A Desktop Study Investigating the Presence of Submerged Sand Deposits in Mā'alaea Bay, Maui

Prepared for County of Maui

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Abbreviations

DLNR OCCL	State of Hawaii Department of Land and Natural Resources Office of Conservation and Coastal Lands
Ft	foot
Km	kilometer
LiDAR	light detection and ranging
M	meter
Mi	mile
MSL	mean sea level
Nmi	nautical mile
NOAA	National Oceanic and Atmospheric Administration
RSM	regional sediment model
TMK	tax map key
USACE	United States Army Corps of Engineers
Yd	yard

Purpose

This desktop study has been conducted to explore the existing evidence for the presence of sand deposits in Māʻalaea Bay that are suitable for use in beach nourishment projects. It is intended to provide guidance for a field campaign that will search for sand deposits using a towed sub-bottom profiler, benthic sediment coring device, and diver operated jet-probe system. This study sets out a rational approach for identifying and ranking areas where the presence of sand is anticipated and raises questions about seafloor composition that can be satisfied by the planned field work.

Introduction

In recent years satellite and aerial imagery have been used heavily in the initial stages of searching for sand to be used in beach nourishment projects. This approach is quick and effective, as the quality of light reflected from seafloor materials in shallow water is starkly different, and sand is readily distinguishable from coral reef, algae, and rocky outcrops (**Figure 1A**). While sand can easily be distinguished from these other benthic classes, without building a complex spectral analysis model, it can be difficult to confidently distinguish rock, reef, living and dead coral from one another, and this difficulty may increase with water depth and turbidity. Thus, in the present work we will refer to these four classes simply as "reef", without speculating on their composition. Analysis of LiDAR (Light Detection and Ranging) bathymetry is often a useful tool for validating the location of sand deposits. In nearshore reef systems, sand can be caught in areas of the seafloor that form bowls or pockets. The surface of a sand deposit is often smooth or gently sloped in LiDAR visualizations (**Figure 1B**) and forms a stark contrast with the high relief of rock and coral reef formations. Fossilized reef and limestone formations can also have an appearance of low relief in LiDAR visualizations, so the secondary evidence of a bowl or catch pocket helps to distinguish between a usable sand deposit and limestone bench with or without a veneer of sand covering it.

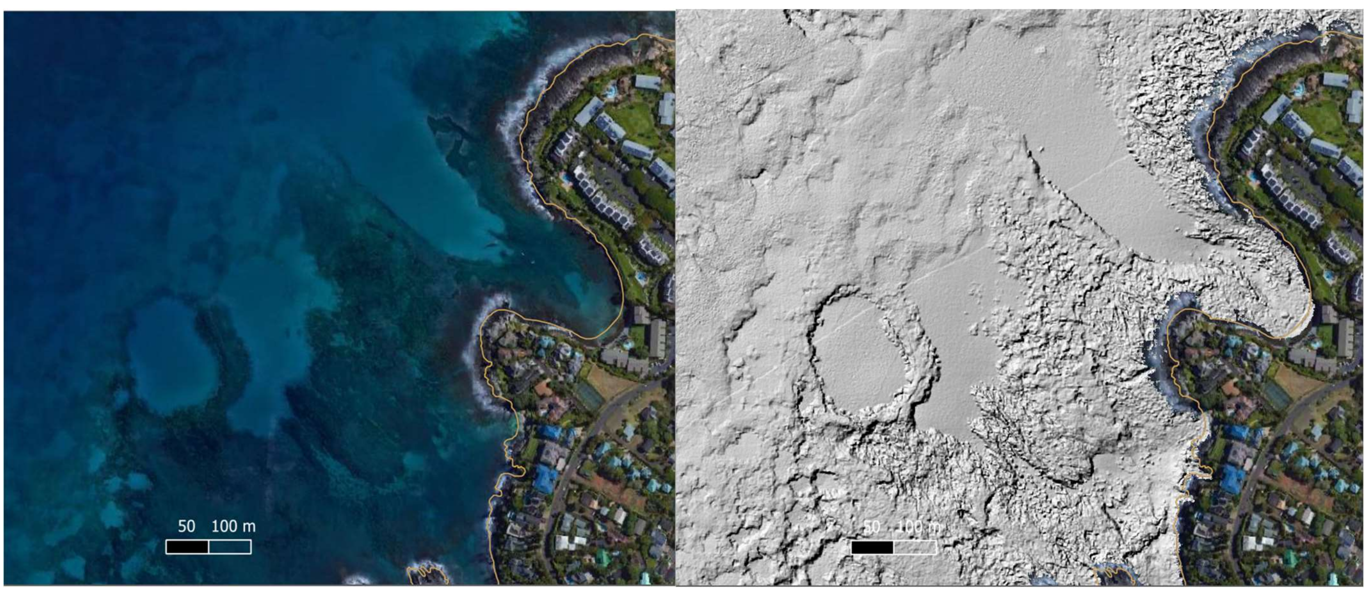

Figure 1 Aerial Imagery of Sand Deposits
Satellite imagery of nearshore sand deposits among reef structures (**A**); A hillshade representation of the same area, showing of LiDAR bathymetry with smooth plains filling depressions in the reef.

Aerial imagery provides excellent, rich, and easily accessible information under the best of conditions, however the qualities of light, the sea-surface and atmosphere can contribute to uncertainty in the interpretation of seafloor composition. When image mosaics are prepared from satellite imagery, it is not always possible to exclude all clouds or their shadows. Either a cloud or its shadow can reduce the contrast in light reflection, leading to images that are difficult impossible to interpret with confidence. Similarly, the sea state, either from surf, or heavy winds can cause glare, and even make the sea surface appear entirely opaque, depending on the angle of the image sensor.

Photographs preserve "snapshots" of the resource they image, and inherently do not individually provide information on how that resource changes over time. Yet, we know that sand moves freely through shallow nearshore waters and may move in and out of deposits from season to season or year to year. Thus, to build early confidence in the thickness of a sand deposit, or its permanence, we inspect years of aerial imagery in order to consider changes in the area of a deposit. Observing the expansion or reduction in the border of a sand deposit hints at the thickness of sand at its periphery, and at the confidence that a project planner can have that the volume of the deposit will remain similar between initial evaluation and project execution.

Study Area

The study area is located south of the isthmus of Maui, Hawaii. It includes the nearshore waters of Māʻalaea Bay, Maui, Hawaiʻi, between McGregor Point to the west and Kealia Pond to the east; it is a region contained within two nautical miles of the project beach and within the coastal boundaries of the ahupuaʻas of Waikapʻū and Ukumehame (**Figure 2, Figure 3**). The site of the proposed beach nourishment project is located to the east of Māʻalaea Harbor in front of the Kanaʻi A Nalu Resort (TMK = 238014004). The shoreline of this region is comprised of limestone rock, calcareous sand, and basalt. Limited information is available on the benthic sand deposits in this area. Efforts have been made to classify the benthic habitat from satellite imagery (such as Marine Research Consultants 2011 and NOAA National Centers for Coastal Science, 2007). These reports agree on the nature of the seafloor as being largely unconsolidated sediment, possibly including sand and algae. Reeftop sand fields have also been identified from aerial imagery (USACE and HI DLNR OCCL 2011), however, in the study area, these deposits are very near to shore, located in shallow water and insufficiently large for the proposed project.

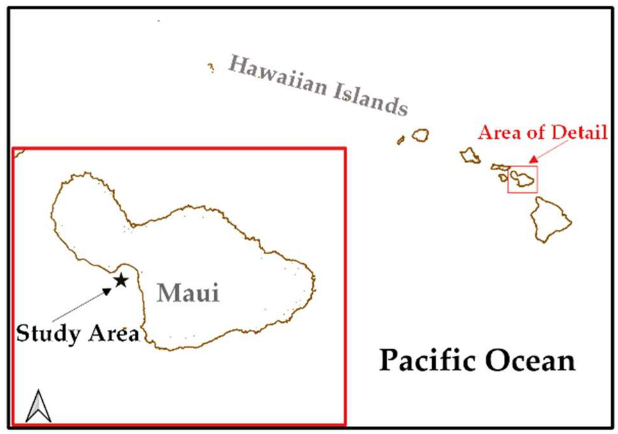

Figure 2 Study Area Location

Methods

Search Area Definition

The search area was centered on the Project Beach in front of the Kana'i a Nalu Resort. The logistical difficulty of delivering benthic sand to a project beach generally increases with distance we consider the distance of a potential borrow site from the project beach to be important. The highest priority search zone was placed within approximately one nautical mile (1,852 meters [m]) of the project beach. This measurement was not used to indicate a specific logistic threshold, but to provide a tool for visualizing the study area. This approximately one nautical mile arc includes the Waikap'ū ahupua'a and small section of the Ukumehame ahupua'a; it also includes the Māʻalaea Bay Beach, Mā'alaea Harbor and West Mā'alaea littoral cell boundaries, as defined by the USACE RSM (2011).

We also included the region between one and two Nmi (1,852 m to 3,704 m) from the project beach in our analysis. This was identified as a lower priority area as it falls outside of the preferred location of a sand borrow site. To the east, while it remains within the Waikap'ū ahupua'a, this region falls within the Kealia littoral cell. To the west, the shoreline falls within the Ukumehame ahupua'a, but remains within the west Mā'alaea littoral cell.

The search area was constrained by water depth and included a stretch of seafloor situated between 10 and 40 feet (ft) below mean sea level (MSL; 3 to 12 meters [m]). Dredge logistics become more complex with water depth, and surface sediments become progressively finer with depth and distance from shore.

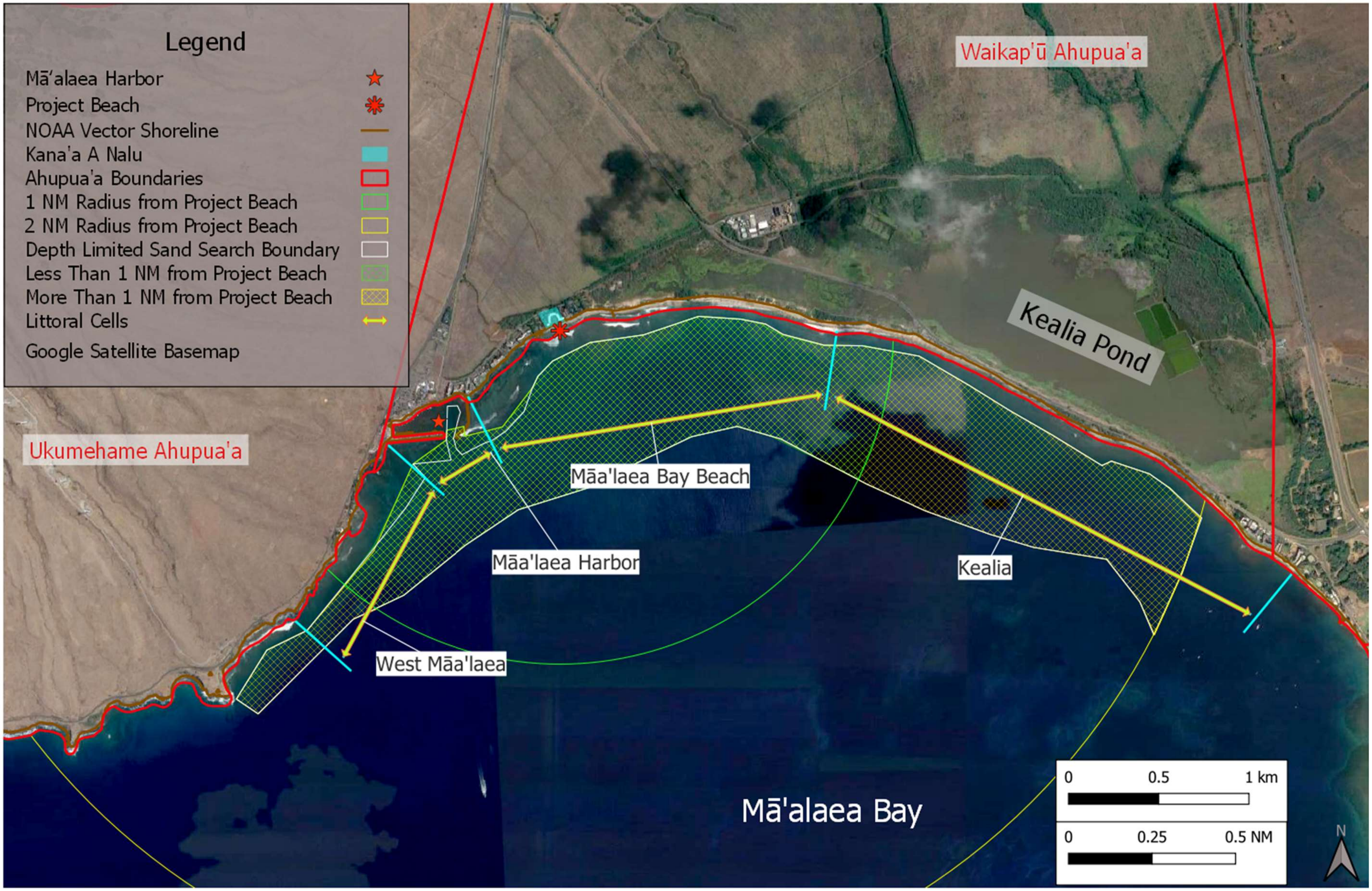

Figure 3 Sand Search Area

The sand search was constrained by the -10- and -40-foot contours below mean sea level as well as distance from Mā’ alaea Harbor. Areas less than 1 nautical mile from the harbor were considered to have a higher priority than areas between 1 and 2 nautical miles from the harbor.

Data Sources

Publicly available high resolution aerial photography and satellite images have been used as a primary resource to visualize the composition of the seafloor. These data included mosaiced tiles from ESRI, Bing Earth, Google Earth, and Google Satellite, as well as historical mosaics from the University of Hawai’i School of Ocean and Earth Science and Technology Coastal Geology Group’s web site[1] that contained images from 1949 through 2016 over Māʻalaea Bay and in front of Kealia Pond. We explored the possibility of using Copernicus, ASTER and LANDSAT data as well, from the USGS and EU, however the pixel size of available images was generally too large to provide additional insight. LiDAR (OCM partners, 2021) was also used to characterize the absolute depth and roughness of the seafloor.

Analysis

Aerial images and mosaics were entered into a geodatabase and overlaid on a vectorized shoreline of Maui, using Quantum GIS (QGIS Geographic Information System, Version 3.20, QGIS Development Team 2021; Open Source Geospatial Foundation). Individual images were visually inspected for the presence of sand deposits. These areas were traced to form simple polygons and were given a score (from 50 to 100 percent), reflecting the confidence in the classification, which was associated with image quality, cloud cover, cloud shadow, sea surface reflection, water turbidity, and mosaic composition. A second score was assigned to each polygon to indicate whether it appeared to contain only sand, or sand and reef; this was “percent cover” and ranged from 50 to 100 percent. The same process was followed to identify and outline areas that contained substrate that appeared to be reef. As previously mentioned, in this stage, we did not attempt to differentiate among reef types, but used visual evidence of discrete changes in benthic substrate composition to distinguish reef from sand.

These two datasets were overlaid to identify regions of the seafloor that consistently appeared to have sand deposits, be free of reef, and exist within the search area. These regions were extracted, their centroids, areal extents, and distance from project area were calculated using GIS software. Priority scores were assigned to each region based on their distance from the project site, area, confidence, and percent cover.

Results were considered in the context of benthic habitat classification maps made from the visual interpretation of IKONOS hyperspectral imagery (NOAA National Centers for Coastal Science, 2007), qualitative observations of benthic substrate composition (Hawai’i Statewide GIS Program, 2002), benthic cover from hyperspectral imagery (Marine Research Consultants, 2011)

Results

Search Area Description

The mauka limit of the search area was comprised of a simplified line following the 10 ft (3 m) contour below MSL. This falls between 110 and 330 yards (yd; 100 to 300 m) from shore. This is a depth where boat work is safe and sand harvesting is possible. In the greater Māʻalaea Bay area the 10’ contour is close to where reef crest is situated, with a reef flat of variable width extending mauka, and a pseudo spur and groove formation that meets a benthic plain around -25’ MSL, which is characterized by low relief and a gradual (ca 3%) slope. Toward McGregor point, the transition is abrupt, near the harbor entrance, there is a broad reef flat, with a discrete reef slope to the benthic plain, and farther to the east, beyond the project site, the reef and reef flat have much more variable structure and the transition is more gradual. The seaward limit of the study area was defined as the 40’ depth contour (12 m), which generally falls between 700 and 900 yds from shore (0.3 to 0.5 nmi; 0.5 to 0.9 km). This depth contour does not mark a distinct transition in geomorphology of the bay but represents a practical limit for the logistics of low-cost dredging.

[1] http://www.soest.hawaii.edu/coasts/index.php/resources/historical-mosaics/ and ftp site ftp://ftp.soest.hawaii.edu/coastal/webftp/Maui/Mosaics/; accessed 7/15/2021; They can also be accessed via an interactive web map at https://www.soest.hawaii.edu/coasts/index.php/resources/hawaii-shoreline-study-web-map/

Analysis

Analysis of aerial imagery identified 128 polygons containing sand and 94 polygons containing reef from 21 images and image mosaics. Confidence in classification was variable, based on image quality, but had and average and median of 76% and 85%, respectively, for sand, and 85% and 90%, respectively, for reef. The score for percent cover was similarly variable, and for sand averaged 82%, with a median of 90%; reef scored an average of 84%, with a median of 85%.

The overlap of the sand polygons was used to identify regions in the search area of Māʻalaea Bay that consistently appeared to have sand. To visualize this overlap, each sand containing polygon was assigned a transparency based on its confidence and percent cover scores, with greater transparency corresponding to weaker confidence and lower percent cover (**Figure 4**) In the figure the transparencies and colors were additive, and areas with high confidence of sand presence over time are shown with both darker coloration and a color shift from green to yellow.

Similarly, areas that were consistently contained reef structures were overlaid and used as a mask (**Figure 5**). Reef polygons were visualized by layering high transparency white polygons, so that overlapping regions had increasingly opaque white fill. Thus, the aggregation of sand cover likelihood, masked by reef presence likelihood was used to outline ten polygons that were observed to regularly contain sand deposits over the 72-year span that the images covered (**Figure 6**). These polygons were located throughout the two nmi search radius and comprise the unranked search polygons.

The area and perimeter of each polygon were calculated in the GIS software, as was the practical distance between each polygon and the project beach (**Table 1**). Practical distance was calculated as the distance along a route from the polygon centroid to a point beyond the reef in front of the project beach and then over the reef onto the project beach. This was always greater than the line-of-sight distance from the polygon to the project beach. The route was notional and does not reflect an in-depth logistical analysis. The polygons were assigned initial ranks to prioritize them for exploration. A priority score was calculated using the following equation:

$$priority = \frac{confidence^2 \times area \times \%cover}{distance^4}$$

The equation was formed to place the highest weights to the proximity of a sand source to the project beach, and confidence score assigned to each polygon in the analysis process. The area of the polygon and its percent cover score were less emphasized. Priority scores were ranked from highest to lowest to establish our preliminary ranking.

Search Polygon Descriptions

Appendix A includes plots of each search polygon overlaid on a hillshade view of the LiDAR bathymetry data. The search area statistics table (**Table 1**) presents a numerical summary of the data discussed below.

Polygon 1: Located close to shore in front of Kealia Pond, Polygon 1 has a huge area (43 acres). It was formed from the overlap of 14 individual sand-presence polygons and sits just beyond the reef slope in water between 9 and 34 ft below MSL. Falling between one and two nmi from the project site, it is part of the low priority search area in the Kealia littoral cell. This region of the bay was not well imaged in many photographs, as clouds were common closer to the south Maui mountains. LiDAR data indicate that it is contiguous with a much wider region of seafloor that has low relief, however, modest striations in the LiDAR are also visible over much of the region that Polygon 1 occupies. These suggest the presence of hard substrate. It has a priority score of 0.8 and is ranked 7th among the ten search areas.

Polygon 2 is another massive (47 acre) search area, located within one nmi from the project site, within the Māʼalaea Bay Beach littoral cell, in water from 14 to 37 ft below MSL. It is formed by the overlap of 16 sand-presence polygons, had a mean confidence score of 68% and a mean cover score of 78%. It also sits at the seaward edge of the reef slope has low roughness, a very gradual seaward slope, and few distinguishing features. It has a priority score of 23.9 and is ranked 3rd among the ten search areas.

Polygon 3 is located just to the east of the project beach and west of Polygon 2 within the Māʼalaea Bay Beach littoral cell; it has an area of 8.9 acres and represents the overlap of 6 sand-presence polygons in water between 26 and 37 feet below MSL. It is the closest search area to the project site. This area had a mean confidence level of 63% and a mean cover score of 84%. This search area is also on the benthic plain just beyond the reef slope and is characterized by low relief in the LiDAR data. However, to the west, the seafloor rises somewhat, and LiDAR suggests that there is more complexity. It has a priority score of 28.2 and is ranked 1st among the ten search areas.

Polygon 4 lies to the west of the project beach, located within Mā'alaea Bay Beach littoral cell, and is the second closest to the project site. It has an area of 6.2 acres and is located between 30 and 40 feet below MSL on the benthic plain beyond the reef slope. It represents the overlap of 14 sand-presence polygons and has a mean confidence score of 75% and mean cover score of 81%. The LiDAR data for this site also indicate that it has an uncomplicated seafloor, with very low relief and no distinguishing features. It has a priority score of 25.6 and is ranked 2nd among the ten search areas.

Polygon 5 is located west of the project site and in front of Mā'alaea Harbor, within the Mā'alaea Bay littoral cell. It has an area of 6.3 acres and sits in water between 26 and 46 feet below MSL. This area has a confidence score of 75% and cover score of 86%. LiDAR data show that the seafloor here is smooth, with no distinguishing features. However, southeast of this search area, three mounds rise above the benthic plain. This search area has a priority score of 6.7 and is ranked 4th among the ten search areas.

Polygon 6 is in the mouth of Mā'alaea Harbor, within the Mā'alaea Harbor littoral cell, between 9 and 20 feet below MSL. It has an area of 1.9 acres and has a mean distance of one mile to the project site. It represents the overlap of 15 sand-presence polygons and has a confidence score of 77% and a percent cover score of 83%. Polygon 6 has a priority score of 0.6 and was ranked 8th among the ten search areas. This area is contiguous with the harbor itself, where visibility from aerial imagery was typically poor.

Polygon 7 is located to the west of the project site and to the west of Mā'alaea Harbor, within the West Mā'alaea littoral cell. It sits below the reef slope at a water depth of 30 to 42 feet below MSL and represents the overlap of 10 sand-presence polygons. It has a total area of 3.2 acres and has a mean distance of 0.9 miles to the project site. It has a mean confidence score of 77% with a mean percent cover of 82%. The seafloor in this area appears to have low relief with few distinguishing features. A smooth low rise appears northwest of Polygon 7‘s center. The area has a mean distance of 0.89 miles to the project site, a priority score of 1.7 and is ranked 6th among the ten search areas.

Polygon 8 is the smallest area identified in this search. It is a natural sand catchment perched on the reef flat in water between 8 and 9 feet below MSL. It has a total area of 0.5 acres, represents the overlap of 12 sand-presence polygons and is 1.16 miles from the project site. It has an 90% confidence score and 91.7% cover score. This area is easily distinguished and is part of a network of sand deposits along the reef flat, but it has a margin that expands and shrinks among images. Its immediate surroundings have moderate relief in visualizations of LiDAR data, especially compared to the benthic plain where most of the other search areas that have been identified in this study. It is likely surrounded by coral. It has a priority score of 0.1 and is ranked 10th among the ten prospective search areas. It is unlikely that this polygon can be visited with the sub-bottom profiling equipment given the depth of the water.

Polygon 9 is located 1.1 miles from the project beach, within the West Mā'alaea littoral cell, in water between 13 and 44 feet below MSL. It has a total area of 13.9 acres, a confidence score of 90% and estimated percent cover of 87%. The mauka portion of this area has a somewhat steeper slope than the rest of the benthic plain. Otherwise, the seafloor in this area has no areas of higher relief, or sharply distinguishing features. Polygon 9 represents the overlap between 14 sand-presence polygons, has a priority score of 4.5 and is ranked 5th among the ten search areas.

Polygon 10 is in a 950-yard strip along the shoreline east of McGregor Point, in the West Mā'alaea littoral cell, and it represents the overlap of 14 sand-presence polygons. It sits in a narrow band beyond the reef slope in water between 21 and 48 feet below MSL and has a total area of 6.6 acres. This area is likely to have active coral growth. It was visually distinct in many images and earned a mean confidence score of 79% and cover score of 87%. In LiDAR data visualizations, most of the seafloor in this polygon has a smooth appearance, however the bulbous patch to the southwest has a more rugose appearance. It has a priority score of 0.4 and is ranked 9th of the ten search areas. It is long and narrow and is located more than one Nmi from the project site, in the lower priority zone.

Discussion

In areas of high physical relief, such as lava rock and coral reef, areas where sand accumulates are visually distinct, as the color of light that sand and reef reflect are different (e.g., **Figure 1**). Often these observations are supported by high resolution bathymetric data, which allows areas of smooth flat bottom to be easily distinguished from areas of high relief or complexity Typically, these two classification strategies have a high correlation. The examination of collections of aerial and satellite imagery collected over time can provide a clear picture of the expanding or shrinking margins of sand deposits. These changes over time can hint at the thickness of sand in a deposit. When sand is present in some images and absent in others the deposit may be thin or ephemeral. In either case, the confidence that one can have in finding large amounts of sand in that deposit in any given year must be tempered by the apparent changes in volume.

Unlike many other sand searches, we have conducted, the seafloor between 10 and 40 feet below MSL in Māʼalaea Bay has a gentle seaward slope, and few distinguishing features. Atmospheric effects (clouds, wind, shadows) played a large role in the quality with which the seafloor could be viewed in any individual image. While we would typically see the margins of a discrete sand patch expand or contract over a number of years, in this search, we found that regions where the seafloor was clearly visible varied among images. Rather than simply following several discrete patches of visible sand in sequential images, we had few images that showed the entire search area clearly at any time point accompanied by a generally sandy search area, with shifting areas of dark coloration (reef). Thus, reef-presence, here benthic substrate that was visually distinct from sand, became an important factor in trying to identify the boundaries of areas that consistently had sand cover. The sand search polygons proposed in this desktop study, thus, are different from our typical sand search polygons: rather that having identified areas where we know sand deposits are persistent, we have identified areas that consistently appear sandy and are consistently free of reef across the timespan of the image collection. These appear to be sand patches. It is also notable that the bathymetry of this area, beyond the reef, is free of structures that might act as sand catchments.

Uncertainty in image analysis

Satellite imagery and aerial imagery are both regularly collected above the level at which clouds can form. Clouds can directly interfere with imaging the earth's surface. Shadows cast by clouds that are not in between the sensor and the earth's surface can be of varying opacities and can also hinder interpretation of the quality of light reflected from the seafloor. Similarly, reflectance of light at the sea surface can mask the reflectance of light from the seafloor even in shallow water, reducing the confidence in substrate classification. Even in the best of images, water depth and turbidity can also affect classifications. Image mosaics prepared by the UH Coastal Geology Group and the Google Earth Satellite image providers (often Maxar Technologies, Westminster, Colorado) are preferentially assembled from frames with low cloud cover. (This is also true of the mosaics that we prepared using Earth Engine.) However, few of these data sources are free of all forms of interference, and the eastern aspect of Māʼalaea Harbor were more often obscured than any other area. Across the image collection that we used, the combination of sea surface reflectance and cloud cover created the greatest interference. However, the composition of seafloor itself contributed to uncertainty in the analysis. Without the clear boundaries provided by high-relief structures that are corroborated in LiDAR, visual evidence of dark patches in Māʼalaea Harbor was not always classifiable. Large scale patterns of striation and patchiness were not uncommon and raise questions about whether they are areas of high-density algal colonization over sand deposits, high-density algal colonies over rock bench, or uncolonized rock bench.

Other data

Several studies have also analyzed high resolution satellite imagery to classify benthic substrate composition and benthic habitat in this region. One such study relied on visual inspection of mosaic prepared from IKONOS hyperspectral imagery (**Figure 7**; NOAA National Centers for Coastal Science, 2007). They determined that at the time their image was collected, most of the seafloor in Māʻalaea Bay was comprised of sand and unconsolidated sediments. Similar results are shown by the bottom type classifications extracted from NOAA charts (Hawaiʼi Statewide GIS Program, 2002; also shown in **Figure 7**). However, the NOAA chart data indicate the presence of fine sands and mud in addition to coral and coral rubble. The presence of these finer deposits has also been reported in personal communications with divers, although diver reports were not spatially explicit.

much more rigorous study was performed by Marine Research Consultants (MRC; 2011), in which photographs of 359 sites were used to model and validate the spectral reflectance of benthic communities, as visualized in satellite imagery. The purpose of this study was to characterize the condition of coral and algal communities in Māʻalaea Bay, especially in the context of rapid degradation of coral health between 2005 and 2010 in the area near the harbor. None of these calibration points fall within our proposed search areas (**Figure 8**), but the extrapolation of their model to the greater bay is interesting. In general, our search polygons are modeled to have little cover of the habitat classes they extracted, however, polygon 2 may have algal cover, polygons 2 and 3 may have coral, and polygons 2 and 3 may also contain mud (**Figures 9, 10 and 11**, respectively. The mauka aspect of polygon 9 was also modeled to contain mud. Unfortunately, the NOAA bottom type classifications do not align spatially with MRC's modeled areas.

Site Prioritization

The initial priority scores calculated will likely change as more data become available. They were computed based on numbers generated in our analysis and did not consider specific project-related logistics. With the added information of sand depth, granulometry and surface composition, to be provided by the planned sand search boat work, the uncertainty metrics generated from scoring the satellite imagery will have less prominence in the evaluation, and a new ranking system will emerge.

Sediment from the harbor is on the table for consideration in the proposed project. Current physical characteristics of the sediment in the harbor are not known. However, it is thought that much of the sediment accumulated here is terrestrial in origin, as the harbor functions as a stilling basin for sediments that enter the harbor via drainage ditches (US Honolulu Army Engineer District 1992)

Initial data from the analysis of aerial imagery can only be used to conceptualize the extent of potential sand resources in the bay. The thickness of deposits at these potential sites cannot be known or guessed from these data. Previous sand searches have explored borrow sites in catch pockets on nearshore submerged reef structures. The presence of these natural depressions leads to higher confidence in the presence of deposits from year to year. Similarly, in settings where reef structures are clearly delineated from sand deposits, individual sites can be easily delineated. In the present study, we have used similar techniques. The LiDAR data do not indicate many obvious pockets in the reef or seafloor where sand would naturally accumulate. Polygon 8 is one such area but is very small and far from the project site. Another possible site like this lies west of Polygon 3, where there is a hint of a pocket in the LiDAR data enclosing 0.35 acres of seafloor. The absence of pockets from this area could be because such pockets are already filled with sand, or because they do not exist in the first place.

If sand deposits are present in appreciable thickness at the proposed search areas, **Table 2** projects volumes of sand that might be extracted for given sand depths.

Sand Exploration and Borrow Site Selection

The desktop study provides a rational foundation for boat-based exploration of the potential sand resources in Māʼalaea Bay and Māʻalaea Harbor. The proposed sand survey will use techniques including sub-bottom profiling, side-scan sonar, coring, jet-probing, and surface sample collection. Each of these techniques will contribute to a better understanding of the resources. Sub-bottom profile data will provide data that maps the thickness of sediment deposits in the bay. Side-scan sonar will enrich those data by providing spatially referenced information about the surface complexity, which could help to describe the surface composition of the seafloor. Jet-probe measurements are performed by divers, who visually inspect and photographically document sediment characteristics, such as thickness, composition, and color; the divers also provide commentary on benthic occupancy and collect surface sediment samples. Together, side scan sonar and diver visualization will provide sufficient information on the presence of coral or other sensitive benthic resources near the prospective borrow sites to make educated decisions about the risks of sand extraction to the local environment. The collection of cores will provide information on the thickness of a sediment deposit, and also confirm the vertical structure of sediment deposits calculated by the sub-bottom profiler.

These data collected during the sand exploration will provide the critical information needed to prioritize prospective sand sources. These data include sediment grain size analysis, which determines whether a borrow site contains sand that is suitable for placement on the project beach per the DLNR standards (HI DLNR OCCL 2005).

Questions the field study should answer, addressing remaining uncertainties

Do sub-bottom profile data, jet-probe data and coring data support our interpretation of visual data? Are the areas we believe to be reef actually reef and not sand. Are the areas that we believe to be sand actually sand and not simply bare substrate.

Do the dark striations that appear mid-bay in satellite imagery reflect emergent reef rock, or the presence of benthic algae? In the latter case, does it preclude the presence of thick sand deposits beneath the algae.

MRC benthic substrate composition is wide ranging, but they were not focused on sand resource identification. Do the MRC observations reflect the qualities of benthic composition that are relevant to beach nourishment?

Summary

Aerial and satellite imagery of Māʼalaea Bay have been analyzed to characterize the areas of the bay that appear to have persistent sand cover, without the presence of reef. These observations were weighted by confidence in the interpretation in order to identify consensus areas that have a high likelihood of persistent sand cover. These areas should be prioritized in the planning of boat-work to search for viable sources of sand for regional beach nourishment projects.

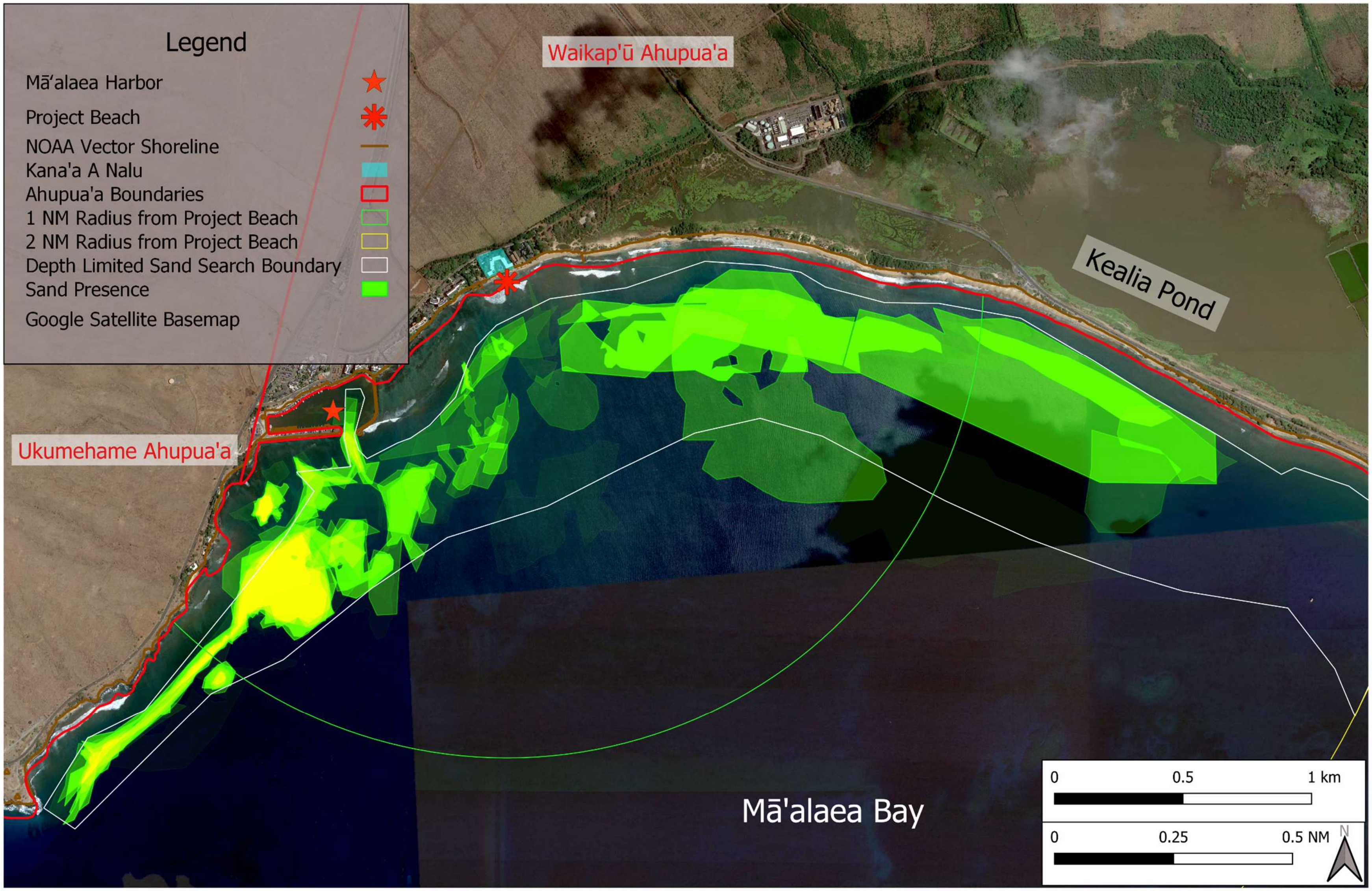

Figure 4 Sand-Presence Polygons

Polygons tracing the outline of sand deposits visualized in individual aerial images were overlaid. The transparency of each polygon was calculated as a function of the confidence score. Overlap of polygons creates areas of higher opacity, with a color shift toward yellow in areas of higher confidence.

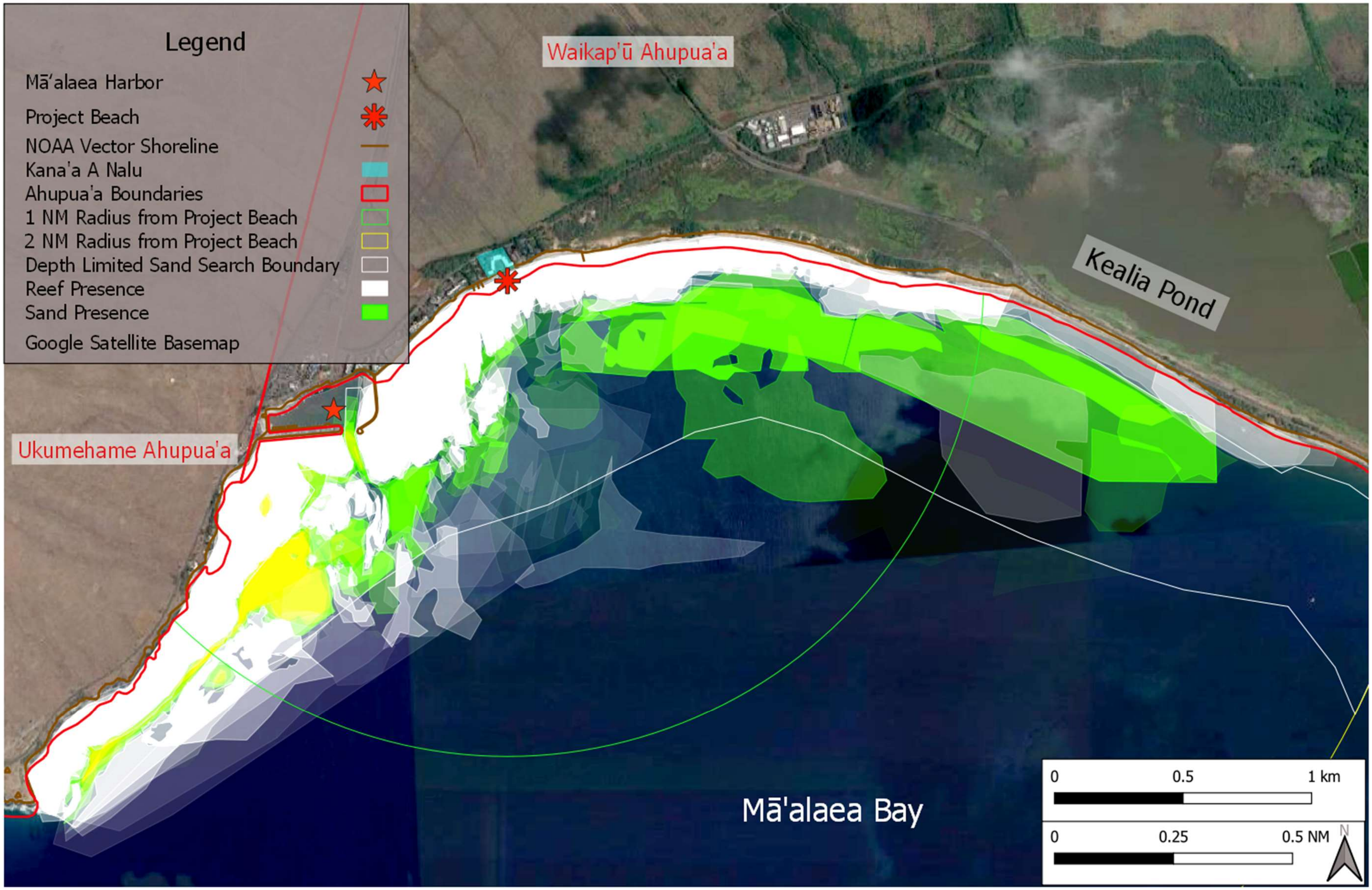

Figure 5 Reef-Presence Polygons

Polygons tracing the outline of reef patches from individual aerial images were overlaid. The transparency of each polygon was calculated as a function of its confidence score. Overlap of polygons creates areas of higher opacity appearing as opaque white in areas of high agreement.

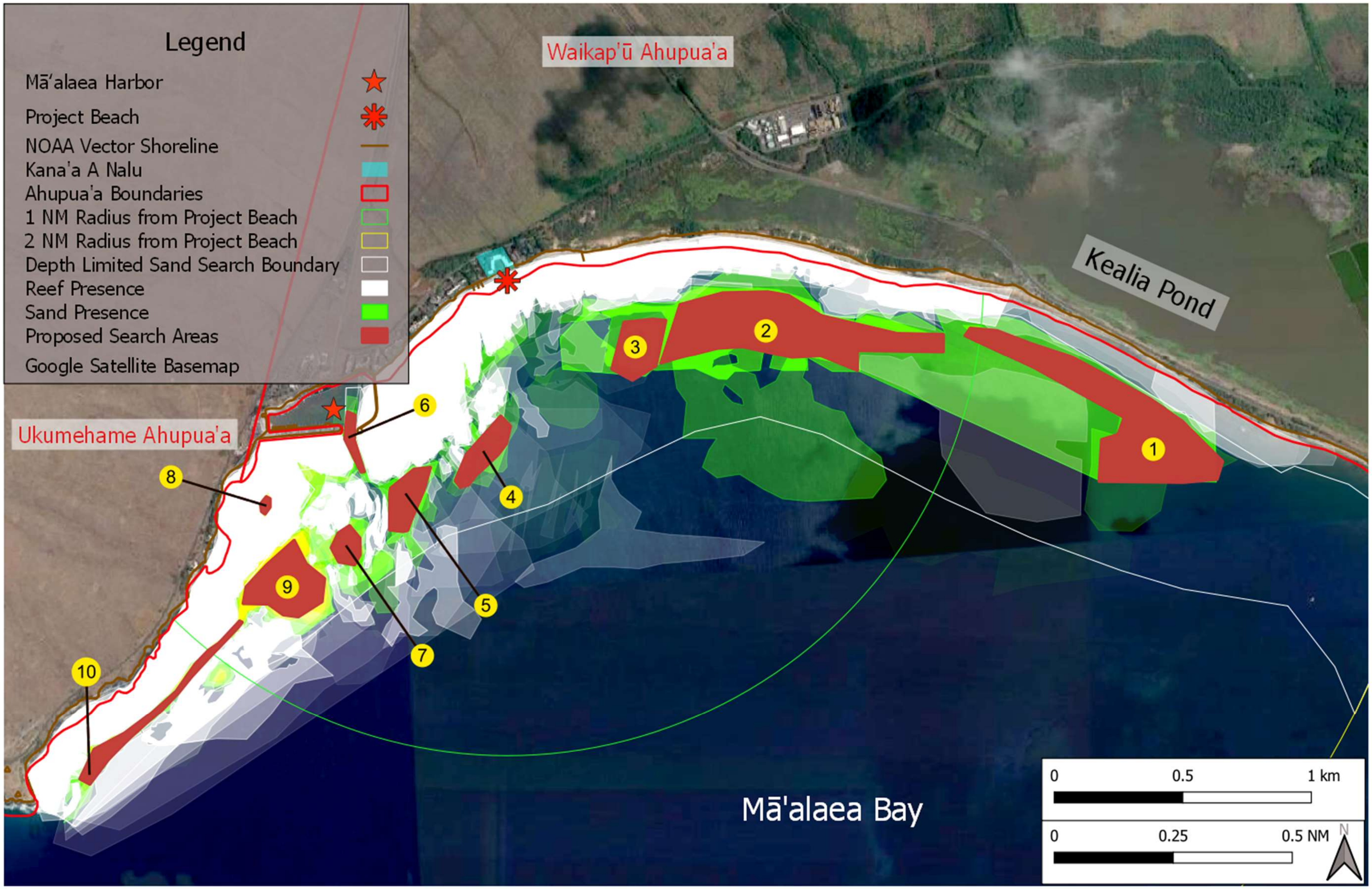

Figure 6 Identification of Sand Search Areas

The difference between the reef presence mask (white) and sand-presence polgyons (green to yellow) was used to trace polygons with high agreement for use in the sand search. Summary data were calculated for each sand search polygon.

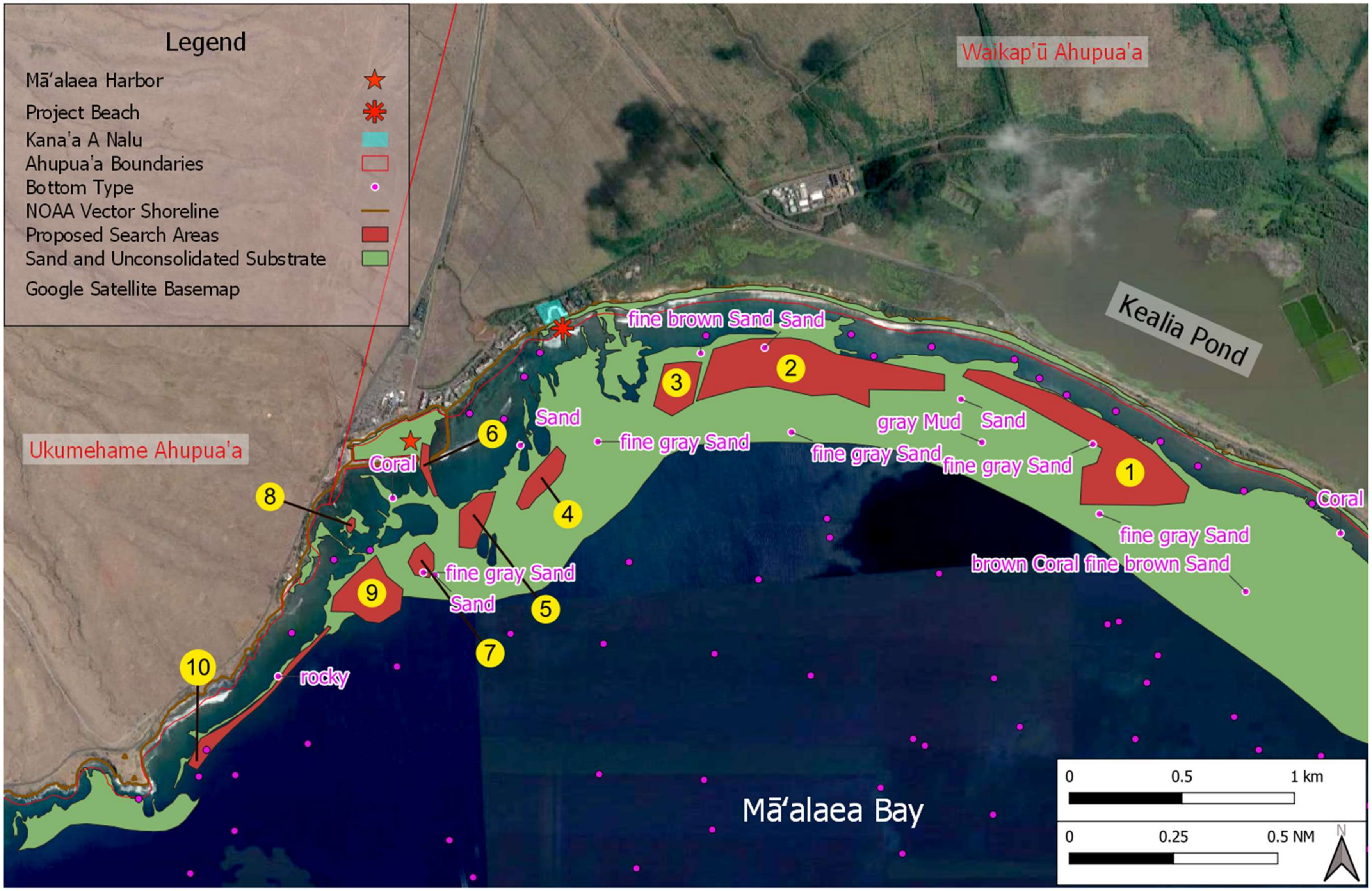

Figure 7 Benthic Habitat and Substrate Composition

The benthic habitat classifcation (NOAA National Centers for Coastal Science, 2007) identified the entire search area as containing sand and unconsolidates ubstrate (green polygon). Bottom type observations (Hawaii Statewide GIS Program, 2002) are shown in pink, and points withing the search area are labeled with their classification.

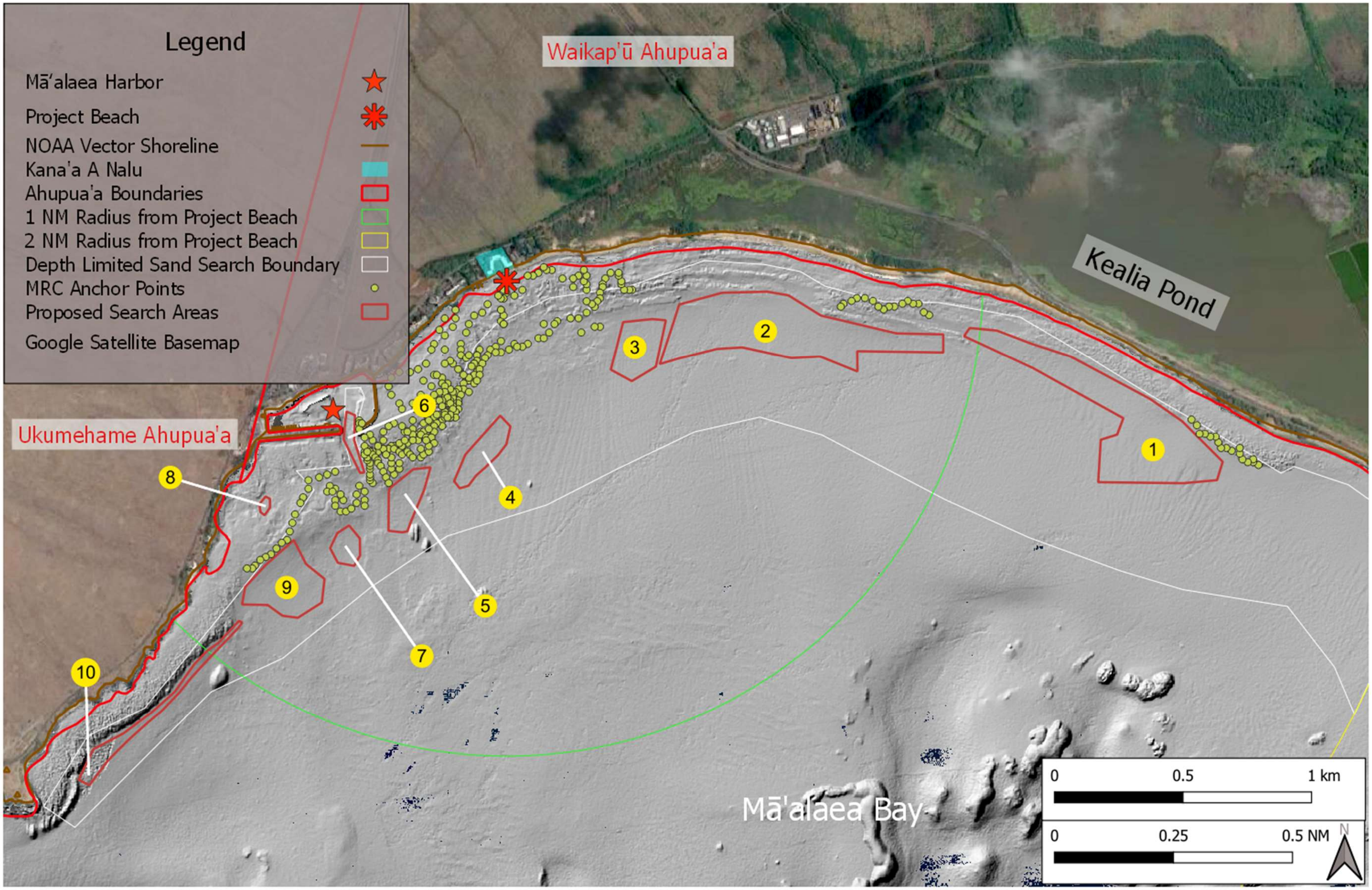

Figure 8 MRC 2011 Calibration and Validation Points
The benthic habitat classification prepared by MRC 2011 include 359 points, shown here in yellow dots, over LiDAR. These points focused on reef habitat, which we specifically avoid in our search polygons. Unsurprisingly there is no overlap between their dataset and our proposed search polygons.

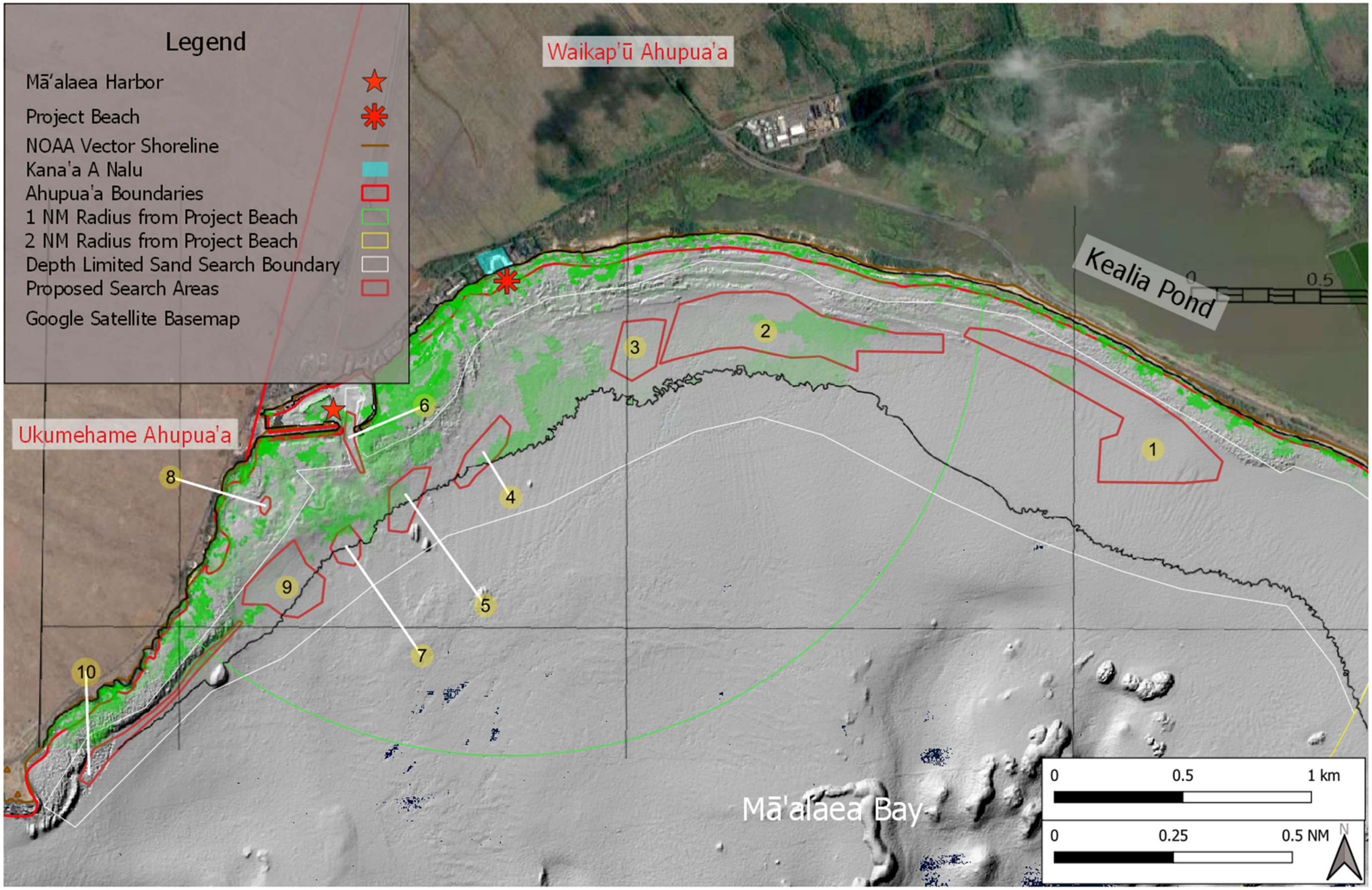

Figure 9 MRC 2011 Projected Algal Presence

The benthic habitat classification prepared by MRC 2011 used spectral reflectance to project where areas with algal cover might exist. Their results figure is overlaid on this map (including the original grid). Green shading shows their projection of algal cover. The black line is from their original figure and shows a ten-meter below MSL contour.

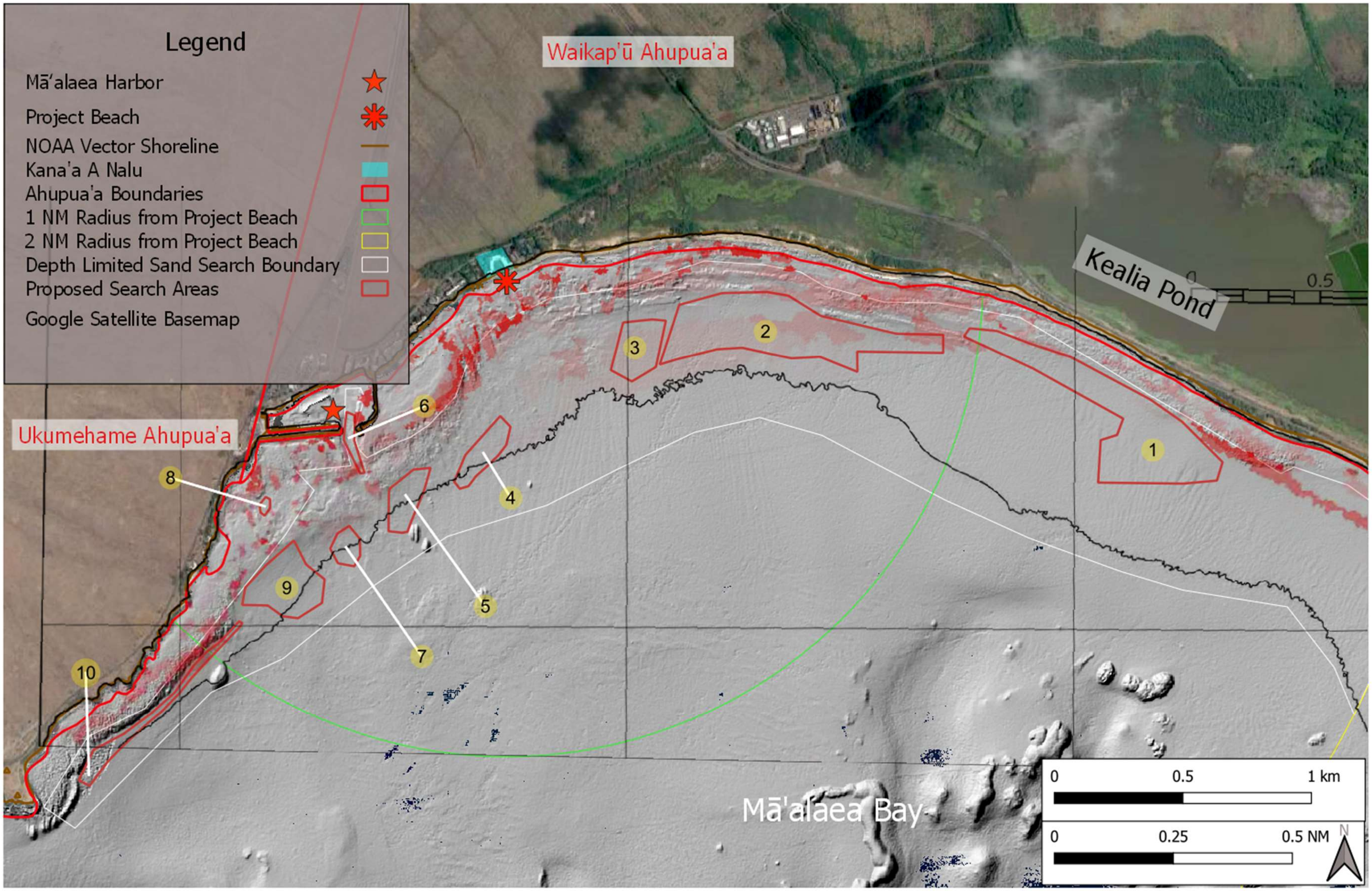

Figure 10 MRC 2011 Projected Coral Presence

The benthic habitat classification prepared by MRC 2011 used spectral reflectance to project where areas with coral cover might exist. Their results figure is overlaid on this map (including the original grid). Red shading shows their projection of coral cover. The black line is from their original figure and shows a ten-meter below MSL contour.

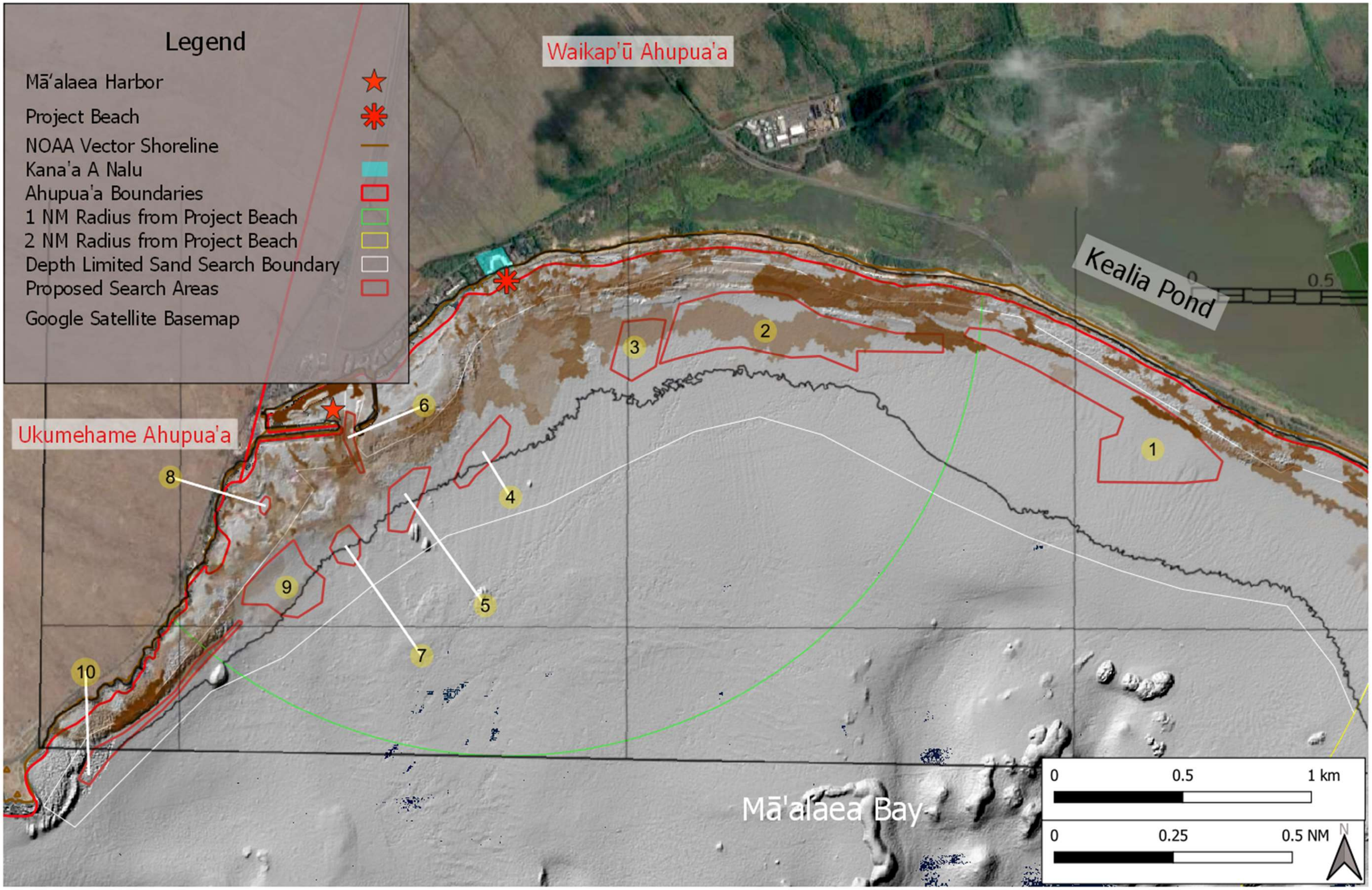

Figure 11 MRC 2011 Projected Mud Presence

The benthic habitat classification prepared by MRC 2011 used spectral reflectance to project where areas with mud cover might exist. Their results figure is overlaid on this map (including the original grid). Brown shading shows their projection of mud cover. The black line is from their original figure and shows a ten-meter below MSL contour.

Table 1 Sand Search Polygon Characteristics

Summary characteristics for each of the ten areas identified in the sand search analysis are shown below. m = meter, ha = hectare, yd = yard, ft = feet

Metric Units

Polygon ID	Overlapping Sand Polygons	Mean Distance To Site	Polygon Area	Polygon Perimeter	Water Depth			Estimated Cumulative Percent Confidence		Estimated Cumulative Percent Sand Cover		Priority Score	Priority Rank
					Mean	Min	Max						
	#	[m]	[ha]	[m]	[m]	[m]	[m]	mean	median	mean	median		
1	14	2650	17.52	2712	-6.7	-10.4	-2.8	65.0	55.0	72.1	77.5	0.8	7
2	16	1300	19.03	2581	-8.5	-11.4	-4.4	68.0	65.0	78.1	85.0	23.9	3
3	6	750	3.60	747	-9.9	-11.3	-8.0	63.0	52.5	84.2	90.0	28.2	1
4	14	820	2.50	735	-10.9	-12.3	-9.1	75.0	75.0	80.7	82.5	25.6	2
5	11	1180	2.55	691	-10.7	-13.1	-7.9	75.0	75.0	85.5	90.0	6.7	4
6	15	1647	0.76	537	-4.2	-6.0	-2.6	77.0	80.0	83.3	90.0	0.6	8
7	10	1430	1.28	427	-11.1	-12.7	-9.0	77.0	82.5	82.0	82.5	1.7	6
8	12	1870	0.20	179	-2.7	-3.1	-2.5	90.0	92.5	91.7	90.0	0.1	10
9	14	1725	5.62	964	-9.0	-13.4	-4.1	79.0	90.0	87.1	87.5	4.5	5
10	14	2500	2.69	1828	-9.6	-14.7	-6.3	80.0	85.0	86.8	90.0	0.4	9

English Units

Polygon ID	Overlapping Sand Polygons	Mean Distance To Site	Polygon Area	Polygon Perimeter	Water Depth			Estimated Cumulative Percent Confidence		Estimated Cumulative Percent Sand Cover		Priority Score	Priority Rank
					Mean	Min	Max						
	#	[mile]	[acre]	[yd]	[ft]	[ft]	[ft]	mean	median	mean	median		
1	14	1.65	43.3	2966	-22	-34	-9	65.0	55.0	72.1	77.5	0.8	7
2	16	0.81	47.0	2823	-28	-37	-14	68.0	65.0	78.1	85.0	23.9	3
3	6	0.47	8.9	817	-32	-37	-26	63.0	52.5	84.2	90.0	28.2	1
4	14	0.51	6.2	804	-36	-40	-30	75.0	75.0	80.7	82.5	25.6	2
5	11	0.73	6.3	756	-35	-43	-26	75.0	75.0	85.5	90.0	6.7	4
6	15	1.02	1.9	587	-14	-20	-9	77.0	80.0	83.3	90.0	0.6	8
7	10	0.89	3.2	467	-36	-42	-30	77.0	82.5	82.0	82.5	1.7	6
8	12	1.16	0.5	196	-9	-10	-8	90.0	92.5	91.7	90.0	0.1	10
9	14	1.07	13.9	1054	-29	-44	-13	79.0	90.0	87.1	87.5	4.5	5
10	14	1.55	6.6	1999	-32	-48	-21	80.0	85.0	86.8	90.0	0.4	9

Table 2 Potential Sand Volumes at Proposed Search Areas
Potential sand volume were calculated by multiplying the polygon area by potential sand thicknesess and accounting for a 50% dredge efficiency. m^3 = cubic meters; yd^3 = cubic yards.

Metric Units

Polygon ID	Possible Mean Sand Depth [m]				Priority Rank
	0.3	0.6	0.9	1.5	
	50% Yield Sand Volume [m^3]				
1	26,707	53,414	80,121	133,535	7
2	29,008	58,017	87,025	145,041	3
3	5,481	10,962	16,442	27,404	1
4	3,803	7,605	11,408	19,013	2
5	3,888	7,775	11,663	19,438	4
6	1,159	2,317	3,476	5,793	8
7	1,952	3,904	5,857	9,761	6
8	310	619	929	1,548	10
9	8,561	17,122	25,682	42,804	5
10	4,096	8,192	12,288	20,480	9

English Units

Polygon ID	Possible Mean Sand Depth [ft]				Priority Rank
	1.0	2.0	3.0	5.0	
	50% Yield Sand Volume [yd^3]				
1	34,931	69,863	104,794	174,657	7
2	37,941	75,883	113,824	189,707	3
3	7,169	14,337	21,506	35,843	1
4	4,974	9,947	14,921	24,869	2
5	5,085	10,170	15,254	25,424	4
6	1,515	3,031	4,546	7,577	8
7	2,553	5,107	7,660	12,767	6
8	405	810	1,215	2,024	10
9	11,197	22,394	33,591	55,985	5
10	5,357	10,715	16,072	26,787	9

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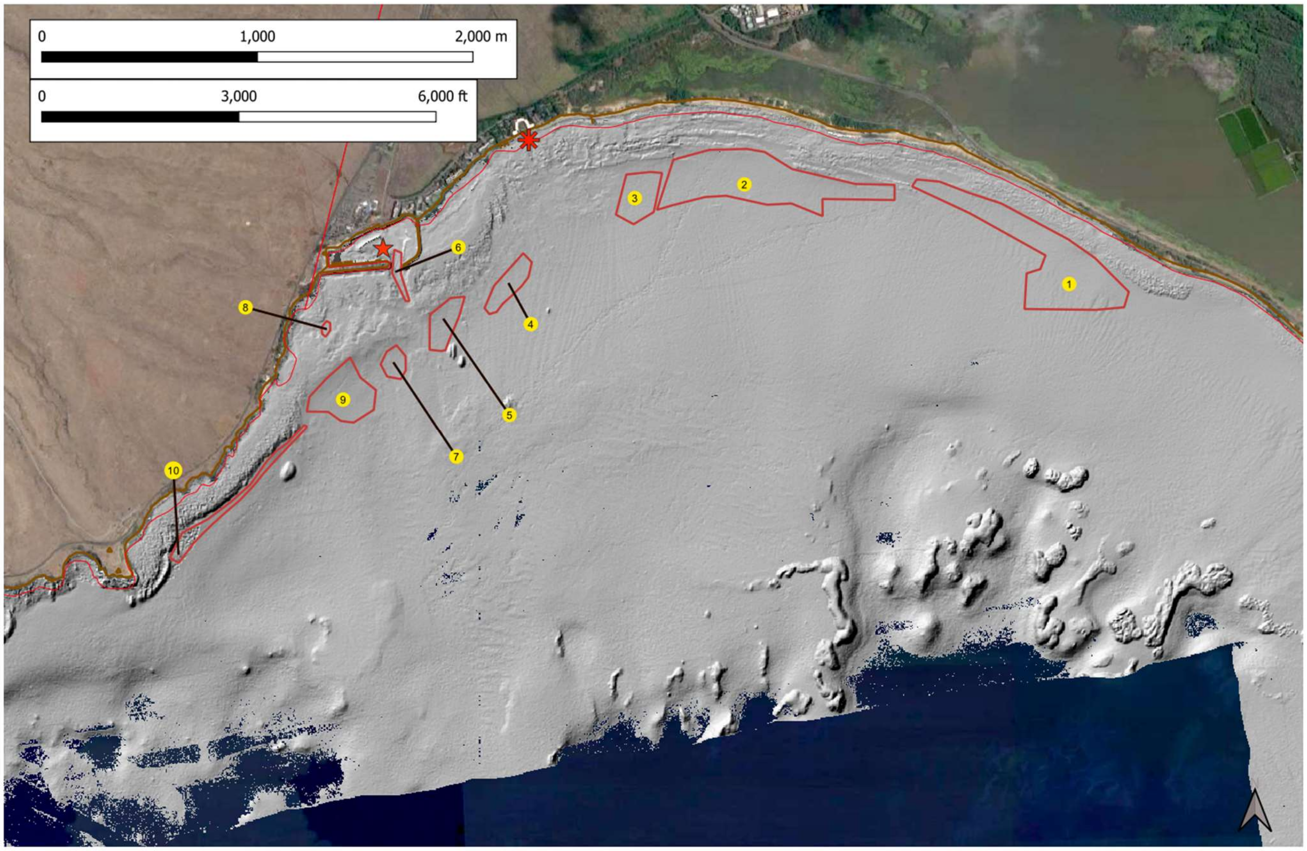
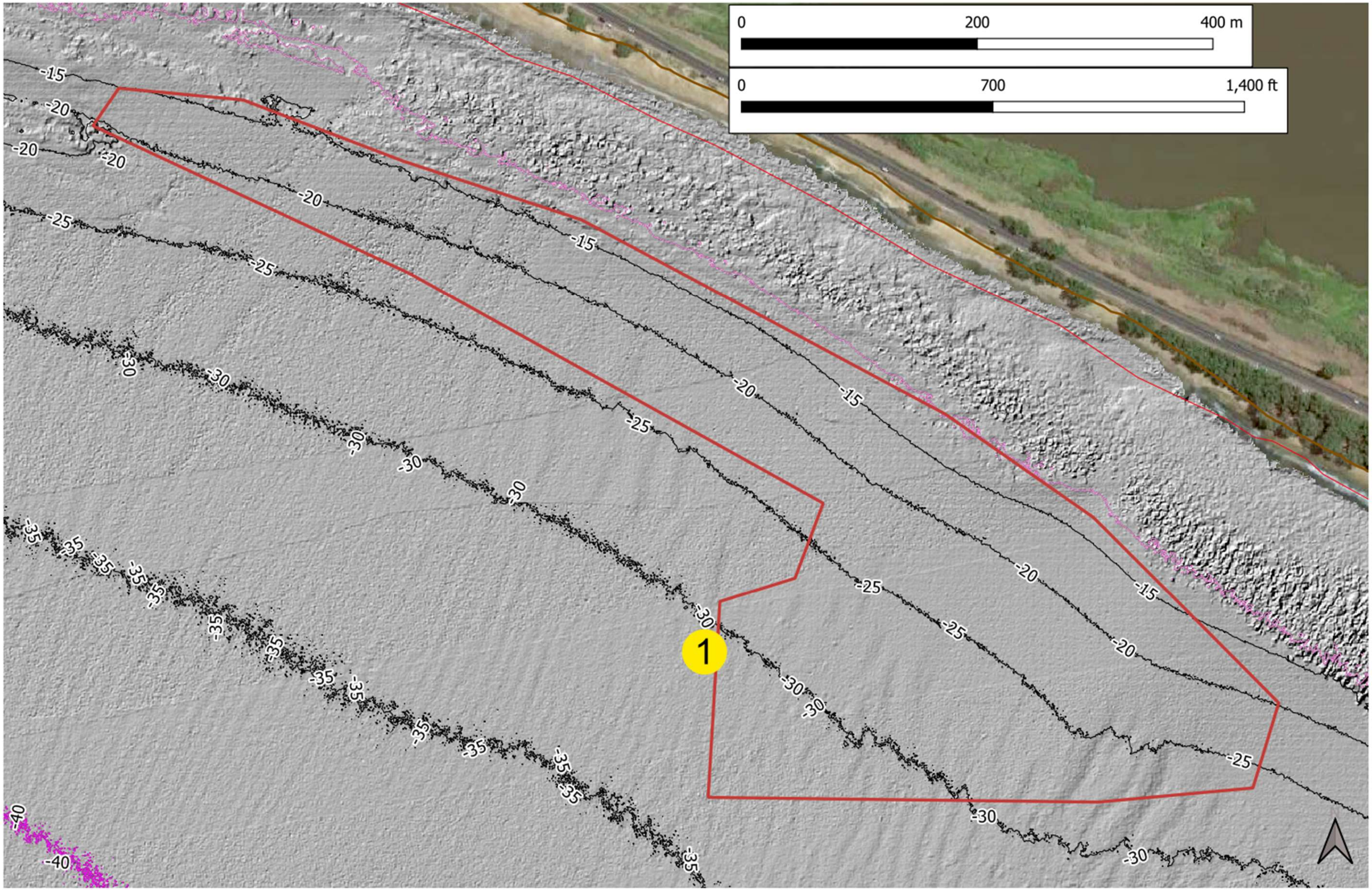
[2] Made from visual interpretation of IKONOS hyperspectral image mosaic; available at: https://cdn.coastalscience.noaa.gov/datasets/e97/2007/mosaics/Maui_IKONOS.zip; accessed June 2021.

Appendix A

Detailed maps of individual sand search polygons overlaying a hillshade representation of LiDAR bathymetry and a Google Satellite basemap. The project beach is shown with a red asterisk, while Mā'alaea Harbor is shown with a red star.



Search Polygon 1



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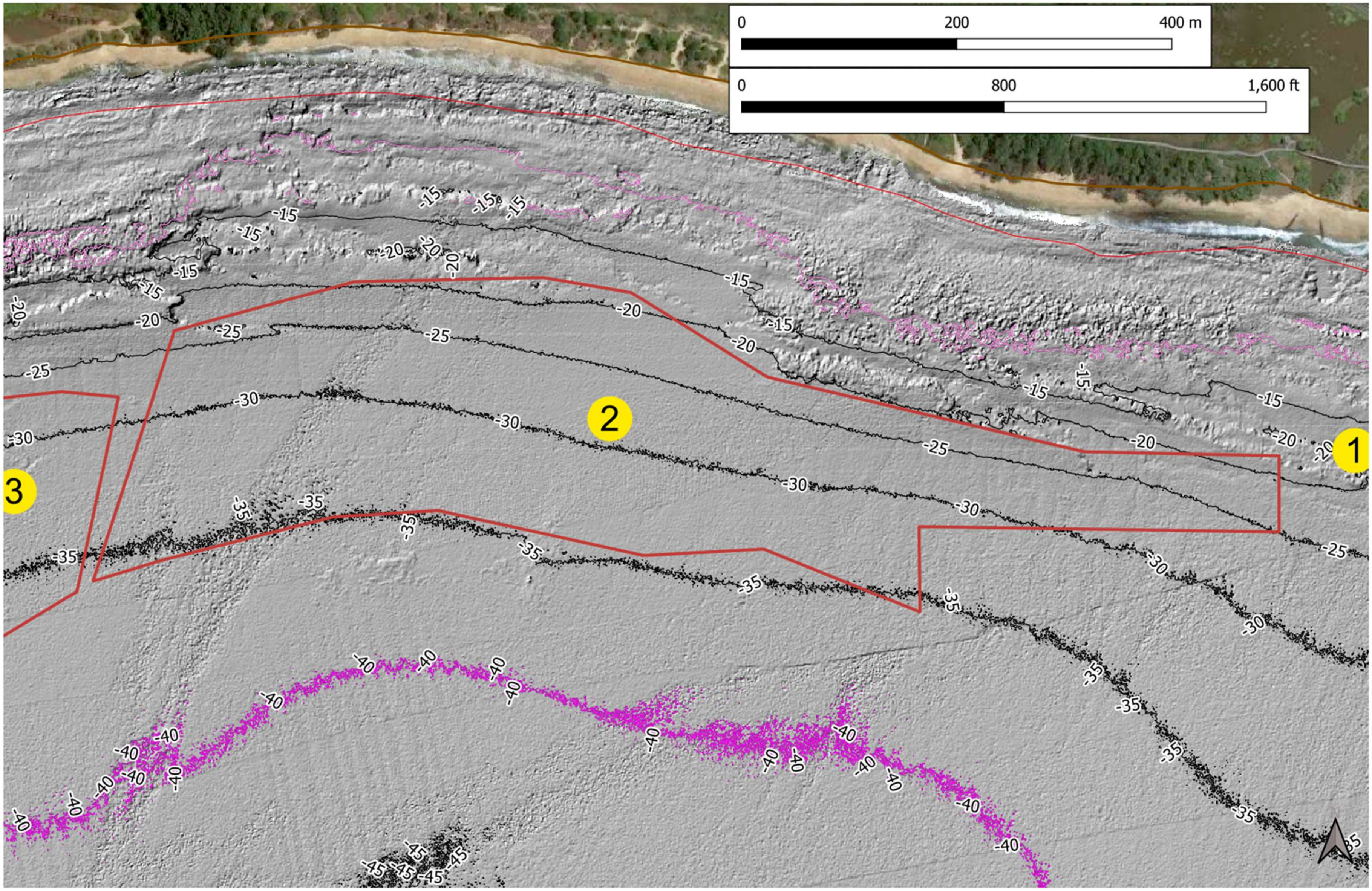

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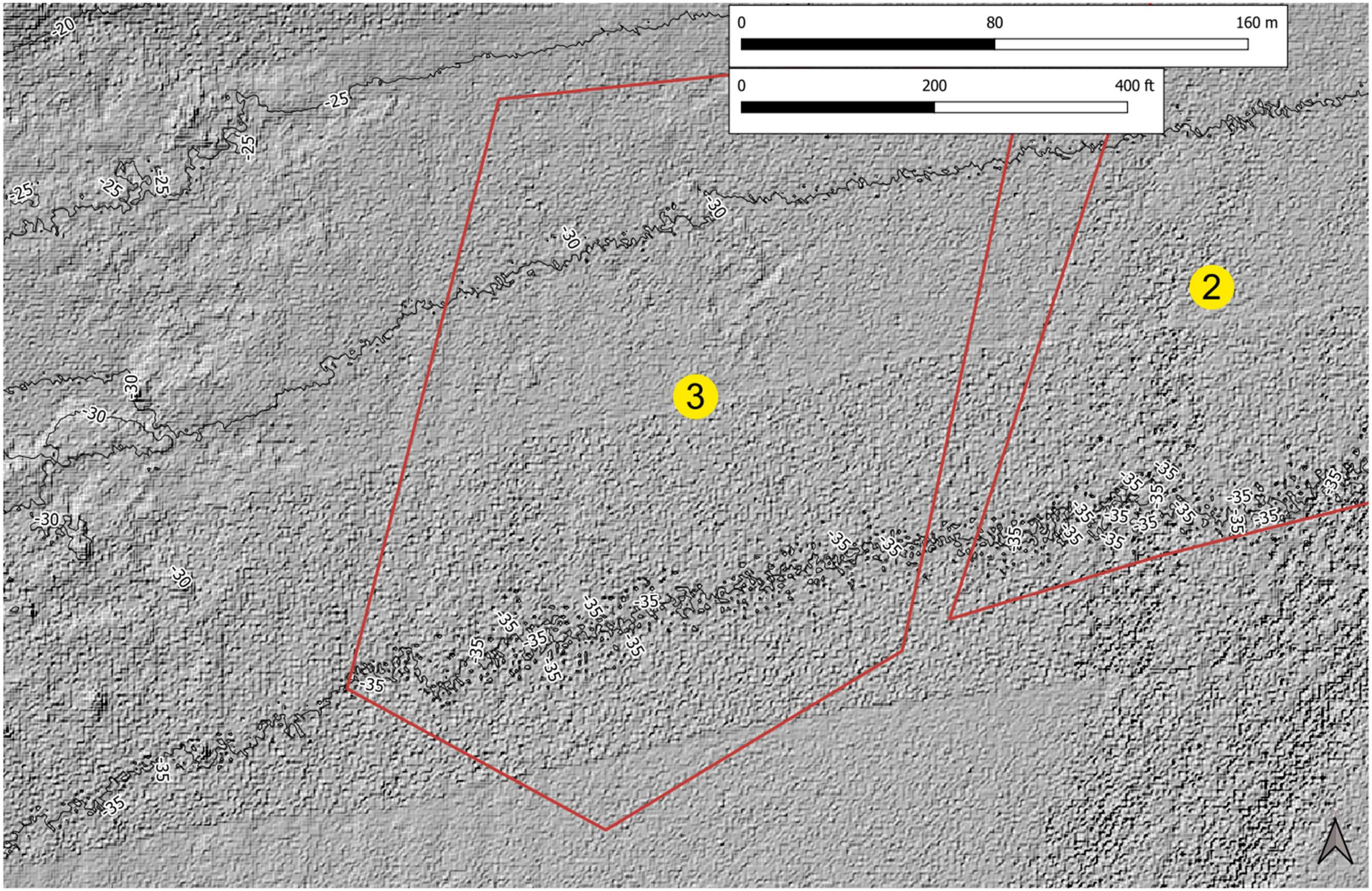

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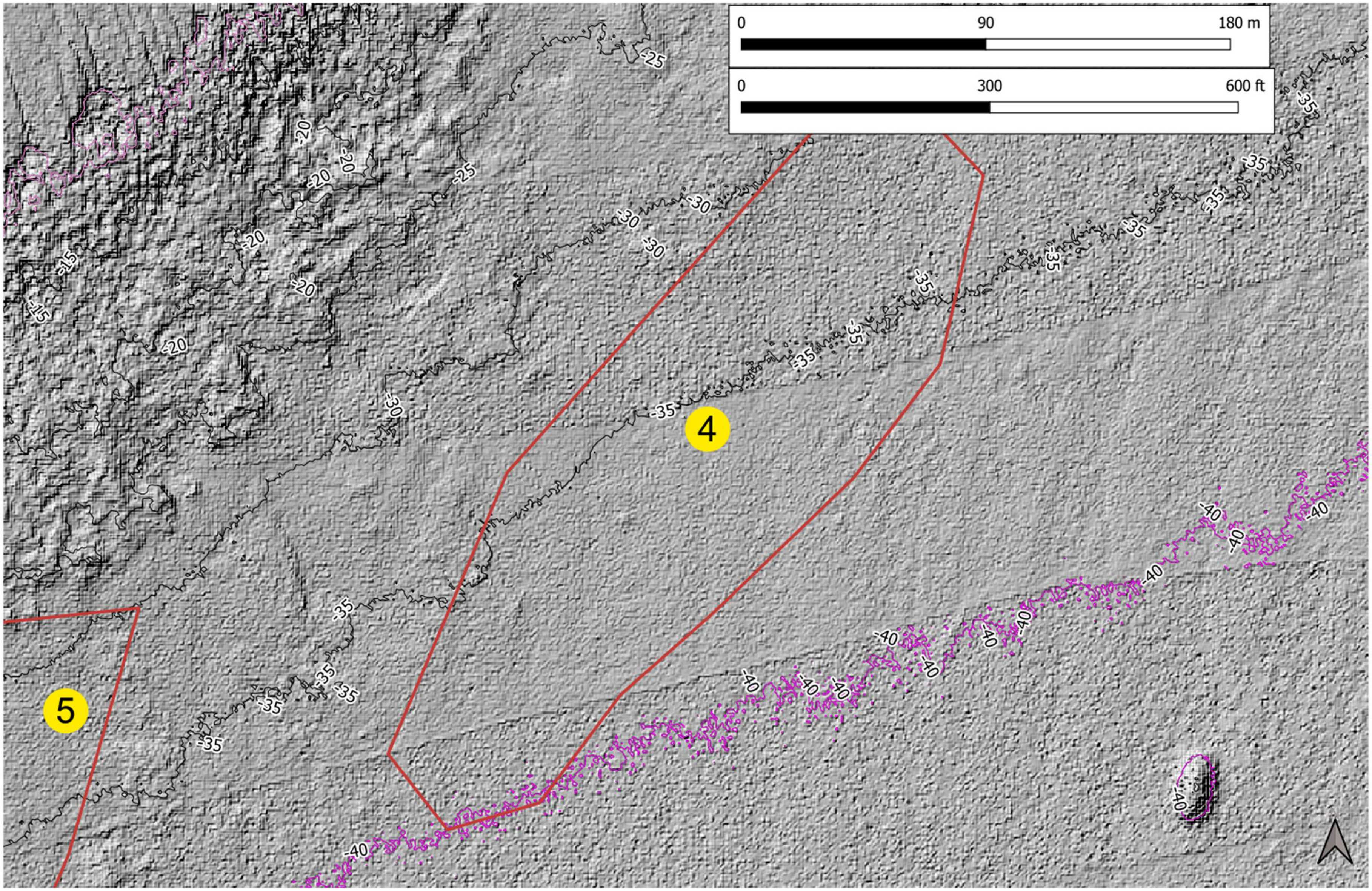

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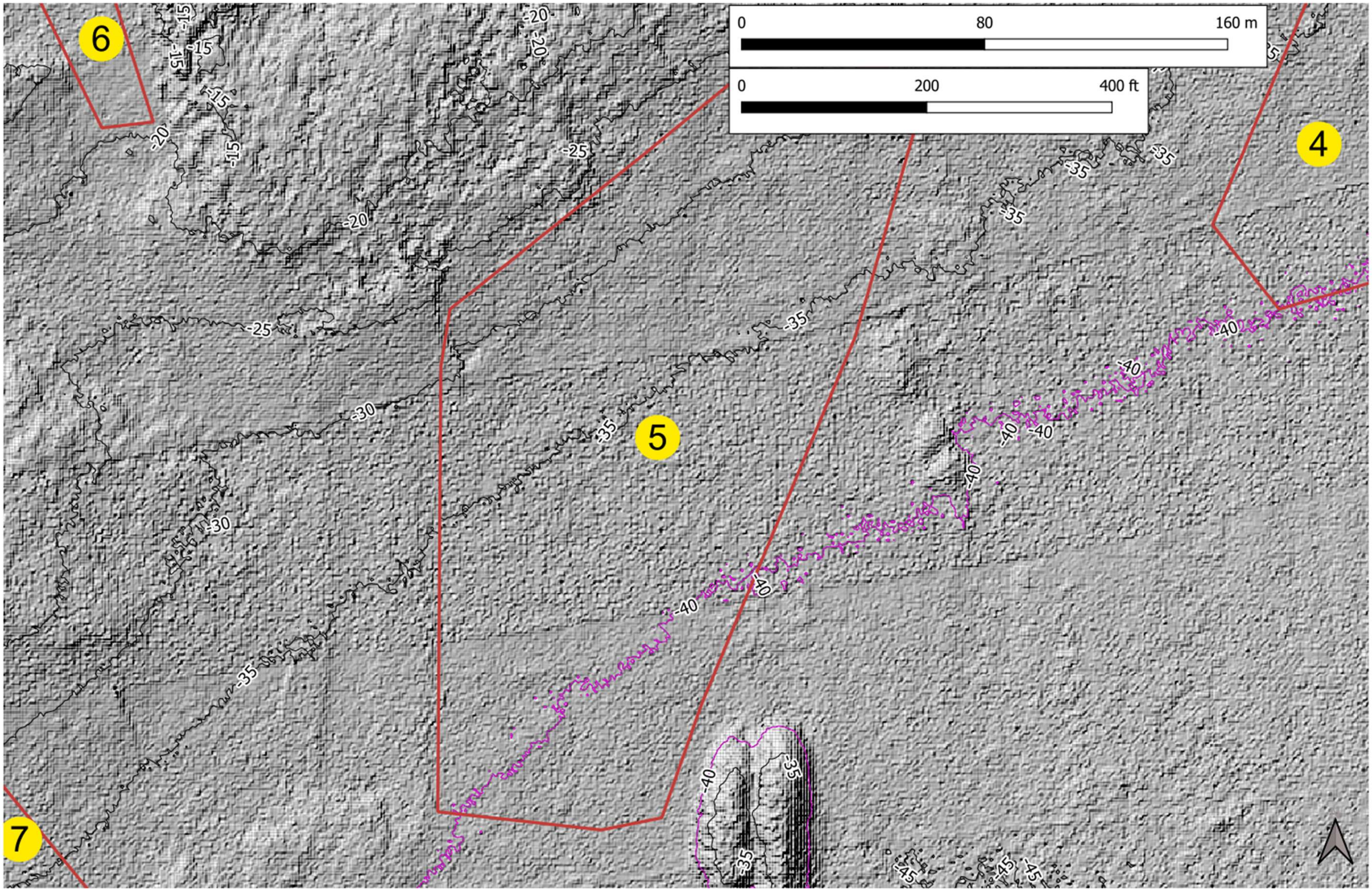

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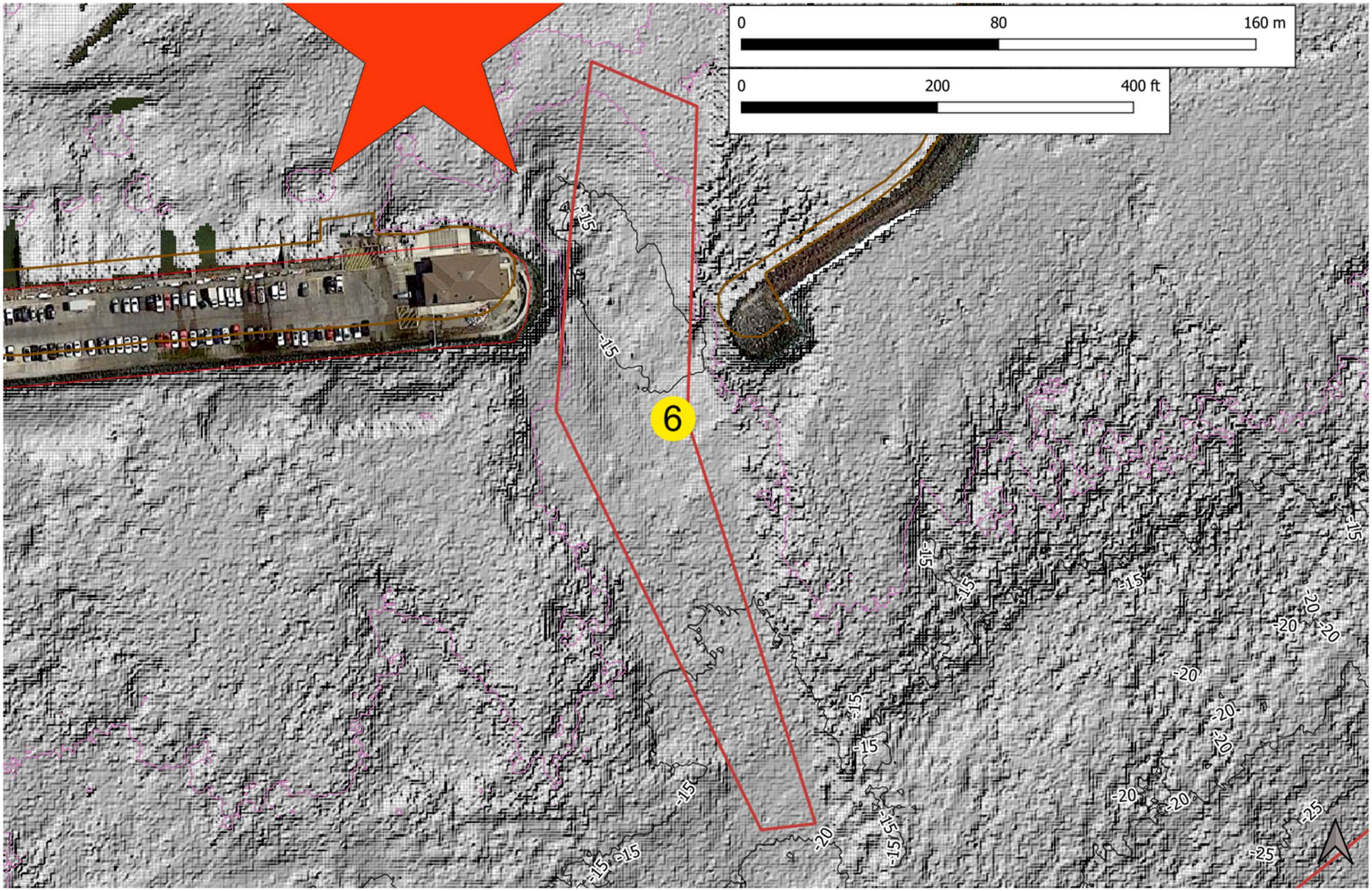

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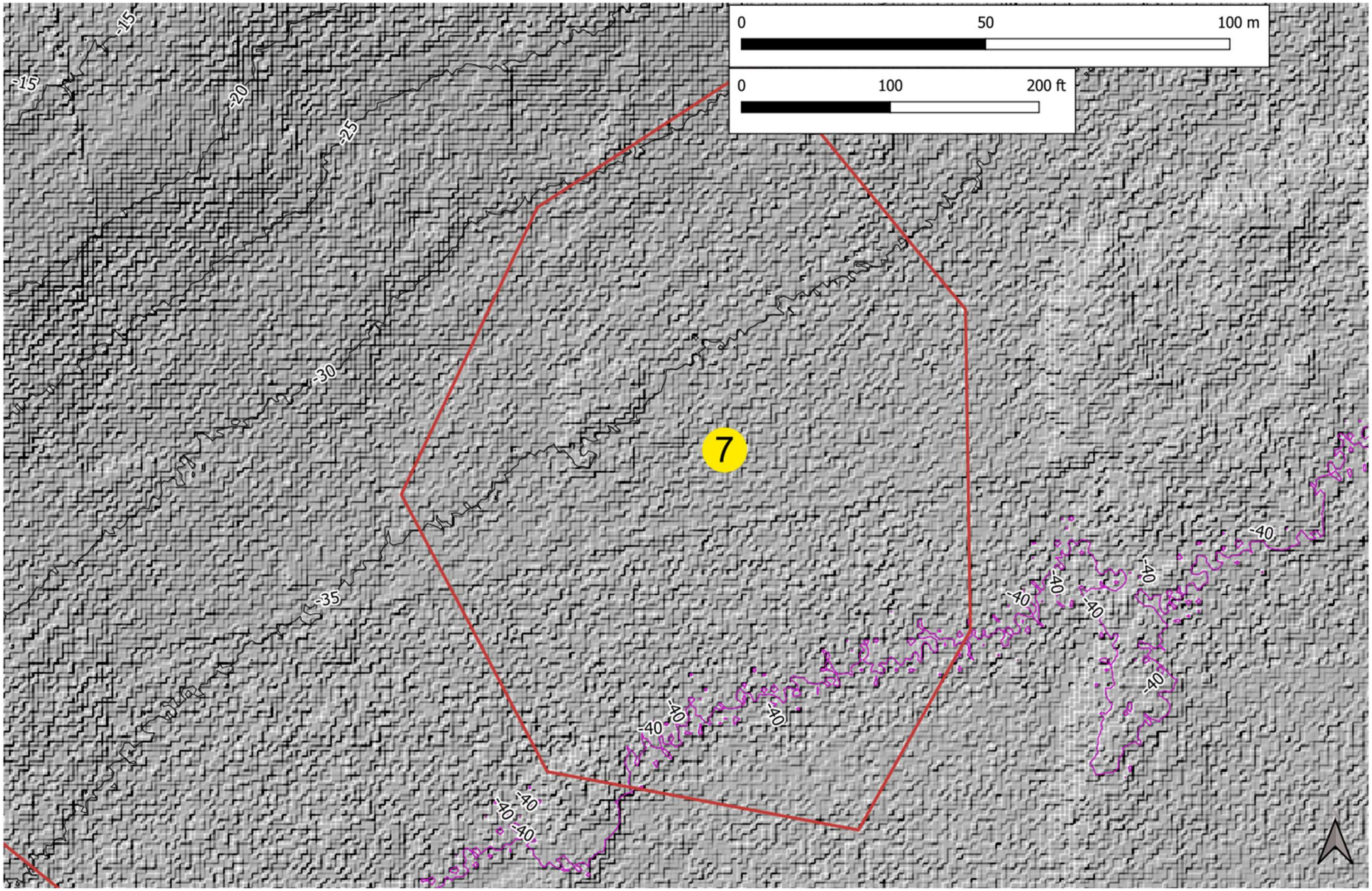

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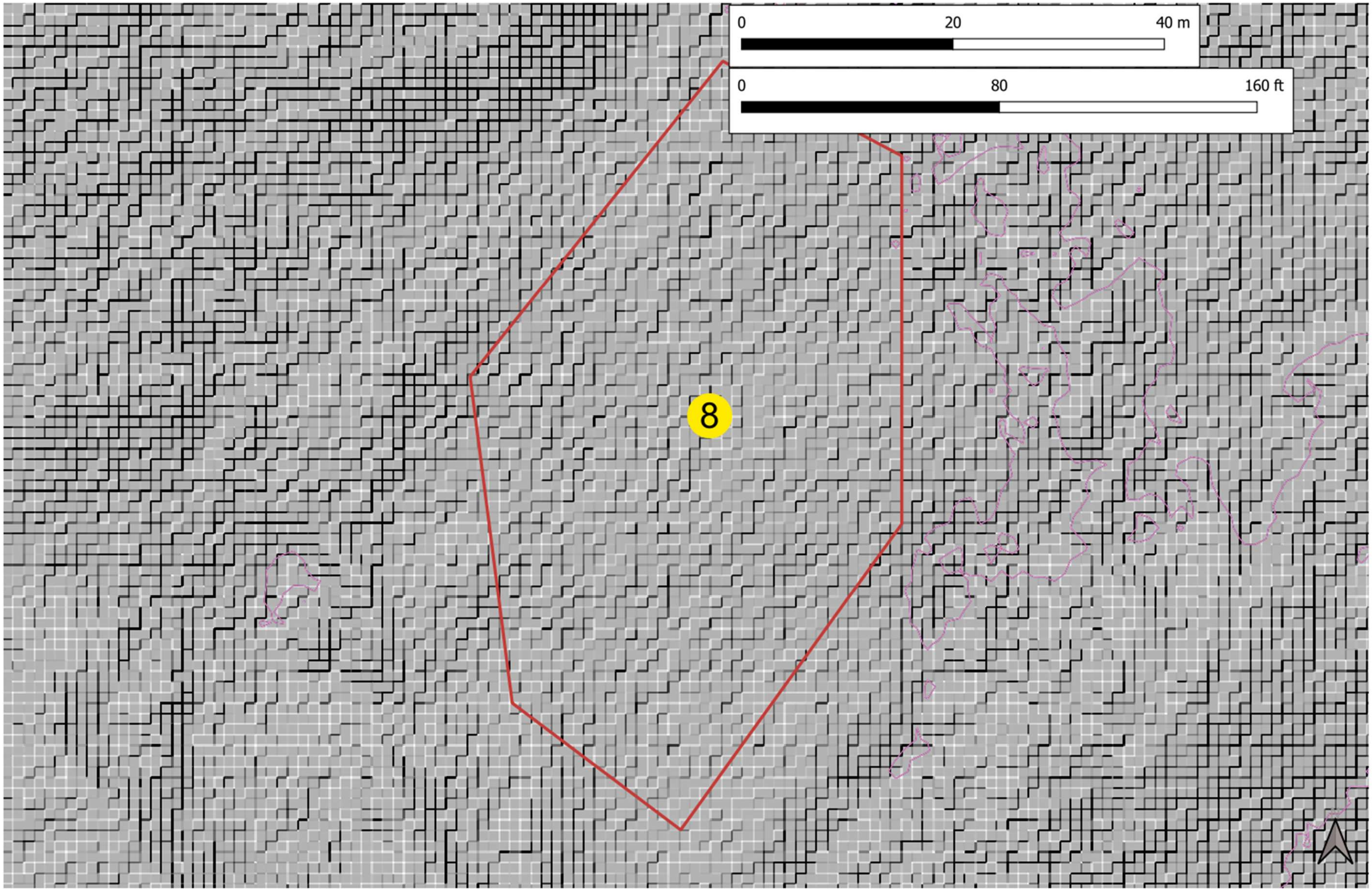

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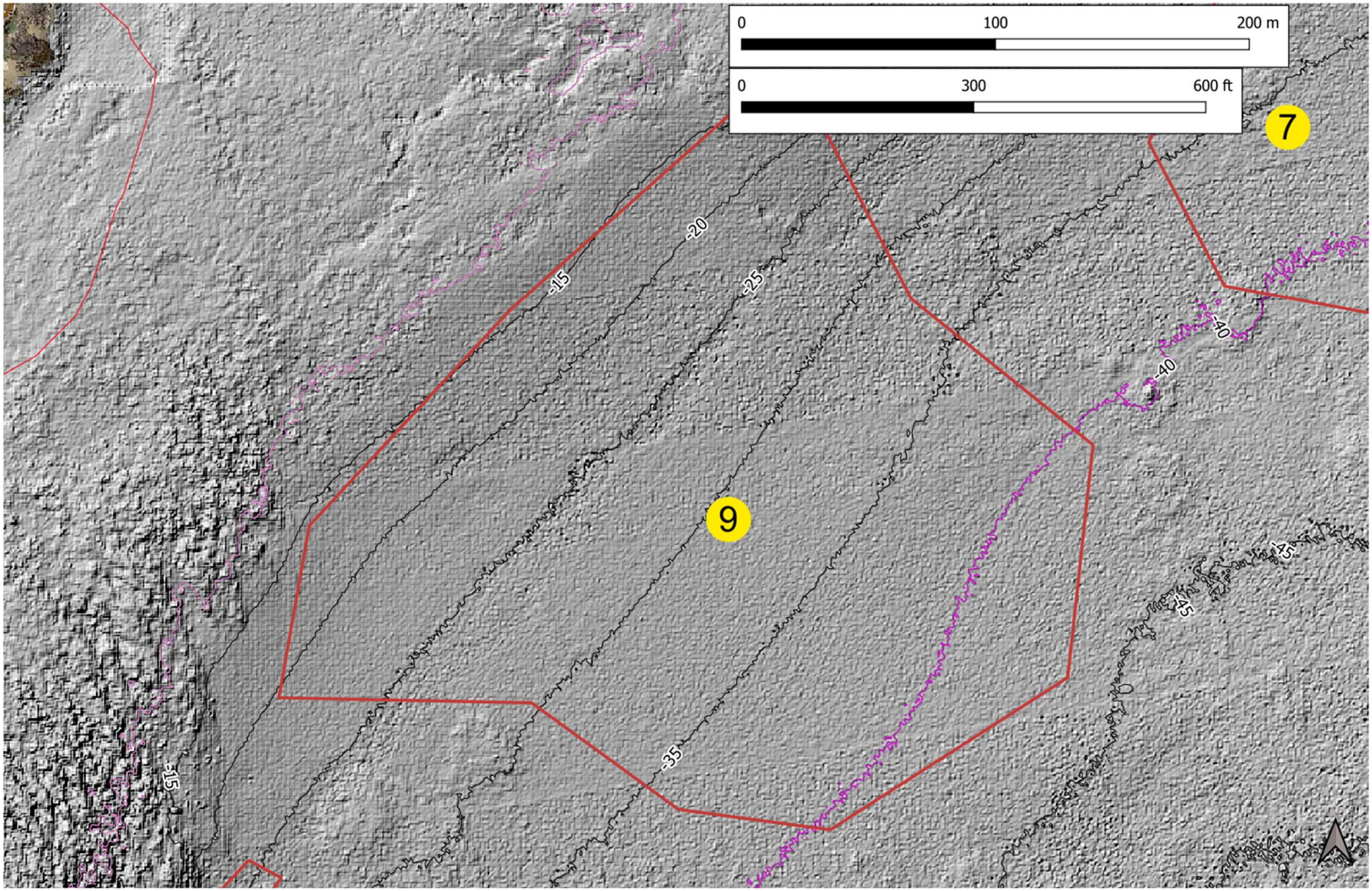

Search Polygon 10