Guidance for Flood Risk Analysis and Mapping

Coastal General Study Considerations

May 2016

U.S. Department of Homeland Security

FEMA

Requirements for the Federal Emergency Management Agency (FEMA) Risk Mapping, Assessment, and Planning (Risk MAP) Program are specified separately by statute, regulation, or FEMA policy (primarily the Standards for Flood Risk Analysis and Mapping). This document provides guidance to support the requirements and recommends approaches for effective and efficient implementation. Alternate approaches that comply with all requirements are acceptable.

For more information, please visit the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage (www.fema.gov/guidelines-and-standards-flood-risk-analysis-and-mapping). Copies of the Standards for Flood Risk Analysis and Mapping policy, related guidance, technical references, and other information about the guidelines and standards development process are all available here. You can also search directly by document title at www.fema.gov/library.

Document History

Affected Section or Subsection	Date	Description
First Publication	May 2014	Initial version of new transformed guidance. The content was derived from the Guidelines and Specifications for Flood Hazard Mapping Partners, Procedure Memoranda, and/or Operating Guidance documents. It has been reorganized and is being published separately from the standards.
Sections 4.8.1, 4.8.2, and 4.8.3	May 2016	Added information regarding topographic data sources and methods, to address requirements resulting from Section 216 of the Biggert-Waters Flood Insurance Reform Act of 2012, as amended by the Homeowner Flood Insurance Affordability Act of 2014.

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1.0 Overview

This guidance document provides an overview of coastal flooding processes and describes general study considerations that are germane to FEMA coastal flood hazard studies. Flood hazard studies are considered coastal studies when the flooding being evaluated is a combination of elevated water levels, typically due to storm surge, and wave action. Coastal study methodologies are used to evaluate flood hazards along the shorelines of the Atlantic Ocean, Gulf of Mexico, Pacific Ocean, and Great Lakes. Bays, tributaries, and other lakes are also considered to have coastal floodplains when they are subject to water level and wave hazards processes similar to those on the open coasts.

2.0 Settings and Contributors to Coastal Flooding

Coastal flooding is typically caused by a combination of increased water levels and/or high energy wave action. A primary driver of elevated water levels is storm surge. In general terms, storm surge is the water pushed toward shore by storm winds. The height of the storm surge is affected by many factors, including the intensity, path, and speed of the storm; the presence of waves; the depth of water offshore; and the shape of the shoreline.

Storm surge is often combined with other local or regional processes including tides, freshwater input, and fluctuating lake levels to produce elevated water levels that result in flooding. Weather patterns such as El Niño can also have an impact on storm surge. Waves are an important component of the coastal flood hazard because they increase the elevation of the flood hazard and have the potential to cause significant structural damage to buildings. Flood hazards related to wave action include wave setup, wave runup and overtopping, and overland wave propagation. The contribution of these various coastal flood hazard components vary in magnitude and relative importance by coastal region.

2.1 Atlantic and Gulf Coasts

Coastal flood hazards on the Atlantic and Gulf coasts are associated with large coastal storms. The most severe Atlantic and Gulf coastal storms can generally be classified as one of two types: tropical and extratropical. The risks associated with flood hazard events vary spatially along these two coastlines.

Tropical storms, including hurricanes, are characterized by large wind fields driven by pressure gradients from a central low pressure and temperature gradients in the atmosphere. They can sustain winds of more than 150 miles per hour and are accompanied by large storm surges and waves. The states along the Atlantic and Gulf coasts, from Texas to New York, are most at risk, though hurricanes have been known to reach as far north as Maine.

Unlike tropical storms, extratropical are frontal storms that track the shoreline as they progress northwards following the Gulf Stream. They move slowly and although the winds are typically weaker than tropical storms, they still pose a significant risk because they are accompanied by considerable precipitation and can affect a given area for multiple days and cause substantial erosion.

Extratropical storms are primarily hazards for Atlantic coast states from Maine to North Carolina. It should be noted, however, that these regional distinctions are presented for guidance to the Mapping Partner when considering local risks in the study area and do not indicate a prescriptive technique for identifying hazards. Mapping Partners should review study area climatology and local flooding response to determine a suitable methodology for determination of local flood risks from the various storm systems that may affect the area.

2.2 Pacific Coast

The dominant coastal flood hazards differ substantially for the Pacific Coast from those on the Atlantic and Gulf coasts. Whereas the dominant source of coastal hazards on the Atlantic and Gulf coasts is associated with large storm surge (up to 20+ feet) caused by high wind stresses over broad and shallow continental shelves, the narrow continental shelves of the Pacific Coast preclude surges greater than a few feet.

Large waves with long periods can cause both static and oscillating elevation of the water levels at the shore. The combination is referred to as “wave runup”. The oscillating component of wave runup can have periods from tens of seconds to several minutes. Wave runup and the energy of large breaking waves contribute to coastal hazards and can cause significant beach erosion and structural damage. Because Pacific storms often result in large rainfalls, coastal and riverine flooding can combine to increase flood hazards near river mouths.

Although it has the characteristic narrow continental shelf, the Southern California Bight is marked by a large number of offshore islands and banks rising sharply out of deep water more than 60 miles offshore. This results in partial to nearly complete sheltering of some sections of this 200-mile-long coast from wave energy arriving from certain directions, and produces one of the most complex wave environments in the world.

The Pacific Coast, on the eastern rim of a very long wave-generating fetch, is in the path of the westerly winds that dominate the weather in the Northern Temperate Zone. This results in swell and storm waves with very long periods, greater than 20 seconds in major storms. Antarctic-generated swell, with a number of potential great circle paths, results in low southern swell on the Pacific Coast throughout the year, most obvious during the summer when northern hemisphere waves are at a minimum.

The dominant storm waves result from winter storms initiated south of the Aleutian chain. The fetch is often more than 600 miles, such that wave height and period are controlled by wind speed and duration. Because these storm paths are at a low angle to the general coastline trend, the wave energy impacting a particular location is highly variable. In general, these winter storms produce the highest waves in the northwest and the lowest in the Southern California Bight, which is protected by the abrupt coastal direction change at Point Conception and the offshore islands. Thus, the typical La Niña conditions (intervals between El Niño events) provide low southern swell in summer with occasional local storms and a series of major wave events with long peak periods during the winter months (December through March or April.)

The El Niño of 1982-83, the strongest such global climate oscillation in recorded history, resulted in several record-breaking storm wave events, extensive structural damage, and severe erosion (Seymour et al., 1984). During El Niño episodes, for intervals of a year or two, the trade winds normally blowing towards the west near the equator weaken or reverse. This causes a slow sloshing of the Pacific Ocean towards the east and an increase in local sea level that can be as great as 1.5 feet. More significantly, a series of winter storms are spawned north of the Hawaiian Islands with paths directed towards the Pacific Coast.

The 1982-83 storms approached the Southern California Bight from almost exactly west, resulting in extreme flooding and wave impact damage on this coast and slightly lower waves impacting the Northwest. The El Niño of 1997-98, steered on a more northerly track by continental high pressure areas, resulted in larger waves in the Northwest than in Southern California (Komar, 1998). The largest waves recorded off Southern California occurred in a La Niña year resulting from a very tight and intense storm initiated close to the coast in January 1988, which moved rapidly onshore (Shore and Beach, 1989). The largest waves recorded off the North Pacific Coast in the last century also occurred in a La Niña interval (Allen and Komar, 2000). Major storms along the Pacific Coast, regardless of the wave generation area, typically persist for three to four days.

The Pacific Coast is ice-free in spite of the high latitude of its northern boundary because of the moderating effects of the south-flowing current, which originates as the warm Kuroshio Current that cools as it traverses the Northern Pacific. It is broad and slow near the end of its path compared to the relatively narrow and fast-flowing character near its origin. As a result, the North Pacific current (it carries a variety of local names) has negligible effect on the intensity or direction of storm waves reaching the Pacific Coast.

Pacific Coast tides are semidiurnal (two highs per day) and have a range of about six feet in the south increasing to about nine feet in the north.

Exposure to long waves generated anywhere in the Pacific Ocean yields the potential for tsunami impacts anywhere on the Pacific Coast; however, much of the seacoast is protected from extensive tsunami flooding by cliffs, steep coastal slopes, or deep water very close to shore. The magnitude of the amplification at the shoreline of the modest deep water tsunami wave heights is dictated by local bathymetry. Flooding risk from tsunamis is highly variable along the coast. One such susceptible location, Crescent City, in Northern California, suffered substantial damage in 1964 from a tsunami initiated by an earthquake in Alaska (Kanamori, 1970).

The Pacific Coast can be divided into two rainfall regimes. North of Monterey Bay, precipitation is greater and snow accumulation is heavy and reliable on inland mountain peaks, such that rivers flow year-round and spring floods are common. South of this point, rainfall is restricted to the winter months and declines in magnitude with reduced latitude. Rivers flow only in the winter and flooding is highly episodic.

Except at San Francisco Bay, all of the Pacific Coast rivers discharge directly into the Pacific Ocean. Because the sediment load-carrying capacity is strongly related to both rainfall in the watershed and flooding intensity in the river system (Inman and Jenkins, 1999), the supply of sand to the coastline grades from a maximum in the north to a minimum in the south. The combination of this sand supply condition, the varying coastal geology, and the north-south gradient in wave energy levels results in very different beach configurations in the two rainfall provinces.

North of Monterey, beaches are found in the lowered valleys at the mouths of streams or rivers that flow year-round. The sizes of the accompanying spits are related to the sediment capacity of the streams.

South of Monterey Bay and extending to Point Conception, a series of beaches and accompanying dune fields exist as large (10-15 miles long) crescentic bays anchored on the north by large rocky headlands.

Beginning at Point Conception and continuing south and east to the border with Mexico are a series of more or less continuous beaches, broken into littoral cells by rocky headlands (such as

Palos Verdes, Fermin, Dana and La Jolla points), most in the order of 60 miles in length (Inman and Frautschy, 1966).

Thus, the vast majority of the sandy beaches on the Pacific Coast are found in a region that is slightly more than 20% of the total coastline. Their existence in the area with the lowest potential for delivering sand to the coastline owes entirely to the reduced incident wave energy related to latitude and to the substantial wave barriers provided by Point Conception and the offshore islands.

2.3 Great Lakes

Coastal flooding in the Great Lakes can arise due to elevated still water level and/or storm waves, with energetic storm waves occurring concurrently with elevated water levels being of particular concern. In comparison to the Pacific and Atlantic coasts, the Great Lakes are unique in that they are not subject to astronomical tides of any significance; however, they are subject to changes in water level due to a number of other processes, which act over three distinctly different time scales.

One of these processes is long-term lake level change. The added complexity of a fluctuating lake level is analogous to that associated with a varying mean sea level on the open ocean coasts. The magnitude of historic lake level changes renders this a very important consideration. A severe storm occurring during a low lake level might cause no flooding, but at high lake level the same storm could cause devastating flooding. The other two drivers of water-level change are seasonal-scale changes and storm event-scale changes.

Long-term lake level changes take place gradually, primarily in response to fluctuations in precipitation and evaporation. Lower precipitation leads to lower runoff from the watershed; similarly, higher evaporation draws water from the lakes, causing levels to decline. Long-term lake level fluctuations occur over decadal time scales in response to regional and continental-scale forcing, including the El Niño/La Niña cycles and their effect on rainfall.

Lake levels also change on a seasonal basis; they are lowest during the winter, when a majority of the precipitation in the region is frozen as ice and snow, and evaporation increases as dry winter air passes over the lakes. Levels increase during the spring and early summer as a result of the spring runoff of melting snow and ice, and high monthly rainfall. Water control operations also influence lake level variability, with the locks at Sault Ste. Marie influencing Lake Superior’s discharge and the dam on the St. Lawrence River near Massena influencing Lake Ontario’s levels.

Concurrent with these longer time-scale changes, storm events can cause significant short-term increases in water level, or storm surge.

The same winds that cause a storm surge also generate energetic short-period waves, which at elevated water levels can pose a significant coastal flood hazard. Similar to the generation of wind setup, storm wave characteristics (height, period and direction) are strongly influenced by wind speed, direction, fetch, and duration of the wind from a particular direction.

For example, the north and south coasts of Lake Michigan are more vulnerable to higher wave energy than the east and west coasts, because the fetch is much greater along the long axis of the lake. The generation of waves within the lakes is quite complex due to the sometimes rapid movement of storm systems through the region and the rapid changes in both wind speed and direction that occur. Significant wave heights associated with severe storms in Lake Superior can exceed 30 feet, such as the storm that sunk the Edmund Fitzgerald on November 10, 1975. However, the largest buoy observed waves on the Great Lakes exceed 20 feet with wave periods in excess of 10 seconds. In more sheltered areas, storm wave heights and wave periods are generally smaller. Great Lakes storm wave energy tends to grow quickly and diminish just as rapidly, responding directly to increases/decreases in wind speed.

Ice cover along lake and bay shorelines can affect flooding risks. In general, stable ice cover in the winter serves to reduce the flooding risk due to storm surge and wave action. Stable shore-fast ice cover along the coastline can serve to limit or wholly prevent wave energy from impacting the shoreline. Extensive ice cover across any region of the lake also can limit the generation of waves and storm surge as the wind stress has a shorter fetch upon which to act. While ice cover may reduce the risk from flooding, ice can cause significant direct damage along Great Lakes shores.

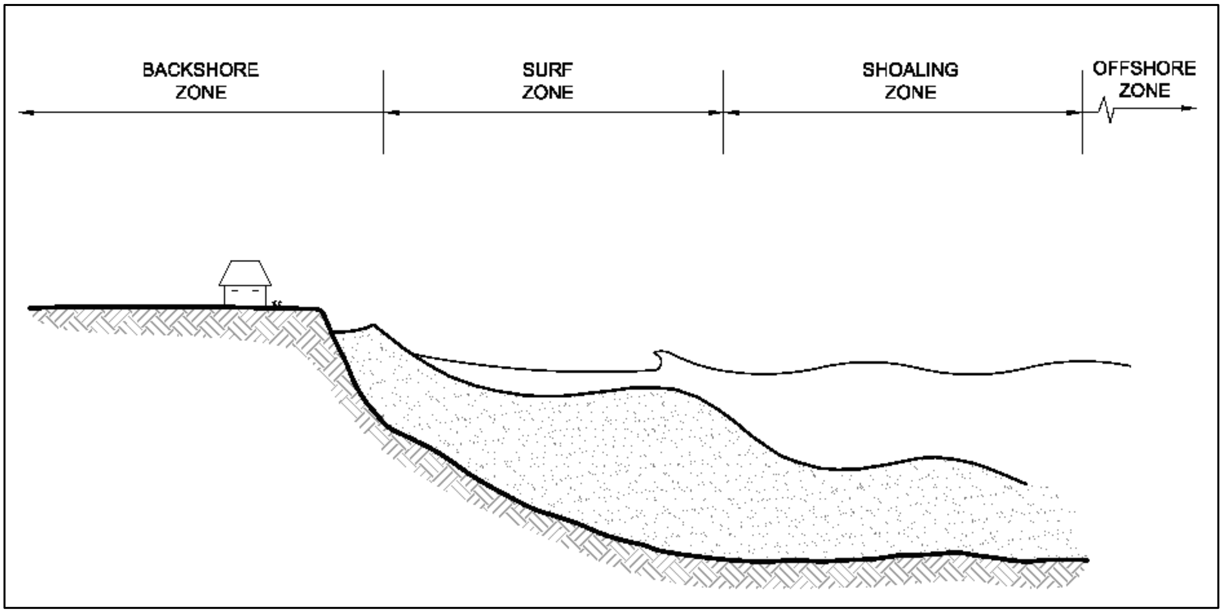
3.0 Coastal Processes

The preceding section described the various components of coastal flood hazards and how they vary by region in significance. This section describes how those components interact with each other and ultimately translate into flood hazards onshore.

3.1 Coastal Zones

Figure 1 shows the cross-shore profile divided into four zones. Computations made in each zone use data from the preceding zone and pass the results to the next zone. Computations generally start in the offshore zone.

Figure 1: Coastal Zones



The offshore zone is the region where waves, and to a lesser degree wind setup, are not substantially influenced by bathymetry. Dominant processes in this zone include (where applicable) lake level, wave growth and propagation, wave energy dissipation due to white capping, astronomical tide, and storm surge.

The shoaling zone is the area outside the surf zone where offshore wave conditions are transformed by interaction with bathymetry or topography and wind has a greater influence on generation of wind setup and storm surge. Wave transformation in this zone includes wave refraction, shoaling, diffraction, energy dissipation due to bottom friction effects and white-capping.

As wind waves propagate into shallow water they refract, or bend. Incoming waves seek to align themselves in such a way that wave crests approach in a direction that is increasingly more parallel to the shoreline with decreasing water depth. This process of wave refraction generally results in decreases in wave height as waves approach the coast, although complex irregular bathymetry can create patterns of locally increased/decreased wave height. In shallow water, wave energy is dissipated due to bottom friction and white-capping and wave heights can decrease further. Waves eventually experience much stronger energy dissipation and subsequent decreases in wave height due to breaking in very shallow water.

The surf zone is where waves break as they interact with very shallow water and wave energy is limited by the local water depth. Dominant processes include fluctuating lake levels (in the Great Lakes), storm surge, wave breaking, generation of wave setup, runup, overtopping, beach and dune erosion, and wave interaction with structures. As waves break moving onshore, wave heights decrease and the flux of wave momentum in the onshore direction is reduced.

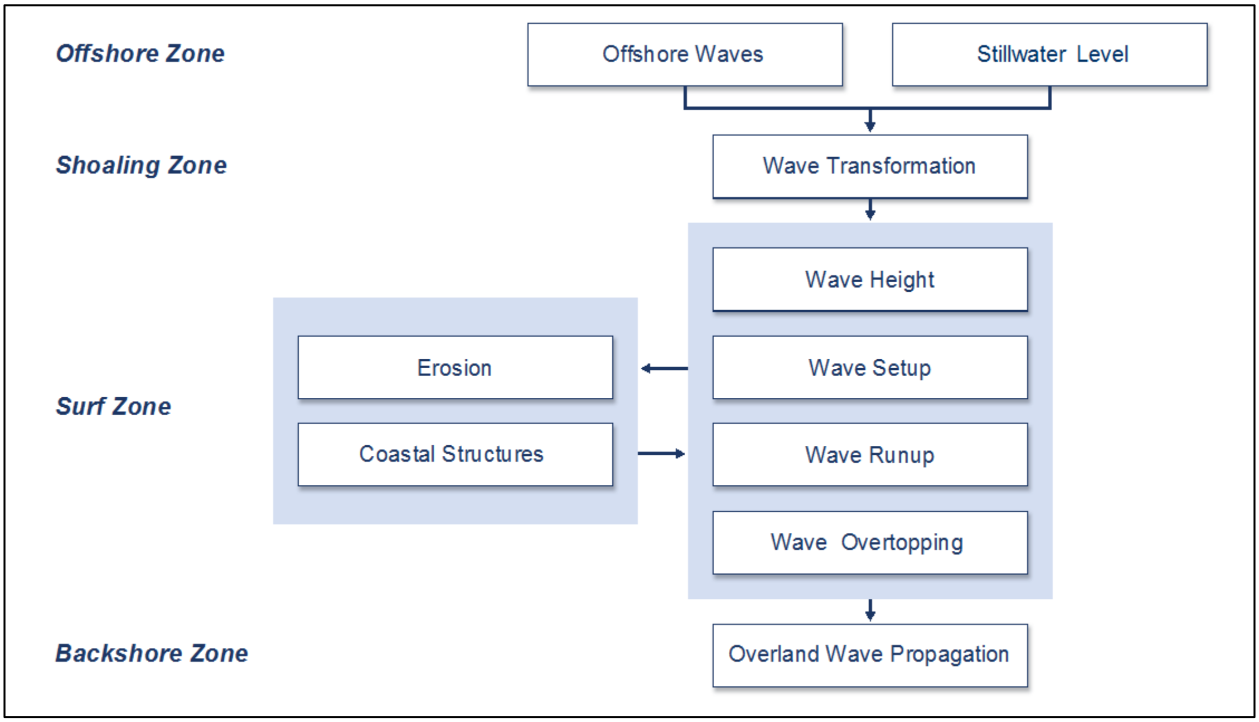
In time-steady conditions, the excess wave force is balanced by a slope in the average water level called wave setup. The magnitude of wave setup is largest in shallow water, and the value is roughly 10 to 20 percent of the incident breaking wave height at the stillwater shoreline. Note that wave setup is only significant in the breaking region, with the most pronounced effect in the inner surf zone and near the stillwater shoreline. At elevated water levels, broken waves runup on beaches and structures where they can pose a significant flood hazard. These wave runup elevations have been shown to reach 15 feet or more for a steep beach slope when incident waves have a significant wave height of 20 feet.

Breaking waves also can erode a beach berm, dune or bluff, especially when the water level is elevated, due either to storms and/or seasonal/long-term increases in lake levels, exacerbating wave runup and overtopping. Persistent overtopping of a dune can lead to further erosion of the dune crest and loss of dune elevation, possibly causing complete degradation of the dune. If dune removal occurs, greater wave energy can propagate inland, with the potential for increased damages to infrastructure and property. The duration of concurrent high water levels and energetic wave action associated with a storm is a strong factor in the magnitude of beach and dune erosion that occurs.

Information from the surf zone is passed to the backshore zone to determine flood hazards, mostly in the form of overland wave height propagation through vegetation and buildings and wave overtopping.

Figure 2 shows the coastal processes that are typically evaluated for a coastal Flood Risk Project. It should be noted that “offshore” does not necessarily imply deep water conditions, which for waves are defined according to water depth and wave length. Although this deep water condition is typical, an “offshore” designation might only mean that the processes being considered are far outside the surf zone. If the offshore zone is not in deep water, then the offshore and shoaling zones are characterized by similar processes.

Figure 2: Coastal Processes



3.2 Shoreline Types

The shoreline morphology determines which analysis tools are appropriate for estimating shoreline responses. The general shoreline settings include:

- Sandy beach, possibly backed by a low sand berm or dune
- Sandy beach backed by coastal development or shore protection structures
- Erosion-resistant beach profile having a small lens of mobile sand
- Cobble, gravel, shingle beach or mixed grain size beach
- Erodible coastal bluffs and cliffs
- Non-erodible coastal bluffs and cliff
- Tidal marshes and wetlands
- Alvars[1]

Details of the specific methods for each coastal setting are given in the detailed guidance units for the various coastal flood hazard analyses.

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[1] Alvars are an ecosystem unique to the Great Lakes consisting of grassland, savanna and sparsely vegetated rock barrens that develop on flat limestone or dolostone bedrock where soils are very shallow.

In all settings, the existing shoreline conditions should be determined. These are required to determine the present location of the shoreline; condition of structures; and to ascertain if the profile includes an erodible sand berm, dune or bluff. Shoreline response to historical events is a good indicator of whether erosion needs to be evaluated as part of a Flood Risk Project. Shorelines having a shore protection structure in the active coastal zone will require consideration of the structure's influence on flood hazards.

Based on the shoreline setting, appropriate models and methodologies are selected for analyses of coastal hazards, including wave setup, runup, overtopping, erosion, and overland propagation. These results are then used for mapping the coastal hazard flood zones.

4.0 Study Methodology Overview

4.1 Regional vs Local Studies

Flood Risk Projects were traditionally performed for a single political jurisdiction, most commonly a community, with the Flood Insurance Study (FIS) Reports and Flood Insurance Rate Maps (FIRMs) being specifically developed for that community. Adjacent communities were only addressed when necessary to ensure that Base Flood Elevations (BFEs) match at the community boundaries. The hydrologic and hydraulic efforts have also typically stopped at the community boundaries, or have extended only so far beyond them as to encompass complete hydrologic units, such as drainage basins, which are necessary to determine conditions within the study community.

This local study approach was followed, in part, due to the demanding computational effort necessary to encompass large regions within the analysis. For example, storm surge calculations require large computational grids, which in turn require large computer capacity and long execution time. Modeling more than a limited portion of the coast was difficult or impossible with the computer capabilities of the past. Similarly, ocean wave simulations were restricted to limited zones in past studies.

Although this community-by-community approach proved tractable, it also had the potential to introduce greater variability into the studies. For example, a long length of coast that was simulated by breaking it into small sections meant that boundary conditions were specified for each segment, with some probable loss in both efficiency and accuracy.

A second source of variability in local studies is that different Mapping Partners may make different assumptions that lead to differences between adjacent studies.

The idea of regional studies is to perform large-scale regional analyses for certain portions of the engineering tasks needed in a community study and to make these analyses available as input to the local studies, for example, large regional databases (e.g., Global Reanalysis of Ocean Waves [GROW] data) of wave hindcast data. These data can be transformed to the nearshore area, just outside the surf zone, as part of a regional study effort covering a very large portion of the Atlantic and/or Gulf Coasts, using a single, consistent, state-of-the-art methodology. The advent of modern computational abilities makes these regional efforts feasible and more cost-effective than community-by-community repetition of a similar effort.

Regional studies can be implemented to varying degrees. Regional studies need not be as large as an entire coastline or a statewide analysis, but instead might cover a limited number of counties. This would be the case if there is a physical characteristic of a region that makes it logical to treat it as a unit, instead of breaking it up into smaller areas. For example, wave studies might be accomplished regionally according to directional exposure, island sheltering, breadth of shelf, or other physical factors. In general, processes that originate in the far field – such as storm surge – are candidates for regional analysis because a single coherent source might affect a large coastal reach. In an event-selection analysis, the selected event might be adopted regionally, controlling behavior within a multi-community basin such as a large sound.

The extent to which regional studies, perhaps focused on particular coastal processes, are available and can be used in local studies depends on planning and implementation of these studies by FEMA. The Mapping Partner should consult with FEMA during the project scoping to determine if relevant regional information or analysis is available and should be incorporated into the study methodology.

4.2 Statistical Analysis Considerations

4.2.1 1-Percent-Annual-Chance Flood Elevation

One of the goals of a FIS is to determine the frequency of recurrence of flood elevations throughout the study area, and to establish the 10 percent, 4 percent, 2 percent, 1 percent %, and 0.2 percent annual chance flood elevations in a study area. The 1 percent annual chance flood elevation is also known as the BFE. The BFE has a probability of 0.01 percent of being equaled or exceeded in any given year. The terms flood level and flood elevation are used interchangeably throughout this guidance.

The flood level experienced at any coastal site is a result of a large number of interrelated and interdependent factors. For example, coastal flooding by wave runup depends on both the incident wave conditions and the concurrent water levels.

The water level, in turn, depends on the contribution of the transient storm surge and the sea or lake level at the time of the storm. The wave characteristics that control runup include wave height, period, and direction, all of which depend on the meteorological characteristics of the generating storm. The resulting wave characteristics are affected by variations of water depth over their entire propagation path, from offshore through the surf zone and the foreshore beach slope, and thus depend also on the varying storm surge.

The beach profile is variable, changing in response to wave-induced erosion and causing variation in the wave transformation and runup behavior. Catastrophic erosion of a dune system might also cause a fundamental change in stillwater elevations. All of these interrelated factors may be significant in determining the coastal 1-percent-annual-chance flood levels. Even in a response-based study, which attempts to simulate the full range of important processes over the duration of a storm, simplifying assumptions are inevitable.

It is important to note that 1-percent annual chance floodplain is a statistical rather than a physical surface, so that the flood hazard maps produced as part of a Flood Risk Project do not necessarily display, even locally, the spatial variation of any one realistic physical hydrologic event. For example, the 1-percent-annual-chance water levels just outside and just inside an inlet will not generally show the same relation to one another as they would during the course of any real physical storm event because the inner waterway may respond most critically to storms of an entirely different character from those that affect the outer coast. Where a flood hazard arises from more than one source, the mapped level is not the direct result of any single storm or process, but is a construct derived from the statistics of all storms and sources.

These guidelines offer insight and methods to address the complexity of coastal flood processes. However, the inevitable limitations of the guidance must be kept in mind. No fixed set of rules can be appropriate in all cases, and the Mapping Partner must be alert to special circumstances that require additional elaborations to the methods set forth in the guidelines or even require deviation from the guidelines. Any proposed deviations from the guidelines should be done in consultation with the FEMA Project Officer.

4.2.2 Event Selection Method

Flood hazard analyses may be simplified if one can identify a single event (or a small number of events) which produces flood levels that approximate the 1-percent-annual-chance flood elevations. This may be possible if, for example, a certain storm parameter governs the flooding process, so that the 1-percent-annual-chance value of that storm parameter can be used to predict the 1-percent flood levels.

For example, in determining the wave runup elevation corresponding to a 1-percent annual chance of exceedance, one might identify a significant wave condition (height and period) thought to be exceeded with only 1-percent annual chance, and then to follow this single wave through its nearshore transformation, breaking and runup on the shoreline. This is the event-selection method. Another example is the case of a small inland bay connected to the open ocean via a single narrow inlet. In this case, it is possible to construct a 1-percent annual chance hydrograph whose peak is informed by statistical analysis of historical/simulated water levels at the inlet, coupled with some representative event duration, and to route this hydrograph into the bay using some numerical model to determine flood levels.

When used with caution, this method may allow reasonable estimates to be made with a lessened effort. It is akin to the concept of a design storm, or to constructs such as the standard project storm or probable maximum storm. The inevitable difficulty with the event-selection method is that multiple parameters may be of significant importance, and it may not be possible to assign a frequency to the result with confidence if other factors that are not considered introduce uncertainty. In the wave runup example, for example, smaller waves with longer periods may produce greater wave runup than the larger waves and shorter periods selected for analysis. Or in the case of the inland bay, an event with a longer duration but a lower peak may result in more extensive flooding.

An event-based analysis for evaluation of the overland wave propagation hazard is recommended for all study areas, due to the complexity involved with trying to merge overland wave envelopes from multiple storm events. A number of approaches exist for generating the 1-percent input conditions required by Wave Height Analysis for Flood Insurance Studies (WHAFIS); these are discussed in the Offshore Waves and WHAFIS guidance.

An event-based approach is also typically recommended for runup and overtopping analyses on open Atlantic and Gulf coasts. On the Atlantic and Gulf coasts, nearshore hydraulic analysis have typically been conducted by assuming a 1-percent storm condition (water level, wave height, and wave period) defined just outside the surf. Because increased wave heights and water levels are both associated with the same forcing event, typically a hurricane, this association is reasonable.

4.2.3 Response-Based Approach

With advancements in computing power, a computationally expensive but more robust approach that considers all (or most) of the complexity of the contributing processes has become practical; this is the *response-based approach*. In the response-based approach, one attempts to simulate the full complexity of the physical processes controlling flooding, and to derive flood statistics from the results (i.e., the local storm responses).

The response-based approach can be applied for studies based entirely on historical storm reconstructions or for studies based on synthetic storm catalogs. In the historical storm case, one would simulate all storm events (or a subset consisting of the severest events, selected using some proxy for storm severity) that have occurred over a long enough period of record, saving water level and wave information along the shoreline.

On a wave runup dominated shoreline, for example, one would then compute wave runup (at specific transects) at discrete time steps over the duration of each storm event. An extreme value approach (e.g. generalized extreme value distribution fitted to annual maxima or generalized Pareto distribution fitted to peaks-over-threshold) can then be used to infer return periods for wave runup elevations. Similarly, in the context of a study using synthetic storm events, one would save water level and wave information along the shoreline for each synthetic storm simulation. On a runup dominated shoreline, one would compute wave runup (at specific transects) at discrete time steps over the duration of each synthetic storm event. A weighted cumulative frequency curve can then be constructed using the joint probability masses or storm weights assigned to each synthetic event.

When using parametric probability distributions (i.e. generalized extreme value or generalized Pareto distribution), some problems may be encountered. For example, on certain transects, some events may produce wave runup, while other events result in overtopping flow. This will result in two distinct populations of responses that do not fit any parametric probability distribution.

A response-based approach for the evaluation of water levels, wave runup and overtopping in the Great Lakes was developed and documented by Melby et al. (2012) and Nadal-Caraballo et al. (2012). This response-based approach is the recommended methodology for all Great Lakes coastal Flood Risk Projects. A response-based approach is also recommended for the Pacific Coast where wave runup is typically the predominant wave hazard.

4.3 Sheltered Waters Considerations

For the purposes of these guidelines, “sheltered” is assumed to imply a significant sheltering effect on the inland propagation of storm surge, waves, and wind by land masses and vegetation. “Sheltered waters” are water bodies or regions that experience diminished forces from wind and/or wave action relative to the open coast due to the presence of physical barriers, both natural and human, either on land or under water.

Sheltered water areas are exposed to the same flood-causing processes as are open coastlines (i.e., high winds, wave setup, runup, overtopping), but sheltering effects reduce the wave energy and flood potential. In many cases, sheltered water shorelines are subject only to locally generated waves. The Mapping Partner should evaluate these potential sheltering effects at both a regional scale and a local site scale.

At a regional scale, wind-generated waves in sheltered water areas are highly dependent on the shape and orientation of the surrounding terrain to prevailing wind directions. Wave generation and transformation in sheltered waters are usually limited by the open water fetch distance, complex bathymetry, and often the presence of in-water and shoreline coastal structures. Other processes, such as the effects of flood discharges from rivers, can modify local tidal and storm surge elevations, and relatively strong tidal and/or fluvial currents can combine to create tidal and hydrodynamic conditions only found in sheltered water areas.

General wave transformation conditions within a sheltered water body may be inferred from wave patterns observed on vertical aerial photographs. During field reconnaissance, the Mapping Partner should make field observations to identify conditions that affect selection of a study approach. Jackson et al. (2002) have identified characteristics of sheltered water shorelines that may be useful as a guide for field reconnaissance.

There are four technical considerations that may complicate the analyses of sheltered waters beyond typical open-coast analyses. These may require a substantially greater computational effort on the part of the Mapping Partner and should be considered carefully prior to the initiation of a new study or the modification of an existing study:

- Coincidence (Phasing) Between the Highest Water Levels and the Highest Waves: The highest water levels and the highest waves coincide along many open coast areas due largely to the fact that the same event (such as a hurricane or extratropical storm) controls both. This may or may not be the case in a sheltered water body, and if such coincidence occurs it will likely not occur everywhere within the sheltered water body. Thus, even within the same sheltered water body, flood analyses must deal with a wide range of phasing possibilities - from full coincidence (e.g., hurricane flooding and wave penetration at a segment of a sheltered water shoreline area) to no coincidence (areas with only locally generated waves, astronomical tides, and small surge). If there is no significant coincidence at a sheltered water shoreline, it may be possible to decouple the hydrodynamic and wave analyses, address each independently, and combine the results statistically.

- Number of Events Modeled: It may be necessary to model more coastal flood-producing events in sheltered waters than on the open coast. While a given event may cause a similar flood response everywhere along an open coast, the same event may cause greatly different responses in a sheltered water body (e.g., the event may cause high surge and waves along one shoreline segment, but may concurrently cause a negative surge, a set–down, and no onshore waves along another shoreline segment).

- Complexity of the Sheltered Water Shoreline and Bathymetry: The complexity of the sheltered water body shoreline and bathymetry will dictate the sophistication of the hydrodynamic and wave models required. Simple water body shapes and relatively uniform depths may allow simplified storm surge and wave analyses. More typical complex water body shapes and variable depths will likely require two-dimensional hydrodynamic and wave models unless otherwise dictated by study constraints (e.g., available data, study schedule, and study budget).

- Number of Analysis Transects Required: Many sheltered water bodies have irregular shorelines, changing profile characteristics (e.g., wetland, beach/dune, bluff, and various armored profiles), and variable upland development patterns. These factors may dictate a reduced transect spacing (down to a few hundred feet in places) and may require many more transects than might be used along an open coast shoreline of the same overall length. It is not possible in most sheltered water flood studies to place transects close enough to capture all of the alongshore variability. However, an experienced Mapping Partner should be able to interpolate between transects using topographic, shoreline structure, land cover, and backshore development information, thereby significantly reducing the number of transects required.

Sheltered water physical processes can be complex and may require detailed numerical modeling to adequately define the flood hazards. Given the availability and relative ease of use of modern numerical models, the Mapping Partner should consider a numerical modeling approach to a sheltered water study where simpler methods do not appear reliable.

Model selection should be made with consideration of the level of complexity of physical processes, data available for calibration, flood risk, and available study budget. If the physical scale of the sheltered water coastal flood study is small and the geographic setting and physical processes are relatively well understood and simple, the Mapping Partner should confer with the FEMA Project Officer about the feasibility of using simplified analytical approaches instead of numerical models. A limited analytical approach may also be appropriate to obtain a quick assessment of physical conditions and/or to provide a check of the results from a numerical modeling approach.

4.4 Beach Nourishment and Constructed Dunes

FEMA does not accredit beach nourishment and/or constructed dunes with providing protection during base flood conditions. However, mapping Partners should be aware that flood hazard mapping of coastal areas could potentially be affected by various types of beach nourishment, and that current topographic data may reflect beach nourishment efforts. The Mapping Partner should determine whether beach nourishment affects a study area, research any beach nourishment projects identified, identify any available data that would allow the performance of the beach nourishment project(s) to be assessed, and determine whether the beach nourishment is likely to persist and have an effect on flood hazard mapping. If it is determined that beach nourishment will likely affect flood insurance risk zones or BFEs, the Mapping Partner should contact the FEMA Project Officer to determine whether presence of beach nourishment should be reflected in topography used for flood hazard modeling and mapping.

Typically, beach nourishment projects are reflected in FEMA Flood Risk Projects only when the nourishment project is significant (i.e. has the dimensions necessary to affect 1-percent-annual-chance flood hazards) and will be maintained for many years. Otherwise, beach nourishment is treated as a temporary shoreline disturbance not capable of withstanding the 1-percent-annual-chance flood conditions. However, if the nourishment project predates the topography being used in the study by multiple years, the beach will likely have adjusted and reached an equilibrium profile and the topography may be considered acceptable for use in a FEMA Flood Risk Project.

Treatment of dune construction or reconstruction projects is similar—the Mapping Partner should treat constructed or reconstructed dunes (i.e., “artificial” dunes) as natural dunes during the study process only if they meet the criteria set forth in the National Flood Insurance Program (NFIP) regulations. Paragraph 65.11(a) of the NFIP regulations does not allow an artificial dune to be considered an effective barrier against coastal flooding unless it has well-established, longstanding vegetative cover, regardless of its size and cross section.

4.5 Primary Frontal Dune

Primary frontal dunes (PFDs) have an important role as the first line of defense against storm surge, waves, and flooding. Given their importance, FEMA regulations protect PFDs from manmade impacts or physical alterations that could increase potential flood damage. These regulations also support hazard-specific building standards and land use requirements. These important floodplain management actions are implemented by designating the entire PFD as part of the coastal high hazard area. Effective October 1, 1988, FEMA included the following revised definition in Section 59.1 of the NFIP regulations:

> *Coastal high hazard area* means an area of special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any other area subject to high velocity wave action from storms or seismic sources.

FEMA also added a clarification of this matter, a definition of PFD, in Section 59.1:

> *Primary frontal dune* means a continuous or nearly continuous mound or ridge of sand with relatively steep seaward and landward slopes immediately landward and adjacent to the beach and subject to erosion and overtopping from high tides and waves during major coastal storms. The inland limit of the primary frontal dune occurs at the point where there is a distinct change from a relatively steep slope to a relatively mild slope.

Thus, the PFD is one of the criteria used to identify and map the coastal high hazard area (Zone VE).

It should be noted that there are some locations in the Great Lakes Basin that feature very large relic coastal dunes that formed following a high phase in Great Lakes water levels known as the Nippising Transgression over 4,000 years ago (Baedke and Thompson, 2000; Figure 3). These dunes, often parabolic in shape, can exceed 100 feet in elevation and have a footprint of many hundreds of feet inland. Further, there can be successive rows of the parabolic dunes and thus the overall footprint of the dune field can be very large. Although these dunes are susceptible to toe erosion at high lake levels, the entire dune will not erode for single storm events.

Although these large dunes often form a continuous ridge and the face is subject to erosion at high lake levels, given their overall size, care must be taken when determining the location of the PFD as Section 59.1 of the NFIP regulations may not apply to these features.

4.6 Debris

Debris may be entrained in tidal floodwaters and cast inland by storm surge and wave propagation. Natural debris consists of floating woody debris, such as drift logs, branches, cut firewood, and other natural floatable materials. Wave-cast beach sediments, such as cobbles and gravel, also constitute natural debris.

Figure 3: Sample of a Large Relic Dune, Mount Baldy, Indian Dunes National Lakeshore, Lake Michigan

Debris from human sources may originate from flood damage. This debris may include broken pieces of shore revetment cast inland by extreme surge and wave attack, or floatable materials, such as construction materials, building materials, and home furnishings.

Debris hazards depend on the beach type and configuration, debris sources, the inland extent of wave propagation, the proximity of insured structures to the shoreline, and the height of the structures above the BFE. At present, debris hazards are not explicitly included in FEMA flood insurance risk zones and, therefore, a detailed debris analysis is not required. However, the Mapping Partner should note significant debris hazards in a study area, document the hazards in the "Principal Flood Problems" section of the FIS Report, and confer with the FEMA Project Officer so relevant information may be shared with community floodplain managers.

4.7 Tsunami

Much of the Pacific Coast and the sheltered waters along the Pacific Coast are subject to tsunami hazards. The most recent major tsunami to affect the Pacific Coast was the 1964 Great Alaskan Tsunami that affected California, Oregon, and Alaska. Tsunamis are very long waves of small steepness generated by impulsive geophysical events such as earthquakes and landslides. Currently, guidance does not exist for inclusion of tsunami hazards in a FEMA Flood Risk Project. The Mapping Partner should confer with the FEMA Project Officer to discuss treatment of tsunami hazards in a particular study area if it is possible that tsunamis may contribute to the base flood.

4.8 Data Requirements

Coastal Flood Risk Projects require a wide variety of quantitative data and other site information necessary to perform the required analyses.

4.8.1 Topography

Use of accurate, high resolution topography data is of primary importance when undertaking Flood Risk Projects. The topographic data, usually in the form of digital elevation data or maps, must be recent and must reflect current conditions including changes due to subsidence or rebound or, at a minimum, conditions at a clearly defined time. Data should extend onshore to the inland limit of flooding at the 0.2-percent level. Transects do not need to be surveyed unless available topographic data are unsuitable or incomplete. The Mapping Partner should examine the topographic data to confirm that the information to be used in the analysis and mapping represents the actual planimetric features that might affect identification of coastal hazards.

If possible, the Mapping Partner should field-check shore topography to note any changes caused by construction, erosion, coastal engineering, or other factors. The Mapping Partner should document any significant changes with location descriptions, drawings, and/or photographs.

The community, county, and state can be sources for topographic data, including Light Detection and Ranging (LiDAR) data. LiDAR data, where available, can be used to define both topography and bathymetry elevations. Other sources are LiDAR surveys flown by the United States Army Corps of Engineers' Joint Airborne LiDAR Bathymetry Technical Center of Excellence (USACE JALBTCX), United States Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA). If gaps in the LiDAR data exist, the next best available data in those areas should be identified. If the best available data does not meet the accuracy standards (FEMA Standards 40-49, 158, and 547), the Mapping Partner should consult with the FEMA Project Officer for approval of its usage.

4.8.1.1 Great Lakes Special Topographic Datum Considerations

Topographic data must extend down at least to the Low Water Datum (LWD) defined for each Great Lake, as listed in Table 1. LWD was established in 1933 and has remained unchanged. While vertical datums used on the Great Lakes have changed several times since 1933, the definition of LWD has not. Presently, LWD is described in terms of the International Great Lakes Datum of 1985 (IGLD85). The Mapping Partner should convert to the North American Vertical Datum of 1988 (NAVD88) from IGLD85 for each coastal flood hazard analysis site. There needs to be some care in transferring IGLD85 elevations to NAVD88. If elevations used are based on land benchmarks, hydraulic correctors and/or dynamic height adjustments may need to be applied.

Table 1: Elevations of Low Water Datum on the Great Lakes

Location	Low Water Datum Elevation, Feet Above IGLD85	Low Water Datum Elevation Feet Above NAVD88
Lake Superior	601.1	601.0
Lake Michigan	577.5	577.6
Lake Huron	577.5	577.6
Lake St. Clair	572.3	572.5
Lake Erie	569.2	569.4
Lake Ontario	243.3	243.4

4.8.2 Bathymetry

Bathymetry data are required for the regional-scale storm wave and water-level modeling, nearshore wave transformation modeling and wave runup calculations. In general, the best available data that meets the resolution requirements of the modeling effort should be used.

For transect analyses, it is not possible to provide precise guidance on the extent of bathymetry needed. The extent primarily depends on the magnitude of incident storm wave conditions. For most shore types and open coast settings, bathymetry out to water depths of approximately 40 feet is required for wave transformation evaluations. In more sheltered areas with less energetic storm wave conditions, bathymetry out to water depths of 10 feet or even less might suffice.

Where turbidity is low, LiDAR data can provide an excellent source of shallow water bathymetry data for characterizing the surf zone and inundation zones, from which to extract information along transects. Beach profile surveys, or bottom elevations inferred from nautical charts or from USACE bathymetric surveys, are other alternative data sources for defining nearshore bathymetry. Bathymetric data can be acquired from the NOAA Office for Coastal Management's Digital Coast web site, and USACE for their holdings.

4.8.3 Land Cover

Land cover data is necessary for hydrodynamic surge model setup, runup calculations (slope roughness factors), and overland wave propagation modeling. The necessary information classifies both structures and vegetation into different categories that can be translated into appropriate model parameters, as necessary. There are often several land cover data sources that may cover the project region. These should be reviewed and compared. Some sources of land cover data include NOAA's Coastal Change Analysis Program (C-CAP) Land Cover Atlas, USGS' National Land Cover Dataset (NLCD) and Gap Analysis Program (GAP) datasets, and other regional and local land cover datasets.

4.8.4 Storm, Meteorological, Ice, Wave and Water-Level Data

A number of different types of data are required to facilitate selection of storm events and to develop wave and water-level information for each storm at a regional scale. These data types include storm track and climatology data, meteorological data (such as winds and atmospheric pressures) that constitute forcing for waves and storm surge, data describing ice cover during storms that can influence generation of surge and waves (in the Great Lakes), water-level data for characterizing long-term and seasonal-scale lake level changes (in the Great Lakes), tidal data (on the Atlantic, Gulf, and Pacific Coasts), and wave and water-level data for model skill assessment. Most of the required data sets are produced by, and are available from, federal agencies; although state, local agencies and universities might also be valuable sources of data and local knowledge.

4.8.5 Coastal Structures

The Mapping Partner should obtain documentation for significant coastal structures that may provide protection from the 1-percent-annual-chance flood. That documentation should include the following:

- Type and basic layout of the structure
- Dominant site particulars (e.g., local water depth, structure crest elevation, and ice climate)

- Construction materials and present integrity
- Design documentation and analyses conducted, if available
- A historical record for the structure, including construction date, maintenance plan, responsible party, repairs after storm episodes
- Clear indications of the effectiveness or ineffectiveness of the structure as protection

The Mapping Partner should develop much of this information through office activity, including a careful review of aerial photographs. In some cases, site inspection would be advisable for major coastal structures to confirm preliminary judgements. If there are questions as to whether a coastal structure should be considered in the analysis as providing protection from the 1-percent-annual-chance flood, consultation with the FEMA Project Officer may be required as well as with other federal, state, and local agencies.

4.8.6 Historic Floods

Local information regarding previous storms and flooding can be very valuable in developing accurate assessments of coastal flood hazards and validation of storm-surge models. General descriptions of flooding are useful in determining what areas are subject to flooding and in obtaining an understanding of flooding patterns. Quantitative and qualitative information, such as the areal extent of flooding, high water marks, and location of buildings flooded and damaged by wave action, can be used to verify the results of the coastal analyses. Detailed information on pre- and post-storm beach or dune profiles is valuable in checking the results of the erosion assessment. When quantitative data are available on historical flooding effects, the Mapping Partner should make an effort to acquire all recorded water elevations and wave conditions for the vicinity.

4.9 Floodplain Mapping

A principle objective of a coastal study is to provide legible and accurate FIRMs with appropriate BFEs including the contributions of wave effects. It is not only important that the mapped results of the flood hazard study be technically correct, but also that the FIRM be easy for the community official, engineer, surveyor, and insurance agent to use.

This objective should be considered throughout the study process, particularly during transect placement for wave hazard analyses, and review of the wave hazard analysis results. An effort should made to site transects and map results in a way that avoids large changes in BFEs from one property or reach of shoreline to the next, particularly in areas dominated by wave runup.

Another important aspect of floodplain mapping related to the usability of the FIRM is the size or width of flood zones. It may be useful to set a minimum width criterion for mapped flood zones since these zones are mapped for the purpose of locating buildings or property in a flood insurance risk zone. The mapping criteria and the ability to map all coastal BFE and hazard zone changes is dependent upon the scale of the FIRM. For coastal areas, general guidance is to have a minimum zone width of 0.1 inch on the FIRM—for example, a width of 50 feet for a FIRM at a scale of one inch equals 500 feet, or a width of 100 feet for a FIRM at a scale of one inch equals 1000 feet. Because digital FIRM data can easily be enlarged, the map scale limitations should be reviewed with the FEMA Project Officer and community officials.

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