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THE LEVEL OF THREAT OF UXO TO THE KAHO'OLAWE RESERVE WATERS

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INTRODUCTION

One of the primary impediments to the exploration and conservation of the resources in the Kaho'olawe Island Reserve Waters is the existence of buried and proud (on the surface of the seabed) unexploded ordnance (UXO) within the limits of the Reserve Waters (Figure 1). Essential to the management of the resources in the Reserve Waters is an assessment of the risks which are imposed by UXO to human safety and health.

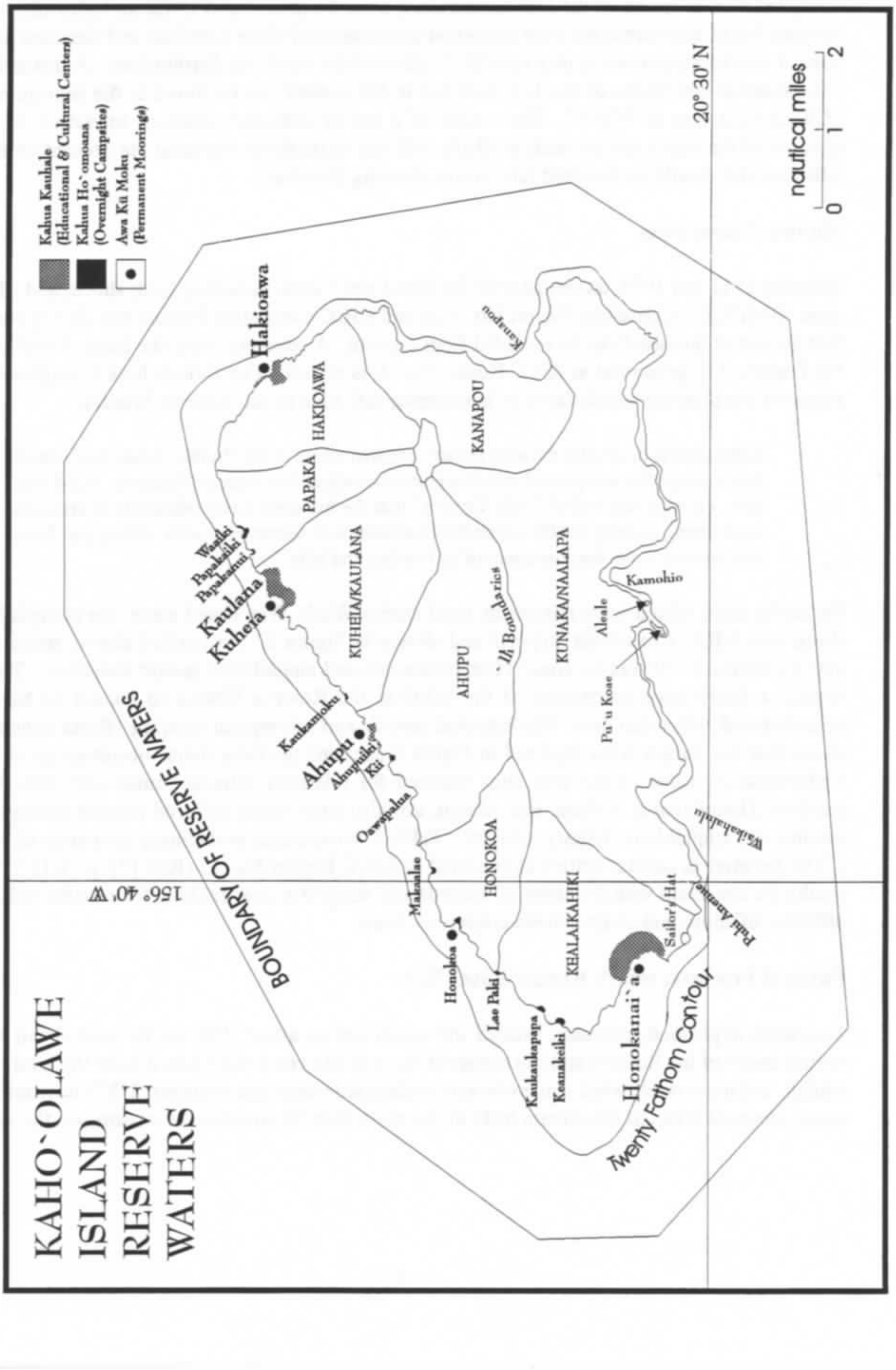
This report reviews the results of available studies on this topic, it examines the inferred seabed distributions of UXO, with a specific focus on the areas of highest interest for potential human activities. It provides specific outcome scenarios which describe: a) the likely chemical and physical transformations which would accompany weathering for proud or buried ordnance, and b) the outcomes to be expected from interactions of humans and UXO. It also provides ranked priorities for relative liabilities related to various activities which are expected to take place in Reserve Waters. This study is focused primarily on shallow seabed (< 20 fathoms) and coastal areas, since these areas are both expected to have the highest densities of UXO and the highest probabilities for human interactions with UXO.

SEABED DISTRIBUTIONS OF UXO

After the attack on Pearl Harbor, the United States declared war on Japan in 1941 and started to use Kaho'olawe and the adjacent marine waters as a military test and practice range. Operations included bombing, gunnery practice, torpedo testing, and simulation of nuclear blasts, with the most intensive activity taking place during World War II and the Vietnam War.

There is a paucity of available information concerning the amounts and types of ordnance deployed, the locations for the deployments, and the percentages of ordnance which did not explode after deployment. Most of these activities took place during wartime, and the deployment of ordnance was in general not the precise technology that can be today. Also, the priority for other uses of the island was not properly acknowledged until relatively recently. In addition, natural weathering processes of sediment redistribution have been operating on the UXO of Kaho'olawe, in some cases for more than fifty years. Even if there were perfect knowledge of where UXO were left and their initial conditions, these processes have had ample opportunity to modify the situation significantly.

Figure 1: Site Map



Two reports prepared for the Kaho'olawe Island Conveyance Commission (KICC) [1,2] have compiled what is known of the activities resulting from the presence of UXO on Kaho'olawe. The sections below summarize the most important conclusions of these activities and describe how the natural weathering processes may have likely affected the resultant distributions. A discussion on the potential conditions of the UXO on and in the seabed can be found in the section entitled "Characterization of UXO." The results of a model ordnance clean-up operation of small portions of the island, not currently available, will also be useful in assessing the present conditions offshore and should be factored into future planning decisions.

Known Target Sites

Between 1941 and 1970, targets all over the island were used, including land, shore, and offshore sites. Both KICC Consultant Report No. 3 [1] and KICC Consultant Report No. 22 [2] conclude that no part of the island can be excluded from concern. A quotation from the book *And Blow Not the Trumpet* [3], presented in KICC Report No. 3, is important to include here to emphasize the scope of the problem which faces us in planning safe uses of the Reserve Waters:

> Kahoolawe is by all odds the most artillery-battered island in the Pacific. It has been stated that more gunfire was poured into this place than either Iwo Jima or Okinawa. For it was here, on what was called 'Little Tarawa,' that the full-dress naval rehearsals of invasion were staged, as many as 800 vessels from battleships to destroyer escorts, taking part from time to time in the bombardment of its beaches and hills.

Particular sites, which were repeatedly used during World War II and since, are compiled from these two KICC Consultant Reports and shown in Figure 2. As implied above, much of the activity before 1970 was on coastal bombardments and amphibious assault exercises. Thus we expect a fairly large percentage of the UXO in the Reserve Waters to consist of hardware manufactured before that date. The historical records and subsequent clearing efforts consistently show that the Target Area depicted in Figure 2 contains the most dense occurrences of UXO. Unfortunately, three of the four sites selected for relatively intense human activities, Kahua Kauhale Honokanai'a, Kuheia, and Ahupu, are also sites which suffered intense damage from marine and amphibious military assaults. Table 1 summarizes preliminary estimates of seabed UXO densities in coastal waters as reported in KICC Report No. 22 (Ref. [1], p. 3-16). These results are consistent with the historical records and suggest a clear ranking for relative risk in the different offshore and coastal areas considered here.

Physical Processes which Redistribute UXO

Two kinds of physical processes, rainfall and ocean waves, affect UXO in the coastal and marine environments of the Reserve and can transport them to the coast and seabed from the land. First, rainfall, and more rarely wind, can erode surrounding sediments and transport UXO downhill from steep, elevated areas to the stream beds of the more than 69 intermittent streams on the island,

Figure 2: Military Targets

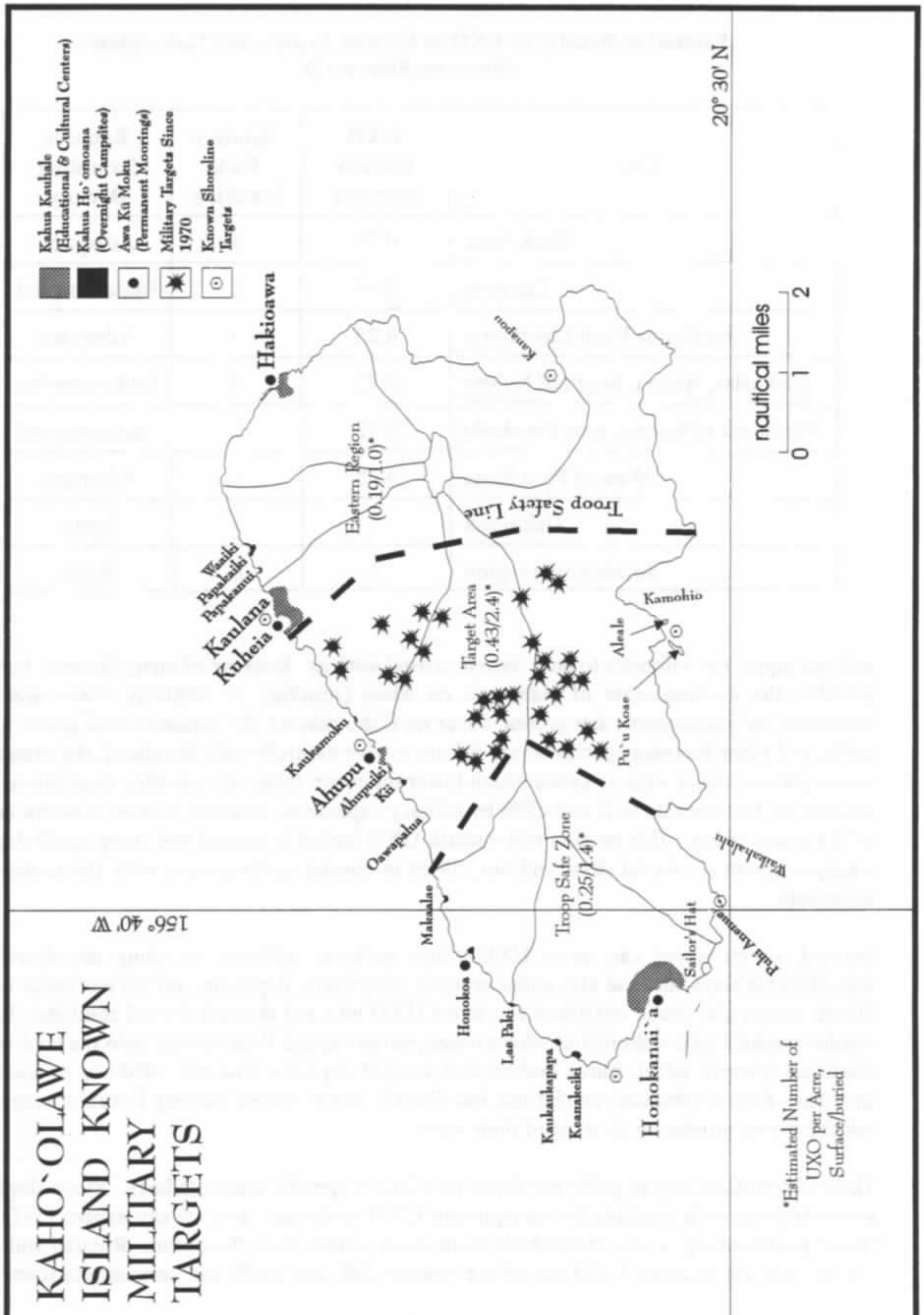


TABLE 1

Estimated Density of UXO in Coastal Waters Off Kaho'olawe
(Data from Reference 2)

Site	UXO Density (#/acre)	Relative Risk Ranking	Relative Sampling Density
Black Rock	0.76	1	Adequate
Kanapou	0.64	2	Undersampled
Southwest Point Lighthouse	0.25	3	Adequate
Makaalae, Ahupu, South of Kuheia	0.22	4	Undersampled
Northeast of Kuheia, near Papakaiki	0.12	5	Undersampled
West of Pu'u Koae	0.08	6	Adequate
Hakioawa	?	7	None
Southeastern region	?	8	None

and can supply the sediments to bury them in coastal settings. Because of many factors: including possibly the de-forestation of Haleakala on Maui (resulting in relatively lower downwind humidities and consequently less ground cover on Kaho'olawe); the persistence of goats, rabbits, cattle, and other foraging species which did not evolve naturally with the island; the presence of exotic phreatophytes such as kiawe which lower the water table; and possibly even the repeated assaults on the coastal bluffs and cliffs by military explosives; extreme erosion is active on soils of the island today. This erosion will unearth UXO buried in coastal and steep uphill deposits, transport them to coastal sites, and bury them in coastal environments with the re-deposited sediments.

Second, ocean waves can move UXO either onshore, offshore, or along the shoreline in unpredictable ways, and can also either erode or bury them, depending on the particular setting. Ocean waves also erode coastlines and move UXO into and through littoral conduits. Littoral conduits consist of the shorelines where ocean waves expend their energy onto the land and the resultant currents which move seabed and coastal deposits onshore, offshore or along the shoreline. Storms bring both rainfall and, less directly, ocean waves, causing littoral transport and rainfall-driven erosion to do most of their work.

These observations help to guide our focus on UXO to specific areas offshore. Steep slopes and streambeds provide conduits for transporting UXO to the sea, and we can expect UXO to be found preferentially where streambeds from steep terrain meet the ocean. Rainfall and ocean waves will act to erode UXO out of the coastal cliffs and bluffs and concentrate them in the littoral zone. Also, much of the military activity consisted of coastal bombardments and amphibious assaults. For these reasons, we can expect anomolously high concentrations of UXO on the beaches and nearshore seabed. Unfortunately, these coastal environments are also places most likely to be frequented by people.

Potential for Quantitative Assessment

There is a considerable overlap between the coastal and seabed areas where UXO are most likely to be found and the areas where human presence is to be expected. Thus, some consideration must be given to the means of location and classification of UXO on the beach and seabed, so that they can either be removed or at least clearly marked. The following section examines the current state-of-the-art technology to detect and identify UXO.

It is important to note, that, unlike on land, it is currently not possible to certify any seabed area clear of UXO, and given the mobility of UXO and sediments in coastal environments, an area which is carefully swept can exhibit new UXO occurrences after a storm.

During the past ten years or so much progress has been made in our ability to conduct high resolution seabed surveys, due mostly to the great advances in navigation and computing efficiency and portability. Currently, the author of this report is the principal investigator of a University of Hawaii/U.S. Navy project (Office of Naval Research Grant N00014-95-1-0828, entitled "Location and Classification of Ordnance-Like Objects in Coastal Waters to Depths of 50 Meters") dedicated to testing the capabilities of commercially available systems in finding UXO in tropical coastal waters.

In August of 1995 engineers and technicians from the U.S. Naval Facilities Engineering Service Center (NFESC) deployed many different types of deactivated ordnance, from 20-mm ammunition to 1,000-lb bombs, both proud and buried to shallow depths in the Barking Sands Test Range offshore Kaua'i. High resolution navigation was used to place the ordnance in well known locations. The project team then conducted two weeks of intensive surveys in the area with optical, electromagnetic, and acoustic tools to investigate the effectiveness of various systems for finding and classifying UXO. The project is still ongoing as the data from this exercise are being processed and evaluated. The following description of the tools used and preliminary evaluation of the results provides a reasonable assessment of the state of the art today.

1. Side-Scan Sonar System. This system consists of a handline-deployed, high frequency (100 and 500 kHz) shallow-water towfish connected to shipboard data acquisition and processing systems. The side-scan system was used with the bathymetric sonar, described below, as the initial tools for identification of potential targets and identification of unconsolidated sediments for subsequent surveys. These systems provide the basis for the multi-sensor data acquisition system to integrate all data products.

   Preliminary Results. Preliminary plotting of the targets identified during acquisition in the calibration zone of the test range shows consistency with the known positions, particularly for the larger classes of targets in shallow water.

While the data were being collected, likely targets (i.e. small targets with high back-scatter) were selected from the incoming data stream by the workstation operator, and 250 x 250 pixel samples about these selected targets were recorded in separate files.

One general conclusion should be noted, which is probably applicable for all modern high resolution side-scan sonar systems, when used with appropriate navigation. These systems clearly have the potential for accurate location of proud UXO, given their impressive horizontal resolution and the wide dynamic range of backscatter returns. They could be valuable tools for periodic monitoring of changes of the seabed. After an area has been initially swept for UXO, periodic surveys with side-scan systems (which are economical to deploy) could be compared to previous surveys to find specific changes which might indicate the uncovering or introduction of UXO in the swept area.

2. Reson, Inc. SeaBat 9001 Multibeam Bathymetric Sonar System. This is the most compact, lightweight high resolution, multibeam sonar currently available on a commercial lease. It surveys over a swath of 90° across track (45° above vertical to port and starboard) with an along-track beam width of 1.5°. It can be operated either from a towed or hull-mounted platform, and can be used at high speeds, up to 10 kt. It can be used in shallow water (< 5 m to 600 m) and provides bathymetric data with resolutions approaching 5 cm. It is generally hull-mounted. To accommodate for the motions of the survey vessel, pitch, roll, and heave sensors were also deployed simultaneously.

   Preliminary Results. The SeaBat® produced excellent bathymetric data which were readily integrated into the acquisition process. The data are consistent from line to line and appear to be accurate to within about a 2-m water depth, with horizontal resolutions of a few meters. The system is a good complement to the sidescan sonar, producing quantitative data to remove some of the ambiguity of the time-series returns received by the side-scan system.

   Currently several commercial firms are developing side-scan systems which can simultaneously collect accurate bathymetric data. When these systems are developed to the point where they can be launched reliably using handlines from small vessels, the entire process of surface surveying will be greatly simplified and easily amenable for routine deployment.

3. University of Mississippi Phased-Array Sub-Bottom Acoustic Profiling System. This system, developed and tested by the Marine Mineral Technology Center of the University of Mississippi, is basically a cross between a high resolution shallow profiling system and a reduced-scale 3-D oil-field seismic system. It is composed completely of components which are commercially available.It can be triggered at 0.25-second intervals to provide seabed and subsurface resolutions of approximately 0.5 m. It penetrates the seabed and retrieves useful returns to depths of more than 50 m in carbonate sands.

   A specially designed 24-channel hydrophone array receives the reflected energy from this source. It is constructed in three separate segments of eight channels each, with 1-m group intervals. This can produce the 0.5-meter along-track common depth points for signal stacking. The three-hydrophone groups are tightly spaced so that, while they effectively cancel random noise, no high frequency signal loss occurs at extreme angles of incidence. An Elics Delph24® processing system is used to receive and digitize the data. This system can sample 24 channels at 12 kHz, sufficient for the resolution required for this purpose.

Preliminary Results. Processing of the data has been initiated at the University of Mississippi. Monitoring of the field acquisition showed that excellent data were collected, but preliminary examination of the data show that the width of coverage (no more than about 10 m across track) is so small that only a small percentage of the range was covered and significant portions of the data are unusable due to several technical reasons. Significant development will be necessary before UXO which is buried in the near-surface will be detectable through this or some other acoustic method.

4. Sea Engineering, Inc. Chirp Sub-bottom Profiler. During the past five years frequency modulated (i.e., "chirp") acoustic systems have undergone extensive development and are available commercially. This particular system was developed specifically for high resolution profiling of carbonate sand bodies by Lester LeBlanc and Steven Schock, the original developers of chirp acoustic instrumentation. It has a lower frequency band than the other commercially developed systems (about 500-1,500 Hz) and is available for local lease from the Oahu-based firm Sea Engineering, Inc. It is field tested and confirmed effective in carbonate sands in Hawaii for high resolution, shallow profiling to depths of at least 50 m.

   This system is highly complementary to the phased array system in that it provides the hydrophone receiving array with a frequency-modulated source for independent processing. Using the two systems together (with the chirp system providing an outgoing signal to be received by the trailing receiver array) offers the advantages of the beam-forming and swath width of the hydrophone array (enhancing horizontal resolution) and the wide-beam, resonance imaging capabilities of the chirp system.

   Preliminary Results. Because the chirp system by itself can retrieve data only from a cross-track swath even more narrow (<3 m) than the seismic array, its application for practical ordnance location and classification depends upon the array of receivers deployed by the University of Mississippi and discussed above. The chirp data received by the seismic array has not yet been processed. The system does provide an excellent real-time characterization of the seabed type, however, which was very useful for confirming the soft-substrate types identified by the SeaBat® back-scatter records.

5. Geometrics, Inc. Model G-822A Cesium Magnetometer. By using cesium instead of protons as the medium to measure the ambient magnetic field, it should be possible to improve greatly the sensitivity and sampling rate over standard proton precession instruments. The G-822A has a potential sensitivity of less than 0.0005 nT/√Hz RMS and a routine sensitivity of 0.003 nT peak-to-peak at sampling rates of 10/second. This system has the capability of detecting ferrous objects on and under the seafloor to burial depths of about 2 m, when towed within 3-4 m of the sea floor.

Preliminary Results. Unfortunately, Geometrics was not able to get this new system ready for use in this project. If they are successful in solving the technical problems which have apparently slowed down the commercial production of the system, it should be used as a two-dimensional gradiometer, with at least four sensing units deployed in a rigid geometry. This deployment would have great potential for use in areas such as Kaho'olawe where the baseline magnetic field is highly variable.

6. J.W. Fishers Mfg., Inc. Pulse 12 Time-Domain Electromagnetic Detector. This sensor is capable of detecting both ferrous and non-ferrous metals on the surface and buried less than 0.5 m. It has been extensively field tested and used by many salvage and treasure hunting operations. This system can detect non-ferrous, but conducting objects, such as brass or other non-magnetic metals. It has a range slightly less than a magnetometer but was intended for use here as a means for classification of targets already located.

   Preliminary Results. Initial testing of the sensor showed that it does not provide reproducible results which can be used for target classification. Because its range is too short to be used as a location tool, it was not deployed in the test range.

7. SETS Technology, Inc. Advanced Airborne Hyperspectral Imaging System (AAHIS). This system is a flight-tested, visible/near-infrared (432 nm to 830 nm), Hyperspectral (288 bands, effective band width of 5.5 nm/band) imaging system optimized for use in maritime and near shore applications. It is a "pushbroom" type imager which builds the image line-by-line. Light is collected through a f/4 50-mm lens and an imaging spectrometer onto a 385 x 576 CCD and then transferred through SCSI-2 interfaces to a computer hard drive and ultimately to Exabyte tape. SETS Technology has developed processing software which is specifically designed for detection and location of anomalous targets.

   Preliminary Results: Based on discussions with SETS Technology personnel it is probable that this system in its present configuration is not effective in location and classification of most of the targets. However, operational problems do limit somewhat the confidence of this assessment and modifications to the system could have significant impacts on the system's effectiveness for this purpose. Due to airspace restrictions placed by the Pacific Missile Range Facility on the airplane collecting the data, it was not possible to get good data from the northern half of the range. Due to the theft of a calibration panel placed on the beach before the overflight occurred, data processing options for the collection were significantly limited.

   To date, the highest spatial resolution possible is limited chiefly by the turbulence-induced motions of the aircraft. These effects are mitigated somewhat by an inertial navigation system in the aircraft, but the ultimate pixel size is presently still limited to approximately 1 m. Targets which are significantly smaller than this size can be detected when their contrast with the ambient spectral pattern is sufficiently strong to produce a significant difference between the overall spectral pattern for the pixel in which they lie and its neighbors. The threshold for such detection can be lowered somewhat if the spectral characteristics of the targets are known.

The AAHIS system was successful in detecting the sub-pixel sized targets placed on the beach, because they met these criteria. The reduced spectral variability caused by sea-surface reflections and light scattering by the seawater itself, however, left insufficient contrast for confident detection of the known seabed targets. If AAHIS can improve the spatial resolution, probably through improvements in the stability of the scanner or more precise corrections for aircraft motions, its potential for ordnance location and classification would be greatly enhanced.

In summary, it is clear that much more progress needs to be made in this field before confident location and classification can be assumed. To date, the most reliable method for shallow seabed location of UXO is through direct diver observation or video interpretation, as was conducted on a small scale in the Reserve Waters and is reported in Reference [2]. Other, more exotic methods, including synthetic-aperture sonar and airborne or shipboard laser scanning also hold some potential, though they also have yet to be demonstrated. It is very likely that there will never be a single effective system, and that a multi-sensor approach will be necessary to achieve confidence that all UXO can be located and identified.

CHARACTERIZATION OF UXO

Most of the UXO to be expected in the area, and those with the most potential to inflict harm through accidental explosions, are military high explosives. High explosives, also called "detonating" explosives, consist at minimum of a detonator and main explosive charge. Frequently in military applications they also include a "booster" which is set off by the detonator and helps to ensure a successful detonation of the main charge. They are distinguished from "low" explosives (i.e. gun powder) by creating much higher velocities of explosion (microseconds for complete consumption instead of milliseconds)and much higher explosive pressures (millions of pounds per square inch (psi) instead of tens of thousands of psi).

Military requirements for explosives are generally much more demanding than those for explosives used in mining, construction, and other applications. Detonators in general need to be more complicated and able to withstand the rigors of safe handling during battle situations while still effective in detonating after delivery through the air or water. The main explosive must also possess more brisance (the ability to shatter steel, concrete, and other very hard structures) generally than commercial explosives [3].

The following sections discuss the various general characteristics of the UXO to be expected offshore and on the beaches of Kaho'olawe.

Types of UXO to Be Expected

Table 2 lists the types of ordnance which are known to have been used on the island and offshore, (extracted from KICC Consultant Reports Nos. 3 and 22 [1, 2]). As noted in both reports, this list is not comprehensive, since the record keeping was not reliable. These ordnance will usually include high explosives and low explosives.

TABLE 2

**Types of UXO to be Expected
Offshore and On the Beaches of Kaho'olawe**

Description	Size of Main Explosive (lb)	Possible Composition of Main Explosive
General Purpose Bombs	100 - 500	TNT
Demolition Bombs	1,000 - 2,000	TNT
Armor-piercing Bombs	500	TNT
Explosive Rockets, 2.75 - 11.75 inch diameter	<1,000*	TNT
Artillery Shells, 20 mm - 16 inch diameter	<200*	TNT, PETN
Torpedoes, 10-21 inch dia., 6-25 ft. long	<2,000*	TNT, HBX, RDX, Torpex

*Estimated roughly as approximately half the expected volume of the ordnance. The density of TNT is 1.65 g/ml and used for the estimate for all explosive charges..

Low explosives contained in incendiary munitions, discarded, unshot artillery rounds, flares, and other ordnance would pose serious local hazards. Included in this type of UXO would be phosphorus, smokeless powder, and other propellants and incindiaries. These materials may ignite spontaneously and be very dangerous through direct contact. Their effects would be fairly localized, however, as discussed below.

High explosive UXO, however, pose a much more serious threat. The primary components in these UXO include:

1. A steel, brass, aluminum or other alloy casing;
2. A primary detonator device of various materials and a primary explosive (such as mercury fulminate, lead azide, diazodinitrophenol, lead styphnate, or nitromannite), ignited usually through some combination of time and impact force.
3. A booster device and high explosive booster charge such as Tetryl (N,2,4,6-tetranitro-N-methylaniline); and
4. A secondary main charge of TNT (2,4,6-trinitrotoluene), Tetryl, RDX (cyclotrimethylenetrinitramine), PETN (pentaerythritol tetranitrate), picric acid (2,4,6-trinitrophenol), ammonium picrate, ammonium nitrate, DNT (dinitrotoluene), or EDNA (ethylene diamine dinitrate). The detonator and booster can include such materials as aluminum, waxes, plastics, and other materials.

Explosive Potential and Weathering Processes

According to all the experts consulted for this study and consistent with the data presented in KICC Consultant Reports Nos.3 and 22, there is no well defined upper limit for the longevity of dangerous explosives in the marine environment. Although the processes of weathering will surely in time destroy the detonators and boosters and reduce the main charges to nitrate fertilizers, the amount of time involved can be many decades at least. In Europe, fully functional ordnance from World Wars I and II are not uncommonly found to this day. Naval experts in submarine UXO removal and detonation report recovery and virtually 100% detonation of ordnance forty and fifty years old (Walter J. Dennison, personal communication). The following discussion is included to show possible outcome scenarios which may be accurate for a significant percentage of seabed and coastal UXO. Prudent planning efforts must assume that there is significant potential for finding fully functional UXO in the Reserve Waters.

Corrosion of Casings

Much of the UXO found has relatively intact casing material which can shield the explosives from the environment. Corrosion rates of casings will vary widely according to the alloys present and the immediate chemical environment faced by the metals. Corrosion of metals in seawater oxidizes the metals with rates which are dependent upon the chemical potential between the metal and oxygen.

The general reaction is:

$$O_2 + \frac{4T}{n} + 2H_2O \rightarrow \frac{4T^{n+}}{n} + 4OH^- \quad (1)$$

Where T is the metal in question and n is the resultant oxidation state of the oxidized metal cation. Galvanic or two-metal corrosion can also occur and results in the enhanced corrosion of the metal with the relatively higher potential with respect to oxygen and a decreased corrosion of the metal with the lower potential. This is the principle behind protective zinc plates used to decrease the corrosion of metal ship hulls.

Seven forms of corrosion are recognized which could affect UXO in Reserve Waters, including:

1. Uniform, or general attack over the entire surface;
2. Galvanic, described above;
3. Crevice, where corrosion is accelerated in areas which are exposed to seawater but not included in the general circulation;

4. Pitting, where corrosion is accelerated autocatalytically in chloride solutions such as seawater by the local enhancement of chloride within the pits, leading to more rapid hydrolysis of the metal;
5. Intragranular, where localized corrosion occurs because of irregularities in the alloy composition and density;
6. Selective leaching, where one component will dissolve and leave behind another component; and
7. Erosion, where the momentum of the ocean currents and waves and their suspended sediments enhance corrosion by physical abrasion and constant replenishment of oxygen.

The slowest rate of corrosion among these is uniform corrosion, which will occur with all metals at varying rates. Galvanic corrosion will occur where any two different metals come into contact with each other. Crevice corrosion will occur within couplings, flanges, and other structures in the UXO which can act to isolate small volumes of seawater from the general circulation. Pitting will occur on nearly all surfaces which are not exposed to high water currents, and will be especially effective on steel and high-copper aluminum alloys. Intergranular corrosion occurs with stainless steel and over time results in a complete loss of strength. Selective leaching occurs in cast iron, termed graphitization, resulting in loss of iron and a layer of graphite on the surface. Selective leaching also occurs in brass, resulting in the selective dissolution of zinc and loss of structural integrity [4].

Overall corrosion of ordinary steel in seawater occurs at rates more than 0.04 cm/yr in the active splash zone to less than 0.007 cm/yr in muddy deposits (Figure 3).

Pitting corrosion of steel occurs at higher rates, between 0.04 and 0.11 cm/yr. Erosion corrosion and pitting correlate with uniform corrosion and will both be at a maximum in the splash zone where water currents are highest [4, p. 95]. Other metals in seawater have pitting rates ranging from nickel/chromium alloys which pit at rates greater than 0.13 cm/yr, to Admiralty brass and titanium, which exhibit negligible pitting [4, p. 374-375]. Thus, for example, a booster detonator with a casing wall of ordinary steel 0.35 cm thick [3, p. 18] will be penetrated by normal corrosion in about eight years if it is in the splash zone, or just over three years, if pitting is maximal. However, it could take more than 50 years to be penetrated if it is buried in mud in the seabed or covered by sealife in the intertidal zone.

Weathering of Main Explosive Charges

Once the casings are penetrated, most of the high explosives used in these UXO should be expected to weather into relatively benign products. TNT and the other primary charges noted above are all fairly insensitive to shocks directly, so once the detonation train is disrupted, through corrosion or physical destruction of the detonator or booster devices, these materials are only susceptible generally to burning, and are not likely to explode. With time, these materials will weather ultimately to inorganic carbon and nitrogen species. If exposed to sunlight, this breakdown will proceed fairly rapidly. Under water or soil, however, these reactions proceed only very slowly.

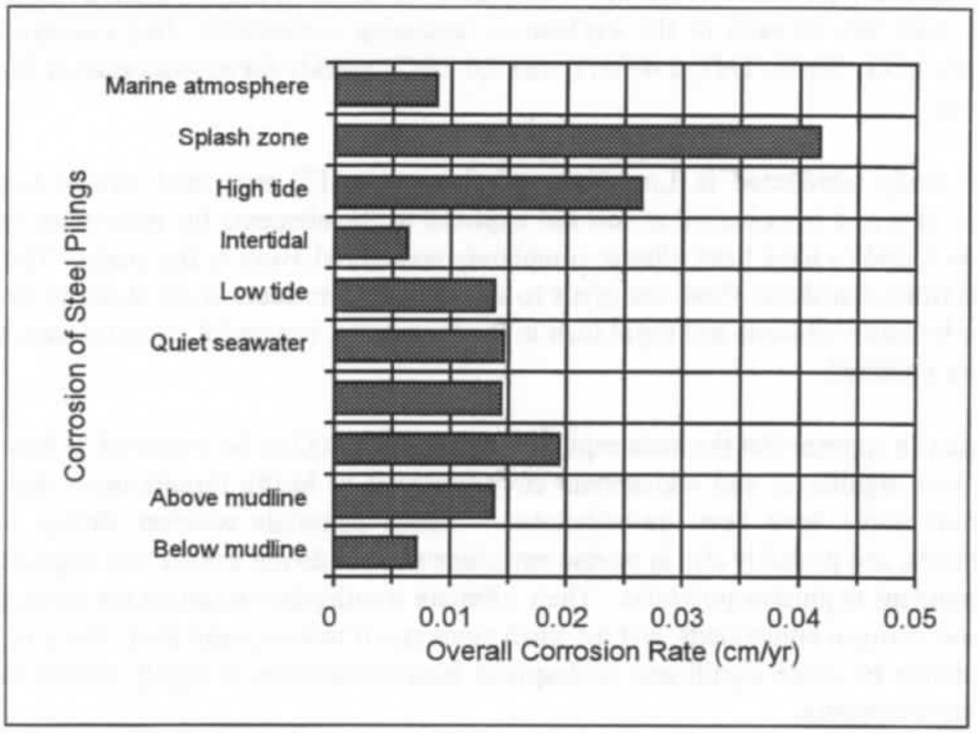


Figure 3, Overall Corrosion of Ordinary Steel (Ref. [4], p. 374)

No studies related directly to marine weathering of high explosives are currently available, but directly relevant research in terrestrial soils has been recently reported. Scientists at the Aberdeen Proving Grounds recently performed synthetic weathering experiments with soils heavily contaminated with TNT, 2,4-DNT (dinitotoluene), 2,6-DNT and other nitrogenated aromatics associated with burning and weathering of these explosives [5]. These explosives and their oxidation products TNB (trinitrobenzene), 2-amino-DNT, and 4-amino-DNT all migrated vertically but <7.5 cm (3 inches) deep into the soil. In less than nine months of synthetic weathering, TNT, TNB, 2,4-DNT, and 2,6-DNT all became irreversibly bound to soil particles in the top soil horizon.

In another study by virtually the same research team [6], compounds investigated were the nitramine explosives cyclotetramethylenetranitramine (RDX) and cyclotrimethylenetrinitramine (HMX), as well as the nitro-organics TNT, 2,4-DNT, and 2,6-DNT. Compounds were monitored for transport and transformations in a controlled environment housing intact soil cores of Clarksville-Fullerton cherty loam soil from Anniston Army Depot, Alabama. Concentrations of the chemicals in leachates and in soil were determined over 228 days. Concentrations of RDX, HMX, TNT, 2,4-DNT, and 2,6-DNT in leachates had levels detectable by HPLC (High performance liquid chromatography), with trace levels of 2-amino-4,6-DNT and 4-amino-2,6-DNT. RDX and HMX were quite mobile in the soil while TNT was quite immobile, with 2,4-DNT and 2,6-DNT slightly more mobile than TNT. The majority of the RDX, HMX, TNT, 2,4-DNT, 2,6-DNT, 2-amino-4,6-DNT and 4-amino-2,6-DNT extractable from the soil was found within the top horizon of this soil. Weathering of the compounds resulted in greater affinity for soil, with less of each of the explosives remaining extractable. This occurred for all the explosives, RDX, HMX, TNT, 2,4-DNT, and 2,6-DNT; quickly for nitroaromatics, less so for the nitramines.

Another study conducted at Los Alamos Laboratories [7] examined twelve high-explosive materials that had been buried in soil and exposed to the elements for more than twenty years. TNT was found to have been almost completely weathered away in the study. The weathering reactions which transform these materials to simple, inert products in the Reserve Waters would probably be more efficient and rapid than in the temperate, terrestrial environments where these data were obtained.

In summary, it appears that the main explosive charges of UXO to be expected in Reserve Waters do not pose significant and widespread environmental or health threats once their associated detonation trains have been de-activitated. These materials weather slowly in terrestrial environments, and probably also in marine environments, but do not exhibit any large-scale toxicity or independent explosive potential. Their ultimate weathering products are essentially benign carbon and nitrogen compounds, and the small amounts of mercury and lead, likely in detonators, are not liable to cause significant, widespread bioaccumulation in highly mobile and oxidized coastal environments.

Unfortunately, since the corrosion processes which destroy the UXO detonation trains all require oxygen and water to be effective, isolation of the UXO from either or both will greatly impede their progress. On the seabed, UXO have been reported to be thoroughly encrusted with coral, which will greatly diminish corrosion rates. In bays and stream outwash zones it is quite likely that the high erosion rates from the island will bury UXO in sediments and greatly lower ambient oxygen concentrations. On the island itself, significantly more UXO have been found buried than proud (see Figure 2), presumably due both to burial on impact as well as burial by sedimentary processes. Given the arid nature of Kaho'olawe, many of these buried UXO can be expected to experience very low corrosion rates until they become unearthed and transported into streambeds and coastal areas. Thus, the good news is that UXO can be expected to corrode and become nonfunctional fairly rapidly when they are exposed to active coastal environments. The bad news is that there is no guarantee that all UXO will be rendered harmless in the forseeable future.

LEVELS OF INTERACTION FOR DIFFERENT ACTIVITIES

It is not possible to eliminate specific areas from concern for the threat from UXO, but it is possible to identify particular activities and particular areas in the Reserve Waters and adjoining shoreline which merit special concern. The potential for damage and tragedy caused by UXO is proportional to the level of interaction associated with the activity and also the relative level of the activity expected in different areas. The following list describes the general kinds of activities, with their associated levels of interaction, which are assumed for this study to take place in Reserve Waters and the adjoining coastlines. The activities are ranked by decreasing probabiliity for interaction with UXO. As discussed above, almost all UXO to be expected could only explode if their detonation trains are intact and if they are subjected to some level of direct physical shock or impact. The level of interaction is assessed as is a qualitative, ranked combination of proximity and likelihood for physical impact of the activity on UXO.

1. Direct Contact Activities. These activities include boat landing, walking, shoreline gathering (e.g., spearing from above water, opihi picking, shellfish digging), some forms of netting fish, and underwater spear fishing.

2. Line Fishing. These activities range in probable level of interaction from shoreline fishing, with a relatively high probability for interaction, to deep-water (assumed for this study to be the Reserve Waters with water depths deeper than twenty fathoms, or 36.6 m) trolling, with practically no potential for impact. Activities with intermediate probabilities include shallow water trolling and bottom fishing.

3. Anchoring. Clearly the deeper the water, the lower the probability of interaction.

4. Non-Invasive Activities. These activities include non-invasive scuba and snorkel diving and boating.

OUTCOME SCENARIOS

In the formulation of policies regarding the regulation of the above activities in Reserve Waters and the coastline, it is important to have some assessment of the possible consequences of detonating UXO accidentally. It is also important that individuals who are contemplating activities in this area are thoroughly advised of the potential risks associated with UXO. Given the wide diversity of ordnance and the more than fifty years over which it was used on the island, it is not possible to assign quantitative probabilities for likelihood of interaction with, detonation of, nor damage caused by UXO. However, based upon the general characteristics known for the military high explosives to be expected, it is possible to describe possible results should full detonation occur. The following discussion is intended to give some basic description of this worst-case outcome and how it could affect people, animals, and nonliving resources as a function of distance from the blast.

Explosion Dynamics

The non-atomic high explosives expected in UXO on the seabed and beaches of Kaho'olawe would be detonated through the following sequence of events:

1. The detonator is ignited, generally by physical shock, and produces a sufficient secondary shock, directly or through a booster explosive, to detonate the secondary high explosive.

2. The detonation consists of the very rapid (microseconds) chemical conversion of the explosive to gaseous products, resulting in an initial explosive front or bubble which exerts

enormous pressure, up to several million psi (14.5 psi = 1 bar, or one atmosphere of pressure), on its surroundings.

The resultant pressure front, or shock wave, and its associated gaseous products wreak havoc first on the ordnance casing, often producing shrapnel, and then on its general surroundings. Because air is compressible and water is not, explosions which take place above water have a very different evolution than those which take place underwater; each is described separately below.

Explosions Above Water

Damage from explosions above water occurs from the direct shock wave of the explosive as well as from the shrapnel and other projectiles created by the blast. Such projectiles can have damaging effects beyond the range expected for direct damage from the blast shock wave. Also, if the explosion is focused, as is possible from a burial pit or crevice in rocks, its effect has a larger range which is not possible to quantify without known geometries and compositions of the pit or crevice. For these reasons, the following predictions for above-water explosions must be understood as ***minimum safe distances***. Through extensive studies of accidental and experimental explosions, a general relationship between size of the high explosive and the damage to be expected has been developed (Ref. 3, p. 353-357). This is:

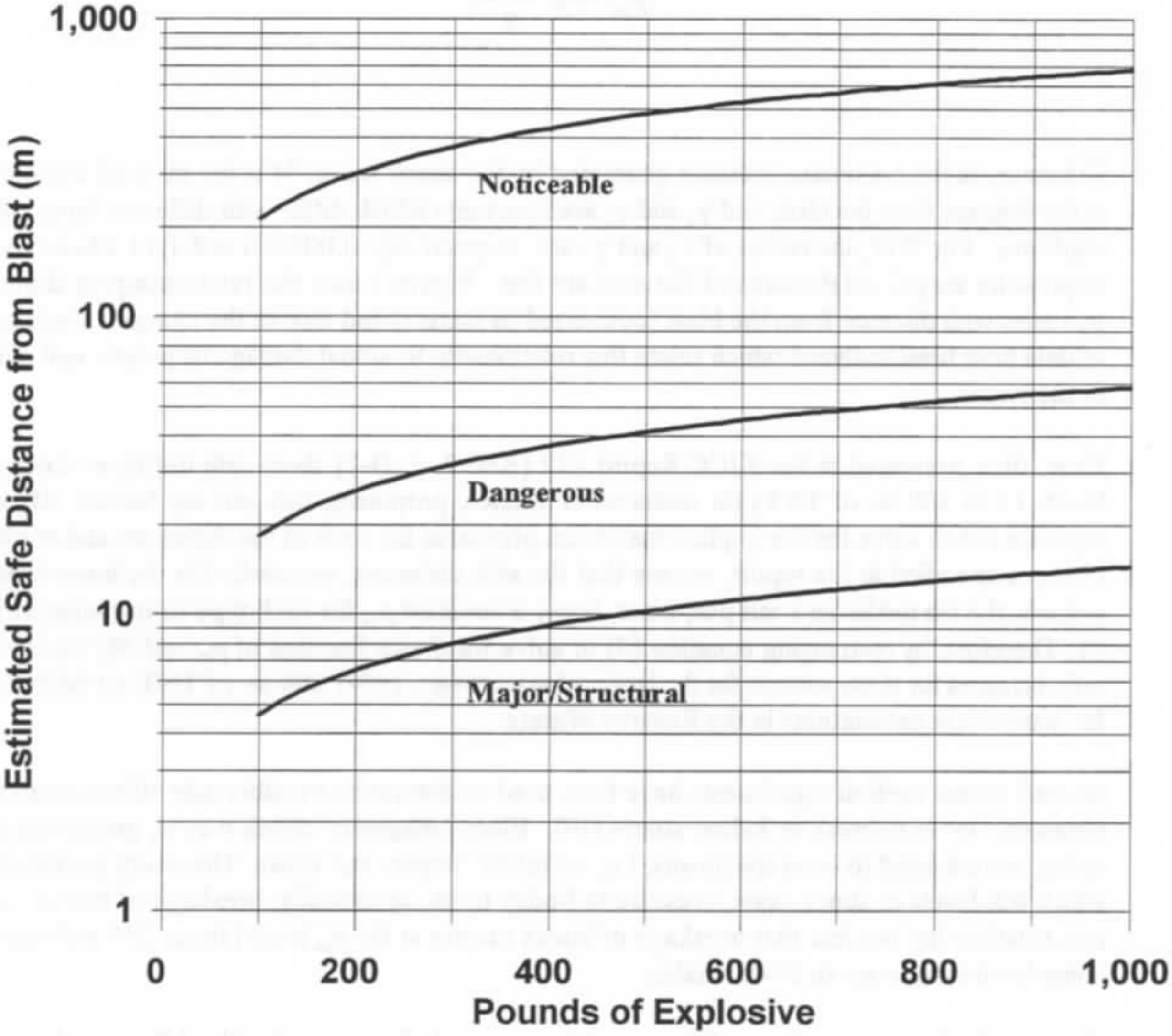
$$S = PM^{a} \qquad (2)$$

Where S is the average safe distance from the blast, P is an empirical factor related to the specific power of a given high explosive per unit mass and the level of safety sought, M is the mass of the charge, and a is an empirical constant, which ranges between 1/3 to 1/2 for different ranges of M. For TNT charges between 100 and 1,000 pounds, the most common situation to be expected, a has a value of about 1/2. Three values of P, 1.5, 6, and 70, are used here in Figure 4. They represent, respectively, *major* damage, capable of causing significant damage to barricaded structures; *dangerous* levels of shock, capable of breaking glass and possibly harming individuals and animals; and *noticeable* levels of shock, capable of causing minor damage, such as cracking plaster.

Underwater Explosions

The danger of damage caused by shrapnel is much less in water, because water is much denser than air and will rapidly slow down and stop projectiles caused by the blast. However, the liability of damage from the explosive shock wave is much higher. In air, much of the blast energy is converted to heat through compression of air in the advancing pressure wave. Water is a much more efficient transporting medium for pressure waves than air, and thus will have more far-

Figure 4
Safe Distances from Blasts in Air



reaching effects. Significant research has been done to quantify the situation in water, and this has led to the following relationships among the size of the charge, distance from the blast and level of pressure [9]:

$$p_m = \gamma_1 \left(\frac{M^{1/3}}{S}\right)^{\gamma_2} \tag{3}$$

Where p_m is the maximum pressure generated by the shock wave, M is the mass of explosive, S is the distance from the blast, and γ_1 and γ_2 are constants which differ with different types of high explosive. For TNT, the values of γ_1 and γ_2 are, respectively, 0.000216 and 1.13 when the units of pressure are psi and the units of distance are feet. Figure 5 uses this relationship to show how p_m varies with distance from the blast (converted to meters) and size of the charge. Various sets of data have been analyzed which relate this relationship to actual damage to people and animals in the water.

First, data presented in the KICC Report #22 [Ref. 2, p. D-1] show safe distances from small blasts (1 to 100 lb. of TNT) for underwater whales, porpoises, fish and sea turtles. By using equation (3) to solve for the implied maximum pressures for each of the distances and explosive charges specified in the report, we see that the safe distances, especially for the more sensitive animals, the sea turtles and calf porpoises, imply a constant p_m for each type of organism (Figure 6). Therefore, by rearranging equation (3) to solve for S as a function of p_m and M, we can infer safe distances for these animals for the larger charge range, 100-1,000 lb. of TNT, to be expected for worst-case detonations in the Reserve Waters.

Second, recent medical experiments have been used to determine possible side effects from using ultrasonic waves to break up kidney stones [10]. Electromagnetic shock waves, generated under water, were applied to bone specimens, i.e., of rabbit femurs and tibiae. The study provides data which link levels of shock-wave pressure to bodily harm, specifically, breakage of bones. Using this relationship we find that breakage of bones occurs at the p_m level (about 250 psi) which is considered dangerous to 20-ft whales.

Third, fishing boats and other craft have widely varying hull types and will exhibit widely varying responses to nearby submarine blasts. Materials used for submarine hulls have yield strengths between 36,000 and more than 150,000 psi. Yield strengths of wood and fiberglass hulls are fractions of this, but usually significantly greater than 1,000 psi [11,12].

The results of these exercises are presented in Figure 7 and represent our best current estimates of safe distances from blasts of different sizes.

Effects on Life and Property

Figures 4 and 7 can now be used directly to infer general outcomes for detonation of UXO through the kinds of activities assumed to take place in the Reserve Waters. These are as follows:

1. Direct Contact Activities. The consequences of full detonation of even the smallest high explosive ordnance would be grave and probably fatal to the individual or animal that causes the detonation and probably also to bystanders. The consequences of ignition or detonation of the low explosives to be expected would be unpredictible and range from negligible to fatal.

2. Line Fishing. Figure 4 suggests how the liability of the fisherman could vary with distance from the blast, assuming the baited end of the line is the instrument which detonates the charge. Even the smaller charges could be harmful or fatal within 20 m, while dangerous conditions for the individual are unlikely if the distance is greater than 60 m.

3. Anchoring. The bottom curve in Figure 7 suggests how close the anchor would be to the boat before major damage to the boat could be expected, if we assume a yield strength for the hull of 1,000 psi. Thus, if the boat is less than 23 m from the anchor when it detonates a 100-lb. charge, or 48 m when it detonates a 1,000-lb. charge, then significant damage to the boat might be expected.

4. Non-invasive Activities. Given the basic assumption of this scenario, that UXO will require some significant physical impact for detonation, these activities should be very unlikely to cause any detonation.

SITES OF SPECIAL INTEREST

Interactions with UXO are more likely with increasing levels of these human activities as well as increasing levels of UXO density. The levels of activity are assumed for this study to be consistent with the priorities for land use described in the *Kaho'olawe Use Plan* [8]. To date, no areas of specific and local interest have been identified in deep water (> 20 fm). Moreover, as discussed in the previous section, the most severe outcomes possible from interactions with UXO are expected to take place in the shallow waters and on the beaches.

Thus, the specific sites considered here are focused on the coastline and shallow water areas (water depths < 20 fm) identified in the land use plan. These consist of four Kahua Kauhale (educational and cultural centers), thirteen Kahua Ho'omoana (overnight campsites), and one Nā Mea Kanu/Nā Holoholona a Me Nā I'a (botanical/wildlife preserve). The following discussion considers these special sites for of the eight 'Ili of the island.

Figure 5
Shock Pressure, Underwater Blasts

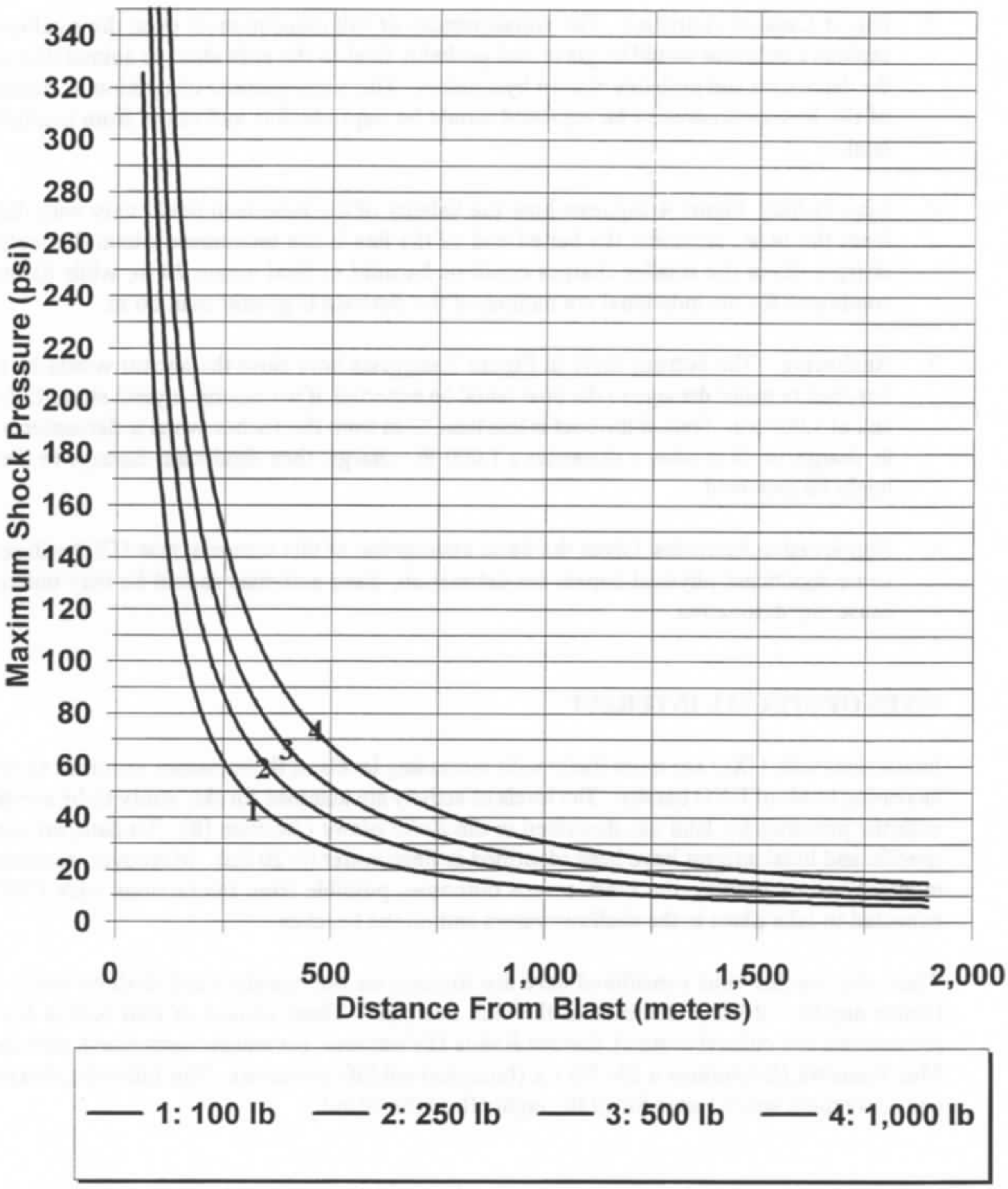


Figure 6
Inferred Shock Pressures

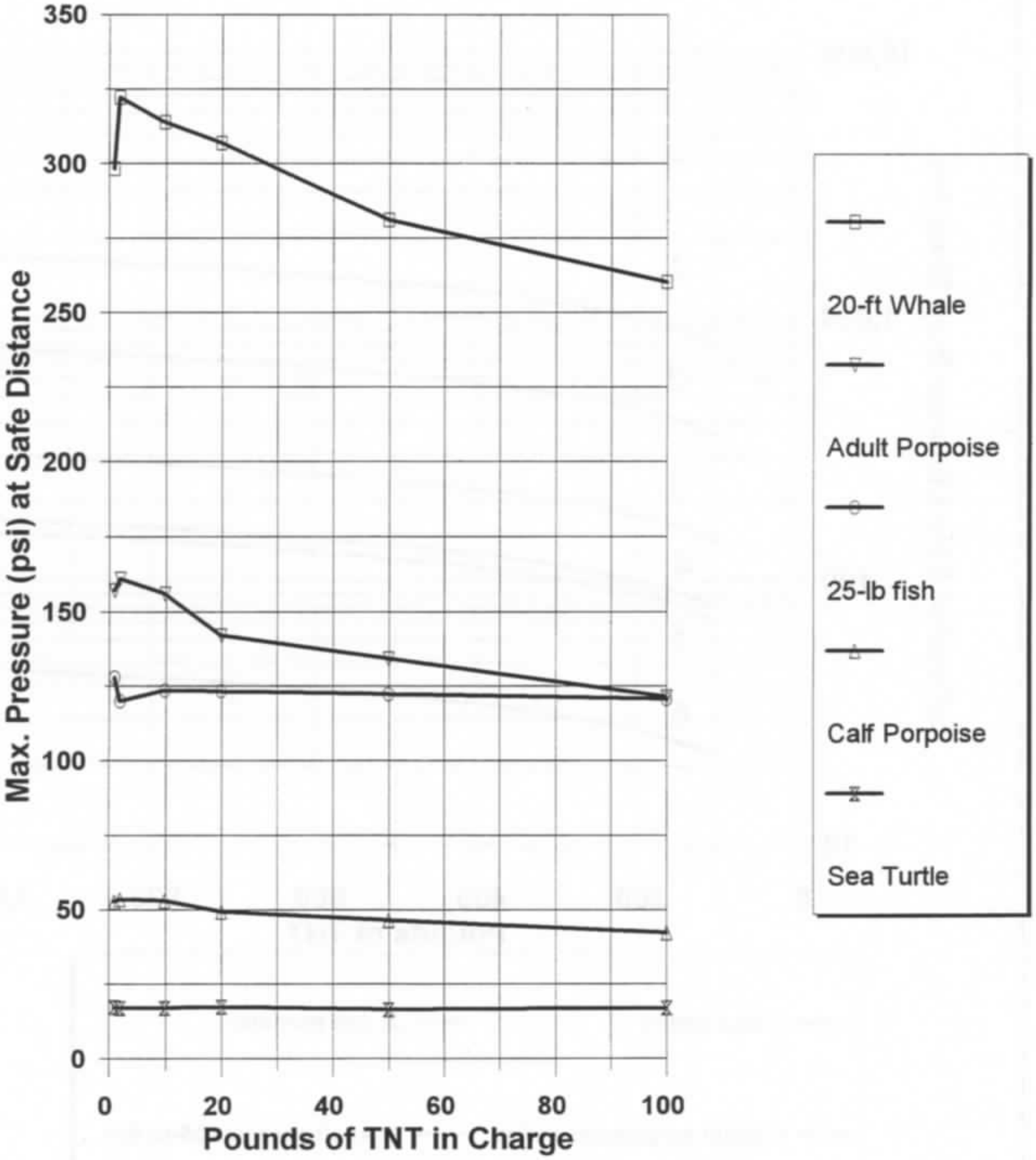
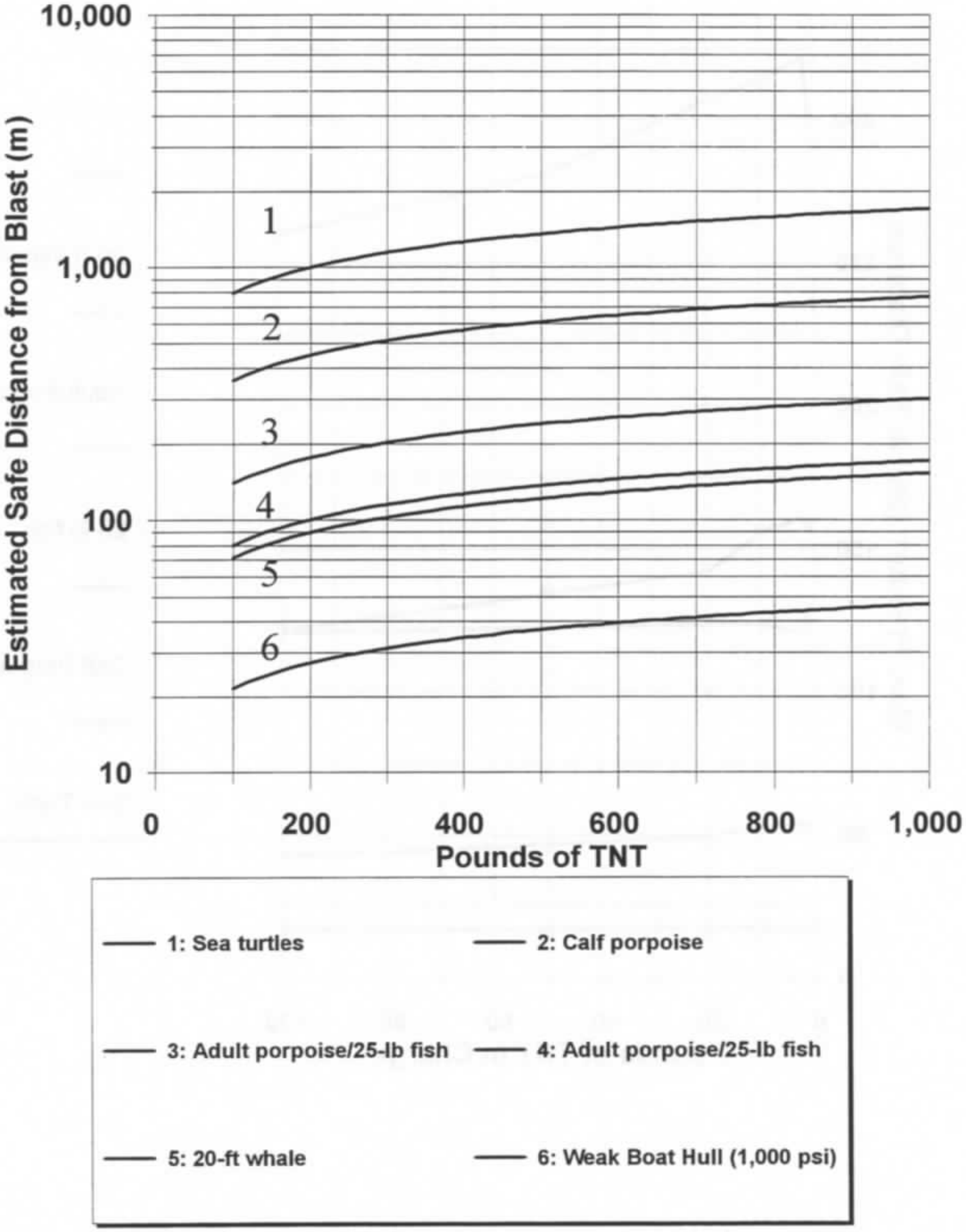


Figure 7
Safe Distances from Blasts in Water



Hakioawa ʻIli

The Hakioawa ʻIli is on the northeastern corner of the island (Figure 8). The Hakioawa Kahua Kauhana is ranked as Priority 2 for Tier 2 (subsurface) cleanup. The shaded offshore area (approximately 0.59 km^2) in this map consists of the shallow seabed and coastline bounded by the headlands which contain the drainages into the Kahua Kauhale. As discussed above, UXO are most likely where steep drainages meet the sea. Thus, the shaded area is identified as being of particular interest for clearance or at least monitoring of UXO. Though the Hakioawa ʻIli ranks low in relative abundance of seabed UXO (see Table 1) this ranking is based solely on historical records. No survey offshore has yet been conducted.

Papaka and Kuheia/Kaulana ʻIli

The Kahua Hoʻomoana in the Papaka ʻIli (Papakanui, Papakaiki, and Waaiki) and also the Kahua Kauhale of the Kuheia/Kaulana ʻIli lie at the mouths of deeply incised streambeds on the windward face of the island (Figure 9). The Kahua Kauhale and Kahua Hoʻomoana in the Kuheia ʻIli are ranked Priority 5 for Tier 2 clearance. The planned area for revegetation and stabilization of the soil in the island's central plateau (Hoʻōla Hou) comes to its lowest elevation, approximately 115 m above sea level, immediately above the Kahua Hoʻomoana at Papakanui. Also, as noted above, the coastlines near Kuheia and Kaulana and the watershed upstream were frequently used as targets and exhibit anomolously high densities of UXO offshore. Clearly this combination of relatively intense usage and high concentrations of UXO is a serious concern. The shaded area in Figure 9 (approximately 1.49 km^2) is designed to consist of the shallow seabed and coastlines which contain the drainages which feed these special areas.

Ahupu ʻIli

The Kahua Kauhale and Kahua Hoʻomoana of this ʻIli are ranked Priority 8 for Tier 2 cleanup. The area also lies in the relatively intense region for UXO densities, though drainages that feed into them are not quite as steep as those farther east on the north side of the island. The shaded offshore area (Figure 10, approx. 1.49 km^2) selected here is formulated as described above and also to include the adjoining Kahua Hoʻomoana which can be expected to be visited more frequently than other Kahua Hoʻomoana because of their proximity to the ocean mooring at Ahupu.

Honokoa ʻIli

The Kahua Hoʻomoana of this ʻIli are ranked Priority 9 for Tier 2 cleanup. Because this ʻIli is planned to be left mostly intact as a preservational area without a Kahua Kauhale and because it is only intermediate in its expected density of UXO, the shaded offshore area selected (Figure 11) only includes the immediate area between the headlands containing the plannned Awa Kū Moku (buoy moorings), approximately 0.039 km^2.

Figure 8: Hakioawa Area

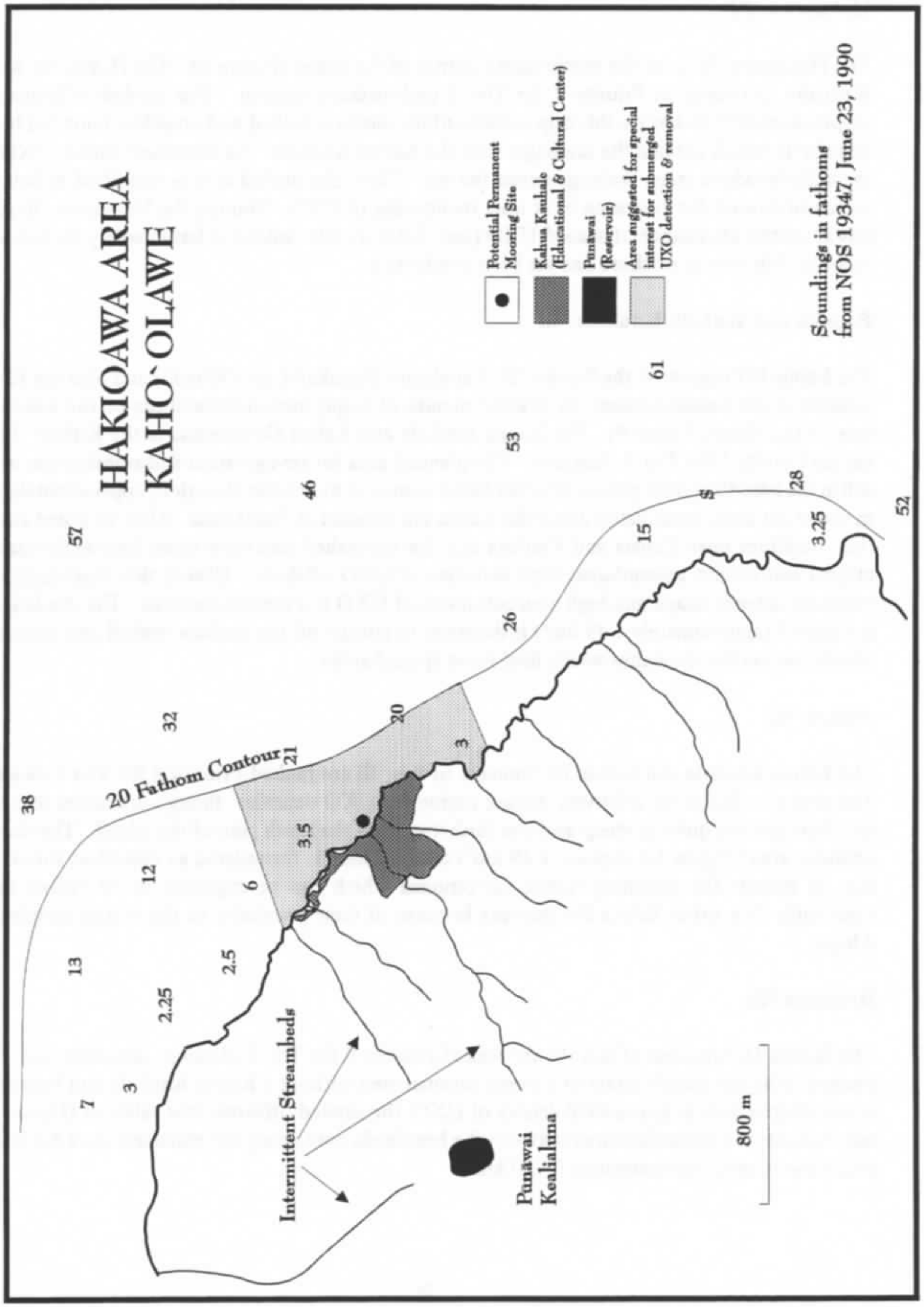


Figure 9: Kuheia/Kaulana Area

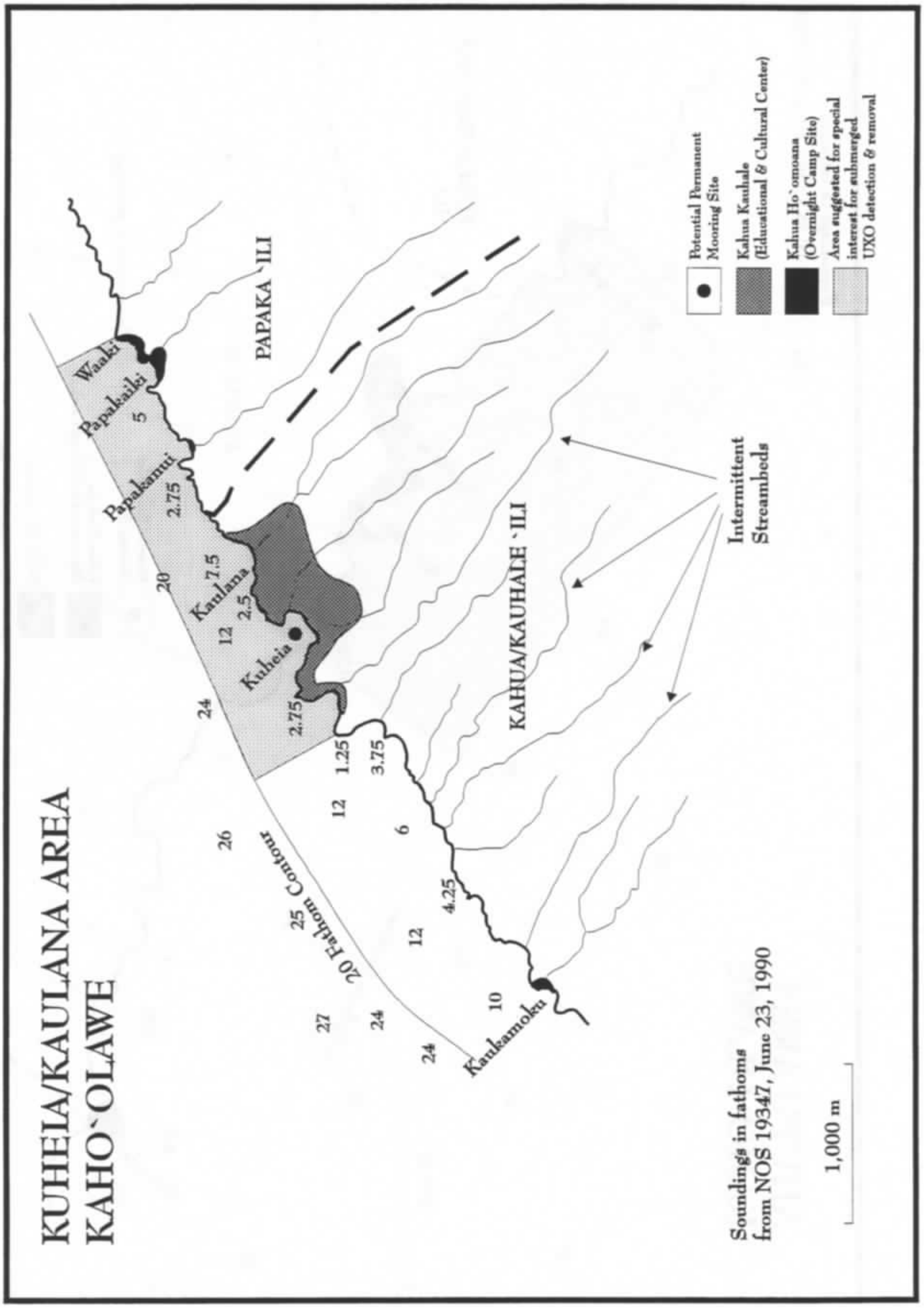


Figure 10: Ahupu Area

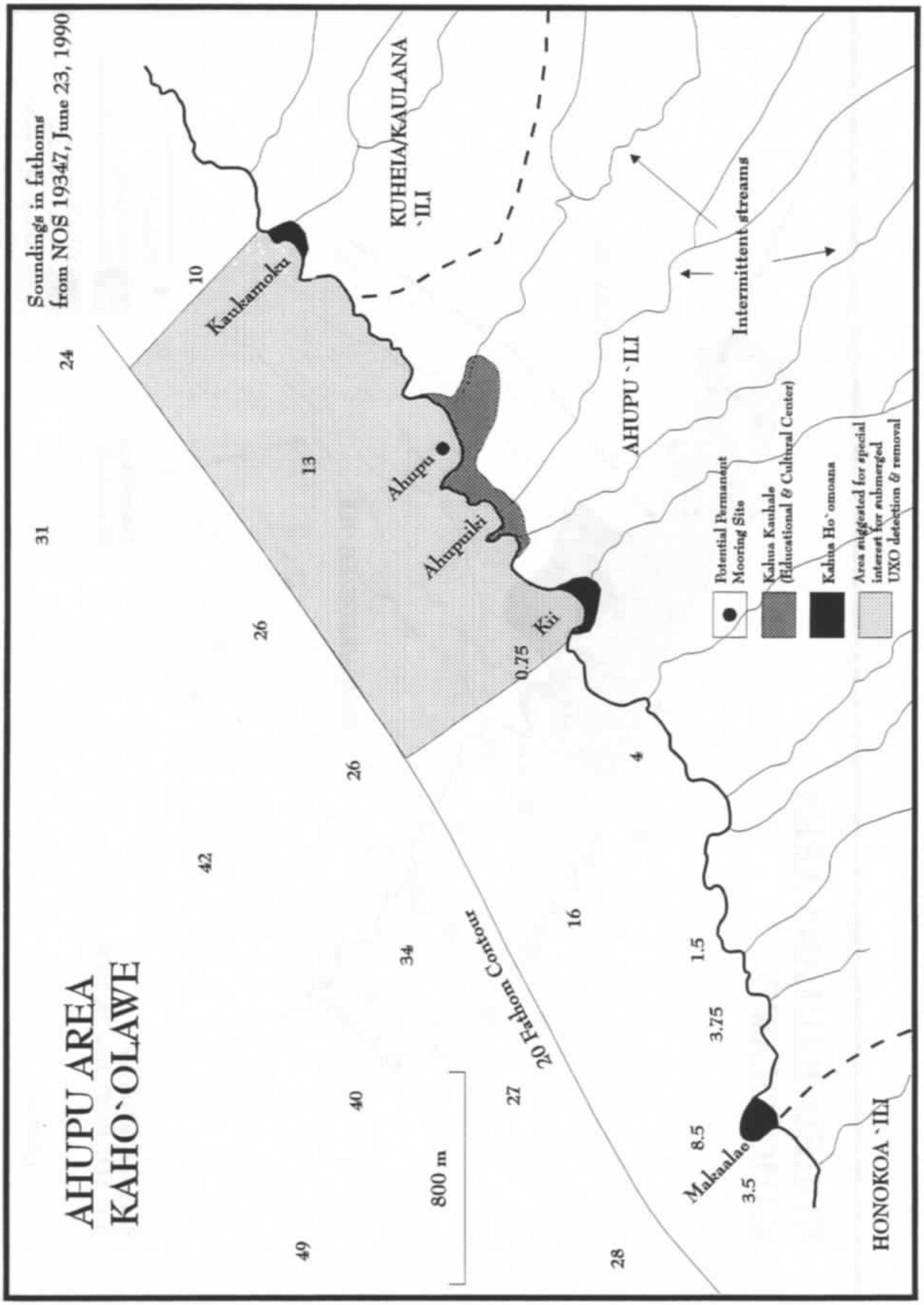
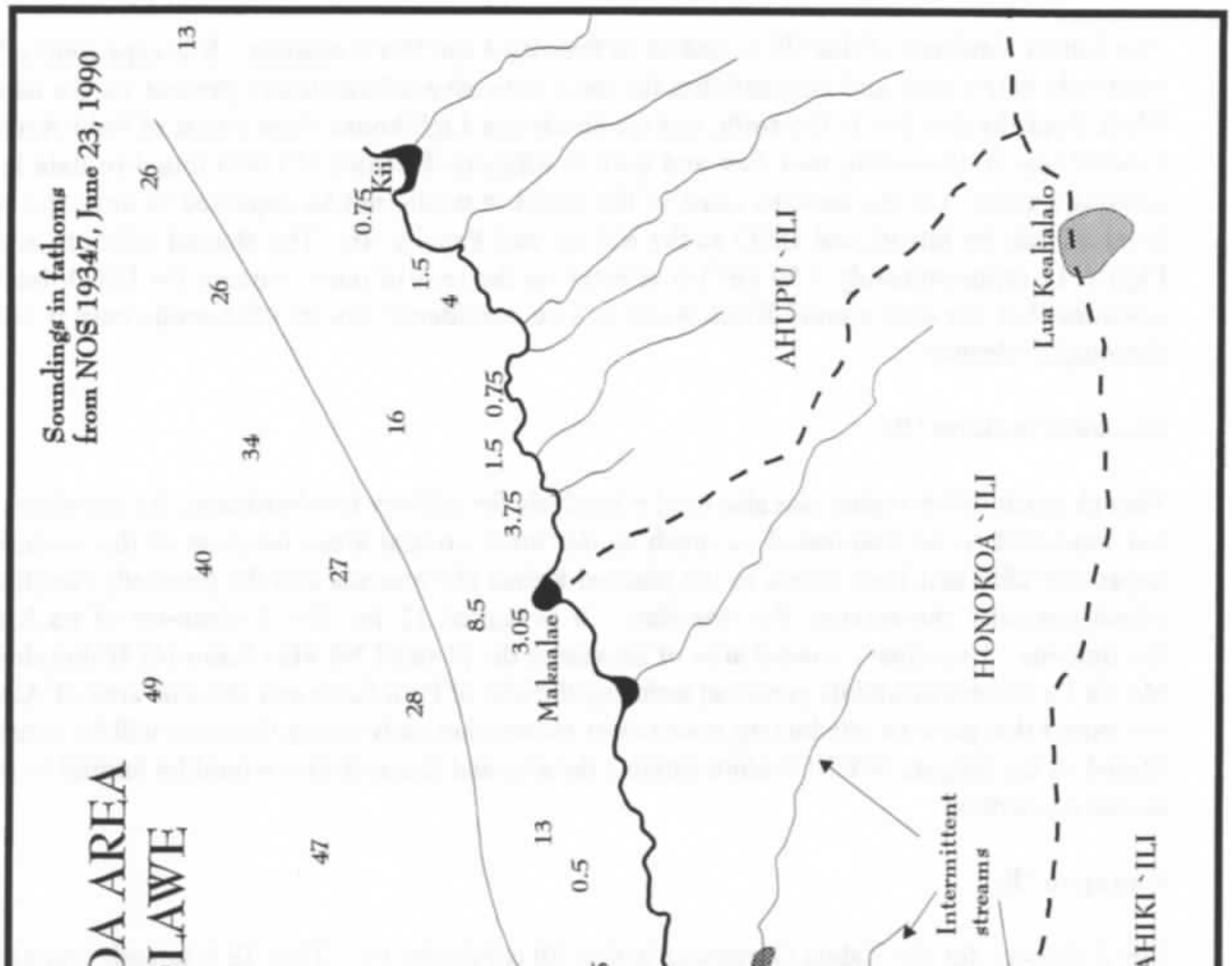


Figure 11: Honokoa Area



Kealaikahiki ʻIli

The Kahua Kauhana of this ʻIli is ranked as Priority 4 for Tier 2 cleanup. It is expected to be a relatively active area and currently has the most extensive infrastructure present on the island. Black Rock, located just to the north, and the Southwest Lighthouse Point (west of Puhi Anenui), located just to the south, rank first and third in offshore densities of UXO found to date in the coastal waters. On the leeward coast of the island, it would not be expected to have the same level of risk for introduced UXO as the Kuheia and Papaka ʻIli. The shaded offshore area in Figure 12 (approximately 0.50 km^2) is selected as the area of most concern for UXO, but this assumes that the area around Black Rock will be considered strictly off bounds until it can be thoroughly cleaned.

Kunaka/Naalapa ʻIli

Though much of this region was also used extensively for military bombardment, its coastlines are not expected to be frequented as much as the other coastal areas because of the essentially impassable cliffs that limit access to the planned Kahua Hoʻomoana and the generally rough seas which normally characterize this coastline. It is ranked 12 for Tier 2 clean-up of its Kahua Hoʻomoana. Its primary coastal area of interest is the planned Nā Mea Kanu/Nā Holoholona a Me Nā Iʻa (botanical/wildlife preserve) including the islet of Puʻu Koae and the cliff area of Aleale. We expect that persons conducting research or monitoring activities in this area will be carefully briefed on the dangers of UXO before entering the area and that activities would be limited to non-invasive activities.

Kanapou ʻIli

Tier 2 clean-up for the Kahua Oʻomoana in this ʻIli is Priority 10. This ʻIli is intended to be left virtually unimproved, and densities of people can be assumed to be very low. However, as discussed above, the area offshore from the Kahua Oʻomoana was used repeatedly for testing and targeting torpedoes. Though access to the sea is limited to times of unusually good sea states, landings and swimming should be strictly limited or prohibited until the Tier 2 clean-up is completed.

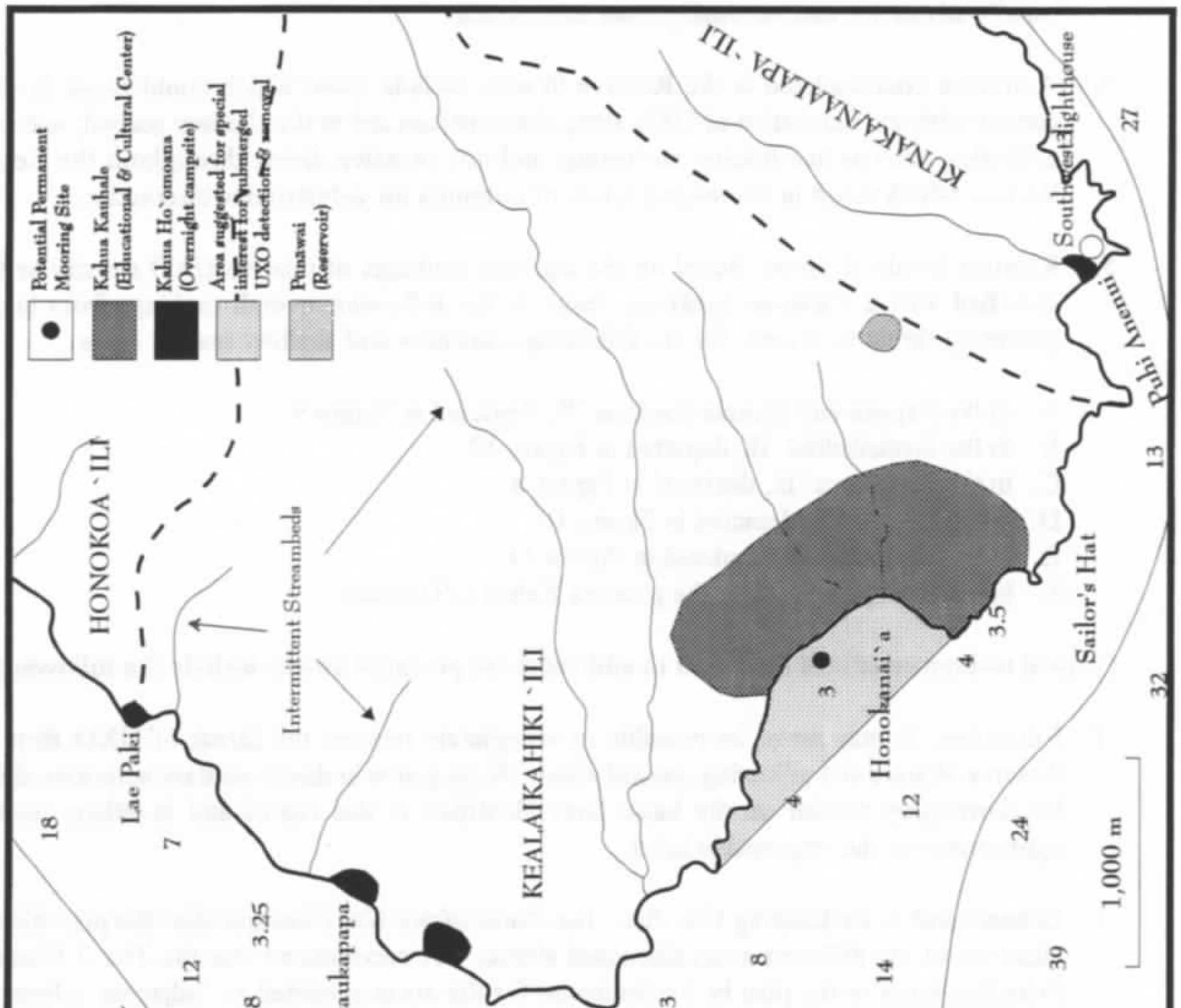
CONCLUSIONS AND RECOMMENDATIONS

The conclusions reached in this study are summarized as follows:

1. Historical and video survey data suggest a specific ranking for likely densities for buried and proud UXO, shown in Table 1.

2. Historical data and consideration of natural processes suggest that UXO will be relatively concentrated in coastal settings. Natural weathering and corrosion processes will tend to preserve the UXO in buried and intertidal environments and occasionally transport them to and uncover them in these areas.

Figure 12: Kealaikahiki Area



3. It is not yet possible to certify a seabed area clear of UXO, but technology in this area is rapidly advancing and becoming more economical.

4. Activities contempleted in the Reserve Waters include those which could result in direct contact with and detonation of UXO along the coastlines and in the shallow seabed, and other activities, such as line fishing, anchoring, and non-invasive diving throughout the Reserve Waters, which result in decreasing levels of potential for catastrophic interaction.

5. Relative levels of threat, based on the summed rankings of relative UXO density and the specified Tier 2 Clean-up rankings, result in the following overall ranking, from highest perceived threat to lowest, for the following coastlines and shallow seabed areas:

   A. In the Papaka and Kuheia/Kaulana 'Ili, depicted in Figure 9
   B. In the Kealaikahiki 'Ili, depicted in Figure 12
   C. In the Hakioawa 'Ili, depicted in Figure 8
   D. In the Ahupu 'Ili, depicted in Figure 10
   E. In the Honokoa 'Ili, depicted in Figure 11
   F. In the Kanapou 'Ili, near the planned Kahua O'Omoana

General recommendations for action to address these potential threats include the following:

1. Education. It may never be possible to completely remove the threat of UXO from the Reserve Waters and adjoining coastal areas. Participants in direct-contact activities should be thoroughly briefed on the basic facts identified in this report and in others deemed appropriate by the responsible kahu.

2. Commitment to the Existing Use Plan. The *Kaho'olawe Use Plan* specifies the priorities for clean-up of the different areas discussed above. We recommend that the Tier 2 Clean-up Priorities listed in the plan be implemented for the areas specified as "adjacent submerged land" in the following way: Tier 2 clean-up should be completed in areas surrounding the Awa Kū Moku to distances of at least 250 m and including possible landing sites and access to cleared trails on land. Tier 1 clean-up should be completed in the coastal areas, between the storm tide and low tide levels which form the landward boundary in the shaded areas described above. All possible efforts should be made to eliminate UXO in these coastal areas. Periodic sweeps, particularly after storms, will be necessary. As a lower but important priority, Tier 1 clean-up should be completed in all of the shaded areas if possible.

3. Periodic Monitoring. Based on the level of funds available, the site priorities specified above, and the state-of-the-art technology at the time, some attempt should be made as often as possible, and particularly after periods of high rainfall or high surf, to survey the coastal areas and shallow seabed to locate and classify surficial UXO. Given the accuracy in navigation possible today, maps can be automatically compared from one survey to the next to identify changes which might indicate newly uncovered or transported UXO. Such anomalies can be pursued through direct observation to identify real UXO that pose significant threats.

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