D.4.2 Study Methodology

This section provides guidance for selecting and combining specific technical methods and data into a study methodology. The selection of methods depends upon the coastal setting and available data.

D.4.2.1 Overview

In this appendix, “methods” means the individual techniques used to make specific computations. “Study methodology” is the combination of appropriate methods and data necessary to develop flood hazard zones for depiction on a Flood Insurance Rate Map (FIRM). A variety of technical methods are presented in Sections D.4.3 through D.4.7 of this appendix. In most cases, several methods may be applicable to a specific coastal setting. The objective of this section is to provide guidance for developing an appropriate methodology based on the coastal setting and available data.

A significant portion of Appendix D is devoted to the presentation of technical methods. It is important to remember that the objective of this document is to provide guidance necessary to develop flood hazard zones and maps. The level of technical analysis should remain consistent with this objective. It is only necessary to obtain data and conduct analyses that are required to accomplish this objective. Because there are often several methods available to conduct similar analyses, the Mapping Partner must choose methods that are technically consistent, are applicable for the study setting, use available data, and are appropriate for project resources.

The recommended generalized study methodology is summarized below. To consider what data and technical methods are appropriate, begin onshore by identifying information that is required to develop the flood hazard zones and mapping. This involves identifying the physical processes that likely contribute to flood hazards in the study area, and their interaction with particular geomorphic settings. In some cases, this initial review will not resolve all of the questions related to coastal processes and hazard zones. However, the review should identify the data requirements for one or more methods that can be applied to make these determinations. For example, it may not be clear at the beginning of a study whether a particular coastal structure or levee will meet Federal Emergency Management Agency (FEMA) criteria. In this case, the data and methods needed to determine whether the structure will fail or not, and the data and methods needed to analyze the failed and in-place conditions, should be identified.

After a review of probable hazards at the shoreline, progress offshore considering what data and analyses are then required at each level and for each setting within the study area to accomplish the previous onshore analysis step. This will establish the offshore limit of the data and computations necessary to conduct the analyses. In most cases, this limit will correspond to offshore conditions. Once the offshore data requirements for the study are established, bring the waves and other information back onshore to determine information to develop the hazard zones. In other words, the mapping needs are established by progressing from the hazard map to the offshore, but the analysis proceeds in the direction of the physics – from offshore to onshore.

Different data requirements are associated with different analysis methods. For example, if methods are based on the deep water unrefracted significant wave height and peak wave period, it is not necessary to examine the details of the spectrum. If it is not necessary to transform the waves across the surf zone, the surf zone bathymetry is not required for this method. More advanced methods generally require additional data.

Figure D.4.2-1 summarizes the basic steps in selecting analysis methods. This logic may be applied to both the overall study (study methodology) and to selection of methods for each major coastal process to be analyzed in developing flood hazard zones. The basic logic begins with the definition of objectives, which should focus on development of flood hazard zones at an appropriate resolution and level of accuracy considering potential damages, inherent uncertainty in the analyses, schedule, and budget. The geomorphic setting is a key factor in identifying dominant physical processes that must be analyzed and the appropriate methods for analysis. Potential methods applicable to a given setting may have different data requirements, and the availability of data may influence the selection of methods. Once a methodology has been defined (combination of methods and data), the Mapping Partner must confirm that the methodology satisfies the study objectives, including time and budget constraints.

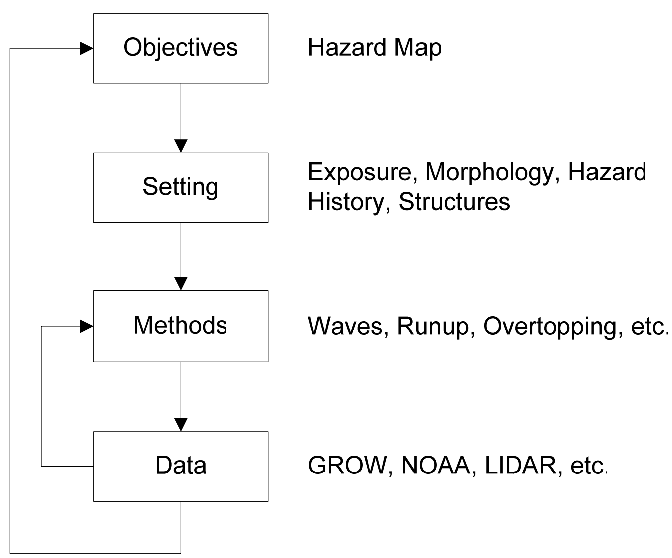


Figure D.4.2-1. Study Methodology Development Considerations

D.4.2.2 Setting

The study area setting and hazard history will determine which methods and data are necessary and/or appropriate. Important considerations include the coastal exposure (open water or sheltered water), the shoreline morphology (e.g., dunes, bluffs, cliffs, etc.), and the shore conditions (topography, development, etc.). Consideration of each of these conditions frames the data requirements and the appropriate analysis methods.

D.4.2.2.1 Open Coast and Sheltered Water

A primary consideration is the exposure of the shoreline; either open coast or sheltered water. Open coast settings are exposed to the full influence of the Pacific Ocean and include processes such as sea, swell, astronomical tides, and El Niño. In sheltered water, the waves are primarily due to local processes, while on the open coast, waves may be generated by both local and distant weather conditions. On the open coast, the interrelationships among waves and water-level processes may be quite complex. As a result, simultaneous measurements and/or hindcasts of these processes are recommended to avoid reconstructing the complex interrelationships. This is a key point for the Pacific Coast. Methodologies prescribed in Appendix D.4 recognize the complexity of describing the interactions between waves and water levels, and as such these processes are analyzed simultaneously in time as they naturally occur in nature.

In sheltered water, the waves are typically generated by local weather, which simplifies the interrelationships. As a result, it may be possible to employ statistical or simulation techniques to analyze these processes. However, additional considerations in sheltered water such as tidal amplification, currents, and the effects of river inflows must be considered. While most methods for open coasts are also applicable for sheltered water, a number of special considerations for sheltered water exist.

D.4.2.2.2 Shoreline Profile Settings

The shoreline morphology determines which analysis tools are appropriate for estimating shoreline responses. The general shoreline settings on the Pacific Coast include: 1) sandy beach backed by low sand berm or high sand dune formations; 2) sandy beach backed by coastal development or shore protection structures; 3) cobble, gravel, shingle beach or mixed grain sized beach; 4) erodible coastal bluffs; 5) non-erodible coastal bluffs and cliffs; and 6) tidal flats and wetlands. Details of the specific methods for each setting are given in Section D.4.6.

Figures D.4.2-2a, b summarize key considerations for each of these six settings. In all settings, the existing shoreline conditions must be determined. These are required to determine the present location of the shoreline, condition of structures, etc. For settings in which beach profile changes are computed (beach/dune and structures), the initial winter profile from which storm-induced changes are calculated must be determined. This initial profile is referred to as the most likely winter profile (MLWP). Profile changes are estimated with the appropriate model to yield an eroded profile. If the eroded profile results in dune breaching, structure failure, or bluff recession, then an adjusted final profile must be determined. Wave setup, runup, overtopping, and overland propagation are then determined for the final profile. These result are then used for mapping the flooding hazards.

1. For a sandy beach backed by a low sand berm or high sand dune, the MLWP is the expected winter condition of the beach profile at the time when a large storm might occur. This is the initial profile condition from which beach changes associated with large storms are calculated. This is an important step because there are significant differences

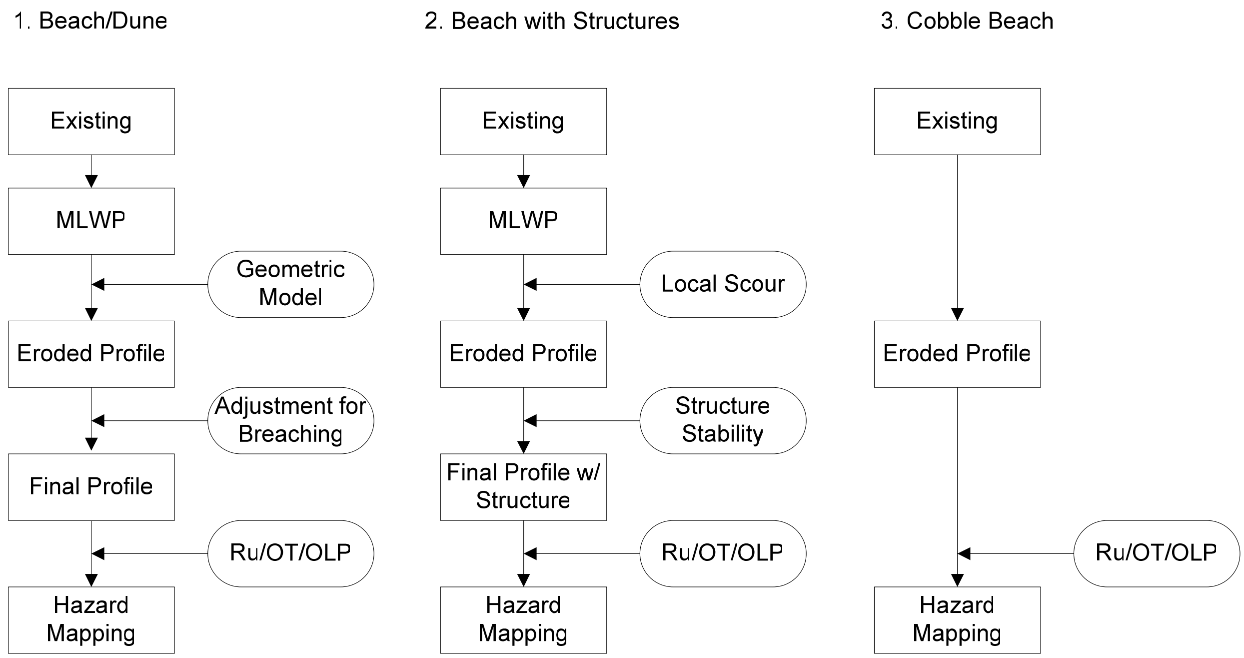


Figure D.4.2-2a. Shoreline Profile Setting Nos. 1 to 3

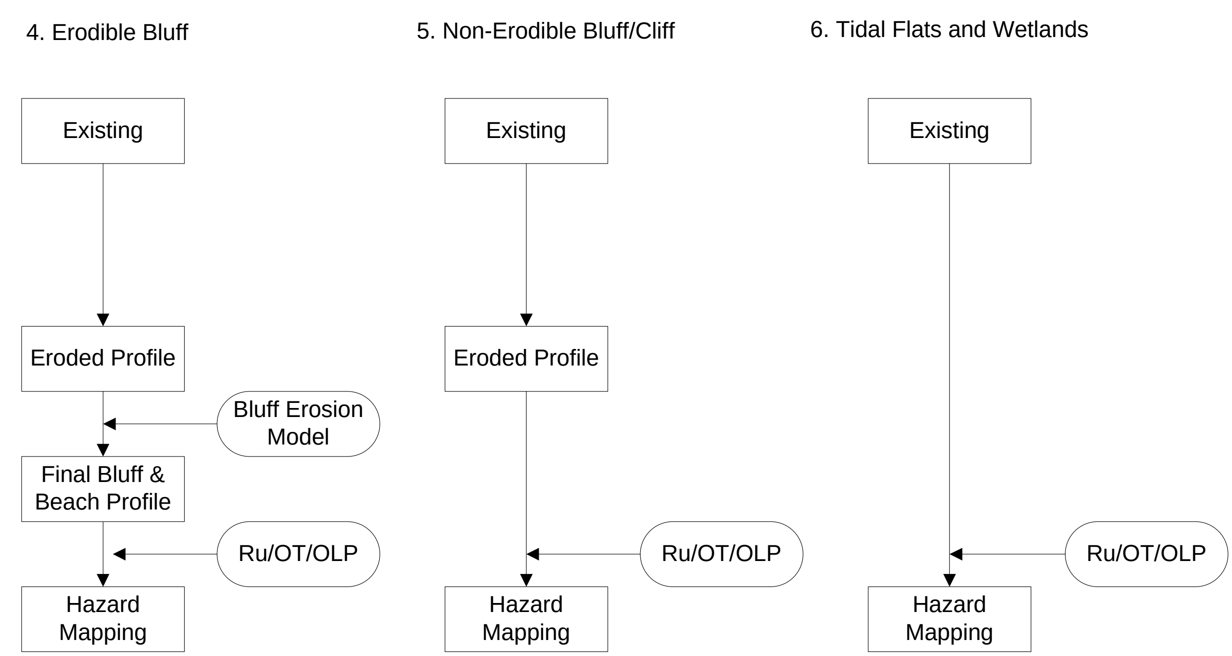


Figure D.4.2-2b. Shoreline Profile Setting Nos. 4 to 6

between the summer and winter profile conditions. The changes are estimated using geometric profile response models to determine the eroded profile. Process-based models are an alternative means of estimating the profile changes. At present, process-based models have not been adequately calibrated for Pacific Coast conditions, and are not recommended without site-specific calibration. If the dune is overtopped or breached, then the profile is adjusted by removing a portion of the dune. The runup (*Ru*), overtopping (*OT*), overland wave propagation (*OLP*), and possibly ponding are then calculated using this final profile.

2. For a sandy beach backed by shore protection structures, the eroded profile is determined from data rather than a shoreline change model. The structure may cause local scour and the structure may fail. The final profile based on these processes is then examined for *Ru*/*OT*/*OLP* and possibly ponding.

3. For a cobble beach, little analytical guidance is available because many of the cobble beaches on the Pacific Coast are mixed grain sizes and are difficult to model. As a result, observed profiles during large events are used as the basis for determining *Ru*/*OT*/*OLP* and possibly ponding.

4. For erodible bluffs, the eroded winter beach profile is determined from measurements. The bluff recession is estimated with a bluff erosion model. The resulting profile is then used to determine the *Ru*/*OT*/*OLP* and possibly ponding.

5. For non-erodible bluffs, the eroded winter beach profile is determined from measurements. This profile is then used to determine the *Ru*/*OT*/*OLP* and possibly ponding.

6. For tidal flats and wetlands, it is assumed that there is no erosion over the timescale of a single storm. Therefore, *Ru*/*OT*/*OLP* are determined on the existing profile for high water level and storm conditions.

D.4.2.3 Coastal Zones

Figure D.4.2-3 shows the cross-shore divided into four zones. The offshore zone is the area influenced by waves and water levels that are not substantially influenced by bathymetry or topography. Dominant processes in this zone include swell, seas, astronomical tides, storm surge, and large-scale climatic perturbations such as El Niño. The shoaling zone is the area outside the surf zone where offshore conditions are transformed by interaction with bathymetry or topography. This includes refraction, diffraction, dissipation, and generation of waves. The surf zone is where waves break as they interact with the bottom. Dominant processes include wave setup, runup, overtopping, erosion, and interaction with structures. The backshore zone is the area that is outside the normal surf zone, but may be subject to inundation during coastal flooding events. This area is subject to development and is the critical area for determination of flood hazards.

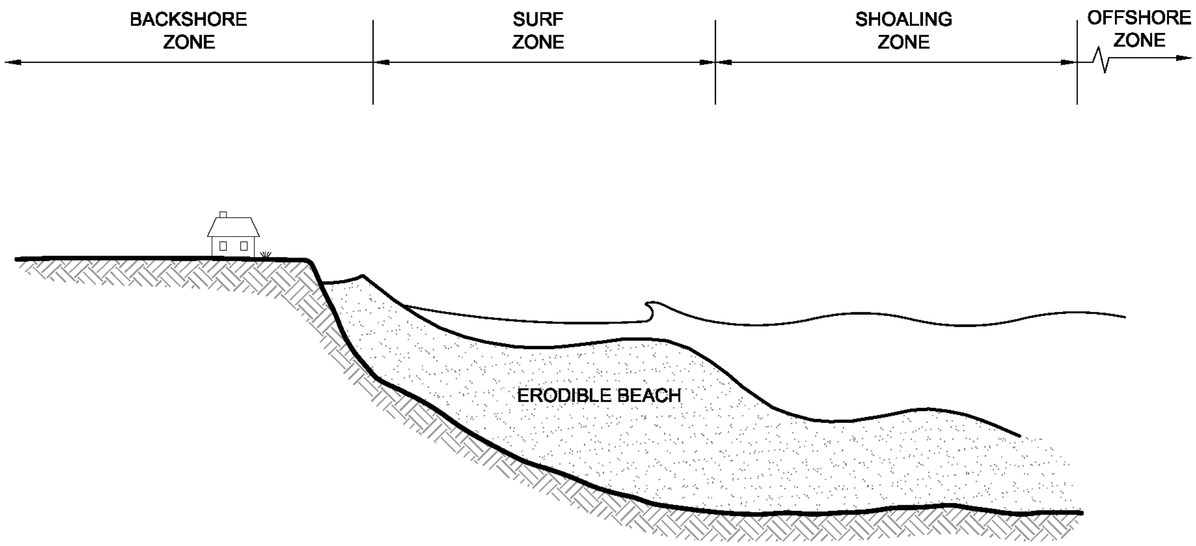


Figure D.4.2-3. Coastal Zones

Typical computations for a coastal Flood Insurance Study (FIS) progress from offshore through the shoaling and surf zones. The transformation of waves and the interaction of waves and corresponding water levels with the backshore zone are used to define hazard zones. The general parameters used for hazard zone mapping are water level (elevation and depth), water velocity, and the product of water depth and velocity squared. This last parameter is used as a threshold indicator for damage potential in areas of sheet flow overtopping.

Figure D.4.2-4 shows the coastal processes as they are referenced to in the analysis methods given in Sections D.4.3 through D.4.7. Note that offshore does not necessarily mean deep water conditions. Offshore simply means outside the surf zone. If the offshore is not in deep water, then the offshore and shoaling zones are combined. Also, the determination of hazards is not restricted to the backshore. Depending on the type and magnitude of event, the flood hazard may also occur in the surf or other 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. Wave information is determined from measurements or hindcasts. Water levels are determined primarily from measurements. The resulting estimates for waves and water levels are then passed to the shoaling zone where wave transformations are determined. The offshore wave conditions are input to wave transformations, but the wave transformations do not influence the offshore wave conditions. Therefore, offshore wave conditions may be determined independently from the transformations.

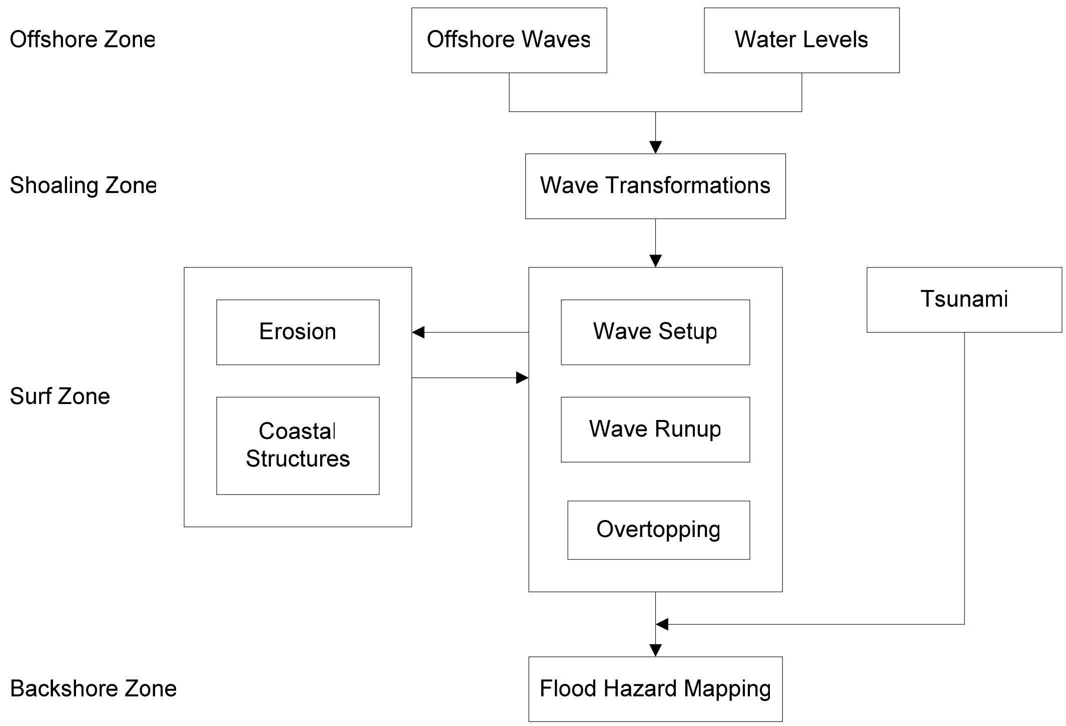


Figure D.4.2-4. Coastal Zones and Processes

In the shoaling zone, the offshore waves are transformed onshore to a water depth outside the breaker line. This requires information for the bathymetry and possibly other factors, such as dissipation over kelp beds, mud flats, or wetlands. Several of the surf zone analysis methods require unrefracted deep water wave conditions. After the waves have been transformed across the shoaling zone, the corresponding unrefracted deep water conditions may also be determined. These results are then passed on to the surf zone. Again, the surf zone results do not influence the wave transformations, so wave transformations may be determined independently of the surf zone. The structure of this appendix reflects this independence. Section D.4.4, Waves and Water Levels, includes processes that occur in the offshore and shoaling zones; these are offshore waves, water levels, and wave transformations.

Surf zone computations use nearshore bathymetry and either the wave conditions determined outside the breaker line or the unrefracted deep water conditions. Setup, runup, overtopping, and erosion are estimated at the shoreline depending upon the specific shoreline conditions. These results are then passed to the backshore zone to determine flood hazards.

In the backshore, information from the surf zone is combined with topography and land use type to calculate hazards and develop a hazard map. For most cases, the backshore does not influence the surf zone and the surf zone is independent of the backshore. However, it is possible that processes in the surf zone are not completely independent of processes in the backshore zone. For example, surface runoff during a storm can increase backshore flooding, but may also develop an ephemeral stream across the beach face that will impact surf zone processes. Unless site-specific conditions that violate this assumption exist, it is recommended that independence be used in the analysis. This key assumption is invoked below to define the transition from analyses based on multiple events to an analysis based on a single event.

D.4.2.4 Event and Response Analysis Considerations

On the Atlantic and Gulf coasts, the 1% annual chance flood has typically been associated with a 1% storm event condition defined offshore and transformed to the surf zone. Because increased wave heights and water levels are both associated with the same forcing event, typically a hurricane, this association is reasonable. However, on the Pacific Coast, waves may be associated with both local and distant storms; water levels are influenced by El Niño, setup, and tides; and low frequency oscillations in the surf zone significantly influence runup. As a result, no single mechanism is responsible for the 1% annual chance flood. Rather, a number of processes are occurring and the statistical interrelationships among these processes are not well defined. Therefore, statistical tools such as joint probability, Monte Carlo, and empirical simulation methods are difficult to apply. An alternative is to use measured or predicted wave conditions along with simultaneous measured or predicted water-level conditions. Bundling the physical processes together as they actually occur in nature eliminates the need to determine the statistical relationships among the various processes. The response in the surf zone and backshore to these simultaneous physical processes may then be determined, and the 1% annual chance flood characteristics are determined from the response statistics rather than the event statistics.

An event corresponds to a set of time-dependent wave and water-level conditions taken as a paired data set with a specific duration. This differs from the concept of independently analyzing a 1% wave or 1% water level. When treated together, no statistical probability is assigned to either the waves or the water levels. Rather, a number of observed large events (i.e., high waves and water levels) are analyzed to determine a number of responses in the backshore zone each year. The largest response from each year is noted and then the annual maxima for the entire period of record are analyzed to determine the 1% annual chance flood response. This general methodology differs substantially from that typically used on the Atlantic and Gulf coasts.

As noted above, the wave and water-level analysis for the offshore and shoaling zones in sheltered water may be treated differently than open water due to a smaller number of independent variables and/or lack of reliable wave data or hindcasts. However, the concept of using a set of conditions to define responses and performing statistical analysis on the responses may also be applied in sheltered water.

The 1% response may be determined at the boundary of any one of the zones shown in Figure D.4.2-3. For example, a 1% annual chance combination of waves and water levels might be statistically determined in the offshore zone by examining the joint occurrence of waves and water levels. This condition could be transformed onshore, setup and runup estimated, and the flood hazard zone mapped. However, it is unlikely that this single combination of waves and water levels with a 1% annual chance in the offshore zone corresponds to the 1% annual chance flood hazard in the backshore zone. Other combinations of waves and water levels that have a lower probability of occurrence may result in higher levels of the flood hazard due to differing responses in the form of runup, setup, erosion, or coastal structure interaction in the backshore zone. These responses are dependent on variables such as wave period and event duration. The

1% annual chance flood is defined as the basis for hazard zone mapping by FEMA; thus, the response at the backshore is the condition of interest. Again, the mapping of the hazard is not restricted to the backshore, and under some circumstances may also occur in the surf zone or other zones.

Although the response-based approach is reasonable theoretically, it may not be practical to include all coastal processes in the computations before statistical analysis in the backshore. This would require a very large set of computations with potentially significant spatial variation in controlling conditions and results. However, the further the response-based approach can practically be carried onshore, the better the estimate of the 1% annual chance flood hazard in the backshore zone. As a standard methodology, it is recommended that the 1% annual chance determination be made on total water level (TWL) elevations. If overtopping occurs, then the determination of the overtopping rate and overtopping volume should be made using the 1% runup and the associated storm. These are the most significant hydrodynamic parameters influencing flood hazards. This standard methodology may require modification where processes in the backshore (ponding, riverine flows, etc.) influence the flood hazards.

Figure D.4.2-5 shows a cross-shore diagram of the transition from multiple storms to a single condition for the case of a dune-backed sand beach. Waves and simultaneous water levels are determined for multiple storms each year. Each of these storms is then transformed to the nearshore. Then, setup, runup, and dune recession are determined for each of the storms. The largest TWL elevation is selected from each year, and then an extreme value statistical analysis is conducted on the annual maxima from all years of the record to determine the 1% annual chance runup event. This single event is then used to determine the corresponding 1% overtopping rate and volume. These terms are then used to determine hazards. Hazard indicators include the water depth, velocity, and product of depth times velocity squared.

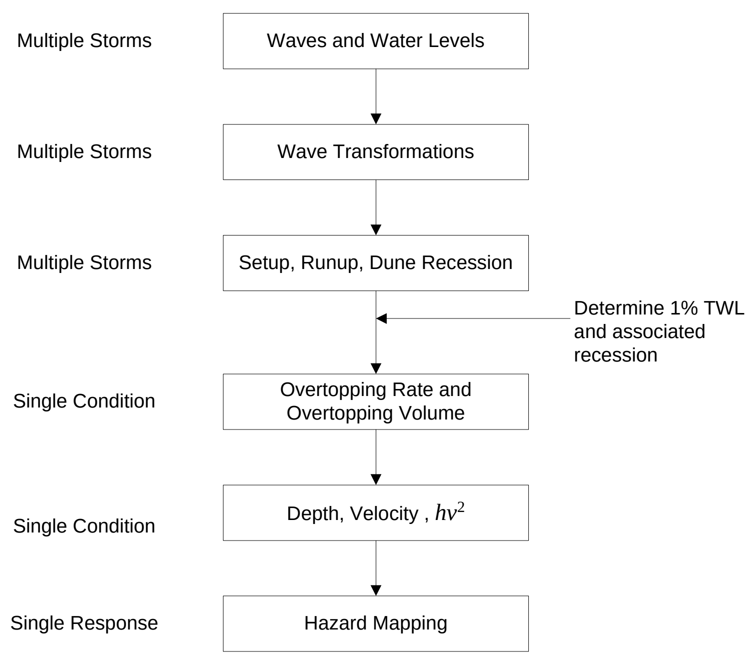


Figure D.4.2-5. Transition from Multiple to Single Events

D.4.2.5 Selection of Events

D.4.2.5.1 Open Coast

Offshore wave conditions, as either measured data or hindcasts, are available for most of the open coast shorelines of the Pacific. It is recommended that these data be used for offshore wave conditions. Each storm year, the largest 10 to 20 storms from these data are selected for analysis. The water levels occurring at the time of each of the storms are determined from measurements or calculations. By examining the 10 to 20 largest storms each year, it is very probable that one of these, along with the associated water levels, captures the largest actual response for the year. The largest storms should be based on largest wave height and the largest resulting runup. The largest response for each year of the simulations (annual maximum) is used in an extreme value statistical analysis to determine the 1% annual chance flood response. Concerns about capturing the relevant storm each year may be addressed by analyzing more storms each year.

D.4.2.5.2 Sheltered Waters

For open coasts, wave conditions can be determined from existing data, either wave measurements or wave hindcasts. In sheltered waters, if these data are available, then analysis methods similar to open water coastlines are recommended. If these data are not available, wave information must be estimated through hindcasts. These hindcasts should be based on two-dimensional (2-D) numerical models or using the parametric methods prescribed in the Coastal Engineering Manual (CEM) (USACE, 2003). Winds used in the hindcast model should correspond to the largest storms each year. The resulting waves are combined with water levels occurring at the same time to estimate the responses. The largest response for each year is selected and analyzed to determine the 1% annual chance flood response similar to the methods used in open waters.

Conducting this type of analysis for a number of storms each year for a number of years requires substantial amounts of data and a significant computational effort to combine actual water levels with hindcast waves. It may not be practical or possible to conduct this number of computations. For these cases, joint probability methods may be used. In this approach, a limited set of wave and water-level conditions are used to estimate joint probabilities. A number of responses are then calculated based on the data from these distributions. The results are then analyzed to determine the 1% annual chance flood response.

Sheltered waters are the only exposure setting in which joint probability methods are applicable. They are only to be used where data are not available or sufficient hindcasts cannot be conducted to capture the annual maximum response.

D.4.2.5.3 1% Annual Chance Conditions

The determination of the 1% annual chance flood hazards based on a 1% annual chance response at the shoreline (as opposed to estimation of 1% annual chance storm conditions offshore) provides a more direct connection between the actual causal events and the flooding response. However, as soon as the 1% annual chance response is statistically estimated through extemal analysis, the resulting flood parameters (e.g., elevation, velocity, depth, volume) are no longer coupled to the forcing physics.

The still water level (SWL) is the elevation of the free surface in the absence of waves and wave effects. The primary components are the astronomical tide, El Niño, and surge. The TWL is the SWL plus the wave effects. The primary wave effects are static setup, dynamic setup, and runup. The TWL is an important parameter for identifying coastal flood hazards because it is the primary term that identifies if overtopping will occur. Therefore, the TWL is the variable upon which the selection of the 1% conditions is based. However, the TWL is not the only important variable for determining flood hazards. Other variables include the profile change, the overtopping rate (q), and the overtopping volume (V). The determination of the 1% q and V somewhat complicates the analysis.

The 1% TWL does not correspond to any single physical event. Rather, it is an extrapolation of the TWL conditions from the largest events because of the limited duration of the available data. If the TWL exceeds the backshore elevation, the overtopping rate and overtopping volume are also calculated. The TWL primarily depends on the water level, wave conditions, and the beach face or structure slope. The overtopping rate depends on these variables and the height of the dune or structure. The overtopping volume depends upon these variables and the duration of the overtopping event. In the 1% annual chance determinations, the 1% overtopping rate and overtopping volume are all assumed to be associated with the 1% TWL events. This may not always be the case. Mapping Partners may propose an alternative statistical approach for defining the 1% annual chance flood if this assumption is not appropriate for specific conditions.

A similar concern may exist if multiple transects are considered for a ponding calculation. The 1% annual chance overtopping volume would correctly be addressed by considering all transects that contribute to the ponding simultaneously in the overtopping analysis. However, this may be computationally intensive and not justified by the accuracy of other steps in the analysis. Unless there are unique site-specific reasons to do otherwise, it is recommended that the 1% values of TWL, overtopping rate, and overtopping volume calculated for each transect be used.

The following discussion outlines the procedure for determining the 1% overtopping rate and volume using the TWL as the basis for selecting the most significant conditions. For this discussion, it is assumed that the wave data have 20 storms per year for each year of 30 years of wave data. For each storm, the following terms are computed: the maximum TWL; the maximum wave height (H) and the associated wave period (T); peak enhancement factor of the spectrum (γ); the storm duration (D); the storm duration recession reduction factor (α); the maximum overtopping (q) (if overtopping occurs); and overtopping volume (V) (integral $q\,\mathrm{d}t$). H corresponds to the appropriate wave height for the analysis. For a beach, it is the offshore wave height, but for a structure, it is the wave height at the toe of the structure.

The values for the computed terms that correspond to the largest TWL each year are saved for the extreme value analysis. Again, the TWL is the indicator for selecting the most significant conditions. In addition, the largest storm in the wave data is noted and the time series of both the waves and the water levels are recorded.

For all storms, the TWL is computed and therefore it is straightforward to make a 1% estimate of TWL based on the annual maxima. The determination of the 1% overtopping rate and volume are more complicated and fall into three categories.

- **Case 1:** If the 30 years of wave data do not result in overtopping and the extrapolation to the 1% conditions does not result in overtopping, then it is not necessary to consider overtopping. The results correspond to the adjusted profile and the 1% TWL conditions.

- **Case 2:** If at least one storm in each year of the 30 years of waves results in overtopping, then an extreme value analysis may be directly conducted using the TWL, overtopping rate, and overtopping volume. The profile corresponds to the adjusted profile with overtopping.

- **Case 3:** If there is not an overtopping event for each year of data, it is more difficult to determine the 1% overtopping rate and volume. For this case, the 1% q is calculated from the appropriate overtopping equation using the 1% estimates for H and T (and other variables if required). The profile corresponds to the adjusted profile with overtopping. The 1% V is more difficult to estimate because it depends on the variation of wave conditions and water levels during a storm. A 1% storm is approximated by linearly scaling up the largest storm time series in the record by the 1% H, T, and D. Overtopping is then computed using the 1% storm, the water-level changes associated with the 1% storm, and the data for SWL. The overtopping is integrated over the storm duration to yield the 1% V. Note that this 1% storm is only used in Case 3 and only then for estimating V. It is not a 1% design storm condition as is commonly used on the Atlantic and Gulf coasts.

To summarize the three cases:

- **Case 1:** There is no overtopping.

- **Case 2:** The annual maxima provide sufficient data to make a direct statistical determination of the 1% Q and V.

- **Case 3:** The annual data are not sufficient to make a direct statistical determination, so the variables needed to compute q and V are determined (by scaling) at the 1% level and then these are used to calculate the 1% q and V.

In general, the application of these procedures to shoreline settings that may experience profile changes (berms/dunes, erodible bluffs, and structures) are more difficult than settings that do not have profile changes (cobble beaches, non-erodible bluffs/cliffs, and tidal flats/wetlands). Figure D.4.2-6 shows a general flow diagram for all shoreline settings. For settings that do not have profile changes, the profile change boxes do not apply. For cases with changes, then the appropriate type of profile change for the setting shall be used.

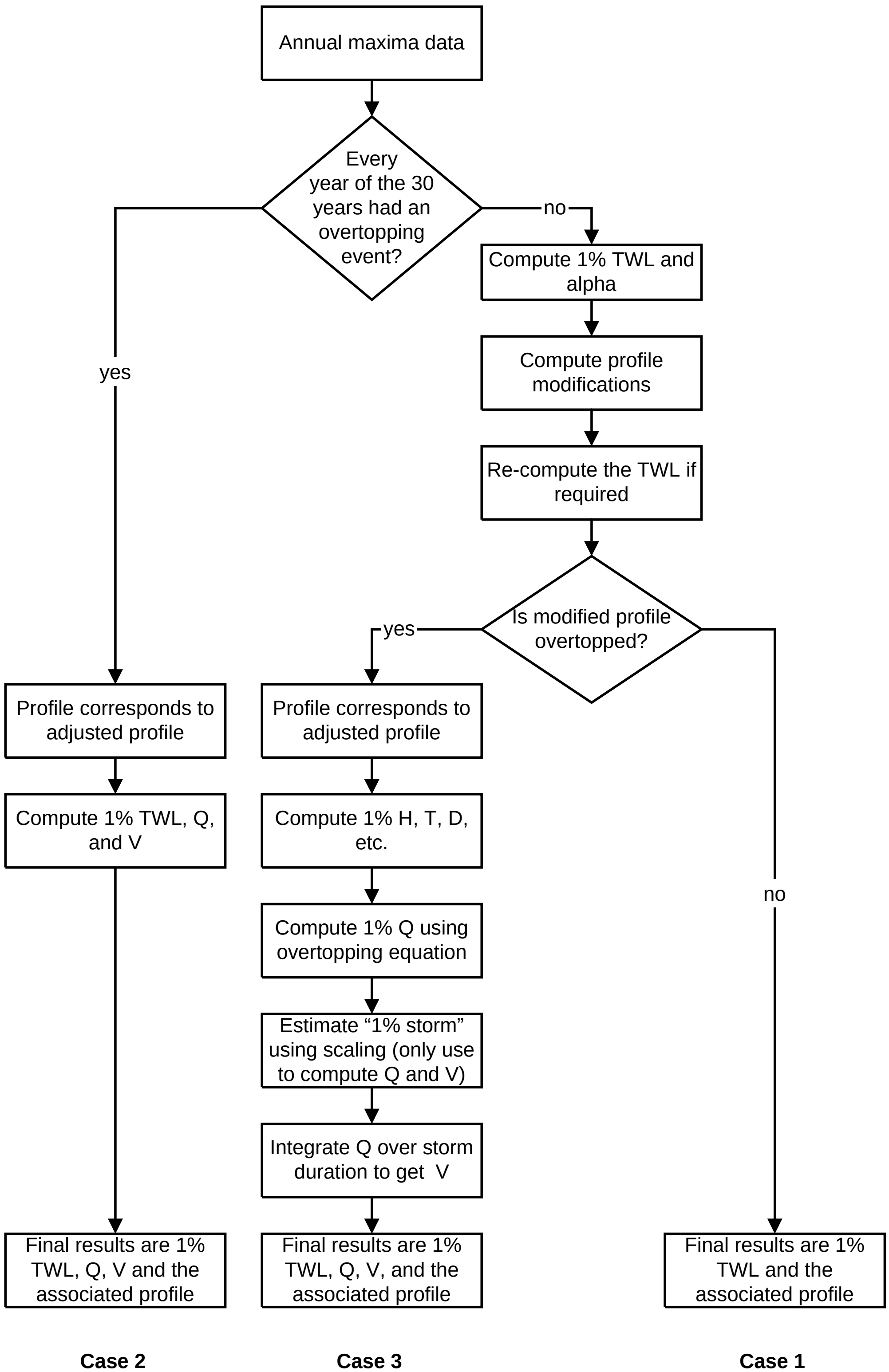


Figure D.4.2-6. Determination of 1% Conditions

Example: Sandy Beach Backed by Berm or Dune (Setting No. 1)

For each of the 20 annual storms:

1. Determine static setup and/or TWL as required by geometric recession model to calculate the potential recession for the storm, $R_{\infty storm}$.

2. Determine storm duration recession reduction factor for the storm, α.

3. Determine duration limited recession for storm, R_{storm}, and if the berm/dune is breached.

4. If runup is different on modified profile, re-compute runup.

5. If runup results in overtopping, then compute overtopping. Save the maximum overtopping value. Compute the overtopping volume as V = integral q dt over duration of storm.

6. For each year, save conditions corresponding to the largest annual TWL conditions: TWL, q, V, α, H, T, D, γ, etc.

Determine 1% conditions:

If every year of the 30 years has overtopping (Case 2):

- The profile corresponds to the adjusted profile.

- Directly compute 1% estimates of TWL, q, and V (Generalized Extreme Value [GEV] and maximum likelihood).

If there are any years with no overtopping:

- Determine the 1% setup and/or TWL α, and R_{storm}.

  If there is no overtopping at the 1% level (Case 1):

  – If runup is different on modified profile, re-compute TWL.

  If there is overtopping at the 1% level (Case 3):

  – The profile corresponds to the adjusted profile.

  – Compute the 1% H, T, D, etc.

  – Calculate the 1% q from overtopping equations.

  – Select the largest storm, and scale it up by the 1% H, T, and D to define 1% storm to obtain q and V.

  – Using the 1% storm, water-level changes due to the 1% storm, and the measured SWL, determine the 1% V by integrating q over the duration of the storm.

Example: Beach Backed by Structure (Setting No. 2)

For each of the 20 annual storms:

1. Determine the TWL and wave height at structure.

2. Compute scour and adjust profile as required.

3. Determine structure stability. If structure fails, completely or partially remove structure.

4. If runup is different on modified profile, re-compute runup. (Note: Runup requires wave height at the toe of the structure.)

5. If runup results in overtopping, then compute overtopping. Save the maximum overtopping value. Compute the overtopping volume as V = integral q dt over duration of storm.

6. For each year, save conditions corresponding to the largest annual TWL conditions: TWL, q, V, α, H, T, D, γ, etc.

Determine 1% conditions:

If every year of the 30 years has overtopping (Case 2):

- The profile corresponds to the adjusted profile (structure removed or partially failed).
- Directly compute 1% estimates of TWL, q, and V (GEV and maximum likelihood).

If there are any years with no overtopping:

- Determine the 1% TWL and local H.

  If there is no overtopping at the 1% level (Case 1):
  - If runup is different on modified profile, re-compute TWL.

  If there is overtopping at the 1% level (Case 3):
  - The profile corresponds to the adjusted profile.
  - Compute the 1% H, T, D, etc.
  - Calculate the 1% q from overtopping equations.
  - Select the largest storm, and scale it up by the 1% H, T, D.
  - Using the 1% storm, water-level changes because of the 1% storm, and the measured SWL, determine the 1% V by integrating q over the duration of the storm.

The methodology for determining the 1% overtopping rate and volume is similar for the other settings, cobble beach, erodible bluff, non-erodible bluff or cliff, and tidal flats/wetlands.

D.4.2.5.4 0.2% Annual Chance Conditions

The 0.2% annual chance conditions (500-year conditions) are used to map the X zones. The determination of the 0.2% conditions and the associated flood hazards is completely analogous to the methods used to determine the 1% conditions. The 0.2% conditions are determined using the same GEV results as the 1% conditions (but evaluating at the 0.2% level) and all of the same physical processes are addressed in a similar way.

D.4.2.6 Summary of Methods

Table D.4.2-1 is a summary of methods presented in Section D.4. This table provides an overview of available methods and reference to the appropriate section of the document.

Table D.4.2-1. Summary of Methods Presented in Section D.4

Zone/Process	Method	Comments
All Zones	**Statistics (D.4.3)** 1% condition - GEV and maximum likelihood fit Peak over threshold with Pareto distribution Joint Probability Methods (JPM), Monte Carlo, Empirical Simulation Technique (EST)	Annual maxima are used to determine the 1% condition. JPM, Monte Carlo, or EST are only used in sheltered waters
Offshore Zone	**Waves (D.4.4)** Measured NDBC, CDIP Hindcast GROW, WIS, WAVEWATCH III Wave Generation 2-D models CEM parametric model	The use of significant wave conditions (height, period, direction, storm duration) or directional spectra depends upon the choice of the methods selected for determining setup, runup, and overtopping. The wave record must be long enough (30 years or longer) to reasonably estimate the 1% annual chance condition. Wave generation methods are only applicable in sheltered waters or a regional-scale offshore model.
Offshore Zone	**Water Level (D.4.4)** Measured Water Level astronomical tide, surge, El Niño Sheltered Waters Seich, tidal amplification, rivers	In most cases, the measured TWL, corrected to local conditions, is used in the analyses. A number of other factors can influence the water level in sheltered waters.

Table D.4.2-1. Summary of Methods Presented in Section D.4 (cont.)

Zone/Process	Method	Comments
Shoaling Zone	**Wave Transformations (D.4.4)** Straight and parallel contours shoaling and Snell's Law Spectral methods transformation coefficients, CDIP Nearshore transformations 2-D spectral and time domain models Sheltered waters seiching, inlets	Numerical models are typically only required for complex bathymetry
Surf Zone	**Wave Setup and Runup (D.4.5)** Beaches DIM parametric DIM numerical Advanced Models - Boussinesq Structures van der Meer, CEM	Methods combine setup and runup. Parametric method only requires significant wave height. Advanced models are only necessary for complex conditions.
Surf Zone and Backshore Zone	**Erosion (D.4.6)** Beaches Geometric Models Process-Based Models Shore Protection Structures CEM scour equations Cobble Beaches Observed storm profiles Erodible Bluffs Nobel bluff erosion model Non-Erodible Bluffs and Cliffs No erosion Tidal Flats and Wetlands No erosion	Process-based models are not recommended for the Pacific Coast at this time. The Atlantic and Gulf Coast "540 Rule" is not recommended for the Pacific Coast.
Backshore Zone	**Overtopping (D.4.5)** Beaches CEM Structures CEM, Besley	
Backshore Zone	**Overland Flow (D.4.5)** Cox and Machemehl, WHAFIS	

Table D.4.2-1. Summary of Methods Presented in Section D.4 (cont.)

Zone/Process	Method	Comments
Backshore	**Hazard Indicators (D.4.8)** Runup depth Overtopping splash distance Depth times velocity squared Wave height Primary frontal dune	

D.4.2.7 Examples

There are many methods and data sources presented in this appendix. The development of the details for a specific study methodology depends on the coastal setting, available data, and project resources. However, the overall methodology for most studies is likely to be similar. Consider the three cases shown in Figure D.4.2-7.

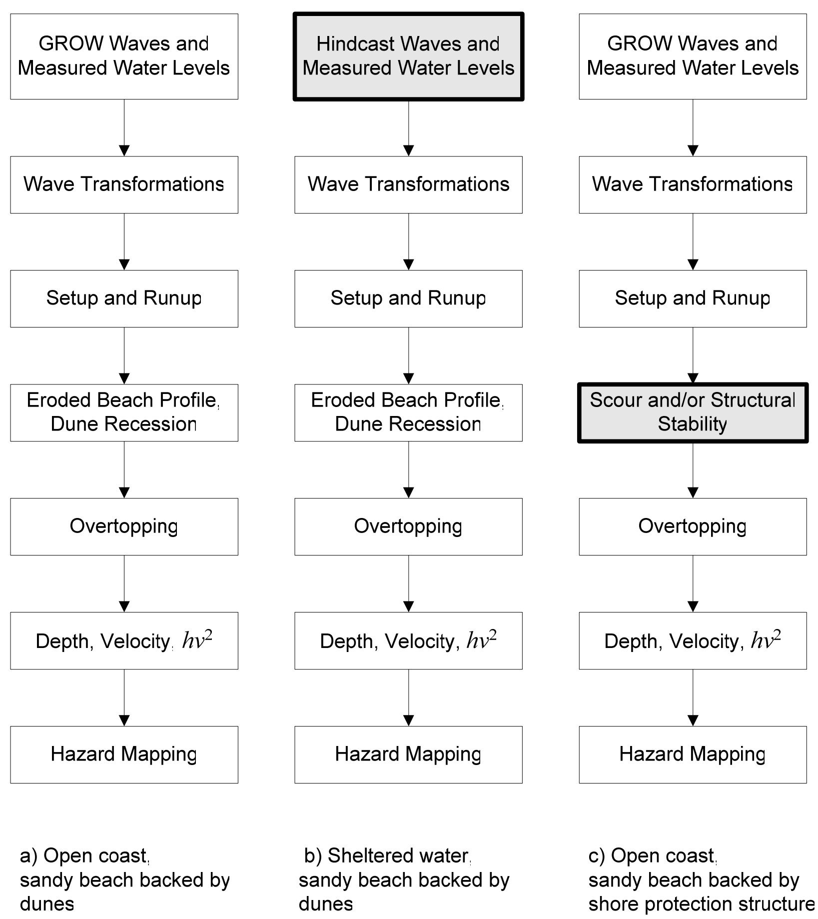


Figure D.4.2-7. Methodology Examples

Case (a) is for an open coast exposure, with a sand beach backed by dunes. The principal steps are:

1. In the offshore zone, determine the wave and water-level conditions.

2. In the shoaling zone, transform the waves to the nearshore.

3. In the surf zone, determine the setup, runup, dune recession, eroded beach profile, and overtopping.

4. In the backshore zone, determine the hazard indicators: depth, velocity, depth times velocity squared (hv^2), overtopping, etc.

5. Map the hazards.

Now consider the setting for Case (b). The only difference between Cases (a) and (b) is that the setting for Case (b) is in sheltered water. The most significant difference in the methodologies is that in sheltered water, wave information is generally not available and must be hindcast or statistically estimated. The waves and water levels are then combined and transformed onshore to the study area. There are differences in the magnitude of specific components in wave transformations between open coasts and shelter waters (i.e., dissipation over shoals), but the overall processes are similar. The same comment is also true for the surf zone and backshore processes.

Case (c) is similar to Case (a), except that rather than a dune, there is a coastal shore protection structure. The only significant difference in the analysis is the method to estimate dune recession is replaced by a method to estimate structure responses. All of the other principal steps in the two methodologies are similar.

The principal steps in the methodology are similar for most study cases. However, there are differences in the specific methods that may be employed at a given step. The following examples demonstrate the selection of specific methods. These examples are for demonstration purposes and may not correspond to an actual study site.

D.4.2.7.1 Open Coast, Dune Backed Beach Scenario Using *Parametric* DIM Model for Setup/Runup

Setting: Open coast, bottom contours that are nearly straight and parallel, and a sand beach backed by dunes.

Data: Offshore GROW hindcast data and measured water levels. Winter season beach and dune profiles. Sand grain size.

For this example, the parametric DIM model is selected to estimate setup and runup, and overtopping is estimated with empirical equations.

The hazards are determined primarily from the 1% annual chance TWL. The 1% TWL is determined at the corresponding eroded beach profile location. This final TWL may be based on the results from the DIM parametric runup model or re-evaluated on the eroded profile using the more complex DIM numerical runup model. If there is overtopping, this may cause additional erosion of the dune. This is addressed in a very simplistic manner. For the modified Komar and Allan method, the MLWP slope is extended until it daylights out the back side of the dune. For the Kriebel and Dean method, the profile is recessed until it daylights out the back of the dune. For this breached condition, the 1% overtopping rate and volume are determined using the wave and water-level conditions corresponding to the 1% TWL.

The DIM model (both the parametric and numerical versions) provides estimates of the total runup. The total runup is the sum of the static setup plus the dynamic setup plus the wave runup. For random waves, the runup corresponds to the value exceeded by 2% of the runup events. This is a short-term statistic associated with a group of waves or associated with a particular storm. It is a standard definition of runup and is commonly denoted as $R_{2\%}$. This 2% is different from the 1% annual condition that is associated with long-term extreme value statistics. The 1% condition has an annual probability of occurrence of 1%, which approximately corresponds to the 100-year condition, while the runup corresponds to the 2% exceedance in several hours of waves. To avoid confusion, the 2% runup is referred to as the *total runup* or just the runup and is denoted as R. Unless otherwise indicated, the runup in all sections of D.4 is defined as the 2% runup.

The GROW waves are analyzed for each storm year to determine the 10 storms that have the largest wave height and the 10 storms that have the largest runup, yielding up to 20 storms per year. The parametric DIM model is used to estimate the setup/runup that depends upon the product of the wave height and wave length. Therefore, the 10 storms that have the largest wave height-length product are selected. Many of the storms selected by the height and by the height-length criteria may be the same. The parametric DIM model is based on the unrefracted deep water significant wave height. The dune recession model is based on the peak runup that occurs during the storm and the duration of the storm. Therefore, the required wave conditions for each storm are the peak unrefracted deep water wave height, the wave period, and the storm duration. No computations regarding the spectral or time series details of the waves are required, nor are details of the waves in the surf zone.

The dune recession model requires the determination of the MLWP. This is the expected condition of the beach profile during the winter season when a large storm might occur. The MLWP may be determined from winter beach profile data, average winter wave conditions, or historical information. For this example, winter profile data are available.

Next, each storm in each storm year is examined with the dune recession model. The model can start each storm from the MLWP or sum the recession from multiple storms over a season. Unless there are data or other information available to suggest that multiple storms be considered, a single storm-by-storm analysis is used. For the present example, this would yield 10 to 20 TWL estimates per year. The conditions corresponding to the largest TWL each year are saved. These annual maxima for each storm year of wave data are then analyzed using a GEV and maximum likelihood. The methods discussed in Subsection D.4.2.5.3 are used to determined the 1% overtopping rate and volume. Using these values and an overland flow model, the depth, depth times velocity squared, and wave height are estimated in the backshore. The hazards are identified based on these results.

Specific methods for each of these steps are identified in Table D.4.2-2. In Table D.4.2-2, H_s is the significant wave height, T_p is the peak wave period, D is the storm duration, $H_{s\ max}$ is the maximum significant wave height during the storm, L_0 is the deep water wave length, h is the water depth, q is the overtopping rate, and v is the water velocity.

If the 0.2% annual chance flood conditions are to be determined, the steps starting from the statistical analysis are repeated at the 0.2% level. It is not necessary to repeat any of the analyses before this step. The results from the GEV are used to determine the 0.2% values. These are then used in the remaining steps following the same procedures as for the 1% conditions.

Table D.4.2-2. Open Coast, Dune Backed Beach Example using Parametric DIM Model for Setup/Runup

Zone	Processes	Recommended Methods	Comments
Offshore	Waves	GROW hindcasts for H_s, T_p, and direction every 3 hours	Empirical runup equations use H_s and T_p, so spectra are not required for waves.
	Water Levels	Measured Water Levels	Not required to separate components (i.e., El Niño, astronomical tide, surge, etc.). Correct water levels to same times as waves.
Shoaling	Transformations	For straight and parallel contours, use shoaling and Snell's Law refraction. For complex bathymetry, use numerical models.	Determine unrefracted deep water wave conditions. Only transform H_s and T_p.
		Select 10 largest wave height storms per year and 10 largest H_sL_0 storms per year	At the peak of each storm, determine H_{smax} and T_p, and determine D. Note annual storms along with waves and water levels.
Surf	Setup and Runup	Parametric DIM model	DIM is for total runup, which includes static setup, dynamic setup, and wave runup.
	Event Based Erosion	Geometric methods: MK&A or K&D	Determine MLWP from survey data or waves and local conditions. Determine maximum SWL and/or TWL each year for the appropriate geometric method, compute eroded beach profile and dune recession.
	Overtopping w/ dune breaching → Beach Profile Adjustment; Overtopping w/o breaching → Setup and Runup; No Overtopping → Statistical Analysis	If dune breaching, daylight specified profile on back side of dune.	For MK&A, extend MLWP slope to back side of dune. For K&D, translate profile shoreward.
	Setup and Runup	DIM parametric or numerical model to estimate TWL on modified profile.	If profile adjustments influence TWL, recompute TWL.
	Statistical Analysis	GEV and maximum likelihood to estimate 1% TWL and other variables as required.	Using the largest TWL event from each year, determine the 1% conditions.

Table D.4.2-2. Open Coast, Dune Backed Beach Example using Parametric DIM Model for Setup/Runup (cont.)

Surf	Beach Profile Adjustment	Geometric Method: MK&A or K&D	Determine eroded beach profile and dune recession for 1% TWL and if overtopping, include profile adjustment for dune breaching.
	Overtopping	Empirical equations	Determine the maximum overtopping rate and estimate the overtopping volume.
Backshore	Overland Flow and Ponding	Cox and Machemehl	Determine the depth, velocity, and flow.
Hazard	Hazard Assessment	Determine quantities necessary to map VE, VO, AH, AO, BFE, etc.	Map the hazard zones.

D.4.2.7.2 Open Coast, Dune Backed Beach Scenario Using *Numerical* DIM Model for Setup/Runup

Setting: Open coast, bottom contours that are nearly straight and parallel, and a sand beach backed by dunes.

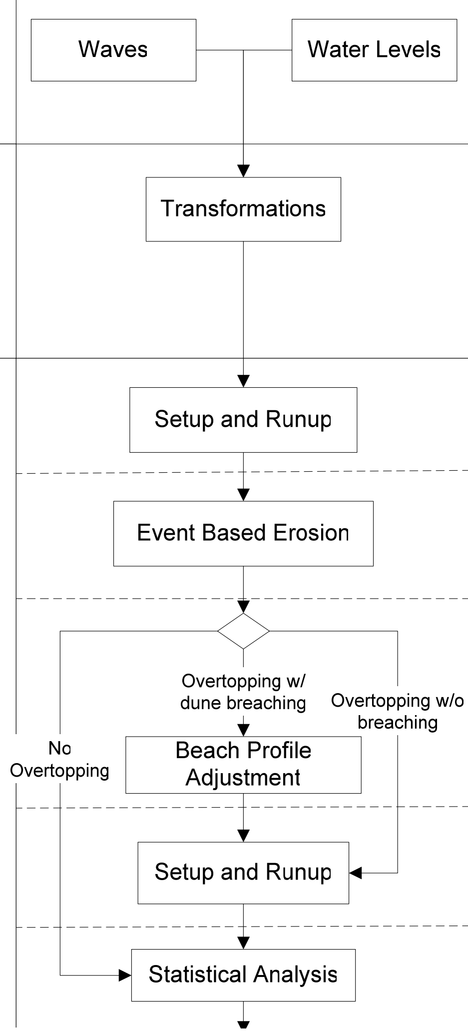
Data: Offshore GROW hindcast data and measured water levels. Winter season beach and dune profiles. Sand grain size.

For this example, the DIM numerical model is selected to estimate setup. Runup is determined by the methods described in Subsection D.4.5.1. All other conditions and methods are the same as in the preceding example. This example shows that the data requirements are dependent upon the choice of analysis methods. An advantage of the DIM numerical model over the parametric version is that the effects of surf zone bathymetry and detailed spectral wave statistics may be included. The DIM model integrates a 1-D wave spectrum across a transect to yield the setup. The dynamic wave setup and the incident wave runup are combined statistically.

A wave time series is developed assuming a JONSWAP spectrum. The magnitude of the dynamic setup is sensitive to the bandwidth of the spectrum that is characterized by the JONSWAP peak enhancement factor, γ. GROW wave data sets provide information to estimate γ. Time series are developed assuming random phases. The DIM model uses the unrefracted deep water wave conditions. The shoaling/refraction may be estimated for the spectrum using the spectral wave transformation methods. Waves on the Pacific Coast, and especially in Southern California, tend to have three energy components; southern swells, northern storms, and local seas. The DIM model can treat each of these as a JONSWAP spectrum and develop a combined time series. Unless there are unusual conditions, this computational effort is not warranted and a single JONSWAP spectrum may be used. The DIM numerical model is 1-D in the cross-shore direction, and a directional spectrum is not required. However, the influence of wave direction on the energy must be considered in the wave transformations.

The DIM numerical model integrates the momentum equations across the surf zone and requires the beach profile as input data. Steps in implementing the numerical DIM model are summarized in Table D.4.2-3. The spectral wave information, wave transformations, and estimates for runup/setup differ from the preceding example. All other steps are similar.

Table D.4.2-3. Open Coast, Dune Backed Beach using Numerical DIM Model for Setup/Runup



Zone	Processes	Recommended Methods	Comments
Offshore		GROW hindcasts for H_s, T_p, direction, and gamma every 3 hours	DIM uses a parameterized JONSWAP spectrum (or multiple simultaneous spectra).
		Measured Water Levels	Not required to separate components (i.e., El Niño, astronomical tide, surge, etc.). Correct water levels to same times as waves.
Shoaling		For straight and parallel contours, use shoaling and Snell's Law. For complex bathymetry, use transformation coefficients.	Determine unrefracted deep water spectral wave conditions (1-D spectrum).
		Select 10 largest wave height storms per year and 10 largest C_gE storms per year	At the peak of each storm, determine H_{smax} and T_p, and determine D. Note annual storms along with waves and water levels.
Surf		DIM numerical model	From spectra for each 3 hour interval of data, develop time series assuming random phases.
		Geometric methods: MK&A or K&D	Determine MLWP from survey data or waves and local conditions. Determine maximum SWL and/or TWL each year for the appropriate geometric method, compute eroded beach profile and dune recession.
		If breaching, daylight specified profile on back side of dune.	For MK&A, extend MLWP slope to back side of dune. For K&D, translate profile shoreward.
		DIM parametric or numerical model to estimate TWL on modified profile.	If profile adjustments influence TWL, recompute TWL.
		GEV and maximum likelyhood to estimate 1% TWL.	Using the largest TWL event from each year, determine the 1% conditions.

Table D.4.2-3. Open Coast, Dune Backed Beach Using Numerical DIM Model for Setup/Runup (cont.)

Surf	Beach Profile Adjustment	Geometric Method: MK&A or K&D	Determine eroded beach profile and dune recession for 1% TWL and if overtopping, include profile adjustment for dune breaching.
	Overtopping	Empirical equations	Determine the maximum overtopping rate and estimate the overtopping volume.
Backshore	Overland Flow and Ponding	Cox and Machemehl	Determine the depth, velocity, and flow.
Hazard	Hazard Assessment	Determine quantities necessary to map VE, VO, AH, AO, BFE, etc	Map the hazard zones.

D.4.2.7.3 Sheltered Water, Seawall Backed Beach Scenario Using Parametric DIM for Setup/Runup

Setting: Sheltered water, bottom contours that are nearly straight and parallel, and a sand beach backed by seawall.

Data: Historical meteorological information and measured water levels. Winter season beach profile. Structure configuration. Sand grain size.

In this example, wave data are not available and must be estimated. There are two methods for estimating waves: 1) 2-D wave generation models and 2) parametric models. The 2-D models are generally superior, but are data-, labor-, and computationally intensive. For this example, the CEM parametric approach is used. The objective is to determine the largest TWL that occurs each year, which is then used in the GEV to determine the 1% conditions. The computational effort may be significantly reduced by carefully selecting which storms to analyze. The wind speed, duration, and fetch length (wave direction) determine the magnitude of the waves. The waves, along with water level (which may include the effects of both tidal and riverine processes), determine the TWL. Different transects in a sheltered water area will have different storms for the 1% TWL because of the wind direction. For many sheltered water areas, the waves will be fetch limited.

Once the waves have been hindcast, they are transformed to the site. The beach profile fronting the structure should be determined from data corresponding to winter conditions. For these conditions, local scour at the structure is determined using the methods from the CEM. Next, the stability of the structure is examined. If the structure fails, or is not a FEMA-recognized structure, it should be fully or partially removed. Details of this procedure are given in Section D.4.8.

Determination of runup on structures differs from beaches in that the wave conditions are evaluated at the toe of the structure rather than in deep water. Simple estimates of the wave height at the toe may be made assuming a breaker index times the total static water depth (SWL plus the static wave setup). Other alternatives are to use the DIM numerical model or Boussinesq models. The specific wave runup equation depends on the structure configuration.

Once the largest TWL for each year has been determined, the rest of the analysis is similar to the previous two examples. Table D.4.2-4 summarizes considerations for a structure in sheltered water.

Table D.4.2-4. Sheltered Water, Seawall Backed Beach using Parametric DIM Model for Setup/Runup

Zone	Processes	Recommended Methods	Comments
Offshore	Waves	Hindcast waves using CEM parametric method	Careful selection of storms can reduce the number of storms analyzed each year.
	Water Levels	Measured Water Levels	Not required to separate components (i.e., El Niño, astronomical tide, surge, etc.). Correct water levels to same times as waves.
Shoaling	Transformations	For straight and parallel contours, use shoaling and Snell's Law refraction. For complex bathymetry, use numerical models.	If the bathymetry is complex, parametric models may not be adequate.
		Select the 2 or 3 largest TWL storms per year.	Determine H_{smax} and T_p, and estimate *D*. Note annual storms along with waves and water levels.
Surf	Local Scour	CEM method	Compute scour and modify beach profile.
	Structure Stability	CEM methods	Compute (broken) wave height at structure and determine stability.
	Failure → Beach Profile Adjustment; No Failure → Setup and Runup	If structure fails, adjust configuration.	Completely or partially remove structure.
	Setup and Runup	DIM model	If profile is complex, use DIM numerical. Need *H* at toe to calculate *R*.
	Statistical Analysis	Use GEV and maximum likelihood to estimate 1% TWL.	Using the largest TWL event from each year, determine the 1% conditions.

Table D.4.2-4. Sheltered Water, Seawall Backed Beach Using Parametric DIM Model for Setup/Runup (cont.)

Surf	Beach Profile Adjustment	CEM method	Determine eroded beach profile and dune recession for 1% TWL and if overtopping, include profile adjustment for dune breaching.
	Overtopping	CEM equations	Determine the maximum overtopping rate and estimate the overtopping volume.
Backshore	Overland Flow and Ponding	Cox and Machemehl	Determine the depth, velocity, and flow.
Hazard	Hazard Assessment	Determine quantities necessary to map VE, VO, AH, AO, BFE, etc	Map the hazard zones.