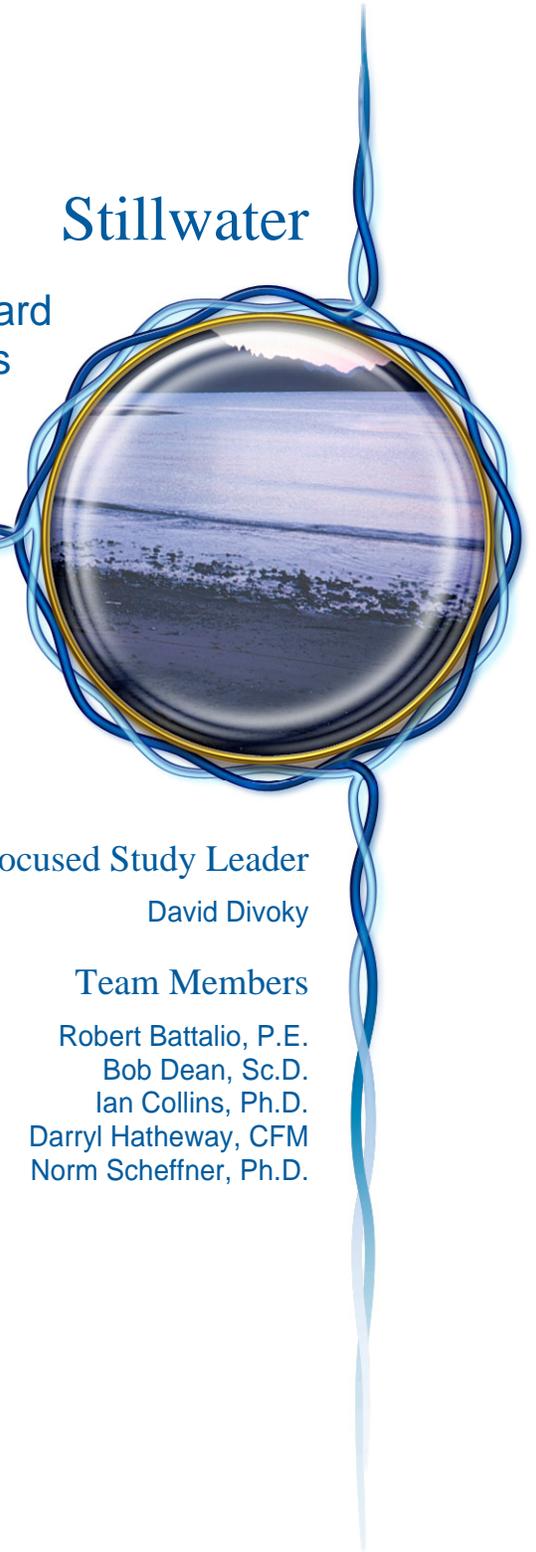


# Stillwater

## FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

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## Table of Contents

1	Introduction.....	1
1.1	Category and Topics .....	1
1.2	Stillwater Focused Study Group .....	2
2	Critical Topics.....	2
2.1	Topic 53: Atlantic/Gulf Storm Surge.....	2
2.1.1	Description of the Topic and Suggested Improvement.....	2
2.1.2	Description of Procedures in the Existing Guidelines .....	2
2.1.3	Alternatives for Improvement.....	3
2.1.4	Recommendations.....	11
2.1.5	Related “Available” and “Important” Topics .....	12
2.2	Topics 54 and 55: Pacific Storm Surge (including Non-Open Coast).....	12
2.2.1	Description of the Topic and Suggested Improvement.....	12
2.2.2	Description of Procedures in the Existing Guidelines .....	12
2.2.3	Alternatives for Improvement.....	12
2.2.4	Recommendations.....	17
2.2.5	Related “Available” and “Important” Topics .....	18
3	Available Topics .....	18
3.1	Topic 52: Stillwater Non-Stationary Processes .....	18
3.1.1	Description of the Topic and Suggested Improvement.....	18
3.1.2	Confirm “Availability” .....	18
3.1.3	Availability—Other Factors.....	19
3.1.4	Related “Available” and “Important” Topics .....	20
4	Important Topics.....	21
5	Additional Observations .....	21
6	Summary .....	21
7	References.....	23

## Tables

1	Summary of Findings and Recommendations .....	22
2	Preliminary Time Estimate for Guideline Improvement Preparation.....	23

**Figures**

1	Illustration of the primary aspects of surge modeling. ....	4
2	Sample comparison of predicted and recorded tides during a severe storm at San Diego. ....	14
3	Sample comparison of predicted and recorded tides during a severe storm at San Francisco. ....	14
4	Flow Chart of Florida Department of Environmental Protection .....	16
5	Example of correlation between one-dimensional and two-dimensional numerical surge models. ....	16
6	Observed sea level trends along U.S. coastlines. ....	19

**Acronyms**

1-D	one-dimensional
2-D	two-dimensional
ADCIRC	Advanced Circulation Model for Coastal Ocean Hydrodynamics
BFEs	Base Flood Elevations
CO-OPS	Center for Operational Oceanographic Products and Services
FEMA	Federal Emergency Management Agency
FL-DEP	Center for Operational Oceanographic Products and Services
<i>G&amp;S</i>	<i>Guidelines and Specifications</i>
GROW	Global Re-analysis of Ocean Waves
LIDAR	Airborne Light Detection and Ranging
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
PWA	Philip Williams & Associates
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WES	Waterways Experiment Station

# 1 INTRODUCTION

## 1.1 CATEGORY AND TOPICS

This report describes a proposed approach for the development of new FEMA Guidelines for the determination of stillwater levels in coastal areas. *Stillwater* means the flood level not including the effects of waves (wave amplitude and wave setup; setup is addressed in a separate Focused Study Group report) or tsunamis, but including storm surge and astronomic tide. The particular topics addressed in this report were determined during Workshop 1 of the project and are identified below.

Stillwater Topics and Priorities					
Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-open Coast
52	Non-Stationary Processes	Provide guidance on non-stationary processes (for example, relative sea level change) when establishing current conditions	A	A	A
53	Reliable Surge Data	Identify reliable existing data to compare to existing FEMA flood studies to test performance of surge models	C	--	--
54 & 55	Surge vs. Wave Height	Develop database for surge versus wave height; develop interim Pacific Coast model for surge (possibly ADCIRC); Review the reliability of Pacific tide data to see if surge is imbedded in the data sets for the purpose of developing surge factors for regions where there are little or no tide data; provide guidance	--	C	C

Key: C = critical; A = available; I = important; H = helpful

Topic 52 is judged to be relatively straightforward, amounting to identification of available information on such non-stationary factors as sea level rise and land subsidence that might affect a coastal study.

Topics 53–55 are construed to address development of general guidelines for storm surge evaluation on both the Atlantic/Gulf (Topic 53) and Pacific (Topics 54 and 55) Coasts, including Pacific bays and estuaries (sheltered water areas). Furthermore, the necessary storm surge guidance is considered to be of two types: 1) guidance regarding storm surge hydrodynamic modeling, which will apply to both the Atlantic/Gulf and Pacific Coast insofar as general tools and principles are involved (addressing both Topics 53 and 54), and 2) guidance regarding other methods to estimate storm surge on the Pacific Coast and in Pacific bays, such as analysis of tide gage records (addressing both Topics 54 and 55). Note that additional guidance is provided in an

accompanying Focused Study prepared by the TWG on “Sheltered Waters,” which addresses many of the coastal flood issues found in non-open coastal areas.

## 1.2 STILLWATER FOCUSED STUDY GROUP

The Stillwater Focused Study Group is made up of Robert Battalio, Ian Collins, Robert Dean, Darryl Hatheway, Norm Scheffner, and David Divoky who served as Team Leader.

## 2 CRITICAL TOPICS

### 2.1 TOPIC 53: ATLANTIC/GULF STORM SURGE

#### 2.1.1 Description of the Topic and Suggested Improvement

This topic includes not only the identification of data sets and methods for verifying and testing surge models, but also development of general guidelines regarding storm surge modeling. The general modeling guidelines developed under this topic will apply equally to modeling on the Pacific Coast (Topics 54 and 55).

#### 2.1.2 Description of Procedures in the Existing Guidelines

Existing guidelines found in Appendix D are relatively brief, consisting primarily of checklists of requirements for data submission and documentation during a study. The material concerned with general surge modeling is contained in Section D.1.2.4, “Hydrodynamic Storm Surge Model,” which, in full, is as follows:

- ④ Report the unique model characteristics used for the study, including a discussion of the specific grid system and sub-grid systems employed, the grid used for bottom topography and shoreline, small-scale features such as harbors and barrier islands, and the location and conditions applied for the open boundaries to the grid.
- ④ Describe and document the adjustment to land features to account for erosion.
- ④ Describe and document the method used to determine average ground elevations and water depths within the cells of the grid system. This discussion is to be augmented by diagrams that show the grid systems as computer listings of the grid data used in the actual model calculations.
- ④ Describe the method used to relate windspeed and surface drag coefficient.
- ④ Discuss the Manning’s “n” values used in the calculation of bottom and overland friction and provide values in tabular form. This information will include a discussion of any sensitivity tests used to estimate these values in nearshore water. Nearshore bottom and

overland friction is an important part of the overall analysis and, therefore, shall be described with care and sufficient detail.

- ④ Provide a graphical depiction of the model cells and grid system as an overlay to the bathymetric charts and topographic maps covering the study area, annotated with the individual cell inputs for the grid system.
- ④ Discuss the method by which barriers, inlets, and rivers have been treated.
- ④ Explain the procedures used to determine inland flooding, including parameterization of local features and selection of the friction factors used for the terrain.

Additional storm surge guidance is contained in Section D1.2.5, “Storm Surge Model Calibration and Verification,” which consists of two paragraphs commenting on verification procedures and required backup documentation; Section D1.4.1, “[Intermediate Data Submission] Before Storm Surge Model Calibration Runs,” consisting of a list of eight items to be submitted for review before proceeding with model runs; and Section D1.4.2, “Before Operational Storm Surge Runs,” consisting of a checklist of seven items to be submitted for review before performing the main set of statistical simulation runs. Additional general material is provided in Section D2.2, “Data Requirements.”

These guidelines are generally based on the use of the FEMA storm surge model, although brief mention is made of the Stone and Webster (1978) northeaster model and the possible determination of stillwater elevations using statistical analysis of available tide gage records, provided those records include 20 or more years of data. Section D.2.2 also states that synthetic computer models for storm surge assessments shall be used where tide gage data is limited and complex shorelines are present which cause appreciable variation in flood elevations for a community.

### 2.1.3 Alternatives for Improvement

#### ***Storm Surge Modeling Guidelines***

A numerical storm surge model simulates the effects of a hurricane, tropical storm, northeaster, or other storm type passing over a given study area. Two basic types of data must be provided to the model. First, the model implementation must include an accurate description of the physical characteristics of the study area, including:

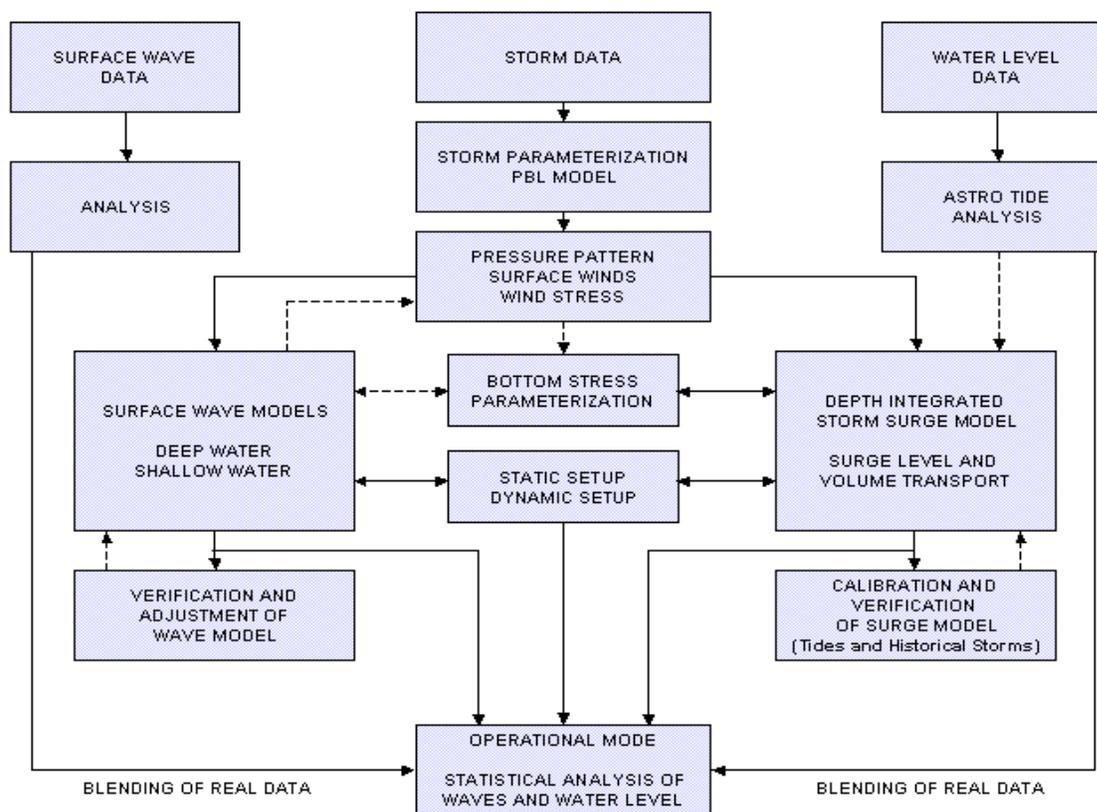
- ④ Offshore bathymetry and onshore topography;
- ④ Roughness characteristics of the ocean bed and landcover that may affect the flow of water;
- ④ The nature of barriers and structures that may impede or divert the overland flow of the flood;

© The extent of elements (especially tall vegetation) that may partially shield the water surface from wind stress.

Second, the model must include a realistic representation of the storm being simulated; in particular, the time- and space-varying wind and pressure fields of the storm must be reflected in the model through use of an appropriate storm submodel. Note that sheltered waters may pose special requirements for both basin and storm description, to account for the sheltering effects of terrain, complex flow resistance through developed areas, and changes in storm properties associated with the on-land weakening known as *filling*. Further details regarding Sheltered Waters are provided herein in a separate Focused Study Report on Sheltered Waters.

In addition to these factors describing the basin and the forcing disturbance, the model must solve a set of equations capable of capturing the essential features of the process, including the effects of wind, pressure, friction, overland flow (wetting and drying of land areas), and tidal forcing and tidal potential terms. This also requires the selection of a large number of empirical factors and functional expressions to describe, for example, bottom friction and wind stress.

Figure 1 (adapted from an unpublished diagram by Professor Robert Reid (Texas A&M)) illustrates the primary aspects of surge modeling, including the determination of the types of waves that produce wave setup.



**Figure 1. Illustration of the primary aspects of surge modeling.**

The static component of setup is, strictly speaking, a stillwater component generated by radiation stress rather than wind stress. The development and application of methods that unify the setup and surge computation remain tasks for the future, however, and are discussed in the separate Focused Study Group report on Wave Setup.

It is proposed that new guidelines should include general guidance regarding these factors. Several candidate storm surge models are in current use or development that might be accepted by FEMA for future storm surge studies. It would not be the intention of the proposed work to evaluate specific models or to attempt to describe the details of use of any of those models at this time, because model documentation and user's manuals are not available at the present time.

Instead, the proposed new guidelines would involve the development of more general, high-level guidance incorporating explanatory discussions of modeling factors that should be understood and considered by a study contractor or a FEMA project officer. Among these factors (in italics) are the following:

- ② The *governing equations* of the model, typically the nonlinear long wave equations accounting for conservation of mass and momentum, with surface wind and barometric pressure terms representing the influence of the storm
- ② The *numerical scheme* used by the model, whether finite differences computed on a grid of rectangular cells (commonly of fixed size) or in curvilinear coordinates, or finite elements represented by triangular or quadrilateral cells (of varying sizes); the numerical scheme may also be explicit or implicit, affecting time step constraints
- ② The *flooding/drying* treatment of cells as the flood advances onto land and then recedes
- ② The *storm representation*, such as a planetary boundary layer model (for a hurricane) or a simpler empirical/parametric description, including both wind and pressure; the storm representation will be quite different for hurricanes, northeasters, and Pacific storms, although the modeling principles remain the same in each case; on-land filling will be significant for sheltered waters
- ② The *wind stress coefficient*, which relates the wind speed at the surface to the stress felt by the fluid
- ② The *sheltering treatment*, adjusting the effective wind stress to account for partial reduction by tall vegetation, terrain, and structures (especially significant for sheltered waters)
- ② The offshore *bottom friction* treatment over the relatively smooth ocean or bay bottom, which retards the flow

- ② The onshore flow resistance treatment accounting for *bottom friction* and *resistance* offered by tall vegetation and structures (critical for sheltered waters)
- ② The *source and quality of bathymetric data*, defining the varying depths at the site
- ② The *source and quality of topographic data*, such as traditional quad sheets or newer LIDAR data
- ② The manner in which normal *storm erosion* alters the topography used in the model
- ② The manner in which *catastrophic erosion* might affect the modeling assumptions, in the event of loss of a major barrier to inland flooding
- ② The *representation* of the bathymetry and topography in the model grid system, which depends on the numerical scheme
- ② The *faithfulness of the grid* to the irregular bathymetry and terrain, including conformance to boundary shapes and inclusion of small sub-grid barriers
- ② The *resolution of the grid*, whether fixed or varying through the study area
- ② The *boundary conditions*, which impose approximate rules along the edges of the model area, both offshore and onshore, permitting termination of the calculations at the expense of accuracy
- ② The *treatment of astronomic tide*, which might be handled as part of the simulation through the boundary conditions or treated as an added effect separate from the surge simulations; if the computational domain is large, tidal potential terms need to be accounted for in a simulation
- ② The *types and limits of calibration* that might be done, including small-amplitude astronomic tide reproduction, for which calibration data are reliable
- ② The role of *verification hindcasts* to confirm the apparent reasonableness of the final model when compared with historical surge records
- ② The role of *wave setup* (a separate topic in this guideline development project)
- ② The general manner in which *surge statistics* are generated from multiple surge simulations (the subject of Topic 50 of the separate Storm Meteorology effort)

These guidelines will be developed through review of the storm surge literature and consultation with developers and users of major storm surge models. Although hurricanes are usually the focus of this discussion, northeasters are also to be included in the guidelines. Numerical

hydrodynamic modeling, and the use of tide gage analysis, will be addressed as envisioned below in Topics 54 and 55 for the Pacific Coast.

No new methodology development is proposed, with one possible exception. The problem of catastrophic erosion of a coastal dune should be considered as a special modeling problem. Consider an embayment and an inland region protected from surge by a high dune ridge. In previous FEMA surge modeling, such dunes may have been overtopped in the course of a simulation, but were treated as being simply submerged. However, as happened near Hatteras during Hurricane Isabel, overtopping can lead to washout of a considerable portion of the dune, creating a new inlet and permitting a sudden large increase in flood penetration not envisioned in the model. For Pamlico Sound, this may or may not have been significant for the overall determination of surge, since the sound is so large that the additional flow occurring during the few hours of high storm tide may not have appreciably affected sound-side water levels. However, a similar circumstance could make a significant difference in a region with a high barrier protecting low, developed areas. (It is noted that Scheffner, in a study for Fire Island to Montauk Bay, included erosion and breaching of the barrier island as part of a surge simulation and found a significant effect in Great South Bay.) This is not a deterministic process, although it is a frequent event during very large storms. It is proposed that its importance to storm surge modeling and stillwater determination be assessed and that, if it is found to be significant, then suggestions for future study beyond the present scope should be developed.

The style of the proposed guidelines will be consistent with the general approach of the existing guidelines, although more descriptive than prescriptive. Topic discussions may be illustrated by examples drawn from past surge studies performed with both finite difference and finite element models (perhaps both the FEMA surge model and the newer ADCIRC model).

The existing guidelines described above are primarily concerned with documentation and interim review of the storm surge modeling effort. That material, added to the guidelines in 2002–2003, was a significant improvement over the original 1995 draft, which was essentially mute on surge modeling. The proposed guidelines would preserve and refine the 2002–2003 documentation and review sections of the most recent existing guidelines.

### ***Extremal Analysis of Tide Gage Data***

Although the discussion above assumes only two-dimensional (2-D) hydrodynamic modeling would be used to determine storm surge levels, the direct use of tide data is another approach that must be considered. As will be discussed below for surge estimates on the Pacific Coast, it is possible to extract stillwater data from tide gage records by subtracting the known astronomical component. The residual data represents the contribution of all other low-frequency (i.e., stillwater) processes, including wave setup, although it should be noted that owing to large spatial variability, the setup captured at the gage may not be representative of setup in even relatively nearby areas.

With a sufficient period of record (the existing guidelines mention 20 years), an extremal analysis of the residual record after tide removal can be used to estimate the 100-year stillwater level at the gage site. Consideration of this approach will be included in the work outlined below for Topics 54 and 55. As discussed there, limiting factors include the quality and duration of the available data and the possibility of significant spatial variation with increasing distance from the gage site. The new work will include reconsideration of the required period of record as it affects confidence levels. The general approach to this task is not unlike extremal analysis in other hydrologic applications, including the problems of selecting an appropriate idealized probability distribution function, such as an extreme value distribution, and a method (e.g., moments, maximum likelihood) of determining the parameters of that distribution based on the local data sample (which could be the annual series of peak events). Many approaches are possible, with a great variety of choices of specific procedures. The proposed work will evaluate these alternatives and specify recommended procedures.

### ***Evaluating the Accuracy of Storm Surge Estimates***

A perceived need in the present coastal flood study program is a way to determine whether or not an existing study gives a reliable 100-year estimate, or whether a restudy that uses newer assumptions or tools is warranted. This is a difficult question, especially on the Atlantic and Gulf coasts where hurricanes are the dominant flood contributors, because hurricanes are extremely sporadic and variable, and because mapped flood levels cannot be identified with any particular storm. Many agencies have different purposes and numerical modeling approaches for evaluating hypothetical storm effects which may also confuse this issue. For example the National Oceanic and Atmospheric Administration (NOAA) prepares hurricane evacuation maps, which depict the inundation of particular hypothetical storms defined by storm track and a Saffir/Simpson rating. The purpose of these maps are different than those needed for FIS studies.

In performing these surge studies, there is little opportunity for so-called model calibration. Beyond minimal calibration of ordinary small-amplitude conditions based on the simulated behavior of astronomic tide, for example, storm surge models are relatively closed-box affairs, assumed to be pre-wired with all the essential physics of the flood processes. In any case, the basic requirements for calibration are rarely well satisfied. To calibrate, one needs accurate knowledge of both the forcing disturbance (the storm) and the basin response (the resulting high water); neither of these are abundant for hurricane surge, although data are available from long-term National Ocean Survey (NOS) stations, publications such as *Characteristics of the Hurricane Storm Surge* (Harris, 1963), and in a variety of reports from the U.S. Army Corps of Engineers (USACE). Storm details are not known with any great accuracy because storms can fluctuate rapidly in size and intensity, and may appear chaotic when compared with the idealized representations used in models. Similarly, the basin response is seldom known with accuracy at more than a very small number of points inside surviving structures and at tide gages; highwater marks obtained in open areas may be contaminated with an undetermined amount of runoff and setup. Gages commonly fail during the most significant events; for example, the gage at Duck Pier, North Carolina, failed just as the surge from last year's Hurricane Isabel began to rise.

In view of these twin deficiencies, robust calibration of a storm surge model is not a common option in a FEMA study. To calibrate a model against typical storm and high water data (for example, by adjusting the wind stress coefficient) would be to build a systematic error into the model that cancels the unknown random errors in the storm description and flood observations. This systematic error would then be imposed on all subsequent simulations made during the development of the surge statistics. In lieu of calibration, modelers perform model validation tests by hindcasting historical storms to ensure that the model produces results that are in qualitative, if not quantitative, agreement with observations. With the luxury of several storms, the modeler might simply hope to be high in some cases and low in others. Still, without a real calibration, it is reasonable to question whether the basic hydrodynamic model might contain a systematic bias, either high or low, affecting all simulations that contribute to the 100-year determination.

After a study has been completed and mapped, new storms will eventually occur at the site and will inevitably be compared with the study. If a storm produces elevations less than those mapped, the conclusion might be reached that it simply was not a 100-year storm because weaker storms occur all the time and so are not surprising. Of course, the entire past history at the site can also be compared with the mapped levels. If the record contains no severe events, then the temptation might be to assume that the study was biased to the high side. Conversely, if a new storm creates levels above those mapped, then it is very likely that the accuracy of the study will be questioned. Worse, if two or more such strong storms occur within a few years after the study, or if the record at the site contains several such events, then it may seem natural to conclude that the study was biased to the low side, is understating the hazard, and should be redone.

This reasoning is not decisive, however, and (when clarified) suggests a way to test the accuracy of the existing 100-year coastal flood levels, and perhaps to help perform a *global* calibration, where a local calibration had been impossible. The key observation is that random events do not occur more or less uniformly over their domain, but instead must exhibit predictable irregularities of occurrence. In the case of floods observed at a large number of sites, some sites must be found that have gone for extremely long periods without experiencing a severe event, whereas other areas must have experienced multiple severe events. There must be “good luck” and “bad luck” communities. If the mapping were to be fine-tuned so that experience and mapping were highly consistent throughout, then the mapping would be flawed.

This suggests the possibility of a statistical test of the reliability of the existing 100-year values, which might proceed along the following conceptual lines. Imagine that the coastline were divided into a series of zones, each large enough so that floods within them could be considered statistically independent—i.e., large enough that a particular storm tends to affect only one such zone, yet small enough that occurrence of a 100-year event affects the majority of the zone. Considering floods of 100-year magnitude, the zone size might be on the order of the radius of maximum winds typical of an area—perhaps just a few tens of miles. This would suggest on the order of 100 zones covering the entire area of the Gulf and Atlantic Coasts.

Next, imagine that, for all zones, there are N years of historical flood data (high water marks). In any given zone, there is a certain probability of having experienced no event exceeding the 100-year level during those N years, another probability of having experienced one such event, or two, or three, and so forth. From these considerations, one can estimate how many of the conceptual coastal zones should have experienced 0, 1, 2, ... floods exceeding the 100-year level in the N years of record. These expected numbers can then be compared with observation. If it were found that the count of observed exceedances was significantly greater than expected, then one would suspect that the mapping systematically understates the flood hazard. Conversely, if the count of exceedances was substantially less than expected, the mapping might be suspected to overstate the hazard.

Had all studies been performed in a systematic way using exactly the same surge modeling techniques, one could imagine performing a global calibration of the model to raise or lower the general levels of the mapping, in order to achieve a reasonable fit between the observed and expected rates of extreme occurrences. In reality, the existing flood studies were not all performed in a systematic way, even when the same surge model was used—different Study Contractors undoubtedly made differing assumptions that would affect the homogeneity of the data used in this conceptual approach. However, a statistical review (such as that recommended above) might help reveal such anomalous local studies, which would be identified as zones of inconsistency with adjacent zones.

This section discusses how an approach might be developed. There are difficulties with the zone idea (presented as a conceptual aid), especially in the definition of such zones (large enough to ensure independence, yet small enough to respond as a unit to the 100-year flood). Consider, for example, a strong alongshore storm that could affect a long stretch of coast, and so violate the independence assumption. For the present, we propose only to investigate (in consultation with a statistician such as Professor Borgman [University of Wyoming]) whether such an approach could prove fruitful and, if so, to outline specific methods for future work. A substantial portion of the effort required in this task would be the identification of suitable data sources. The immediate effort described above remains in the *critical* category; if successful, the follow-on effort would be categorized as *important*, requiring a longer performance period than is presently available.

### **Regional Modeling**

In early FEMA storm surge studies, it was common to perform a separate study for each county. One major reason for this was limited computer capacity, which severely restricted the grid sizes that could be accommodated in even the largest machines at the time. For example, even the vaunted CDC 7600 supercomputer had only 64K words of small-core memory and 512K words of large-core memory, with comparably limited disk storage capacity, and a 36 MHz clock speed (1% of the speed and capacity typical of desktop personal computers today). Use of the CDC 7600 typically cost on the order of \$1 per second. Because each study area was restricted in size, many separate studies were required; because computing costs were high, the original coastal

flood studies were extremely expensive (typically involving computer charges of about \$100,000 per county).

With tremendous recent advances in computational power, as measured by both speed and capacity, many of those early modeling constraints have been eliminated, and direct machine charges are now negligible (although proprietary modeling software may be a substantial cost). This suggests that it might be preferable to plan future surge modeling efforts on a regional, rather than a community, basis.

It is proposed, therefore, to provide general guidance on factors that should be considered in scoping a regional modeling effort. In particular, surge modeling is significantly challenged with the problem of boundary conditions. Performing a regional study encompassing many counties would not only reduce costs, but also enhance modeling accuracy by greatly reducing the number of problematic boundaries. Furthermore, through judicious placement of the regional study boundaries, difficult open-water boundaries may be traded for more tractable land boundaries. Recent work of a regional nature includes studies of the coast of South Carolina and Texas from Sabine to San Luis Pass (Scheffner et al., 2001, and in prep.)

#### **2.1.4 Recommendations**

It is recommended that four distinct tasks be undertaken in response to Topic 53. The first is a general review of storm surge modeling requirements from the perspective of FEMA and coastal flood insurance studies, leading to the development of a set of broad guidelines for conducting storm surge studies. This will require an assessment of many factors that go into conducting a surge study, ranging from the inherent abilities and limitations of numerical surge models to practical considerations of model selection and implementation in particular cases. The guidelines should include illustrative materials drawn from past studies and an annotated bibliography as a resource for more detailed study. It is beyond the scope and intent of the proposed work to evaluate the merits of particular models; that effort will remain separate as part of FEMA's accepted models review process, although the material developed in this study will help to provide a framework for that determination.

The second recommendation is for an outline of procedures to extract stillwater data from tide gage records. This overlaps with Topics 54 and 55 for the Pacific Coast, including Non-Open Coast regions, and is discussed in the following section.

Third, the Focus Study Group recommends an effort to develop a global method to assess the accuracy of FEMA's coastal storm surge studies. The random and sporadic nature of local surge history makes it difficult to determine whether coastal maps are appropriate. Recent catastrophic events may be given more weight than they deserve, since it is to be expected that several events exceeding local determinations must occur at some locations over an interval, while a lack of extreme events should characterize other areas. By considering the global history over the entire length of the U.S. coastline, it may be possible to determine whether the established coastal

elevations are exceeded more or less frequently than expected for the assumed case of accurate maps and random local experience.

The fourth recommendation is for development of guidance regarding study planning—in particular, how studies might be grouped regionally to minimize costs while at the same time improving accuracy. Whereas existing FEMA studies were typically performed on a county-by-county basis, the enormous advances in modeling technology over the past 20 years now permit much greater flexibility in model design. Multi-county and statewide (or larger) efforts are entirely feasible, and may also result in improved accuracy of results.

### **2.1.5 Related “Available” and “Important” Topics**

Table 3 at the end of this report presents estimates of times required to accomplish the tasks in this topic.

## **2.2 TOPICS 54 AND 55: PACIFIC STORM SURGE (INCLUDING NON-OPEN COAST)**

### **2.2.1 Description of the Topic and Suggested Improvement**

Storm surge is of smaller magnitude on the Pacific Coast than on the Atlantic and Gulf coasts and so may not commonly require a detailed numerical model to obtain reasonable estimates. Instead, it may be possible to derive estimates of storm surge from tide gage records or simplified computations. When a 2-D hydrodynamic modeling effort is required, the proposed guidelines discussed above for Topic 53 will be appropriate, provided that the selected surge model has the capability to represent the wind and pressure fields appropriate to the Pacific Coast.

### **2.2.2 Description of Procedures in the Existing Guidelines**

No specific guidelines have been identified for Pacific Coast storm surge, although the Atlantic and Gulf Coast guidelines discussed above are generally applicable. That is, basic numerical modeling considerations will be the same, although site-specific differences including especially the wind and pressure model must be accounted for.

### **2.2.3 Alternatives for Improvement**

#### ***Tide Gage Analysis***

Instead of the storm surge modeling discussed above in Topic 53, an alternate approach is to derive the 100-year stillwater estimate from an analysis of historical data. For this purpose, a wealth of tide gage data are available for coastal stations on both the Pacific and Atlantic/Gulf Coasts. The NOAA CO-OPS data archive ([http://co-ops.nos.noaa.gov/data\\_res.html](http://co-ops.nos.noaa.gov/data_res.html)), for example, includes 117 coastal gages with 25 or more years of data. These data, by their nature, include all stillwater components but do not include the higher frequency wave effects, which are not appropriate to use in a stillwater determination. The stillwater components captured in the

gauge data include storm surge (i.e., wind setup and pressure effects), wave setup, tsunamis, astronomic tide, and possibly a freshwater contribution from stream discharges. Most gauges are located in protected. Sheltered Waters areas in bays and harbors and areas on the open coast without gauge data will be discussed later. Owing to the spatial variability of wave setup, it is noted that although the local setup is captured in gauge data, it may not be representative of other, relatively nearby areas.

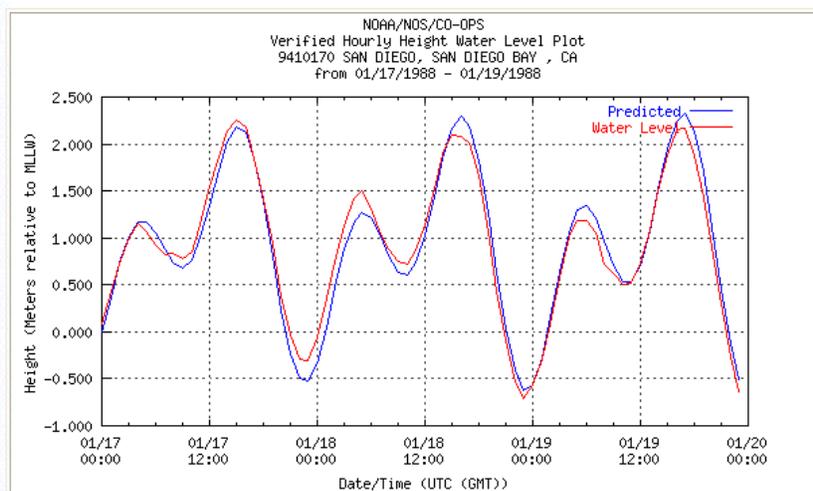
The portion of the record attributable to astronomic tide is considered to be reasonably well known for each gauge site by previous determination of the local tidal constituents. This fact makes it possible to compute the expected tide contribution at any time and then to subtract it from the record, leaving as the difference the sum of all other stillwater contributors. In this approach, wave setup is automatically included with the storm surge component, unlike present surge modeling practice, in which surge and setup are computed separately and appropriately added. In fact, all long-period processes, including tsunamis, are automatically included.

After subtracting the predicted tide from the gauge records, an extremal analysis can be performed on the residual data to estimate the local 100-year level. The quality of this estimate will depend on both the reliability of the data and the duration of the record. Examples of the available NOAA CO-OPS data for two storms are shown in Figures 2 and 3.

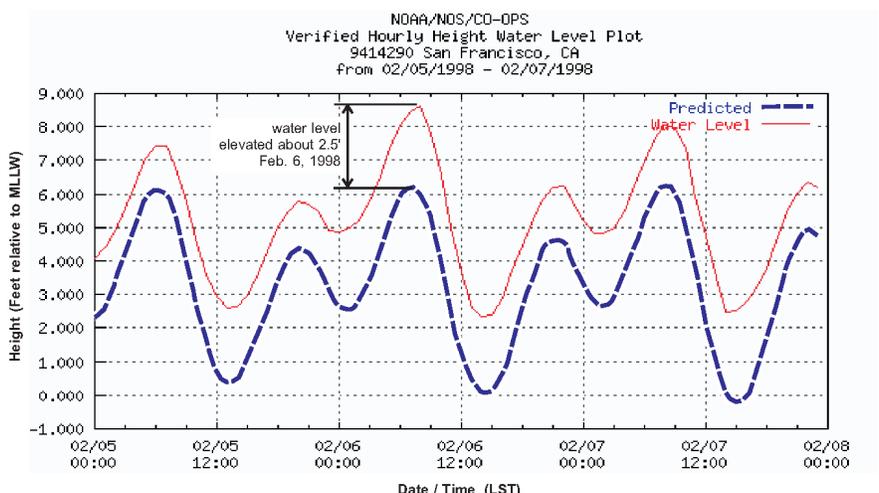
Figure 2 shows data recorded during a January 1988 storm in Southern California, which is thought to approximate the 100-year (or greater) event; despite the severity of the storm, the storm tide component is seen to be quite small. Figure 3 shows data recorded at San Francisco during a 1998 storm. In this case, the water level was elevated above the expected tide by about two feet at the Presidio tide gauge. Part of the anomaly (residual) was attributable to the El Niño climatic condition, which was strong in winter 1997–98. Water levels in the vicinity were elevated an average of one foot for the entire winter. It is interesting to note that Sausalito is within 5 miles of the Presidio tide gauge but experienced noticeably higher stillwater levels. The additional elevation was probably caused by local wind setup induced by strong southeasterly winds, and by rainfall runoff entering San Francisco Bay from upstream drainage basins, including the Sacramento and San Joaquin Rivers (Philip Williams and Associates Ltd. [PWA], 2002). This demonstrates that local variability may be substantial in large sheltered-water embayments, so that direct use of gauge data may be limited to the near vicinity of the gauge. It is noted, however, that in large sheltered waters where gauge data is not comprehensive, and where the simplified one-dimensional (1-D) storm surge model discussed below is not appropriate or adequate, the full capability of one of FEMA's approved 2-D surge hydrodynamic models can be used to determine surge behavior and statistics.

The proposed task is threefold: to identify candidate sources of appropriate tide data, to examine a sample set to determine the extent to which the candidate sources can be used for flood insurance studies, and to estimate the reliability of the derived 100-year flood elevations. As discussed above, the methods of data analysis are similar to the analysis of other stochastic hydrologic data, including selection of an appropriate probability distribution function,

determination of distribution parameters from the site sample, and so forth. Reliability considerations will include not only sample error associated with the duration of the record, but also the potential significance of variability near the site. This is particularly important in sheltered waters where tidal hydrology can vary substantially with location. Recent FEMA flood studies in Puget Sound/Strait of Georgia provide examples of tide gage data analysis approaches (PWA, 2002). Previous baywide studies have also addressed the distribution of high waters using tide gage data (U.S. Army Corps of Engineers [USACE], 1984). The importance of variability is not limited to sheltered waters, however. For example, the contribution from wave setup can vary rapidly from place to place, even along the open coast. The suggested effort will also provide case study examples for inclusion in the proposed guidelines.



**Figure 2. Sample comparison of predicted and recorded tides during a severe storm at San Diego.**



**Figure 3. Sample comparison of predicted and recorded tides during a severe storm at San Francisco.**

### ***Simplified Surge Modeling***

Where adequate records are not available, such as on the Open Coast in areas without gage sites, more traditional efforts such as numerical simulation of surge, wave hindcasts, tsunamis, and combined probability studies may be necessary. However, because the surge component is expected to be relatively small, it may also be possible in many cases to derive estimates of sufficient accuracy from simplified computations. This might be done, for example, following the approach used by the Florida Department of Environmental Protection (FL-DEP) for determining coastal construction control lines.

The FL-DEP applies a storm surge calculation approach that uses both 1-D and 2-D storm surge models (see, for example, Dean et al., 1992). A primary benefit of this approach is the fact that a very large number of simulations (including an appropriate representation of astronomical tide) can be made at minimal cost, from which the 100-year surge levels can be derived. The 2-D model is applied for verification of historical storms and for calibration of the one-dimensional model. Once calibrated, the 1-D model is used for the numerous production runs.

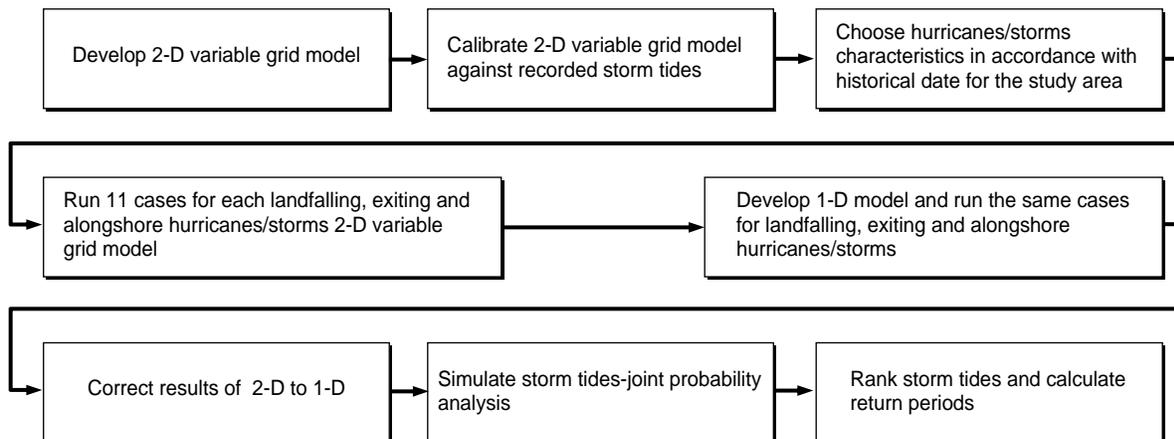
A flow chart of the procedure, taken from a FL-DEP study, is presented in Figure 4. Any valid 2-D model, such as the FEMA Surge Model or ADCIRC, could be used, although the FL-DEP uses a variable-grid explicit-implicit model that allows for overland flooding. The 2-D model is first applied for comparison with historical storm data (although the chart specifically mentions hurricanes and factors specific to the source study, the procedure would be modified to use Pacific storms for West Coast applications). Generally, no adjustments are made to the 2-D model, which is used at this stage primarily for validation and/or to estimate the degree to which it agrees with the historical data.

Following the verification stage, the 2-D and 1-D models are run for a common set of storms with ranges of storm parameters bracketing those anticipated to produce the 100-year surge. For various classes of storms, correlations are developed between the 2-D and 1-D generated maximum surges in the linear form:

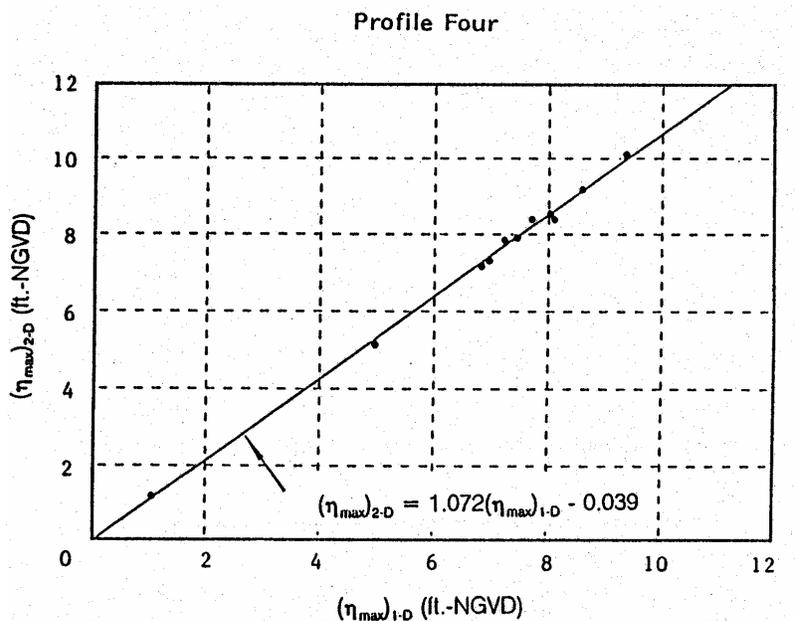
$$(\eta_{\max})_{2-D} = m(\eta_{\max})_{1-D} + b \quad (1)$$

An example result is shown in Figure 5 for landfalling hurricanes on a particular transect (profile) in Palm Beach County, Florida.

It should be noted that the average difference between the 1-D and 2-D simulations in this example is only 7%, and that this is the level of difference found in the FL-DEP study for Palm Beach County, Florida. For the hurricane surge conditions in Florida, a difference of this magnitude approaches 1 foot and so is significant. However, the situation is quite different for the Pacific Coast.



**Figure 4. Flow Chart of Florida Department of Environmental Protection**



**Figure 5. Example of correlation between one-dimensional and two-dimensional numerical surge models.**

If the expected 100-year surge at a Pacific Coast site is on the order of 2 feet, then a 7% difference would amount to less than two inches. In other words, the added effort and cost of 2-D simulations might not generally be needed on the Pacific Coast, unless the 1-D estimate was calculated to be more than, for example, 7 feet, corresponding to a 0.5-foot error. Tests would need to be done for a few typical Pacific Coast conditions (bathymetry and wind fields) to verify the degree of 1-D model accuracy and to provide guidance about when additional 2-D simulations would be needed.

An attractive feature of the FL-DEP approach is that using such an efficient and economical 1-D surge model makes it possible to handle the combination of surge and tide in an extremely natural way. The procedure, discussed under Topic 51 of the Storm Meteorology Focused Study Report, is to randomly choose a different tide history (drawn from the peak storm surge season) to be used as the seaward boundary condition for each 1-D simulation. That is, to determine the 100-year surge, one simulates a large number of storms with different combinations of characteristics drawn from the local storm population. For each of these storms, a starting time is chosen at random from the appropriate storm season. Then the nearshore tide variation is determined, starting at that time and continuing for the duration of the surge simulation. By taking this time-varying random tide segment as the boundary condition, the influence of that tide is accounted for. By repeating this for many hundreds or thousands of storm simulations (fast and inexpensive with a 1-D model), all likely tide amplitudes and phases are reflected properly in the results.

#### **2.2.4 Recommendations**

The Focused Study Group's recommendations consist of two major tasks. The first is to establish procedures for extracting the required surge data from tide gage records and prepare corresponding guidelines for Study Contractors. Recent flood studies in Puget Sound/Strait of Georgia (Region X) can be used as examples of analysis methods (PWA, 2002). This does not require the development of any fundamentally new methodology. However, it will be useful to clearly lay out the procedures for Study Contractors and it will be necessary to identify data sources and perform test studies to verify the suggested procedures and assess limitations of the approach. Discussions of limitations will include statistical limits inherent in the varying lengths of available data records. Separate discussions and guidance should be developed regarding the physical limitations and temporal and spatial variation often found within large bays and sheltered waters. The guidelines to be developed should include illustrative examples drawn from the test studies.

The second major task will be to develop procedures for surge estimation in areas for which an adequate tide gage record does not exist, including most Open Coast areas. Procedures for defining the modeling domain and selecting an appropriate model will be presented. When warranted, the detailed numerical modeling methods used for hurricane studies on the Atlantic/Gulf Coasts would also serve for the Pacific Coast, as long as the adopted numerical models are able to properly simulate Pacific Coast wind and pressure fields. However, because

surge is much smaller on the Pacific Coast than on the Atlantic/Gulf Coasts, simplified methods may suffice. In particular, the use of a 1-D surge model may be adequate for most cases, minimizing the costs of model implementation and simulation. An assessment of storm meteorology and data sources would be necessary to determine the best manner for specifying winds and pressures and their associated frequencies. Test studies should be performed at selected sites to verify the feasibility of the recommended approach. New guidelines summarizing the procedures would be developed, including illustrative examples.

### **2.2.5 Related “Available” and “Important” Topics**

Table 2 at the end of this report presents estimates of times required to accomplish the tasks for these topics.

## **3 AVAILABLE TOPICS**

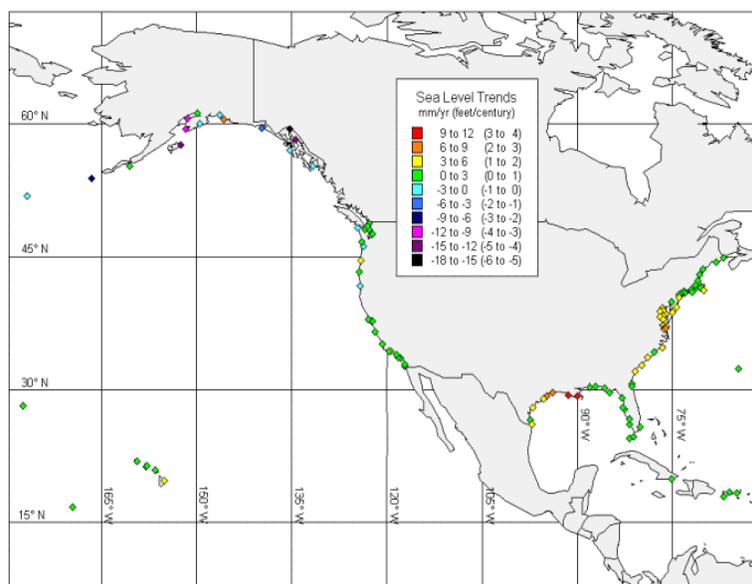
### **3.1 TOPIC 52: STILLWATER NON-STATIONARY PROCESSES**

#### **3.1.1 Description of the Topic and Suggested Improvement**

The task identified under Topic 52 is a straightforward effort to provide guidance alerting a Study Contractor to the possible importance of non-stationary (or non-steady) processes in a study. The guidance might include, relative sea level rise, tectonic uplifting, land subsidence, or a combination of these processes (effective elevation change). These might need to be accounted for in the interpretation of historical data, whereas ongoing subsidence would need to be considered for its immediate impact on a new study and discussed with the FEMA project officer. The effort suggested here is primarily one of providing guidance alerting the user to these possibilities and advising on the availability of suitable data. In addition to relative sea level changes, changes in winds and waves and other climatic features should be addressed. These aspects have been summarized in several books and papers by Komar, including the individual processes of sea level rise, uplift, and subsidence and the effects of combining these, including data and statistics for areas on the Pacific Coast (Komar, 1998, 1988, and 1997).

#### **3.1.2 Confirm “Availability”**

Both sea level rise and land elevation changes (uplift and subsidence) contribute to relative sea level changes; a great deal of data and data summaries exist for both of these processes. For example, the Philadelphia District of the U.S. Army Corps of Engineers maintains a web page ([www.nap.usace.army.mil/cenap-en/slr\\_links.htm](http://www.nap.usace.army.mil/cenap-en/slr_links.htm)) with links to numerous government data sources for sea level change, including the NOAA CO-OPS *Sea Levels Online* site. NOAA has determined the rate of mean sea level rise/fall for 117 long term water level stations and, from these, has determined trends, seasonal cycles, and interannual variations caused by fluctuations in ocean conditions, including El Niño effects. Figure 6 indicates the distribution of those study sites and the approximate magnitudes of the long-term trends that have been determined.



**Figure 6. Observed sea level trends along U.S. coastlines.**

The estimated trends in many regions along the Pacific Coast are seen to be small and may have little importance for flood insurance studies; however, as noted below, it may still be valuable to document the changes and indicate their significance as part of a flood insurance study.

Land subsidence may be more significant than area-wide sea level change for many study sites. The U.S. Geological Survey (USGS) and other sources have documented land subsidence throughout the United States, although subsidence is frequently a very local result of groundwater extraction or oil and gas extraction. Along the Pacific Coast, however, significant tectonic uplifting occurs as a result of regional geologic processes and active plate tectonics. Consequently, despite the great quantity of large-scale data, it will still be necessary for Study Contractors to explore local data sources to identify local problems and determine whether such effects merit discussion with the responsible FEMA program manager. Such sources of information would include discussions with and information from community officials, resource agencies, and local surveyors. New guidelines should identify the major national and regional data sources and provide general advice regarding ways to locate local data. (For example, see San Francisco Bay Conservation and Development Commission, 1987).

### 3.1.3 Availability—Other Factors

There are indications within the literature that weather patterns are changing, and these could have an impact on the interpretation of flood studies and study data. For example, recently revised historical wind patterns that were undertaken for GROW (Global Re-analysis of Ocean Waves; see, for example, Cox and Swail, 2001) appear to show increasing winds and wave

heights in the North Atlantic. However, the real increases in winds may be at least partially the result of the fact that measurement instruments and techniques have changed with time (for example, anemometers on modern ships are at a greater elevation, above the standard 10 meter elevation, than was the case on older vessels). Efforts have been made to account for such effects, but it has not always been possible to determine the actual measurement conditions. Another confounding factor is that the wind measured at most offshore data buoys is at elevation 5 meters rather than the traditional standard of 10 meters.

Additional factors, such as variations in solar (sun spot) activity and El Niño cycles, can also be considered as potentially significant non-stationary factors. However, a database of 20–25 years (the minimum desired to estimate the 100-year event with confidence for FEMA studies) for a process that might be affected should already include the net effects of such phenomena. Study Contractors should be aware of these factors and avoid confusing such cyclic non-stationary influences with other hydrometeorologic processes.

Although standard FEMA practice is to address current conditions only, it could also be appropriate to identify and discuss periodic seasonal changes (such as significant El Niño oceanic conditions) and future changes arising from other significant non-stationary contributions. In a 1991 FEMA report titled *Projected Impact of Sea Level Rise on the National Flood Insurance Program*, for example, the potential impact of rising sea levels was investigated. It was concluded, at that time, that a relative sea level rise of up to 1 foot could be tolerated without major impact, but that a longer term rise of 3 feet would have severe financial consequences. Such background discussion might be appropriately included in the guidelines, even if not deemed essential to performance of a study.

More directly pertinent to a study would be an effort to document the expected magnitudes of non-stationary effects, even though small, and to estimate their projected impact over time; if nothing else, this might allay concerns and questions. If a linear trend were assumed for sea level rise, say, one could easily prepare a table for a given study site showing how the BFEs would change were the trend to continue. With time, the 100-year level would rise in approximately the same way as sea level (as long as the change is small), so that the 100-year level as determined by the study would be a more frequent event at any future date. Were the projected rate of rise to be 2 feet per century, for example, then after ten years (well within the life of a typical flood insurance study) the true BFE would have risen 0.2 foot and the mapped flood would have declined from the 100-year level to, say, the 90-year level. These magnitudes may not be critical in most areas, yet their documentation as part of a study might be useful to both FEMA and the communities.

#### **3.1.4 Related “Available” and “Important” Topics**

Table 3 at the end of this report presents estimates of times required to accomplish the tasks in this topic.

## 4 IMPORTANT TOPICS

None identified.

## 5 ADDITIONAL OBSERVATIONS

None.

## 6 SUMMARY

The Stillwater Focused Study addressed two broad topics: non-stationary processes such as effective sea level rise, and storm surge issues. Non-stationary processes (Topic 52) are categorized as Available; the primary effort will be to identify data sources, provide a discussion of ways in which non-stationary processes relate to flood insurance studies, and provide guidance to Study Contractors regarding their possible significance in a study and what material should be presented to FEMA for consideration.

The storm surge issues are divided into modeling factors for the Atlantic/Gulf Coasts (Topic 53) and alternate and/or simplified methods for the Pacific Coast (Topics 54 and 55), where surge is of less consequence. The primary effort recommended for the Atlantic/Gulf Coasts is to write detailed guidelines regarding storm surge and storm surge modeling, including discussions and recommendations for the numerous factors that affect a modeling effort. A secondary effort will be to review existing and planned coastal studies to suggest how regional study efforts might prove more economical and more accurate than county-by-county studies, as has been the usual practice. A final recommendation is to investigate ways to assess the accuracy of existing and future coastal studies, including a global statistical review and comparison of mapped BFEs with the historical record.

Table 1 summarizes the Stillwater Focused Study topics and recommendations. Table 2 presents a preliminary estimate of time necessary to complete recommended tasks.

**Table 1. Summary of Findings and Recommendations for Stillwater**

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
52	Non-Stationary Processes	AC	A	Y	Identify and summarize data sources for sea level rise and land subsidence and/or uplift; provide basic guidance regarding significance of non-stationarity in flood insurance applications; include guidance on interpretation of historical data. Suggest documentation of projected map impact	--
		GC	A	Y		
		PC	A	Y		
		SW	A	Y		
53	Storm Surge Modeling	AC	C	MAJ	Develop overview guidance for surge modeling; define procedures to assess accuracy of surge estimates ; suggest regional modeling approaches for study economy	6 44-48
		GC	C	MAJ		
		PC	--	--		
		SW	--	--		
54 & 55	Pacific Coast Storm Surge	AC	--	--	Identify tide gage data sources; develop procedures for surge extraction from tide gage records for FIS use (including test studies); develop simplified numerical modeling method for areas without data (1-D Pacific Surge Model)	6 44-48
		GC				
		PC	C	MAJ		
		SW	C	MAJ		

**Key:**  
 Coastal Area  
 AC = Atlantic Coast; GC = Gulf Coast; PC = Pacific Coast; SW = Sheltered Waters  
 Priority Class  
 C = critical; A = available; I = important; H = helpful  
 Availability/Adequacy  
 “Critical” Items: MIN = needed revisions are relatively minor; MAJ = needed revisions are major  
 “Available” Items: Y = availability confirmed; N = data or methods are not readily available  
 “Important” Items: PRO = procedures or methods must be developed; DAT = new data are required; PRODAT = both new procedures and data are required

Topic Number	Item	Time (Person months)
53	<b>Atlantic/Gulf Storm Surge</b>	
	Develop storm surge modeling guidelines	6
	Develop guidelines for surge extraction from tide gage data	Allocated under Topics 54 and 55
	Develop approach for global assessment of surge accuracy and identify data sources	4
	Develop guidance for regional modeling	2
	<b>TOTAL</b>	<b>12</b>
54 & 55	<b>Pacific Storm Surge (including Non-Open Coast)</b>	
	Identify sources and assess tide gage data for surge extraction	3
	Perform test/example studies of tide gage surge analysis including assessment of limitations	4
	Prepare contractor guidelines for tide gage surge evaluation	3
	Develop simplified surge model for Pacific coast applications, including frequency methods and identification of input data types and sources	6
	Perform test/example studies using simplified modeling approach	4
	Prepare contractor guidelines for the simplified Pacific surge modeling approach	4
<b>Total</b>	<b>24</b>	
52	<b>Stillwater Non-Stationary Processes</b>	
	Identify and summarize data sources for sea level rise, land subsidence, and other non-stationary processes	2
	Prepare study contractor guidelines regarding the significance of non-stationary processes, data sources, and documentation requirements	2
	<b>Total</b>	<b>4</b>

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