variable; b) Finescale BPI thresholds at -100 and 100 (unitless); c) Broadscale BPI variable; d) Broadscale BPI thresholds at -100 and 100 (unitless) [See case study data 'shellh05_s3' for input, Shellh05_finebpi for finescale bpi output; and Shellh05_broadbpi for broadscale BPI output].

Due to the relative nature of the BPI calculation, the output will vary depending on the characteristics of the input surface. Users may note that shallower areas of the dataset, such as areas along the coast, may be classed as "high" features (particularly for broadscale BPI). This is because these shallow areas are high in elevation relative to the remaining dataset. Similarly, the deeper areas of the dataset may be classed as a broadscale "low". The sharp change in gradient at the base of a raised outcrop may also appear as a “low” while a profile of the feature may not indicate a low. These issues are inherent to the nature of the calculation, and it is recommended users be aware of this when interpreting the classified output. The use of BPI in morphological classifications of seascapes and landscapes is well established, however due to the relative nature of the calculation, users must be familiar with their own dataset when interpreting the classified product.

Step 3: Depth reclassification (Optional)

This optional tool allows users to generate polygons at depth intervals specified by the user, with depth intervals calculated from zero. For example, an interval value of 10 m for a dataset ranging -17 to -55 m will generate polygons at -10 to -20 m, -20 to -30 m, -30 to -40 m, -40 to -50 m, and -50 to -60 m intervals. This output is not used in any subsequent analysis for the surface elements and landform classifications. It is generated as an extra dataset for use at the user's discretion.

Step 4: Surface drainage (Optional)

The surface drainage tool creates a theoretical drainage of water flows across the surface (Figure 13). Further detail on the theoretical drainage classification is provided in Linklater et al. (2019). It is an optional tool which assists the user in interpreting 'channels' at the landform stage of analysis. 'Depressions and channels' are an aggregate category in the landform classification, and users may utilise the drainage layer to manually separate channels, at the user's discretion.

The surface drainage toolset uses tools within the ArcGIS Hydrology toolbox to define theoretical drainage. A flow direction surface is first created, which is then used to create a flow accumulation surface. This accumulation surface is log-transformed, and data are clipped to 100 m^3 to identify dominant theoretical drainage pathways. The drainage calculation here is not intended as a precise measure of surface volume and accumulation and is instead intended as a guide to inform channel identification. It is not recommended this tool be used for purposes other than the seabed landform classification.

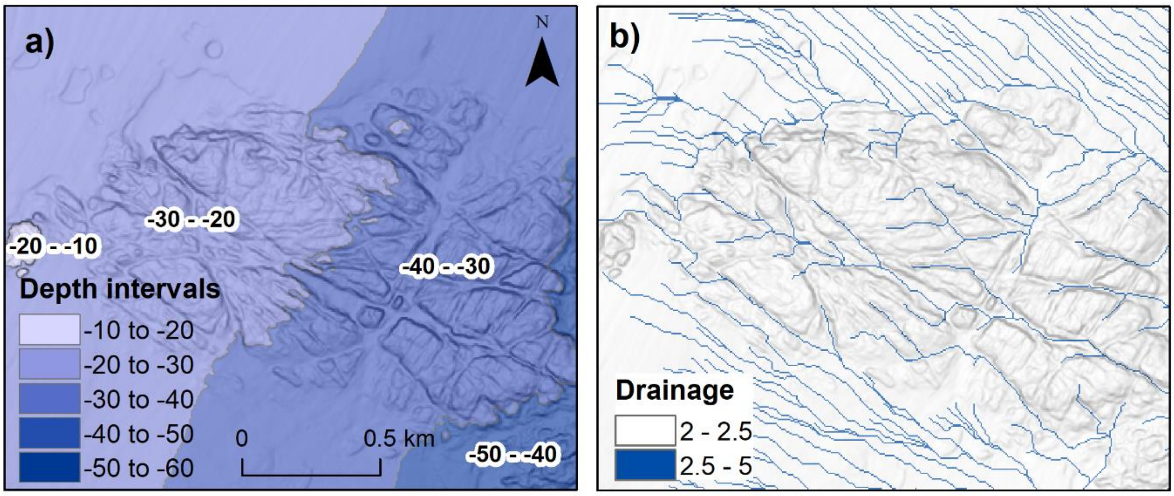

Figure 13: a) Bathymetry data (DEM smoothed x3 iterations); and b) classified theoretical drainage [See case study data 'Shell05_drainage for drainage output, and associated colour schemes].

Step 5: Transfer surface element files

The derived terrain variables, drainage and depth classifications (if generated), and the surface elements classification are transferred across to a new file geodatabase, prefixed with a user-defined label e.g. "SURFEL_Example.gdb" (Figure 13, Figure 14). The surface elements classification can be viewed using the symbology layer provided.

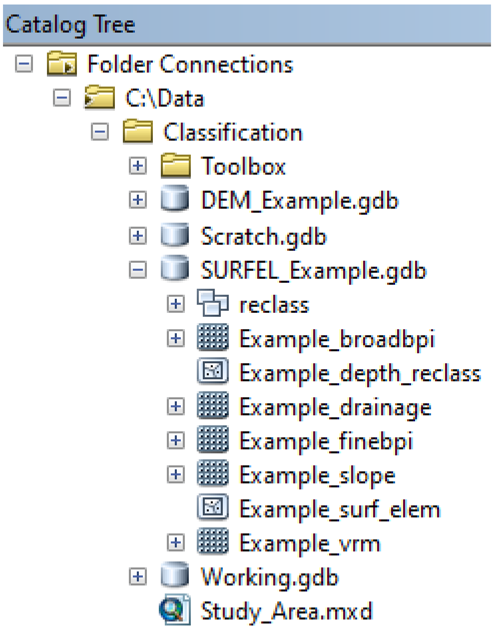

Figure 14: Example outputs of surface elements file transfer with user-defined prefix entered here as "Example".

Table 2: Relationship between surface element and landform terms. Variations in final landform terms may occur at the discretion of the user. BS = Broadscale; FS = Finescale.

Surface elements	Summarised surface elements	Preliminary landforms	Final landforms
BS High Rugose	Rugose Outcrop Peak	Peak	Peak
BS High Smooth	Smooth Outcrop	Plain	Plain
		Peak REVIEW	Peak*
			Plain
BS Low Rugose	Rugose Outcrop	Reef/Bank	Reef/Bank
BS Low Smooth	Smooth Low	Plain	Plain
FS High Rugose	Rugose Outcrop Peak	Peak	Peak
FS High Smooth	Smooth Outcrop	Plain	Plain
		Peak REVIEW	Peak*
			Plain
FS Low Rugose	Rugose Low	Depressions and channels Rugose	Depressions and channels Rugose
		Depressions and channels Rugose REVIEW	Depressions and channels Rugose
			Reef/Bank*
FS Low Smooth	Smooth Low	Plain	Plain
		Depressions and channels Smooth	Depressions and channels Smooth
Plane Rugose	Rugose Outcrop	Reef/Bank	Reef/Bank
Plane Smooth	Smooth Flat	Plain	Plain
		Reef/Bank REVIEW	Reef/Bank*
			Depressions and channels Smooth
Slope	Slope	Scarp	Scarp

* Indicates the final landform class that is attributed without manual editing for "REVIEW" polygons.

Step 6: Classify preliminary landforms (output requiring review)

Seabed landforms are defined from the classified surface elements, where multiple surface element classes may be ultimately grouped to form a landform (Table 2). Landforms represent key features of the seascape, including peaks, reefs/banks, scarps, depressions and channels, and plains (Table 3). These classes do not represent the only landforms that may occur within a seascape and are intended to capture the prominent features observed within a continental or island shelf setting.

A series of procedures are implemented during the classification of preliminary landforms (Figure 15). Attribute and location queries are performed to identify polygons that occur within a rugose outcrop. This enables 'depressions and channels' to be identified within the surface of an outcropping feature. Surface elements classes are queried to create preliminary landform classes (see Table 2). Some preliminary landforms classes are identical to a surface element class/classes, for example all 'Slope' surface elements are labelled as "Scarps" in the landform classification. Other landform classes require further review, as discussed further below.

Note: This step includes buffer processes which apply a 5 km buffer surrounding the input dataset. If the study area contains isolated polygons separated by 5 km distance or more (such as offshore islands), these tools will not work correctly.

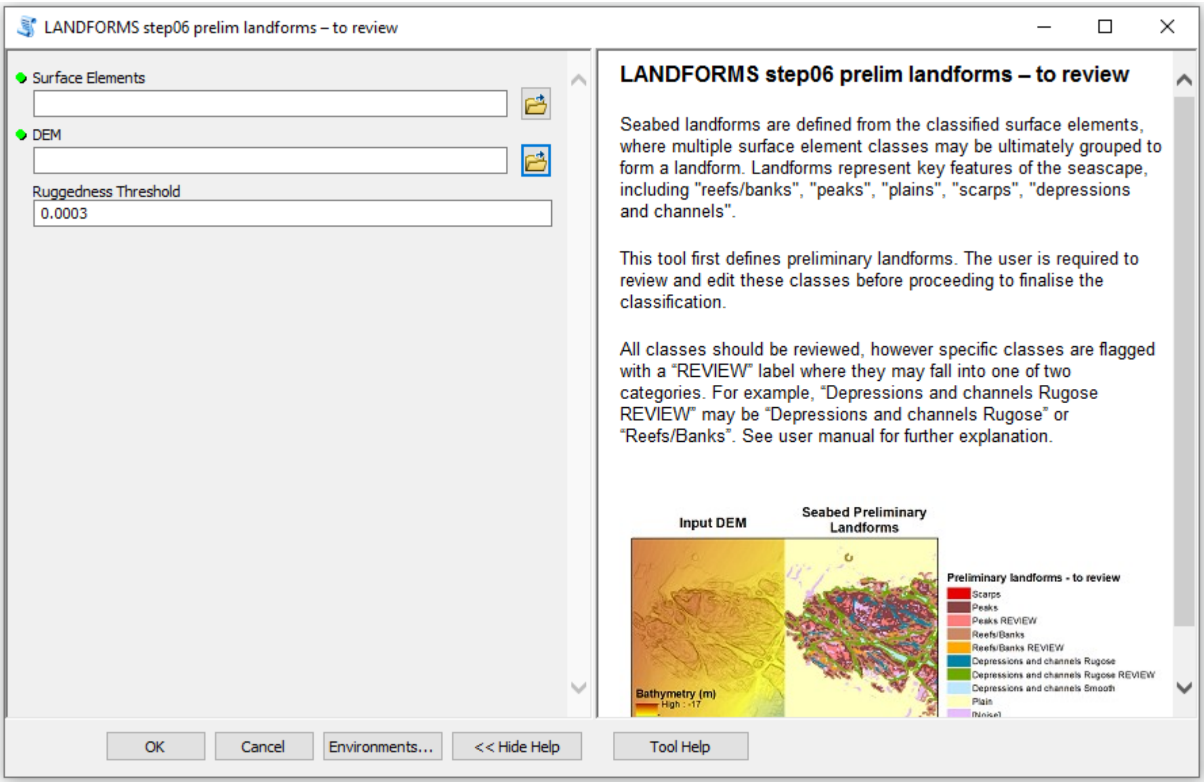

Figure 15: 'LANDFORMS Step 6 Preliminary Landforms – to review' tool interface, with default settings.

The user is required to review and edit the preliminary landform classes before proceeding to finalise the seabed landform classification. All classes should be reviewed, however specific classes are flagged with a "REVIEW" label where they may fall into one of two categories. For example, "Depressions and channels Rugose REVIEW" may be "Depressions and channels Rugose" or "Reefs/Banks".

Tip: Users are encouraged to create a copy of the preliminary landforms 'prelim_landforms' feature class within the Working.gdb to perform manual edits. All new files created within this 'Working' geodatabase will be carried across during 'Step 8 – transfer landform files'.

Table 3: Term definitions for seabed landform features.

Landform	**Definition**	**Source**
Reef	A mass of rock or coral which either reaches close to the sea surface or is exposed at low tide, posing a hazard to navigation. *Note: In this study, the definition of 'reefs' is extended to also include submerged features*	International Hydrographic Organization (2019)
Bank	An elevation of the sea floor, often found in water depths less than 200 m	Dove et al. (2020)
Plain	Any land with a flat or very slightly undulating surface. A flat, gently sloping or nearly level region of the sea floor, for example, abyssal plain.	International Hydrographic Organization (2019)
Peak	A prominent, commonly pointed elevation rising from a larger feature (modified from IHO, 2019).	Dove et al. (2020)
Depression	A general term for a closed-contour bathymetric low.	Dove et al. (2020)
Channel	A general term for an elongated bathymetric low (adapted from IHO, 2019).	Dove et al. (2020)
Scarp	The steep face of a hill.	International Hydrographic Organization (2019)

Determining a suitable noise correction threshold

Procedures are included to identify potential 'noise' polygons. Noise may be erroneous data sourced from the input bathymetry (such as speckled noise in marine lidar data or imagery), or superfluous rugose outcrops. To correct for these additional 'noise' areas, a second ruggedness threshold may be used to identify areas of higher ruggedness, and therefore areas of greater relief which are less likely to be noise in the data.

With a user-defined 'noise' ruggedness threshold (Figure 15), processes are implemented to overlap the 'ruggedness noise threshold' (higher ruggedness value, e.g. 0.0003) with the rugose outcrops defined in the surface elements classification (lower ruggedness value, e.g. 0.00005). Where rugose outcrops overlap with the ruggedness noise threshold, the preliminary landform labels are retained. Where they do not overlap, the polygons are labelled as 'noise'. These 'noise' polygons are to be manually reviewed by the user in later steps to ensure polygons are correctly attributed.

A suitable 'noise' ruggedness threshold can be identified by interrogating the ruggedness layer, and selecting a value which, when overlapped with the ruggedness threshold for rugose outcrops, will retain the most appropriate extent of the rugose outcrop. An example is provided below in Figure 16, which uses the default settings of the tool.

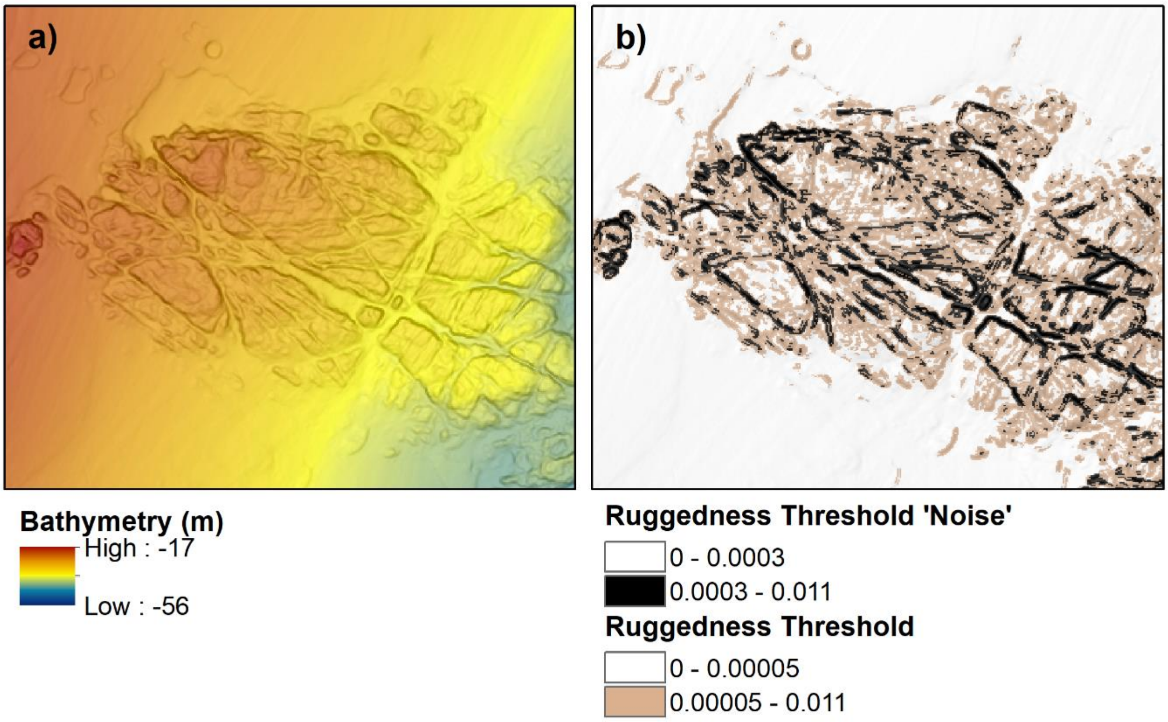

Figure 16: a) Bathymetry (m) DEM smoothed with three iterations; and b) Ruggedness (VRM) threshold ≥ 0.00005 (unitless) for surface elements classification (Step 2) and ruggedness (VRM) threshold ≥ 0.0003 (unitless) for noise correction in the preliminary landforms classification (Step 6).

Default values for the ruggedness noise threshold are based on a 5 m DEM smoothed with three iterations and are intended as a guide. Individual datasets should be interrogated to determine the most suitable threshold settings (See Supplementary Table 1 for example datasets and settings).

Manual review and editing

The 'prelim_landforms' feature class is the preliminary landforms classification output which requires manual review and potential editing by the user. Preliminary landform labels are attributed within the field "PrelimLand". These include: Peaks, Peaks REVIEW, Reefs/Banks, Reefs/Banks REVIEW, Scarps, Depressions and channels Smooth, Depressions and Channels Rugose, Depressions and Channels Rugose REVIEW, and Plains. 'Rugose' and 'Smooth' qualifiers are provided for the depressions and channels. 'Rugose' depressions and channels are be considered part of the outcropping reef/bank surface, whereas 'Smooth' depressions and channels are contained by, rather than a part of the outcropping reef/bank surface. Note: the “LAND_2” field is a duplicate of “PrelimLand” in case the user needs to refer back to the original labels when performing edits.

The landform classification approach is flexible to the user's specific terminology of features and users can add landform terms. The toolset provides classified boundaries which can be reviewed and altered by the user to create the final classification. Any new or altered terms applied during the editing of the preliminary landforms layer will be carried across as final landform labels.

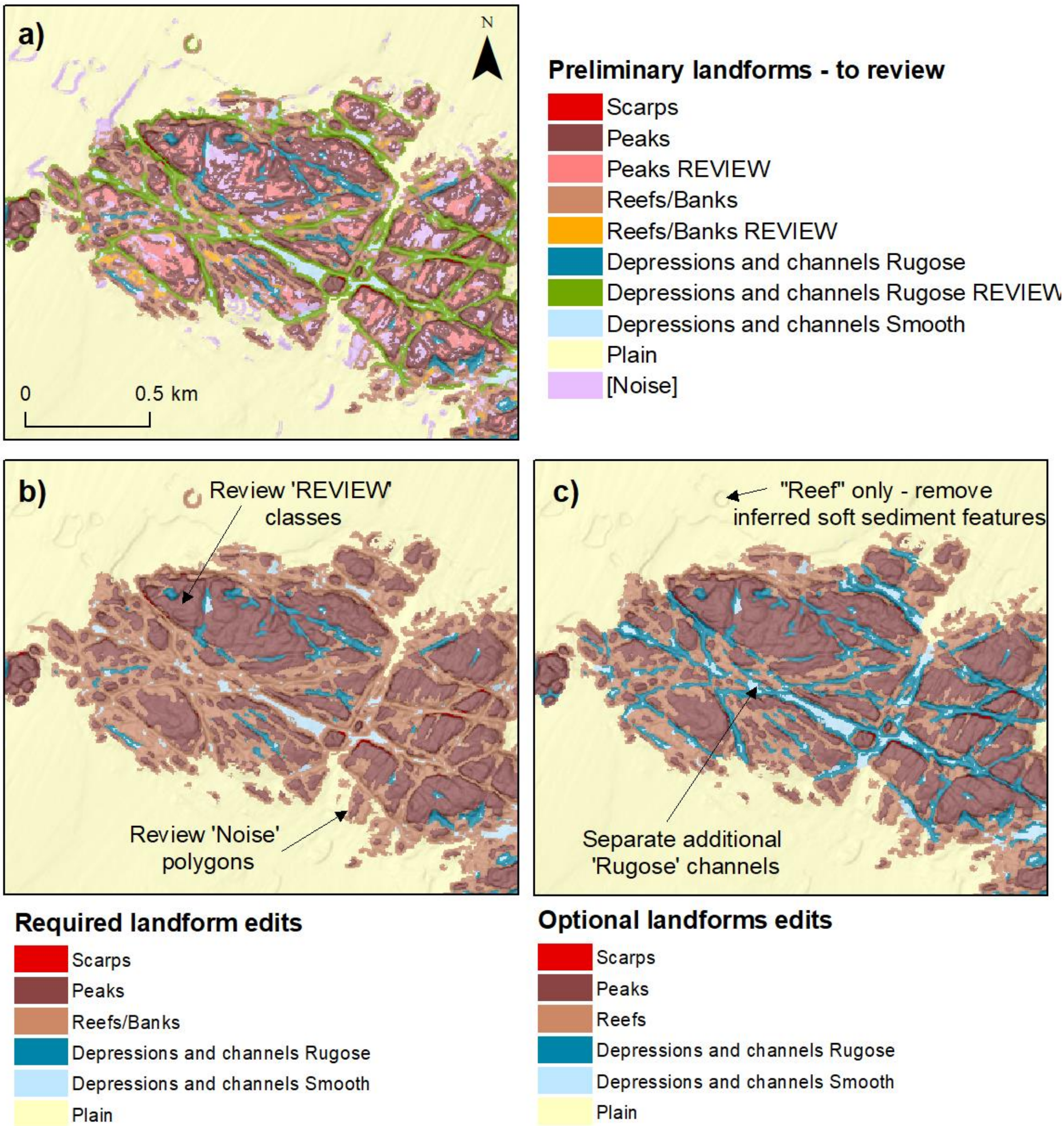

Figure 17: Landforms classifications for Shellharbour case study data including: a) Preliminary landform classification, with classes to be manually reviewed by the user; b) an edited final landforms classification where 'required' edits are performed; and c) an edited final landforms classification where 'optional' edits are performed. Polygons smaller than 25 m^2 eliminated in b) and c) [See 'LANDFORM_Shellh05_RequiredEdits.gdb' and 'LANDFORM_Shellh05_OptionalEdits.gdb' output files and associated colour schemes].

Tip: To review the preliminary landforms, it is recommended the user load in the 'PrelimLandforms.lyr' symbology for the 'PrelimLand' labels, and display the slope grid transparency (e.g. 50%) over the preliminary landforms classification. The input DEM should also be loaded for interrogation, as well as the drainage grid if channel identification is desired (symbology layer files provided).

Required edits

Several classes are labelled with a "REVIEW", including "Peak REVIEW", "Depressions and channels Rugose REVIEW" and "Reef REVIEW". They occur when a class may fall into one of two classes (see Table 2). The most likely class is assigned, however visual inspection is required to confirm or relabel the polygon into the appropriate class.

During the procedure to define preliminary landforms, 'noise' polygons are identified in areas where rugose polygons do not overlap with higher ruggedness areas (Figure 16). These polygons require review and potential editing by the user to ensure the full extent of the observed features are captured. The original landform terms are captured within the 'LAND_1' field, and the 'LAND_2' labels can be updated by carrying across these original labels as required.

Optional edits

The output of the landforms classification creates an aggregated category of "reef/bank". 'Reefs' represent inferred rock or biogenic reef features, and 'banks' are inferred as soft-sediment features (Table 3). While the landform classification is not intended to map substrates, rock/biogenic reef and soft sediment outcrops can be discernable to users familiar with the seascape (as occurs where features are manually digitised), and in such cases they can be considered distinct landforms. While these features are unable to be separated automatically through the toolbox, users can manually edit the output to separate these features, if desired. This flexibility allows users to adjust the landform output to meet their requirements.

Additional 'Rugose' channel features are captured by the 'Depressions and channels Rugose REVIEW' class. These features can be reviewed and manually edited to be included in the final landform classification if the user desires greater detail of variation across the reef/bank surface. Due to the nature of BPI discussed above in 'Preparation: Clip elevations', this class can include the reef/bank edge as a 'low' depression/channel. Therefore, to separate the additional rugose channels, the user must manually edit and cut the channel extent from the 'Depressions and channels Rugose REVIEW' polygon. If this editing is not performed, the 'Depressions and channels Rugose REVIEW' classes will be labelled as 'Reefs/Banks' in the subsequent 'Step 7: Final landforms' tool.

An example of the optional edits to separate reef landforms and rugose channel features is included in Figure 17.

Step 7: Classify final landforms

When the user is satisfied with the preliminary landforms classification, the reviewed layer can be input into 'Step 07 – final landforms' to generate the final landform classification (Figure 18). This tool has optional functionality to eliminate small polygons, with a user-defined polygon area.

This tool should be performed after manual review has been conducted on the preliminary landform classification. In this tool, “Preliminary landform” labels (“PrelimLand” field) are transferred into final landform labels (“LANDFORM” field). Unless the classes have been edited to label otherwise, "Peaks REVIEW" classes will become "Peaks", "Depressions and channels Rugose REVIEW" will become "Reefs/Banks", and "Reef/Banks REVIEW" will become "Reefs/Banks".

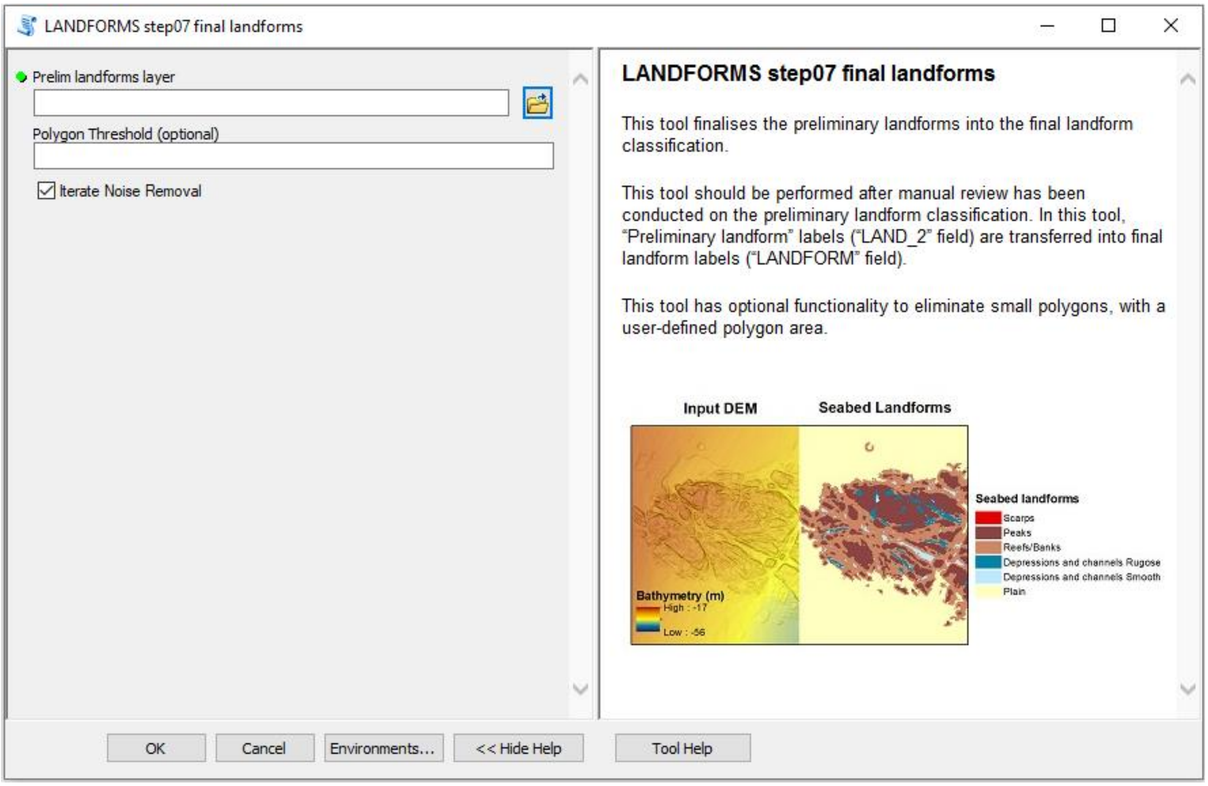

Figure 18: 'LANDFORMS Step 07 Final Landforms' tool interface.

Step 8: Transfer landform files

Files created with tools within Step 6 and Step 7 of the landforms classification are moved across into a new file geodatabase, prefixed with a user-defined label e.g. "LANDFORM_Example.gdb" (Figure 19).

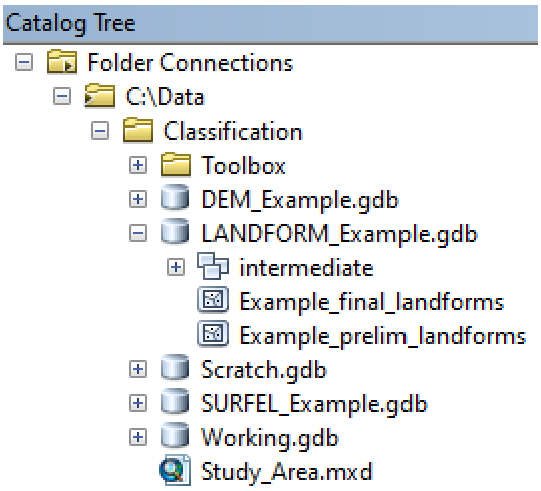

Figure 19: Example outputs of landforms file transfer with user-defined prefix entered here as "Example".

Plain classification

Step 9: Plain landforms

Plain landforms are defined using finescale and broadscale BPI, creating classes including: Plain High, Plain Low, Localised high, Localised low and Plain flat. This classification intends to capture additional detail across the plain area for users focused on the inferred sedimentary environment.

The user is required to enter classification thresholds for each variable (Figure 21), which forms the resultant plains classification (Figure 22). Default values are based on a 5 m DEM smoothed with three iterations and are intended as a guide. Individual datasets should be interrogated to determine the most suitable threshold settings.

This tool has optional functionality to eliminate small polygons, with a user-defined polygon area.

Due to the inherent issues with BPI discussed earlier in the 'Preparation: Clip elevations' section, specifically the classification of "lows" at the edge of a reef/bank surface, it is recommended the plain classification be limited to only defined 'plain' areas. 'Depression and channels Smooth' areas may also be included at the discretion of the user. To achieve this, users will need to extract the DEM over these areas as the input for the plain classification.

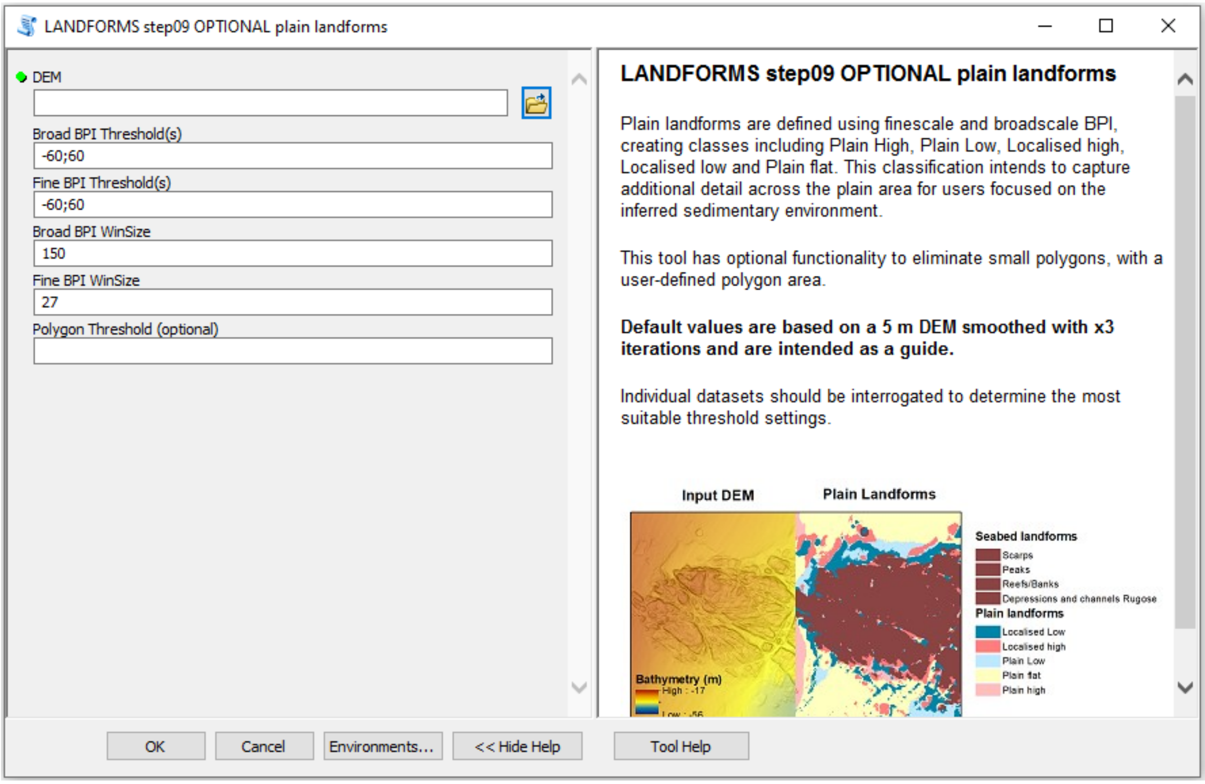

Figure 20: 'LANDFORMS Step 9 OPTIONAL Plain Landforms' tool interface, with default settings.

Step 10: Transfer plain files

Files created with tools within Step 9 of the plains classification are moved across into a new file geodatabase, prefixed with a user-defined label e.g. " PLAIN_Example.gdb"

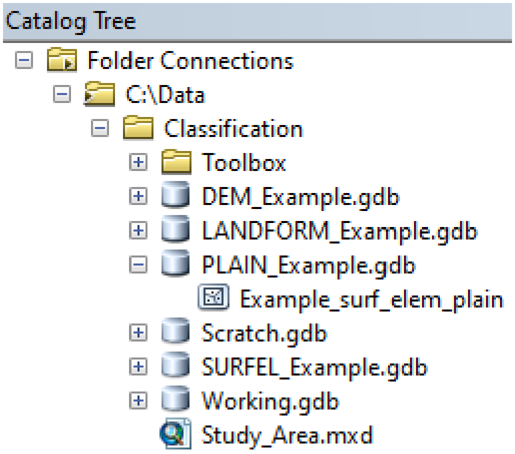

Figure 21: Example outputs of plain classification file transfer with user-defined prefix entered here as "Example".

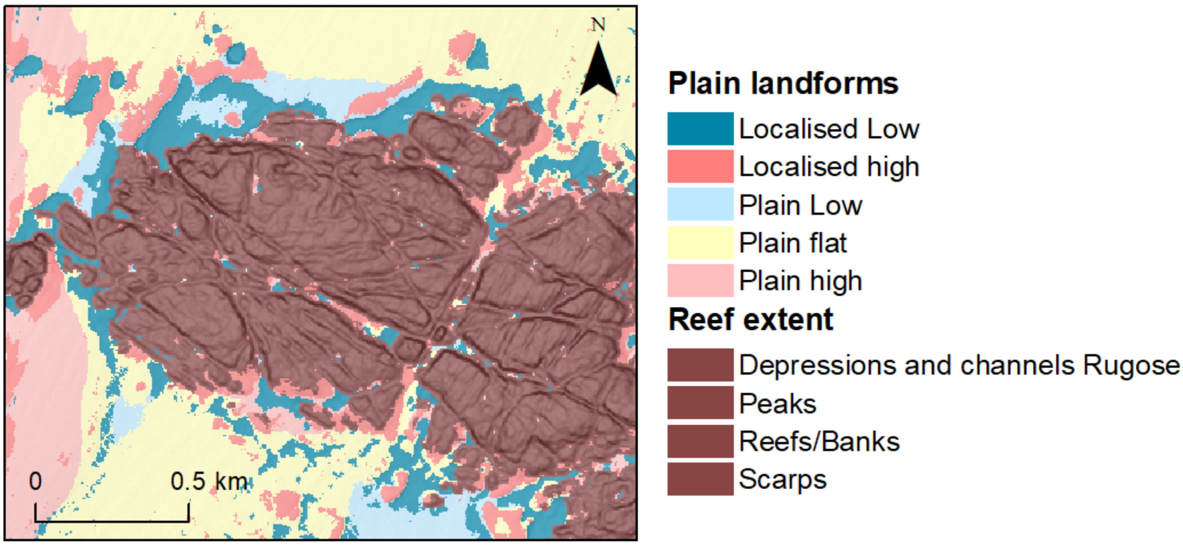

Figure 22: Plain landforms classification for case study Shellharbour data. Polygons smaller than 200 m^2 were eliminated. [See 'Shellh05_surf_elem_plain' feature class output and associated colour schemes].

Citation

Please cite the Seabed Landforms Classification Toolset as:

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Troubleshooting

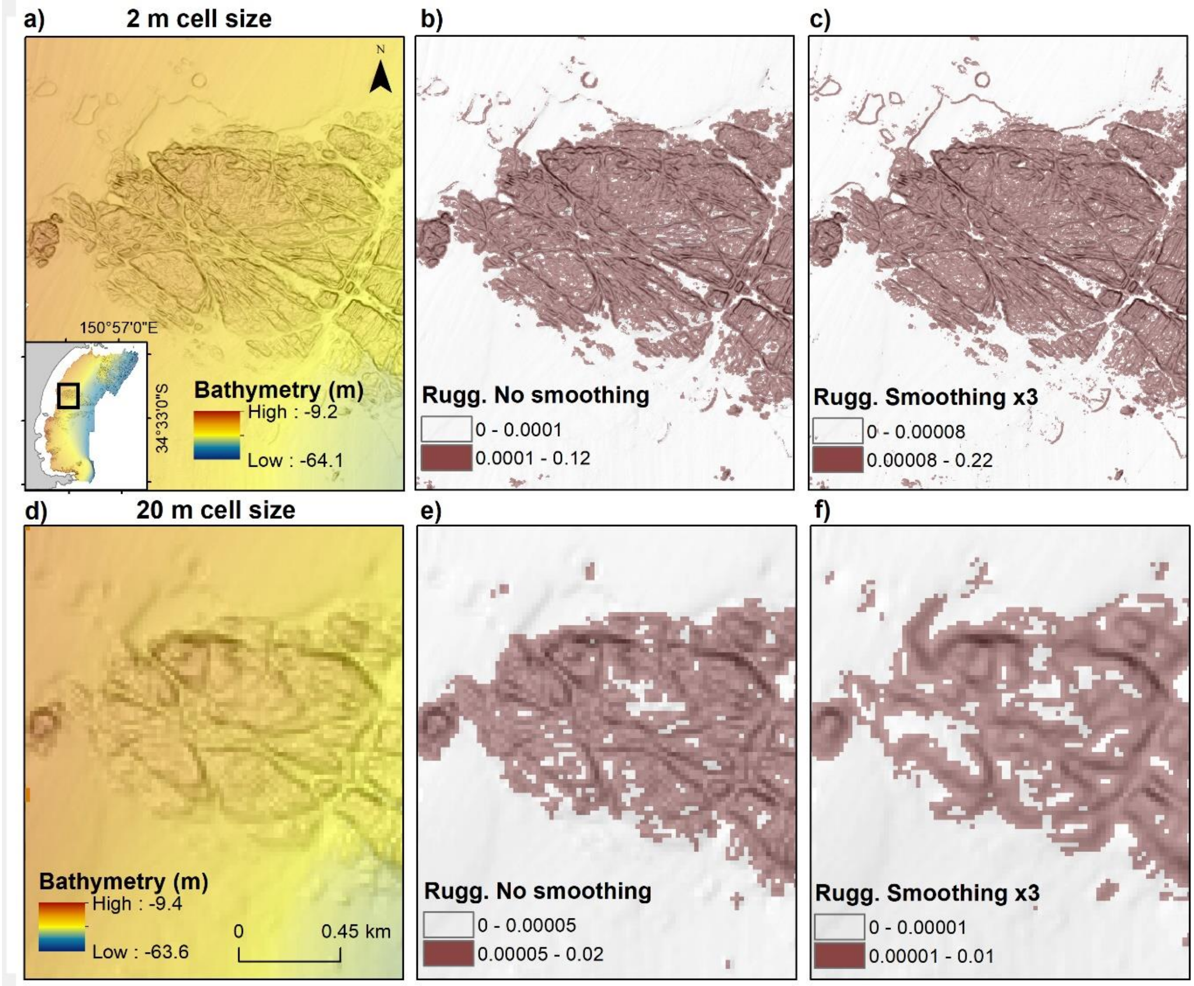
- Make sure the working Arc Map Document (.mxd) is saved. The toolbox needs to know the Map Document location to write the Scratch and Working geodatabases to output the datasets.
- Make sure you have an active Spatial Analyst license
- An error associated with the map's coordinate system may appear if you run the tools on a new ArcMap document which has no set coordinate system. Once a suitable dataset is loaded into the map, this will register the coordinate system in the map document
- In ArcGIS, file names should begin with a letter character and not include spaces or special characters (except an underscore). Starting file names with numbers should be avoided.
- If saving files outside a geodatabase, raster file names are limited to 13 characters, with a total path name length of 128 characters. Longer file names are permitted when stored in a geodatabase (Seabed Landform Classification Toolset stores files in geodatabases).
- Use ArcCatalog to view and manage GIS datasets.

Supplementary Materials

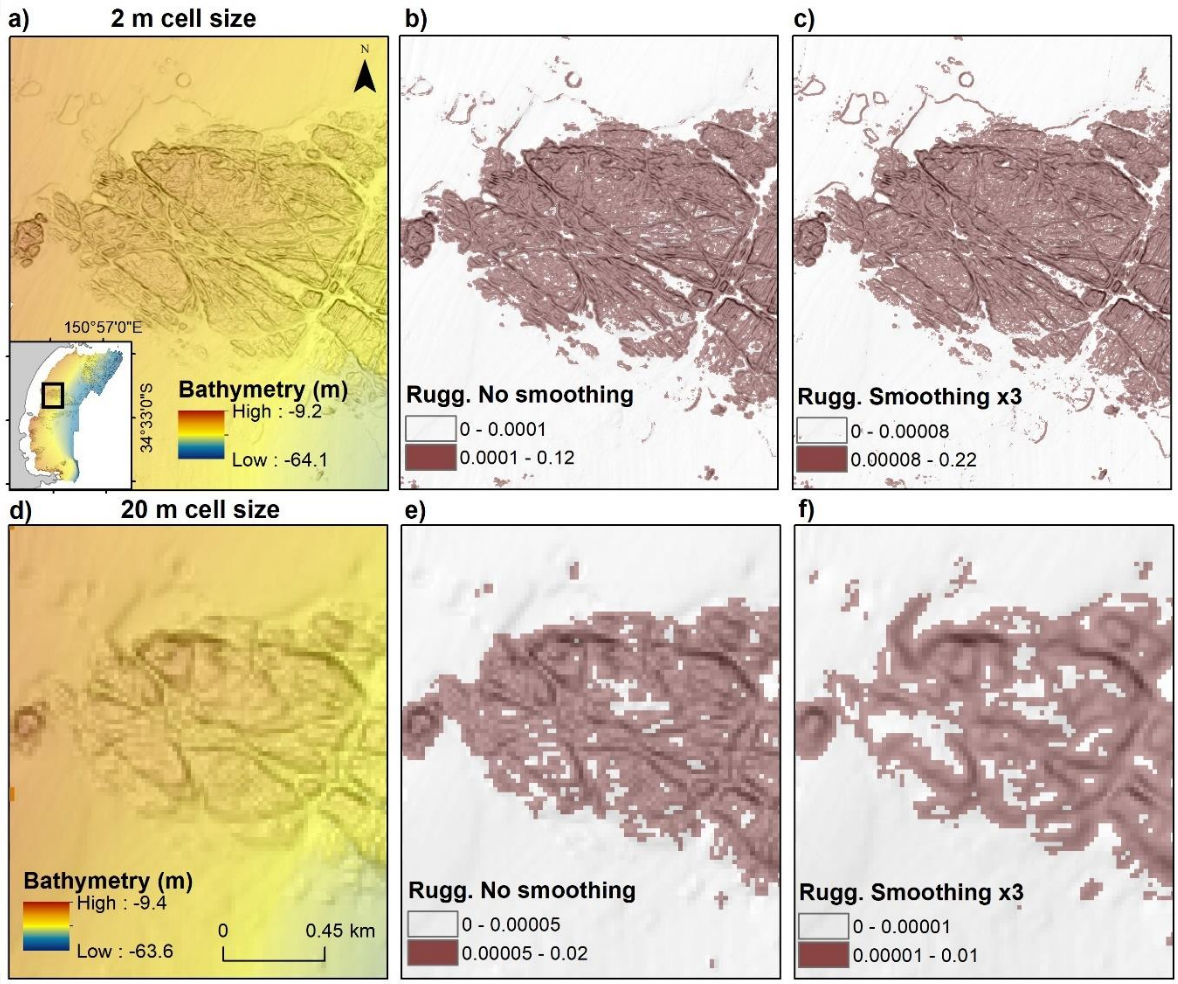
Supplementary Table 1: Example threshold settings for publicly available marine lidar and multibeam echosounder datasets in New South Wales (NSW) and Western Australia (WA), Australia. Shellharbour multibeam echosounder data at 2 m cell size was resampled to 5, 10 and 20 m cell size to indicate how ruggedness thresholds may vary with different resolution inputs and iterations of smoothing.

Bathymetry dataset (resolution)	Res (m)	Smoothing iterations	Ruggedness	Ruggedness Noise	FineBPI	BroadBPI	Slope
NSW marine lidar – Moruya (NSW DPIE)[1]	5	-	0.0005	0.002	Win: 27 -100; 100	Win: 150 -100; +100	10
	5	3	0.00008	0.0005	Win: 27 -100; 100	Win: 150 -100; +100	10
Shellharbour multibeam echosounder (NSW DPIE)[2]	2	-	0.0001	0.001	Win: 27 -100; 100	Win: 150 -100; +100	10
	2	3	0.00008	0.0005	Win: 27 -100; 100	Win: 150 -100; +100	10
	5	-	0.0002	0.001	Win: 27 -100; 100	Win: 150 -100; +100	10
	5	3	0.00005	0.0003	Win: 27 -100; 100	Win: 150 -100; +100	10
	10	-	0.0001	0.0003	Win: 27 -100; 100	Win: 150 -100; +100	10
	10	3	0.00003	0.00015	Win: 27 -100; 100	Win: 150 -100; +100	10
	20	-	0.00005	0.0002	Win: 27 -100; 100	Win: 150 -100; +100	10
	20	3	0.00002	0.00006	Win: 27 -100; 100	Win: 150 -100; +100	10
Middleton Reef (Geoscience Australia)[3]	3	-	0.0003	0.0008	Win: 27 -100; 100	Win: 150 -100; +100	10
	3	3	0.0001	0.0003	Win: 27 -70; 70	Win: 150 -70; +70	10
WA marine lidar - Perth (WA Department of Transport)[4]	5	-	0.0001	0.0005	Win: 27 -100; 100	Win: 150 -100; +100	10
	5	3	0.00008	0.0003	Win: 27 -100; 100	Win: 150 -100; +100	10

[1] New South Wales (NSW) marine lidar - Moruya sample area, New South Wales Department of Planning, Industry and Environment: https://datasets.seed.nsw.gov.au/dataset/marine-lidar-topo-bathy-2018
[2] Shellharbour multibeam echosounder, New South Wales Department of Planning, Industry and Environment: https://portal.aodn.org.au/search
[3] Middleton Reef, Geoscience Australia: https://dx.doi.org/10.26186/144415
[4] Western Australia (WA) marine lidar – Perth sample area, WA Department of Transport: https://catalogue.data.wa.gov.au/en_AU/dataset/composite-surfaces-multibeam-lidar-laser/resource/1a4dec02-6361-4962-99d5-9928084a83a0



Supplementary Figure 1 Example threshold settings for multibeam data collected in Shellharbour, NSW. Ruggedness settings are provided for: a) bathymetry data at 2 m cell size; b) with no smoothing; and c) with 3 iterations of smoothing; as well as d) bathymetry data 20 m cell size; e) with no smoothing; and f) with 3 iterations of smoothing.



Supplementary Figure 2. Example threshold settings for multibeam data collected in Shellharbour, NSW. Ruggedness settings are provided for: a) bathymetry data at 2 m cell size; b) with no smoothing; and c) with 3 iterations of smoothing; as well as d) bathymetry data 20 m cell size; e) with no smoothing; and f) with 3 iterations of smoothing.