FIELD GUIDE FOR MEASURING

TSUNAMI RUNUPS AND INUNDATIONS

State of Hawaii
Department of Defense
Civil Defense Division
Tsunami Technical Review Committee

Preface

This document is intended solely for the use of individuals under the direction of Hawaii's Civil Defense Agencies to facilitate efficient and accurate measurements of tsunami runups and inundations throughout the State.

6/24/02

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INTRODUCTION

This guide is written to facilitate reliable and rapid measurements of runups and inundations by a volunteer corps of observers subsequent to the occurrence of a destructive tsunami. The purpose of such measurements is to: (1) better understand the destructive potential of tsunamis, hurricanes, and storm surges; (2) better define future evacuation zones for such hazards; (3) evaluate potential tsunami, hurricane, and storm surge hazards in heretofore undeveloped or underdeveloped areas of the State; and (4) provide a data base for testing the results of theoretically computed measurements of runup and inundation.

It is hoped that the survey teams will only be deployed for tsunamis that have not resulted in any fatalities or serious injuries. Realistically, however, we remain vulnerable to significant losses until the educational and research components of our efforts further increase awareness of tsunami hazards and further improve the predictive capabilities of our warning system. Be assured that the data acquired by the survey teams will be of critical importance in our efforts to reduce the losses associated with future tsunamis.

SURVEY TEAMS AND AREAS

Survey teams should consist of 2 or 3 members, preferably with at least one member having some familiarity with the island being surveyed. Survey areas have been selected so that the teams should be able to complete their work in 2 to 4 days, although more time may be needed for some areas. The lengths of shorelines to be surveyed are highly variable, depending on the number of accessible sites and the number of measurements required. Special permission may be needed for certain areas (e.g., crossing private lands, military bases, Kahoolawe, Kalaupapa, Niihau, and the Northern Hawaiian islands). This will be arranged by State Civil Defense. Also, the survey teams will be advised of excluded shorelines or islands. Descriptions of survey areas are given in Appendix I.

RUNUPS AND INUNDATIONS

Two of the most commonly used terms in tsunami research are "runup" and "inundation". When a tsunami floods a coastal area, the evidence of that flooding is debris or watermarks on the ground, in trees or in other vegetation, or on man-made structures. If the debris or watermark is on the ground and there is no additional evidence of the tsunami further inland, the location of that debris or watermark is the best estimate of the limit of inland penetration of the tsunami at that point. Thus the distance from that location to the nearest shoreline is called the "inundation limit" (Figure 1a). Adjacent debris lines or watermarks on the ground also represent other inundation limits for those locations. Those other inundation limits may be closer to, or further from, the shoreline. A measurement of the height of debris or the height of a watermark on the ground relative to sea level at an inundation limit is called “runup”. Obviously the tsunami “ran up” and “inundated” all of the land between the shoreline and the inundation limits. However, our primary concern is with the limits of runups and the limits of inundation. Strictly speaking the terms “runup limit” and “inundation limit” should be used, although historically the single term “runup” has often been used to indicate either the runup limit or wave height on land (see below).

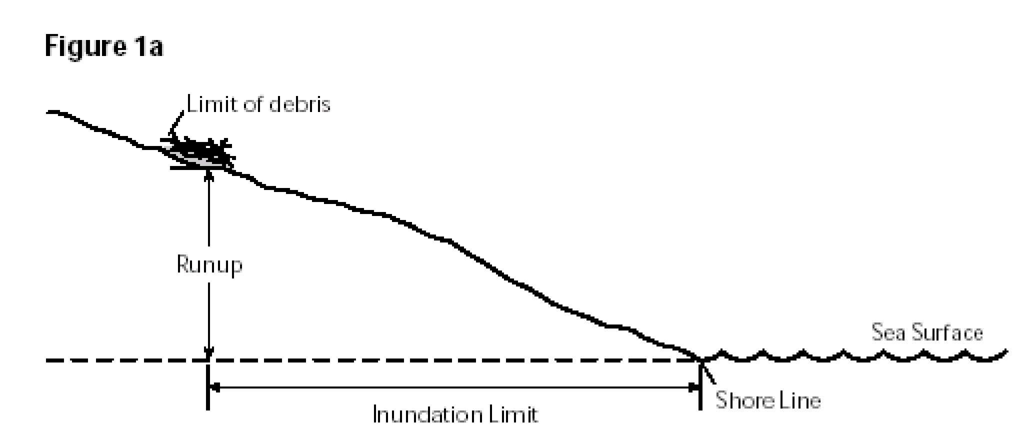


Figure 1a. The height of the debris on the surface of the ground, measured relative to sea level, is a measure of the tsunami’s runup. The land between the shoreline and the debris line was obviously flooded or inundated by the tsunami. The debris line indicates the limit of that inundation or the maximum inland penetration of the tsunami at that location. See text for additional discussions.

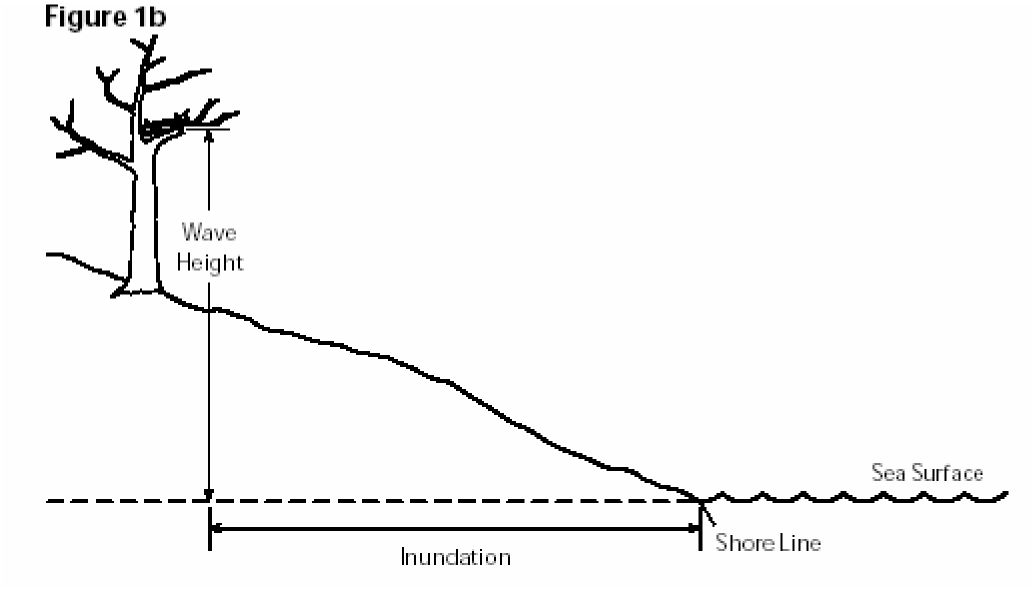


Figure 1b. The height of the debris in the tree, measured relative to sea level, is a measure of the tsunami's wave height at the tree relative to sea level. No evidence is available to determine the inundation limit, even though the water must have penetrated farther inland than the tree. In this example, the only observable debris in the area was that found in the tree. Therefore, the only measures that can and should be taken are the wave height and inundation at the tree. See text for additional discussions.

If the evidence of a tsunami is not on the ground (e.g., seaweed in a tree or a mud line on a building), a measurement of the height of that evidence will give us the water level that existed at that location as a result of the tsunami (Figure 1b). This water level measurement is, strictly speaking, not called a runup because it is not measured at an inundation limit. Obviously, that limit was further inland. In some areas the only evidence of a tsunami may be above ground debris or watermarks. Therefore, such water level measurements may be of critical importance. [Recognition of the distinctions between runups, inundation limits, and water level measurements are not requirements for survey team members. Descriptions of the measurements in the data logging sheets will permit those distinctions later during the analysis of the data.]

GENERAL GUIDELINES

If at all possible, measurements should be taken in the same general areas for which historical data have been gathered for previous large tsunamis (i.e., in 1946, 1952, 1957, and 1960). These areas and runup values are indicated in the historical maps contained in Appendix II. Keep in mind that the relative measures of runup and inundation in different areas may be highly variable for differing tsunamis.

Teams should search for the highest runups (or water levels) and furthest limits of inundation, and measure the height of debris lines or other marks above sea level, as well as the location (GPS coordinates and paced or measured distances from the shoreline) of their measurements. To permit eventual corrections to the data for tidal variations, the date and times of all readings should be noted. If there is any uncertainty in any measurement, it should be repeated. In regions where widespread destruction has occurred, several measurements should be made. In a matter of weeks or days, important measurement sites may disappear through natural processes or human activity. With this in mind it would certainly be better to have more, rather than less, data.

Any locations not indicated on the historical maps that are accessible and of interest to the team members should be measured. Such locations should include those close to power plants, electrical sub-stations, telephone exchanges, water pumping stations, waste disposal treatment facilities, schools, hotels, parks, roads, bridges, and others.

Still camera photos of each measurement site and general area should be taken. If possible, prominent survivable landmarks (e.g., buildings and mountains) should be in the background of the pictures. At some locations it might be possible to mark where measurements have been taken with surveying tape or spray paint. **Voluntary or easily elicited eyewitness accounts should be documented. However, if any fatalities, injuries, or substantial losses of property have occurred in a region, overt efforts to acquire eyewitness accounts might best be abandoned.** Care must be taken to distinguish between those sites at which no effects of the tsunami were observed and sites that were not examined for evidence of the tsunami's effects. In past tsunamis both of these situations have been described by words "no observation". To avoid confusion, use "no effects observed" or "site not examined" along with coordinates or geographic names. If there are any conveniently located benchmarks in the area (look for these in the quadrangle maps in your "Field Guide Packet"), streets, or other landmarks, these could be used to check runup or inundation measurements. This is not required, but may be useful in some situations. Finally, areas that you are unable to reach because of obstacles should be identified; and **no attempt should be made to take readings in inaccessible or hazardous areas.**

RUNUP MEASUREMENT TECHNIQUES

Conventional surveying techniques with high degrees of accuracy are not well suited to the comprehensive and time limited measurements required for determining tsunami runups throughout the State. Normal rainfall, flash floods, heavy surf, and cleanup operations can quickly destroy evidence of a tsunami's effects. Runup measurement accuracies to within a foot, and inundation distance measurements of 10 to 30 feet may be more than sufficient for modeling studies and improved determinations of evacuation zones. Another problem is the cost of purchasing and maintaining conventional surveying equipment for more than 20 survey teams, as well as educating volunteer teams on the use of that equipment. Also, an additional factor is the weight and susceptibility to damage of conventional surveying equipment as it is used in remote, rugged, and often debris covered areas. Therefore, some simple, rapid, and sufficiently accurate methods have been developed for measuring tsunami effects using inexpensive, lightweight, and weatherproof measuring devices.

The Fundamental Concept

A quick and relatively accurate method (i.e., to within the nearest foot) for measuring runup follows. Have one team member (the “rod person”; hereafter referred to as “R”) stand on the shoreline at a point where “R” is as close as possible to the normal wave action without getting his or her feet wet. [“R” might be able to find sea level without any, or far less, wave action in rocky, less sloping portions of the shore. Such locations could allow placement of the base of the rod on the surface of a rock at sea level. This could provide a slightly better determination of sea level and could temporarily avoid the inevitability of wet feet.] With the rod held vertically at sea level, the other team member (the “sighter”; hereafter referred to as “S”) can move up the shore until the sea surface horizon is seen near the top of the rod. At this location (“A” in Figure 2a) “S” should read the height on the rod adjacent to the sea surface horizon (i.e., 9 feet in Figure 2a). Inexpensive binoculars may be useful in making these readings. At “A” the height of the ground level (i.e., the surface of the ground below “S’s” feet) relative to sea level is the reading made by “S” of the height on the rod adjacent to the sea surface horizon less the vertical distance from the ground to “S’s” eyes (i.e., 9 feet – 5 feet, or 4 feet). [We are assuming that the distance from the ground to “S’s” eyes is 5 feet.]

The next step is for “R” to move to the exact position where “S” was standing and again hold up the rod. “S” then moves higher up on the shore and stands at the limit of the tsunami deposited debris line (i.e., location “B” in Figure 2b). Again “S” reads the height on the rod adjacent to the sea level horizon (i.e., 7 feet in Figure 2b). Subtracting out the vertical distance from “S’s” feet to “S’s” eyes, it is determined that location B is 2 feet above location “A” (i.e., 7 feet – 5 feet). Therefore the tsunami deposited debris is 6 feet above sea level (i.e., the 4 feet measured at “A” plus the 2 feet measured at “B”). If the debris line is further up the shore, this method is continued until the line is reached. If the debris had been in a tree (e.g., Figure 2c), it would have been necessary to measure the height of the ground below the debris line relative to sea level (i.e., the 6 feet computed in Fig.2b), and then add the height of the debris above that location (i.e., the 8 feet in Figure 2c) to get the water level that existed (i.e., the 14 feet in Figure 2c) at that point.

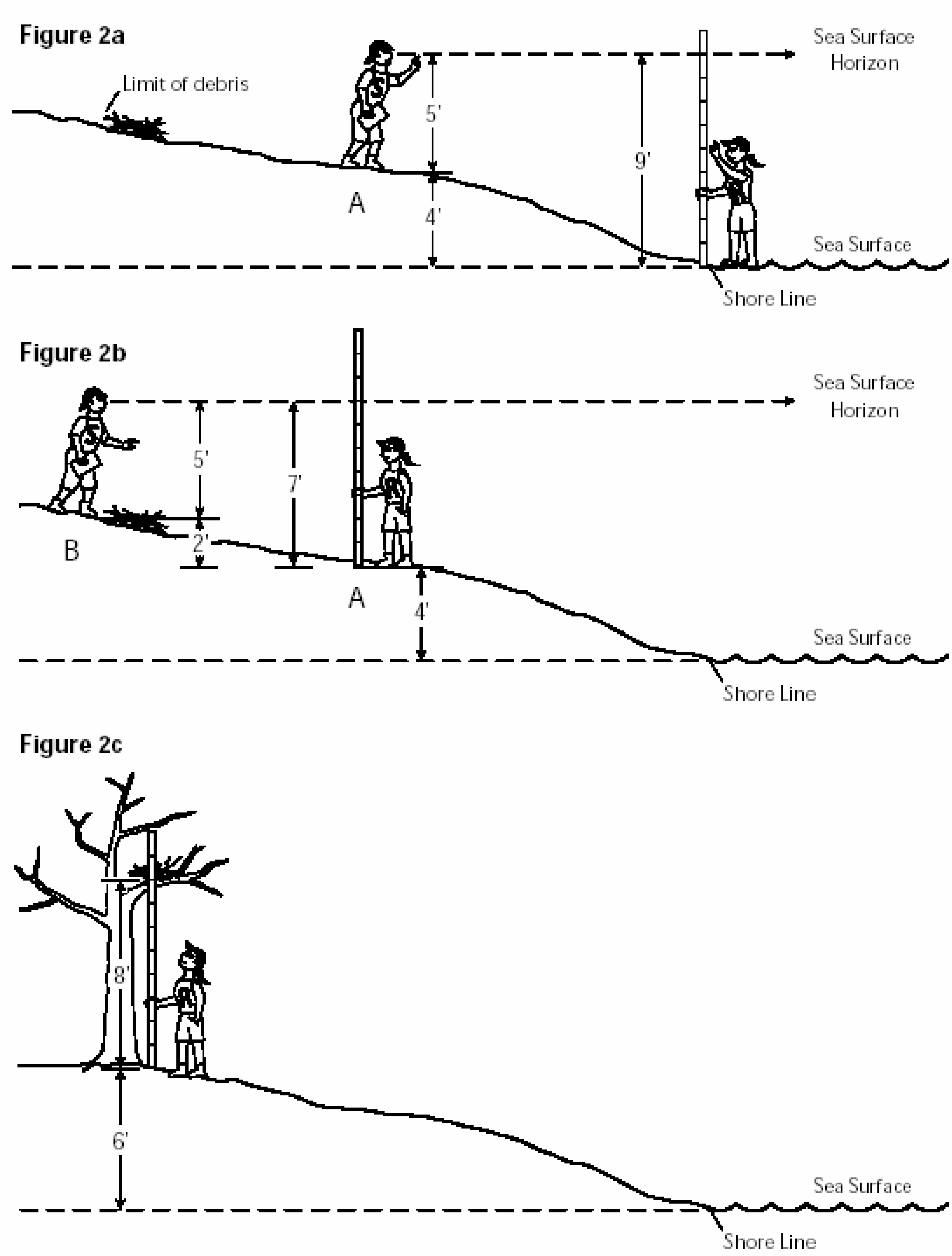


Figure 2. The steps involved in a typical measurement of runup using conventional surveying and the horizon as a reference level. See text for detailed discussions.

A Practical Short Cut

Now, with the understanding of this fundamental method, some additional techniques are suggested which can speed up the measurements and reduce the chance for errors. These techniques require the use of special survey rods made of two 5-foot sections of PVC pipe. The lower 5-foot section of the rod does not have to be marked. The upper section is marked from 1 foot to 5 feet. The sighter ("S") also has an unmarked 5-foot rod. The rod person ("R") holds the 10-foot rod up on the shoreline with the base of the rod at sea level. "S" moves up the shore (toward the debris line or water mark that is to be measured) continually sighting along the top of his (or her) 5-foot rod until the top of this rod and the top of "R's" rod line up with the sea level horizon (Figure 3a). At this location ("A" in Figure 3a) the ground level will be 5 feet above sea level. "R" then moves to "A", and "S" moves closer to the debris line (location "B" in Figure 3b) until the tops of the rods again line up with the horizon. These steps are repeated until the debris line or watermark is reached. At this point the top of the sighter's rod and the horizon will intersect "R's" rod at a point below the top of "R's" rod (Figure 3c). The runup in feet will be this final reading plus 5 times the number of intermediate readings (in this example; 3 ft + (2 X 5 ft) = 13 ft).. "R's" rod should have a brightly colored (i.e.. orange or red) horizontal bar across its top to facilitate accurate alignment with the horizon. Under cloudy or hazy skies, a white or gray bar can be difficult to sight on a white or gray horizon. A plumb bob can also be suspended from the horizontal bar to facilitate accurate vertical alignment of the rod. The 5-foot sections are pressure fitted so that they can be easily disassembled for storage and for transport from one site to another.

The accuracy of this method is estimated to provide measurements within 1 foot of actual values. This is more than adequate for assessing the potential destruction of future tsunamis, hurricanes, and storm surges, for improved determinations of evacuation zones for such hazards, and for testing the result of modeling studies. If the debris or watermark is in a tree or on a building, the height above the ground has to be added to get the water level that existed at that location. In these instances, the tsunami probably traveled further inland than is indicated by the debris or watermark.

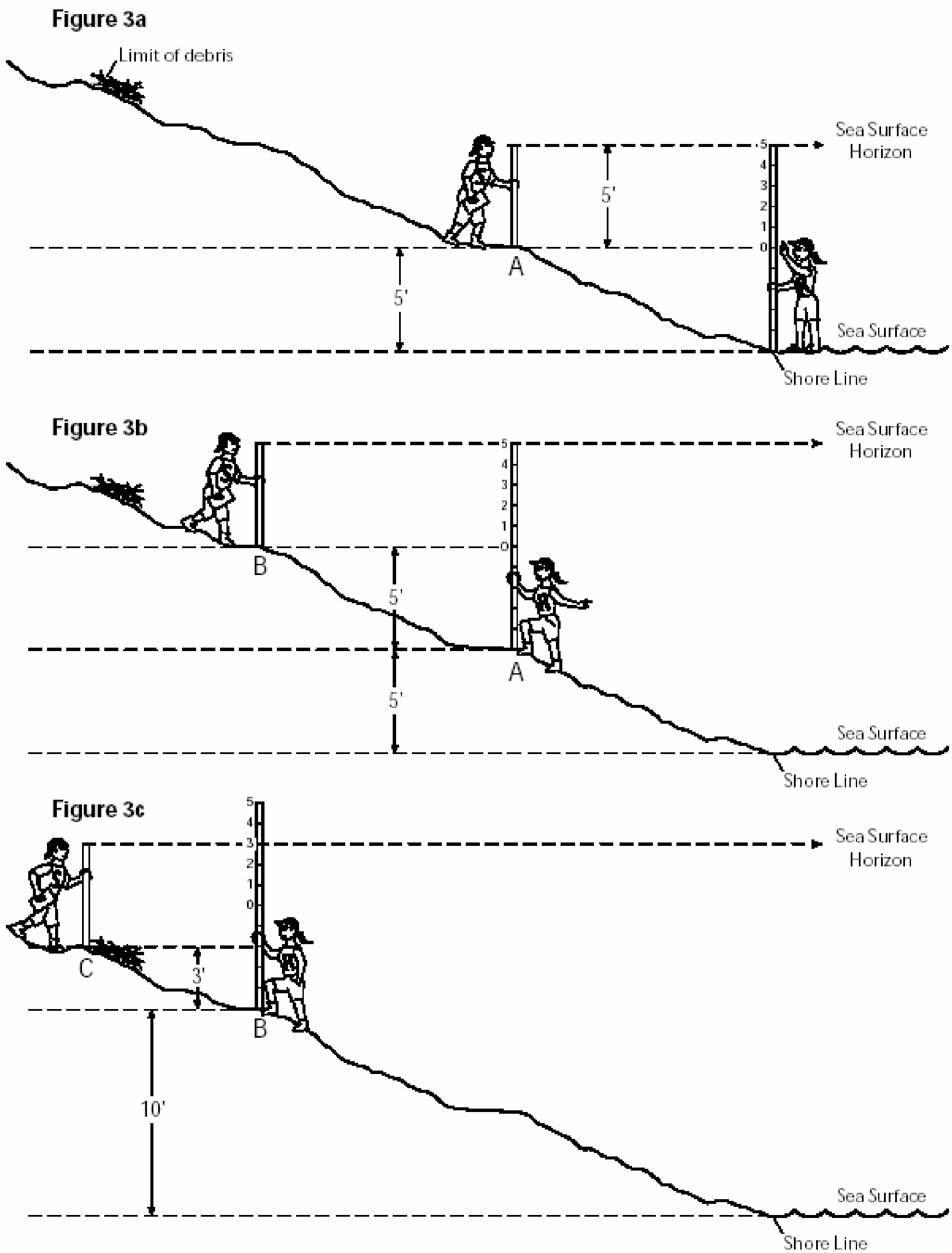


Figure 3. A practical, short-cut method for measuring runup. See text for detailed discussions.

In gently sloping shorelines with small runups, the horizon may not line up with the top of the rods. In this situation the runup will be the value appearing on “R’s” rod adjacent to the sea surface horizon when the horizon is sighted along the top of “S’s” rod. If multiple measurements of this type are needed to reach the debris line, the runup is the cumulative total of readings made.

An additional consideration is that the elevation of an intermediate measurement location may be lower than that of the location where “R’s” rod is being held. Therefore, the bottom 5-foot section of “R’s” rod should be marked so that the appropriate amount can be subtracted from the cumulative total. Also, in areas with large runups, an additional 5 foot section can be added to “R’s” rod, so as to reduce the number of intermediate measurements. In instances where the horizon can not be seen, an instrument known as a hand level should be used. The accuracy of some hand levels may not be as good as sightings to the horizon. [Do not use your GPS for measuring runup heights (altitudes). For this type of measurement the errors are unacceptably large.]

Finally, it should be noted that in the unlikely event that no surveying rods are available, one could somehow use tree branches, assuming one had a tape measure and a way of marking the branch (notching with a pocket knife or marking with a ribbon or string). In the absence of trees or any other substitutes, the “sighter” could simply put his or her head to the ground and “sight” to the horizon intercepting the “rod person’s” head or other prominent body part (e.g., eyes, nose, shoulders, etc.). Actual measurements to body parts and estimates of eye heights of the sighter above ground could be determined later to provide runup or wave height measurements.

INUNDATION MEASUREMENT TECHNIQUES

The inundation limit should be determined by measuring with a 100’ tape, or by pacing from the shoreline closest to the debris line or watermark, and by noting the GPS coordinates of the inundation limit. [GPS location accuracies are dependent on the number of satellites the instrument can “see”. If GPS readings are taken next to steep cliffs or in deeply carved, narrow valleys, pacing or tape measurements may provide more accurate estimates of locations. If pacing, know your average pace to the nearest inch.]

SUMMARY OF ESSENTIAL MEASUREMENTS

The measurements that need to be made in areas or regions of interest are:

- the highest observable water level produced by the tsunami on land relative to sea level;
- the GPS coordinates of the highest water level location;
- the distance to the highest water level location from the closest shoreline, if possible, as determined by measuring with a 100ft tape and noting the compass bearing, or by pacing in a straight line and noting the compass bearing;
- the maximum distance that the tsunami penetrated inland as determined by pacing in a straight line, and noting the compass bearing, or measuring with a tape to the closest shoreline and noting the compass bearing, if possible;

- the height of the water level at the maximum distance of penetration relative to sea level; and
- the GPS coordinates of the location at which the maximum distance of penetration is observed.

In addition to the above measurements, other measures of water levels and inland flooding distances may be needed to get a better understanding of the tsunami's effects in certain areas. Certainly, in large areas of widespread devastation, several readings should be taken.

If possible, readings should be taken where measurements of prior tsunamis have been taken as indicated in the historical maps in the "Field Survey Packet". Readings should also be made at the critical facility sites mentioned earlier under the heading "General Guidelines", or at any location the team believes to be of interest. Again, measurements should not be attempted in inaccessible or hazardous areas. Also, do not use the term "no observation". Use either "no effects observed" or "site not examined". Finally, measuring distances in a straight line to the closest shoreline may not be possible in some situations (e.g., because of debris or a meandering stream channel). In these situations the measurement should be made to the nearest accessible shoreline in a straight line noting the compass bearing.

Additional complementary tasks:

- taking pictures of the debris or water marks at measurement sites, and noting the corresponding disk or film roll and exposure numbers (conventional photos are acceptable, but digital photos are more easily archived);
- if possible, marking each measurement site with distinctive surveying tape or paint; and,
- documenting eyewitness accounts (in areas of property loss, injuries, or fatalities these should be entirely unsolicited, voluntary, and preferably, first person accounts).

The "Field Survey Packet" contains a sufficient number of data sheets for your survey. An example of a completed data sheet is given after the following discussion.

ACCURACY OF MEASUREMENTS

We focus here on sources of error in measurements generally capable of being a few inches or more. Such errors are possible in determining sea level at the time of the first sighting to the rod. In areas with waves washing up and down the shore, estimating where to place the rod could be difficult. This is especially true with steeply sloping shorelines and heavy surf. In this situation it may be necessary to study the waves on the shore to find the sea level location. Also, be aware of the possibility of sets of waves in your determinations, and avoid dangerous surf that could knock you down or sweep you into the ocean. Measurements under such circumstances should be taken at another time when the surf is smaller. Errors in the misplacement of the rod at sea level could generally be plus or minus a few inches under normal conditions, and perhaps a foot or two with larger surf. As already discussed, the “horizon assumption” would generally produce errors of only a few inches. For very large runups (e.g., about 50 feet) and large inundations (e.g., about 400 feet), the error would approach 1 foot (i.e., the reading of runups would be too small by a factor of about 1 foot because true level was slightly higher on the rod than the horizon).

Another potentially significant source of error is in determinations based on debris or watermarks. The debris lines or watermarks are actually produced by a superposition of normal short period (i.e., a few seconds) waves on top of the much longer period (i.e., several minutes) tsunami waves. Other factors are the tides and knowing the time of the arrival of the largest tsunami wave. [In some tsunamis waves arriving as much as two or three hours after the first wave can be the largest.] Storm surges and the large sets of wave associated with heavy surf could also give false high readings. As discussed earlier GPS accuracy may be good to within a few tens of feet if enough satellites are used, but may be much worse in shorelines adjacent to high cliffs or deeply carved and narrow valleys. For this reason pacing or tape measured distances should always accompany GPS readings. Combined GPS and tape measured (or pacing) values along with compass bearings should provide an accuracy of more than 90%. Finally, with thick piles of debris, it may be difficult to determine which part of the pile is indicative of the tsunami’s maximum height.

[The survey teams should not be concerned with possible corrections to the data. This will be the task of others, well after the survey work is completed.]

<u>TSUNAMI DATA LOG</u>

Survey Team:________ Reading No:________ Location Name: ____________________

Date:______________ Time of Reading (Use Hawaiian Time): __________ AM PM

Coordinates (GPS preferred; note if from maps): ________________________________

Height of Reading above Sea Level (in feet): ___________________________________

Distance from Shoreline (in feet): ____

Compass Bearing to Shore: ____

Picture Taken: Yes No Disk or Film Roll No: __________ Exposure No:_________

Nature of Observation: Debris on Land Debris in Tree Other

If "other", describe: ____

In this general area, does this measurement appear to be:
The highest water level? Yes No Not Yet Known
The greatest distance from the shoreline? Yes No Not Yet Known
Calculations, sketches, comments, and additional notes (be sure to place the reading number at the estimated location on your maps):

TSUNAMI DATA LOG

Survey Team: M-2 Reading No: 11 Location Name: N. side of HANA BAY

Date: 11 Dec 2002 Time of Reading (Use Hawaiian Time): 6:32 AM PM

Coordinates (GPS preferred; note if from maps): 20°46.00'N ; 155°59.12'W

Height of Reading above Sea Level (in feet): 12.5 ft

Distance from Shoreline (in feet): 54 ft

Compass Bearing to Shore: 12° E of S

Picture Taken: Yes No Disk or Film Roll No: 1 Exposure No: 13

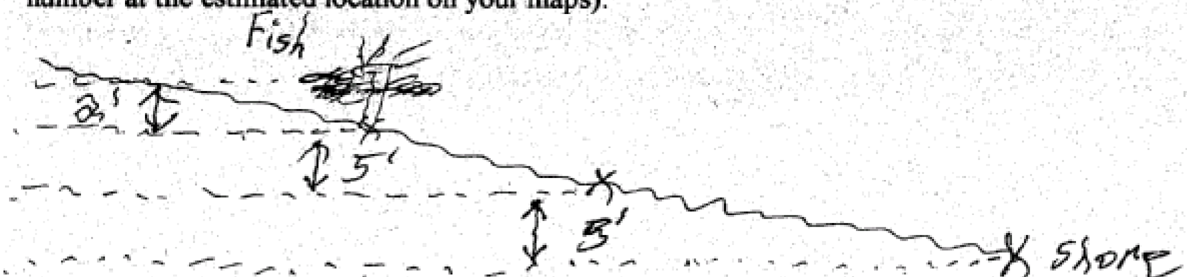
Nature of Observation: Debris on Land Debris in Tree 1 Other

If "other", describe: not applicable

In this general area, does this measurement appear to be:

The highest water level?	Yes	No 3	Not Yet Known 2
The greatest distance from the shoreline?	Yes	No 3	Not Yet Known

Calculations, sketches, comments, and additional notes (be sure to place the reading number at the estimated location on your maps):



1. actually a fish and seaweed in a tree.
2. Will take other measurements in Hana Bay area.
3. Can see that debris is further inland in other areas.
Note: the stream bed area south of this location is too dangerous to get to because of debris. However, stream bed area does not appear to have greatest runup or furthest inundation in the Hana Bay area. Fisherman said third wave was largest at about 11:45 AM.

EQUIPMENT AND SUPPLIES

A listing of essential equipment, supplies, and other items follows. These should be "checked off" before beginning your survey.

Equipment: Survey rods (three five-foot sections for the "rod person", and one five foot section for the "sighter"); GPS; binoculars; compass; hand level; walkie talkies; survey tape; still or digital camera; and clipboard.

Supplies: data sheets, pens, pencils, notebook, batteries, and film or disks.

Other items: Field Guide Packet (including the Field Guide, data sheets, topographic maps, historical runup maps, and, if available, street guide maps); and personal effects (e.g., watch, appropriate footware, water, sunscreen, and umbrella, rain coat, or trash bag).

SECURITY AND IDENTIFICATION

To avoid inconveniencing security and rescue personnel or unnecessarily arousing concerns of residents, survey team members should wear a Civil Defense hat, a Civil Defense T-shirt and/or an orange safety vest, and a Civil Defense ID badge or ID card. Their cars should also display a Civil Defense "Official Business" dashboard placard.

CONCLUDING REMARKS

Data gathered by the survey teams will help to reduce the human and economic losses associated with future tsunamis, hurricanes, and storm surges. For that reason everyone involved in the development of this field guide wishes to express their gratitude to the survey team volunteers on behalf of present and future residents of, and visitors to, the State of Hawaii.

ACKNOWLEDGEMENTS

The contributions of all of the committee members, especially Doak Cox, George Curtis, Gerard Fryer, Laura Kong, and Dan Walker, in the production of this field guide is acknowledged. Advice and assistance on various aspects of this field guide were provided by Mike Blackford of the International Tsunami Information Center, Chip Mc Creery of the Richard Hagemeyer Pacific Tsunami Warning Center, and Stan Goosby of the Pacific Disaster Center. Illustrations were provided by Nancy Hulbirt and Brooks Bays.

Finally we acknowledge the pioneering field survey work of Doak Cox. After the 1946 tsunami, Doak Cox, Gordon Macdonald, and Francis Shepard made more than 300 measurements on all of Hawaii’s major islands over a span of a few weeks. With these data, as well as additional data that Doak assembled for subsequent tsunamis, estimates of evacuation zones were determined for the main Hawaiian Islands. Doak’s interest in tsunamis eventually led to the establishment of a major, long-term research program at

the University of Hawaii. The community of tsunami scientists and the people of Hawaii owe a debt of gratitude to Dr. Cox for his contributions to tsunami research. Indeed, the survey team volunteers should be inspired by his work; and their efforts will complement the field survey research he initiated in 1946.

Appendix I: Survey Teams and Areas

The descriptions of survey areas that follow begin with northernmost areas and move clockwise around the individual islands. Place names can be found in the color topographic maps and quadrangle maps contained in your “Field Guide Packet”.

KAUAI

Four teams will be needed. The K-1 team area extends from Hanakapiai (west of Haena) eastward to Kauapea Beach (west of Kilauea Point). Getting to Hanakapiai from the end of the road will require about one hour of hiking (up one steep mile and down another). K-1 team members must be capable of doing this. The K-2 team area extends from Kilauea Point to Nauwiliwili Harbor. The K-3 team area extends from Kipu Kai (just south of Hoary Head) to Polihale (north of Barking Sands near the far-eastern corner of the island). The team will have to drive through a tunnel (permission required) to get to Kipu Kai (all private property). Some measurements should be made for the Haula to Makahuena Point area. The K-4 team will need a boat or helicopter to survey Niihau (permission required) and the Na Pali Coast (weather permitting). On Niihau, measurements should be made at its northernmost shore (Keamano Bay) and at Kii Landing, Nonopapa, and Keawanui Bay. Water levels of about 20’ and 10’ (locations unknown) for Niihau were reported for the 1946 and 1957 tsunamis, respectively. If a boat is used to survey Niihau, K-4 members must know how to swim and not be prone to excessive seasickness. The K-4 area could be done by other Kauai team members after their areas have been surveyed. Permission will be required to survey Niihau and the Pacific Missile Range Facility at Barking Sands. No attempt should be made to take readings in inaccessible or hazardous areas.

OAHU

Six teams will be needed. The 0-1 team area extends from Kaena Point to Turtle Bay west of Kahuku. The 0-2 area extends from Kahuku to Kahaluu just north of the fishpond. The 0-3 area extends from the fishpond to the Halona Blow Hole at Koko Head, and includes the Mokapu Peninsula (Kaneohe Marine Corps Base) and Hanauma Bay. The 0-4 area extends from Koko Head to the eastern edge of Honolulu Harbor. The 0-4 area includes such waterways as Kuapa Pond (Hawaii Kai), the Ala Wai Canal, Ala Wai Harbor, and Kewalo Basin. Measurements should be taken in all of these areas. The 0-5 area extends from Honolulu Harbor to Iroquois Point and includes Honolulu Harbor, Sand Island, Keehi Lagoon, the Reef Runway, Hickam Harbor, and Pearl Harbor.
The 0-6 area extends from Ewa Beach County Park to the Kilauea Cave area south of Kaena Point, near the end of the paved road past Yokohama Bay. This area includes the Barbers Point Harbor. Several measurements should be taken between the Ewa Beach County Park and Barbers Point (because of recent and planned development in this area), as well as at the Ko Olina Resort and around the Kahe Point power plant opposite the Kahe County Park north of Barbers Point. Permission will be required for surveys of the Kaneohe Marine Corps Base and its training area at Waimanalo, for Pearl Harbor, Hickam, the Reef Runaway and other airport areas (State Department of Transportation), and the James Campbell National Wildlife Refuge at Kahuku (U.S. Fish and Wildlife Service – Department of the Interior). No attempt should be made to take readings in inaccessible or hazardous areas.

MOLOKAI

Two teams will be needed for Molokai. The M0-1 survey area extends along the north coast from Ilio Point (northwest corner) to Lamaloa Head (northeast corner). A boat or helicopter will have to be used to get to some of the areas where measurements were made for earlier tsunamis. Team members must know how to swim and not be prone to excessive seasickness. The M0-2 area extends along the south coast from Halawa Bay to Kepuhi Bay near the northwest corner of the island. Permission will be required to enter the Kalaupapa area. No attempt should be made to take readings in inaccessible or hazardous areas.

LANAI

One team will be needed for Lanai. Most the shoreline of this island is unpopulated and generally inaccessible. The L-1 team should take readings at Manele Bay, Kaumalapau Harbor, the Kahokunui area, at a few sites reasonably accessible on the north shore (Shipwreck Beach), and at any other reasonably accessible shorelines along the western and southern shores. No attempt should be made to take readings in inaccessible or hazardous areas.

MAUI

Four teams will be needed for Maui. The M-1 survey area extends from Waihe'e Point (north of Wailuku) to Kuau (east of Paia). Additional readings should be made in Kahului, especially near the airport, harbor, and power plant areas. The M-2 area extends from Hookipa Park around through Hana to Manawainui east of Nuu Bay on the south shore. There are large areas of inaccessible shorelines in the M-2 area. The M-3 area extends from Kanaio Beach east of La Perouse Bay, northward through Kihei and westward to Olowalu. [The Manawainui to Kanaio Beach area is generally inaccessible]. More readings than have been taken for earlier tsunamis should be taken in the Wailea and Kihei areas, as well as in the Kealia Pond and power plant areas. Getting to Kanaio Beach will require a two-mile hike along the ancient Hoapili (King's) Trail. The M-4 area extends from Awalua Beach (north of Olowalu) north to Kahakuloa Bay. No attempt should be made to take readings in inaccessible or hazardous areas.

HAWAII

Five teams will be needed for Hawaii. The H-1 survey area extends from Laupahoehoe Beach Park south to Leleiwi Point. Several readings should be taken in the Hilo area. In the event of a large tsunami, State and Country agencies can be expected to comprehensively document the inundation limits in the Hilo area. Therefore, the H-1 survey team should focus on measurements of wave heights and runups. The H-2 area extends from Haena (permission needed from the Blackshear family) east and around to South Point. Hawaiian Volcano Observatory personnel will measure runups and inundations in the Hawaii Volcanoes National Park area between Kaimu and Punaluu. The H-3 area extends from Waiahukini (west of South Point; permission from Kahuku ranch required) to Honokohau north of Kailua. The H-4 area extends from Kaloko Point to Hapuna Bay north of Puako. Many measurements are needed in this region because of recent and potential future developments. Because the road is far from the shoreline, a considerable amount of hiking may be required. A four wheel drive vehicle with high clearance might be useful for portions of this area. The H-5 area extends from Kawaihae to Ookala on the Hamakua Coast, and includes Pololu Valley and Waipio Valley. Both of these valleys can be hiked into, and a four- wheel drive vehicle can get down into Waipio Valley. No attempt should be made to take readings in inaccessible or hazardous areas.

OTHER ISLANDS

Some of the northwestern Hawaiian Islands may be surveyed after completion of work on the main Hawaiian Islands. These could include Kure, Midway, Lisianski, and Laysan. All have a sufficient landmass on which tsunami effects could be measured and are far enough away from the main Hawaiian Island to provide potentially useful data for future warning decisions, should instruments eventually be deployed at those sites. French Frigate Shoals, which is instrumented, might also be surveyed. Midway may be reached by regularly scheduled flights. The other sites may only be accessible by ships or helicopters. Permission from the Fish and Wildlife Service (U.S. Department of the Interior) will be required to survey these islands. No attempt should be made to take readings in inaccessible or hazardous areas.

The Office of Hawaiian Affairs should be contacted to see if they would want any measurements made for Kahoolawe. This could be done after surveys were completed elsewhere. No attempt should be made to take readings in inaccessible or hazardous areas.

Appendix II: Historical Runup Data

In these maps of historical data, please note that the locations are estimated and possibly clumped together for differing tsunamis to facilitate plotting and comparisons. However, every tsunami is different with differing runups and inundations. Volunteers are encouraged to search for the largest runups and greatest inundations in the general areas for which historical data are available, as well as in other areas that may now be more important because of subsequent or planned developments. If possible, runup and inundation measurement should also be taken near such critical facilities as power plants, electrical sub-stations, water pumping stations, telephone exchanges, sewage treatment facilities, schools, and hotels. No attempt should be made to take readings in inaccessible or hazardous areas.

These plots of historical data are not intended for use as road maps. Highways, streets, and other reference points can be found in the color topographic maps of James A. Bier published by the University of Hawaii Press or in “Bryan’s” sectional maps if they are available for your island. The water levels in these maps of historical data are measures relative to mean lower low water. Volunteers are to collect raw data that will be corrected later to this historical standard by others during the data reduction process. Note that the latitude and longitude grids are approximations to coincide with those in the “Bier maps”. GPS readings will generally provide more precise values than can be estimated from any of the maps cited here. Finally, actual coastlines may not be identical to their representations in these maps. Various technologies are used to determine coastlines with differing sources of error. Also, coastlines can change over relatively short periods of time. General locations for the tsunamis are: 46 – Aleutians, 52 – Kamchatka, 57 – Aleutians, 60 – Chile, and 64 – Alaska.

[The following information is not required reading for the volunteer observers. Such documentation however, should always be attached to the revised runup maps.]

Sources of Historical Data and Documentation of Discrepancy Resolutions

Primary references, if available, were maps found in the tsunami archives at the University of Hawaii at Manoa in the School of Ocean, Earth Science, and Technology (SOEST). Data from field notes were originally put on to these maps that have scales of 1:62,500 (Kauai and the Big Island) and 1:24,000 (Oahu, Maui, and Molokai). These maps will, hereafter, for convenience sake be referred to as "quads". Some of the quads may not be originals. Some may be second or even third generations of the original quads. However, these data are the closest to the original field notes (also missing) that could be found. The data on the available quads have been color coded for the differing major tsunamis of 46, 52, 57, 60, and 64. Although some of the colors are fading, all are still readable. The values on the quads, as well as the values in all of the references cited, have been corrected to mean lower low water. Secondary references, hereafter referred to as A, B, and C, respectively, follow.

(A) Shepard, F. P., G. A. Macdonald, and D. C. Cox (1950). The Tsunami of April 1, 1946, Bull. Scripps Inst. Oceanog., Univ. of Calif. Press, 5 – 6. 391-528.

(B) Macdonald, G. A., F. P. Shepard, and D. C. Cox (1947). The Tsunami of April 1, 1946 in the Hawaiian Islands, Pacific Science, 1, 21-37.

(C) Loomis, H. G. (1976*). Tsunami Wave Runup Heights in Hawaii, Hawaii Institute of Geophysics, HIG-76-5, (*corrected and reissued January 1980), 95 pp.

Additional references follow.

Macdonald, G. A., and C. K. Wentworth (1954). The Tsunami of November 4, 1952, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 44-3, 463 - 469.

Fraser, G. D., J. P. Eaton, and C. K. Wentworth (1959). The Tsunami of March 9, 1957, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 49-1. 79 - 90.

Eaton, J. P., D. H. Richter, and W. U. Ault, (1961). The Tsunami of May 23, 1960, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 51-2, 135 - 157.

Cox, D. C., and J. F. Mink (1963). The Tsunami of 23 May 1960 in the Hawaiian Islands, Bull. Seismol. Soc. Amer., 53 -6. 1191 - 1209.

Loomis, H. G., (1972). "The Major Tsunami in the Hawaiian Islands" in The Great Alaskan Earthquake of 1964 – Oceanography and Coastal Engineering, Nat. Academy of Sciences, Washington, D. C., 181 - 190.

Lander, J. F., and P. A. Lockridge (1989). United States Tsunamis (Including United States Possessions) 1690 – 1988, National Geophysical Data Center, Publication 41-2, Boulder, Colorado, 265 pp.

There are no missing quads for Kauai or Molokai. Four of 14 quads with data are missing for Oahu (Kahana, Kaneohe, Mokapu, and Ewa). Three of 14 quads with data are missing for Maui (Kahakuloa, Kipahulu, and Kaupo). Five of the 16 quads with data are missing for the Big Island (Honokaa, Kukaiau, Papaaloa, Papaikou, and Hilo). The "new" quad names may not be the same as the names of the missing old maps. [The existing old quads do not always have the same names as the new quads.]

Only data for 1946 is available for Molokai and Lanai. The Lanai quads, if they ever existed, are missing; but only two values were reported for this island (7' at Manele Bay and 7' at Kaumalapau Harbor). Niihau quads, if they ever existed, are also missing. Values of about 20' and 10' were reported for the 46 and 57 tsunamis, respectively. The locations for those readings is unknown.

There was much damage reported along the north shore of Kauai for the 52 tsunami. However, the only reported values were 10' at Wahiawa Bay and 1' at Port Allen (Lander and Lockridge, 1989). [Since Wahiawa Bay is on the south shore of Kauai right next to the 1' reading at Port Allen, the 10' value may be a typo, and possibly should be 1'.] There are no values reported for Maui for 52, but the greatest damage was reported in the Kahului – Spreckelsville area where the tide gauge went off scale (Lander and Lockridge, 1989). All of the quads and references were cross-checked for evidence of discrepancies. Greatest weight was given to the quads, then the secondary references, and finally the additional references. The following is a list of discrepancies, considerations and decisions.

General Observations. In the secondary references, a total of 472 locations statewide were found where runup measurements have been made for the 46, 52, 57, 60, and 64 tsunamis. Of these, 356 are for the 1946 tsunamis. Many of the locations for the 52, 57, 60, and 64 tsunamis (in C) are plotted as being the same as for the 1946 tsunami, and many are not. This seems to differ from island to island. For example, Kauai has many (51 out of 126) locations other than 1946 locations for the other tsunamis, while data for Oahu for all of the tsunamis is nearly exclusively plotted at 1946 locations. Only 2 of the 95 locations for Oahu were non-1946 locations. I don't believe it is possible for readings in 52, 57, 60, and 64 to have been taken at the same locations as in 1946 to the extent possibly inferred by anyone looking at the data in C. Some sort of clumping must have occurred, as Doak Cox and George Curtis have suggested (personal communication); and it is logical to do this for plotting and comparison purposes. Also, there is no point in trying to "unclump" the data. It may not be possible, the process would have its own errors, and there is no clear reason why it should be done.

Kauai

- There is a little bit of “clumping” for Hanalei Bay in C. These values have been “unclumped” using values on the quad.
- There is a value of 33’ (1946) north of Mana in A. On the quad, in B, and in C it is 34’. [Decision: Change to 34’.]
- On the original quad, in A, and in C there is a single reading of 45’(1946) at Haena, but in B there are 2 distinct readings of 45’ at Haena. [Decision: Ignore the 2nd reading.]
- At Haena there are values of 9’ and 14’ (1946) on the quad and in B. These are reversed in C. [Decision: Use the values on the quad.]
- The reading of 21’ (1946) at Kilauea Bay in C is not on the quad. [Decision: Delete.]
- The reading of 29’ (1946) south of Kilauea Bay in C is actually 32’ on the quad. [Decision: Use 32’.]
- At Moloaa there are readings of 30’(1946) in A, 30’ and 40’ in B, and 45’ (inland), 30’ (at shore), and 35’ on the quad and in C. [Decision: Use 45’. The designations “inland” and “at shore” are confusing. Do not use.]
- A value of 30’ (1946) south of Moloaa in A does not appear on the quad or in B or C. [Decision: Do not use.]
- For Kepuhi Point there are readings of 32’ (1946) in B, 32’(at shore) and 38’(inland) on the quad and in C. [Decision: Use 38’ and delete “inland”.]
- At Kalihiwai the value of 21’ (1957) in C was found to be 22’ on the quad. [Decision: Use 22’]
- In map 11 of C the 9 ½’ reading (1960) should be blank as it goes with the 2nd reading in map 1 of C. This is confirmed by the quad. [Decision: Blank it.]
- The 6’ reading (1960) on the north side of Anahola Bay in (C) is not on the quad. [Decision: Delete.]
- Three values south of Kapaa of 7” (1960) are on the quad, but one of these is 8’ in C. [Decision: Use 7’.]
- A value of 14’ (1960) at Hanapepe Bay in C is not on the quad. [Decision: Delete.]
- The value of 6 ½’ (1960) near the middle of map 8 in C is 9’ in Cox and Mink, but 6 ½’ on the original quad. Could have been rounded up to 7’, then a handwritten 7’ was misplotted as 9’. [Decision: Use 6.5’.]
- The value of 8’ (1960) near Kukuiula Bay in map 6 of C also appears on the original quad but shows up as a 7’ reading in Cox and Mink. [Decision: Use 8’.]
- Plotting from the original quad onto figures in C is extremely accurate for Kauai with no corrections for locations required.

Oahu

- Two values (1946) in Pearl Harbor are shown on quads and in A and B, but not in C (maps don’t go there). [Decision: Add these points.]

- A 12’ (1946) value near Maile Point on the quad and in A and B is not in C. [Decision: Add this data point which lies between values of 14’ and 16’.]
- There are 27’ (1946) and 6’ (1952) readings near Kahuku on the quad and in A and B but not in C. [Decision: Add these data points.]
- There is a 2’ (1946) reading on the east side of Kaneohe Bay in A and B but not in C. The quad map is missing. [Decision: Add this data point.]
- There are some duplicate readings in C east of Niu Valley not on the quad nor in other publications. [Decision: Delete these values.]
- There is no 3’ (1946) value for the Ewa Beach area in A or B but is in C. The quad is missing. Scale may be too small for plotting in A and B, or value thought to be too insignificant at the time, or a neighboring value of 3’already plotted may have suggested that plotting not necessary. [Decision: Put in the 3’ value.]
- In C (map 2) the 12’ (1960) north of Punaluu Stream is 7’ in Cox and Mink. The 12’ doesn’t fit with surrounding values. Also, 12’ would be the largest value on the entire eastern and southern coastlines. Perhaps a handwritten comma and a 7 was misplotted as a 12. Quad is missing. [Decision: Use 7’.]
- The 5’ (1960) value next to Koko Head in Cox and Mink is missing in C but is in the original quad but not in a secondary quad. [Decision: Use 5’.]
- A 5’ (1960) reading east of Diamond Head in Cox and Mink is missing in C and in the quad. [Decision: Do not use this 5’ value.]
- A 2’ (1960) reading on the west side of Kaneohe Bay in Cox and Mink is missing in C. Quadrangle map is missing. [Decision: Use 2’ value.]
- All locations in C follow the locations on the available quad maps with the exception of Hanauma Bay. They are on the northern edge in C and more toward the center of the bay on the quad. [Decision: Use the quad location.]

Molokai

- On the quad the 36’ value north of Kepuhi Bay is about 1 mile further north and the 13’ at Halena is about 1 mile further east than in C. [Decision: Move values to location indicated on quad.]
- There is an additional 9’ reading on the quad on the west side of Kalaupapa Peninsula not found in A, B, or C. [Decision: Add this value.]
- There are 7 additional values in B and C around Kalaupapa and 7 additional values in B and C along the southeastern coast that are not on the quads. These values may not have been plotted on the smaller scale map in A because of a lack of space. [Decision: Include these values.]
- A 36’ reading in B and C at the eastern edge of Molokai is 35’ on the quad. [Decision: use 35’.]
- A 30’ reading in C below the 36’ reading is 39’ on the quad and in A and B. [Decision: Use 39’].

Maui

- On the quad and in A and B, the value for Hana Bay is 13' (1946). In C the value is 30' [Decision: Use 13']
- A and B have 24' (1946) at Puuiki (South of Hamoa) but this value is not in C and the quad map is missing. [Decision: Add this value.]
- A value of 7' (1960) is missing in C but is on the quad. [Decision: Add this value.]
- No values at Honokohau Bay or Nakalele Point on the quad, yet are in A, B, and C. Also a quad is missing for Kahakuloa that could have the missing values for Honokohau and Nakalele. This lost quad appears to be an odd one with borders overlapping the existing quads, probably including the Honokohau , Nakalele , and Kahakuloa areas. [Decision: Keep the values that are given in A, B, and C.]
- In addition, quad maps are missing from south of Hamoa south and eastward to La Perouse Bay. Data from C were checked against all original published sources for this area for the 46, 57, 60, and 64 tsunamis (there is little or no data for the 52 tsunami for Maui or Kauai). No discrepancies were found and the data from C were used for these areas of the coast.
- The 7' (1960) for Honolua Bay in Cox and Mink and on the quad is missing in C. [Decision: Add the 7' reading.]
- Plotting from the original quads onto figures in C is extremely accurate for Maui with no corrections for locations required.

Hawaii

- The 25' (1946) reading near Leleiwi Point in A and B is 20' on the quad and in C. Perhaps handwritten 0 was read as 5 in drafting. [Decision: Use 20'.]
- Readings of 7' and 11' (both 1946) for Kailua-Kona on the quad and in A and B are missing in C (no map for this area). [Decision: Use the 7' and 11' readings, and add a map that covers this region.]
- The 11' (1952) for Reeds Bay in Macdonald and Wentworth is missing in C, but is very close to a 9' reading in C consistent with other nearby readings. Quadrangle map is missing. [Decision: Not critical to add the 11' reading.]
- Just north of Keaukaha the 13' for 1952 in Loomis should be for 1957 as indicated in Fraser et. al. There is no 13' value in Macdonald and Wentworth for this location. Quad is missing. [Decision: Make 13' for 57 not 52.]
- The 2' (1952) reading for Kailua-Kona in Macdonald and Wentworth is missing in C (no map). [Decision: Add map and value.]
- At Kauhola Point the 10' and 27' (both 1957) readings in C are indicated as values for 1946 on the quad but are not in A or B (the papers for 1946 - on this small map not every data point could be shown, so they may have been deliberately deleted to reduce the visual clutter). They are in Fraser, Eaton, & Wentworth; and Eaton, Richter, and Ault (the papers for 1957 – but the

57,52,46 order may have gotten reversed). [Decision: Consider the primary source as valid, i.e., the 10’ and 27’ are 1946 values.]

- The 5’ (1957) value for Kailua-Kona is on the quad but missing in Loomis (no map). [Decision: Add map and value.]
- For the two 7’ (1957) readings in the Hilo map in Fraser et. al., no values can be found in Loomis but there are other larger values for 57 close to the same general area. Quad is missing. [Decision: Use C.]
- A 6’ (1960) reading east of Upolu Point near Keawaeli Bay in C is not on the quad or in Cox and Mink. It is the same value and is at the same location as was reported in Loomis for the 1964 tsunami. [Decision: Do not use for 1960 and add for 1964.]
- A 12’ (1960) reading at Pololu in Cox and Mink adjacent to values of 10’ and 11’ also in Cox and Mink, is not in C and does not appear on the quad. [Decision: Do not use.]
- The 8’ (1960) reading in C near the fish pond at Waipio is not on the quad and may be carried over from an 8’ value already indicated just to the west of the pond. [Decision: Do not use.]
- There is no map for Kailua values in C. There is an 8’ (1960) value in Cox and Mink, and on the quad. [Decision: Add maps and value.]
- Values for 1964 are not plotted on any of the quads for the Big Island. Therefore, the primary data sources are the Loomis reports of 72 and 76.]
- In maps 9 and 10 of C, there is duplicate data for 46, 57, and 60. Map 9 has no value for 64, but map 10 has 3’ for 64. The 3’ value is in Loomis (1972). [Decision: Use the 3’ value.]
- A reading of 2’ (1964) at Puako Bay is in C but not in Loomis (1972) There is no map for this area in C. [Decision: Add map and 2’ value.]
- On the quads, there are no values for Honuapo and only some values down to South Point. However, values are present at Honuapo and at other locations extending to South Point in C and in other publications. All of these addition points are in C. [Decision: Use these additional data points.]
- Plotting from original quads onto figures in Loomis extremely accurate for Hawaii. Only two locations had to be moved slightly (near Limukoko Point and Honomalino Bay).

Other data. The only other values for the above tsunamis in the Hawaiian Islands are for Midway: 6.2’ in 1952, 1.6’ in 1957, 2.0’ in 1960, and 0.3’ in 1964 (Lander and Lockridge, 1989). Also, flooding was reported at French Frigate Shoals in 1946 (personal communication, Pacific Tsunami Museum). There are no values from Midway for 1946. Thus far, the only other areas of the Pacific Rim (i.e., other than Kamchatka, the Aleutians, Alaska, and South America) producing double-digit runups in Hawaii were from the Japan earthquakes of 1896 and 1933. Values in excess of 5’ were only observed in Hilo in 1896 and along the west coast of the Big Island with a maximum reported value of 18’ in Keauhou for the 1896 tsunami (Lander and Lockridge, 1989).

Addendum:

Subsequent to completion of the above, field notes of Mink and Takasaki for the 1952 tsunami on Oahu were found in the SOEST archives, consisting of an 8 ½" X 11" map of Oahu on which 54 runups or water levels are indicated. Six of the values on that map are missing in C; but two values in C are not on Mink and Takasaki's map. However, the two additional values in C are identical to immediately adjacent values that do appear on Mink and Takasaki's map. Since a larger scale map may have been available for Loomis to work with in C, these values are retained in the new maps. Regarding the 6 missing values: (1) an 8' reading east of Kaena Pt. near the site of a 31' reading for 1946 has been added; (2) an 8' value in Waialua Bay immediately adjacent to a 13' value for 1952 was considered superfluous and not added; (3) a 10' value near Waialee and Sunset Beach between 13' and 10' values for 1952 was also considered superfluous and not added; (4) an 11' value just south of Hauula was larger than adjacent values for 1952 and was added; (5) a 1' value in Kaneohe Bay was considered superfluous and not added; and (6) a 5' value east of Diamond Head which was larger than surrounding values for 1952 was added. In C the only single values plotted were for the 1946 tsunami. Apparently, if any other tsunami had a unique location where the reading was taken, that value was either not plotted in C or was clustered at another location with other values for other tsunamis. Items (4) and (6) above are the only known remaining values that were not plotted in C because of their unique location.