Appendix C. Methods: Satellite Mapping

The process for deriving estimated depths and classifying benthic features from WorldView-2 satellite imagery and available ground-truth data is schematically shown in Figure 58 and described in detail below.

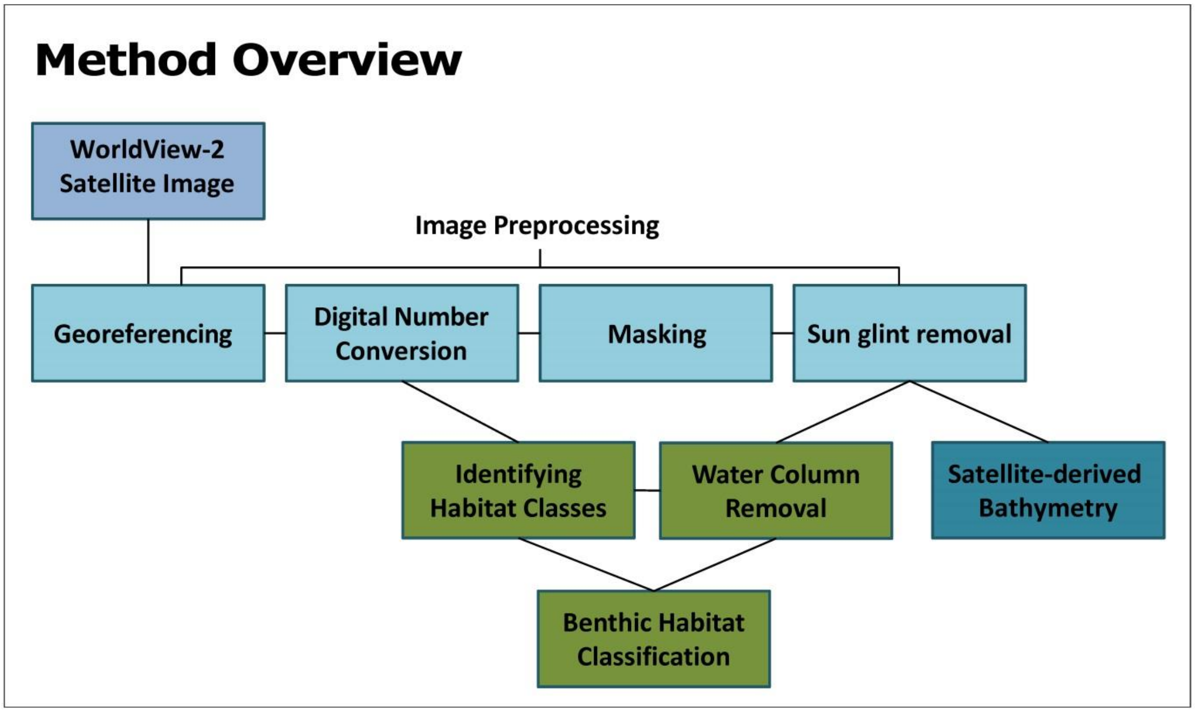

Figure 58. Schematic of deriving estimated depths (bathymetry) and classifying benthic features from WorldView-2 satellite imagery, including the image preprocessing steps.

Image Preprocessing

Prior to deriving depth and benthic habitat classes from the WorldView-2 imagery, four preprocessing steps were performed on the images. The georeferencing and digital number conversion steps correct for distortions due to characteristics of the WorldView-2 satellite system, and the masking and sun glint removal steps account for the atmospheric and ocean conditions, which both vary within and among images. The details for each of the four steps are as follows:

Step 1: Georeferencing

The location information for some of the satellite images was inadequate; therefore, the images did not align properly with each other or with other data (Figure 59). The images were spatially adjusted (georeferenced) to align with ArcGIS basemaps—provided by ESRI with ArcGIS products (http://www.esri.com/data/basemaps). The georeferencing step was performed using the georeferencing tools in ArcGIS 10.X desktop software.

Figure 59. Side by side figures showing a WorldView-2 satellite image overlaid on top of the reference basemap before (*left*) and after (*right*) georeferencing. Partial transparency is applied to the WorldView-2 image, thus features in the reference basemap in the background are visible through the WorldView-2 image in the foreground. The positional error is apparent when comparing the location of a structure between the WorldView-2 satellite image and the reference basemap (yellow arrow).

Step 2: Data Conversion

The pixel values of the WorldView-2 satellite images provided by DigitalGlobe are digital numbers (0-255), which have not been calibrated into physically meaningful units (i.e., solar radiance). The digital numbers must therefore be converted to capture the radiance at the satellite sensor using a calibration formula (Updike and Comp 2010). The satellite sensor is routinely calibrated, and thus the coefficients provided by DigitalGlobe (in the metadata files) are unique to each image. The conversion was conducted in ENVI (Environment for Visualizing Images) image analysis software provided by Harris Geospatial Solutions (http://www.harrisgeospatial.com/ProductsandTechnology/Software/ENVI.aspx).

Step 3: Masking

All nonaquatic or otherwise unsuitable features for deriving bathymetry or benthic features (e.g., terrestrial areas, clouds, breaking surf, boats, and turbidity) were removed from each image by manually digitizing a “mask” that was used for extracting unwanted areas (Figure 60). The ‘Extract by Mask’ tool in the ArcGIS Extraction toolbox was used to perform the extraction.

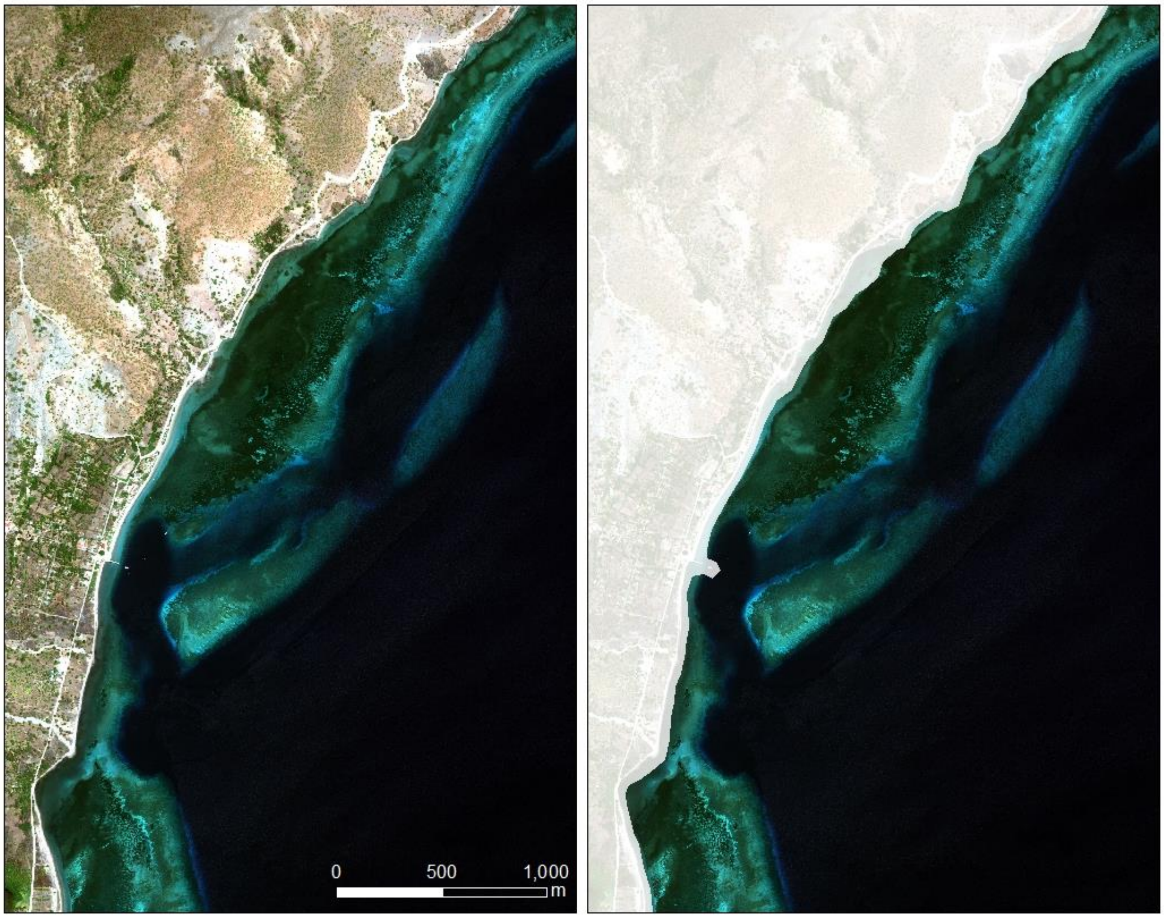

Figure 60. Example of a WorldView-2 satellite image before (*left*) and after (*right*) masking. The light area in the right image is excluded from the analyses to derive bathymetry and benthic habitat classes. Land, manmade structures, and areas covered by clouds are typically masked.

Step 4: Sun Glint Removal

Solar radiance recorded by the WorldView-2 satellite sensor differs from the actual radiance reflected from the surface of the water. To account for this difference, sun glint from the visible bands of the satellite images was removed using the method developed by Hedley et al. (2005; Figure 61). This method is based on the assumption that the amount of sun glint in an image is measured in the near-infrared portion of the electromagnetic spectrum and is linearly related to the amount of sun glint in the visible bands.

Pixel values were extracted from a deep-water area of an image and a linear regression model was created for each visible band against the near-infrared band. The slope value from the regression model was then applied to the formula developed by Hedley et al. (2005). The formula was applied to each band using ENVI software. The resulting image with the sun glint removed is hereafter referred to as the 'deglinted' image.

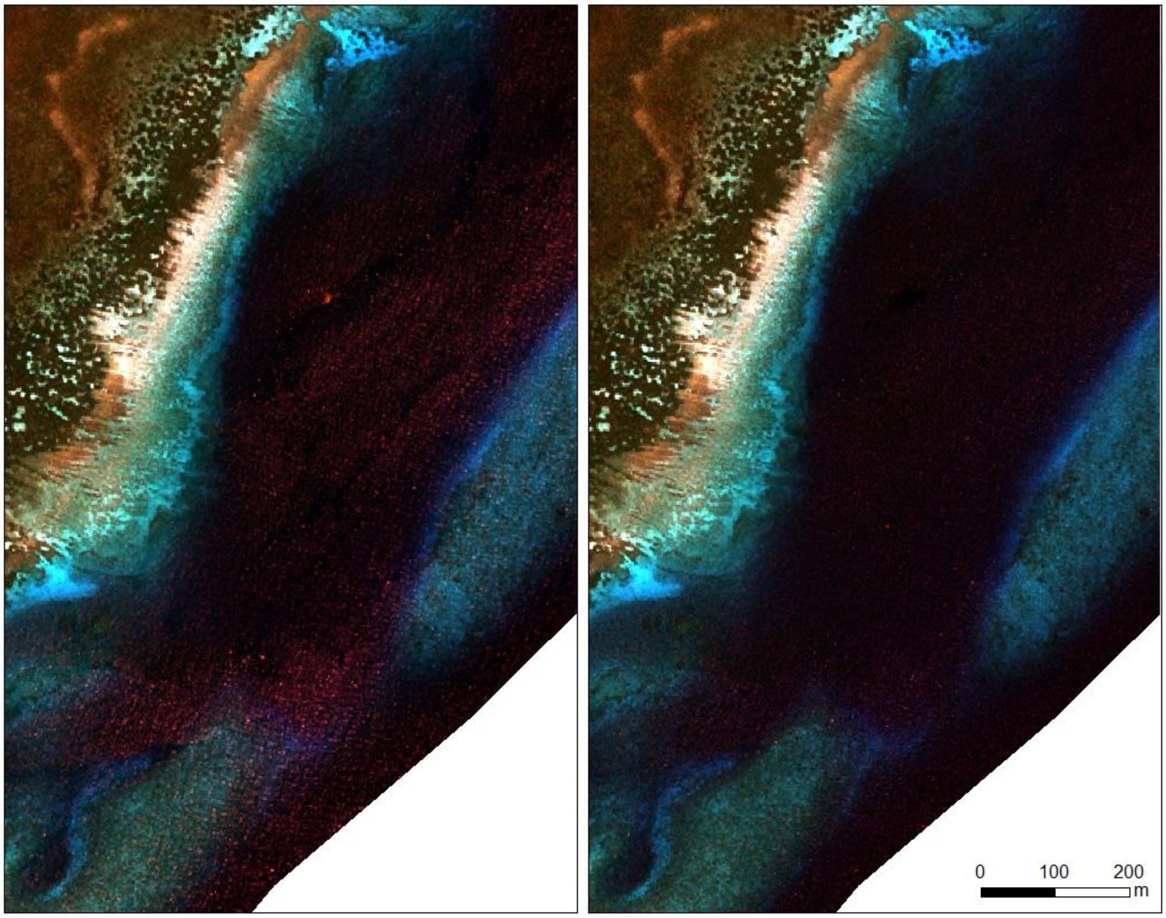

Figure 61. Example of a WorldView-2 satellite image before (*left*) and after (*right*) removing sun glint. After the correction, most sun glint effects are removed from the scene in the deglinted image.

Satellite-derived Bathymetry

Following is an overview of the method for deriving estimated depths from WorldView-2 satellite imagery. See Ehses and Rooney (2015) for the detailed methodology.

A multiple linear regression analysis method developed by Lyzenga (1979; 1981; 1985) and Lyzenga et al. (2006) was applied for deriving depth using the coastal, blue, green and yellow bands of the preprocessed images and depth soundings collected in the field in 2012 and 2013.

The resulting regression slopes and y-intercepts were used in the multivariate equation for deriving depth (Figure 62). The satellite data acquisition time and environmental conditions across the study area were not uniform; therefore, each image had to be processed separately. The method was tuned to each image and a variety of band combinations were used.

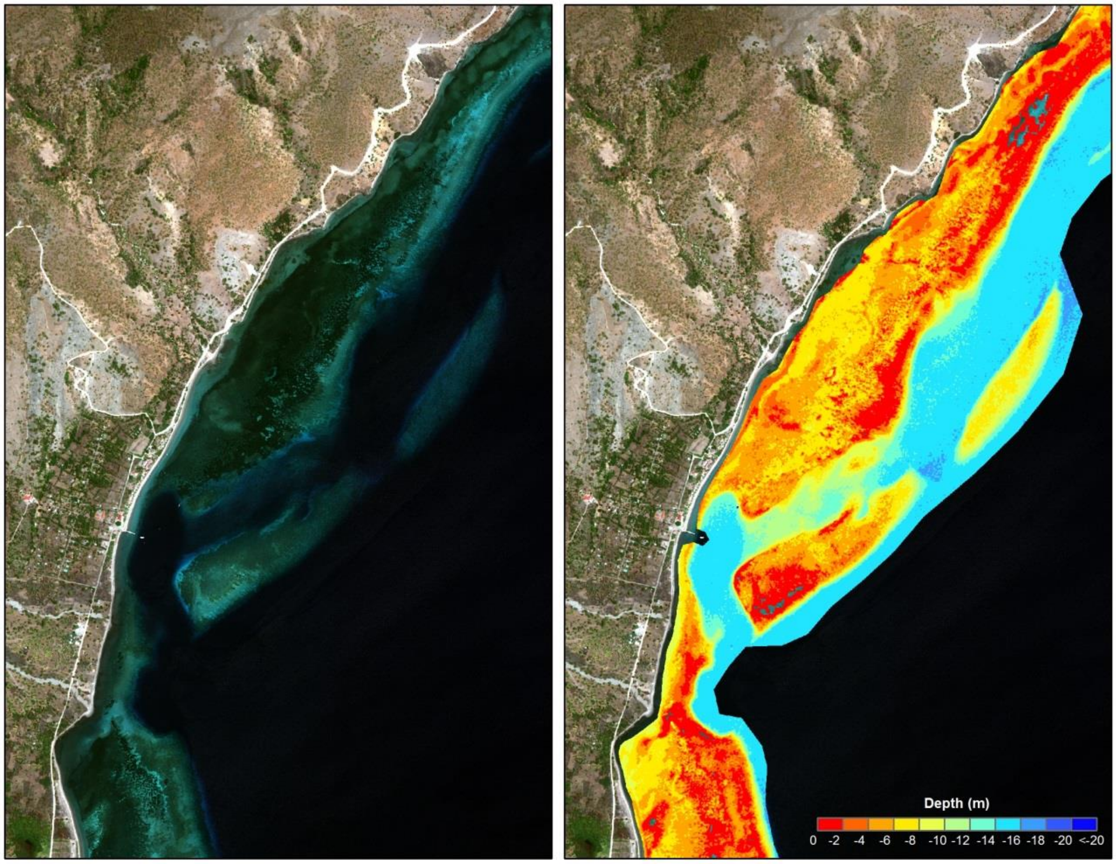

Figure 62. Example of a WorldView-2 satellite image (*left*) and the satellite-derived bathymetry (*right*) for the same area on the east side of Atauro Island.

Benthic Habitat Classification

Following is an overview of the method for classifying benthic features using WorldView-2 satellite imagery. See Watkins (2015) for the detailed methodology. Benthic habitat classification was a multi-step process that resulted in a total of 12 habitat classes identified across the region, including: 1) hard shallow, 2) soft shallow, 3) hard mid, 4) soft mid, 5) hard deep, 6) soft deep, 7) seagrass, 8) mangrove, 9) intertidal, 10) emergent rocks, 11) algae, and 12) lagoon.

The initial step was calculating a depth invariant index layer (Edwards 1999) using the preprocessed WorldView-2 satellite image. Image pixel values were extracted over sandy bottom in shallow and deep waters to investigate the relationship between the spectral signatures of similar benthic features in different water depths. The 3-band pairs with the strongest relationship were identified and used to build a 3-band depth invariant index layer (shallow, mid, and deep).

Based on the radiance multi-band image generated in preprocessing step 2, a region of interest was created for each of the classes, except lagoon. The regions of interest were then used as training classes to determine if a specific image pixel matched one of the eleven habitat classes. A variety of supervised classification methods allow pixel identification across a whole image. Three classification methods in

ENVI software—mahalanobis distance, maximum likelihood, and minimum distance—were applied to both the depth invariant index layer and the deglinted image. The resulting habitat classifications were compared to select the method that produced the best results for each of the WorldView-2 images. If necessary, the post-classification steps 'sieve' and 'sieve clump' were applied to the initial classification output to combine nearby pixels with the same habitat class assignment and remove isolated pixels from the data layer (https://www.harrisgeospatial.com/docs/ClassificationTools.html).

Lagoons (the 12th habitat class) were manually digitized using the habitat classifications generated in the previous step in combination with the satellite image—as the lagoon areas could be visually discerned in the satellite images. This combination of auto and manual classification improved the results of the initially derived habitat features.

Finally, areas where the habitat class could not be resolved, typically in deeper waters, were labeled as unknown (and are excluded from all maps in this report).

See Figure 63 for an example of a subset of the habitat classes that were derived for the nearshore waters around Timor-Leste.

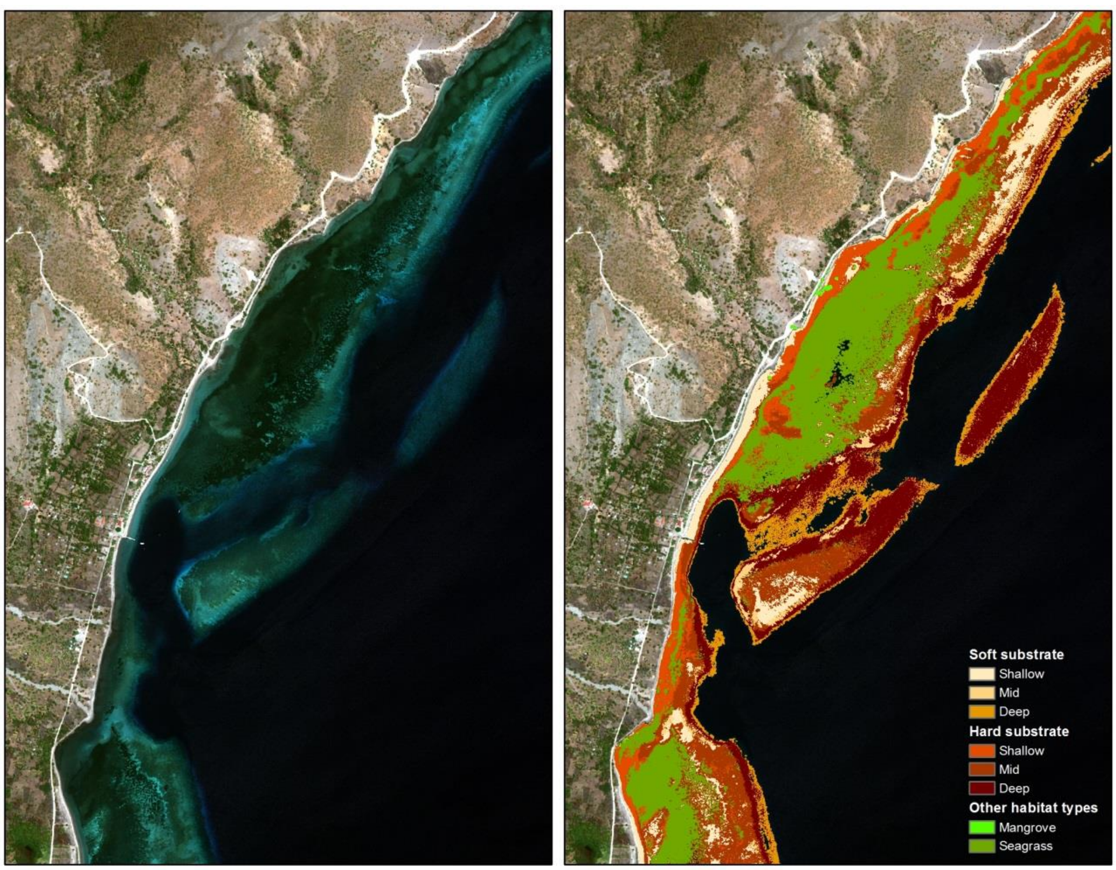

Figure 63. Example of a WorldView-2 satellite image (*left*) and the derived benthic habitat classes (*right*) for the same area on the east side of Atauro Island.