Title

A Framework for Sea Level Rise Vulnerability Assessment for Southwest U.S. Military Installationsmework for Sea Level Rise Vulnerability Assessment for Southwest U.S. Military Installations

Journal

Marine Technology Society Journal, Proceedings of Oceans 11(110426-001)

Authors

Chadwick, D B
Flick, R E
Helly, J
et al.

Publication Date

2011

A Framework for Sea Level Rise Vulnerability Assessment for Southwest U.S. Military Installations

Bart Chadwick[1], Reinhard Flick[2], John Helly[3], Tracey Nishikawa[4], Pei Fang Wang[1], William O'Reilly[2], Robert Guza[2],
Peter Bromirski[2], Adam Young[2], Walter Crampton[2], Bill Wild[1], and Issac Canner[5]
[1]Environmental Sciences Branch, SPAWAR Systems Center Pacific, San Diego, USA, email: bart.chadwick@navy.mil
[2]TerraCosta Consulting Group, 3890 Murphy Canyon Road, Suite 200, San Diego, USA
[3]San Diego Supercomputer Center, University of California San Diego, San Diego, USA
U.S. Geological Survey, 4165 Spruance Road, Suite 200, San Diego, USA
[4]Moffatt & Nichol Blaylock, 1775 Hancock St, Suite 250, San Diego, USA

Abstract—**We describe an analysis framework to determine military installation vulnerabilities under increases in local mean sea level as projected over the next century. The effort is in response to an increasing recognition of potential climate change ramifications for national security and recommendations that DoD conduct assessments of the impact on U.S. military installations of climate change. Results of the effort described here focus on development of a conceptual framework for sea level rise vulnerability assessment at coastal military installations in the southwest U.S. We introduce the vulnerability assessment in the context of a risk assessment paradigm that incorporates sources in the form of future sea level conditions, pathways of impact including inundation, flooding, erosion and intrusion, and a range of military installation specific receptors such as critical infrastructure and training areas. A unique aspect of the methodology is the capability to develop wave climate projections from GCM outputs and transform these to future wave conditions at specific coastal sites. Future sea level scenarios are considered in the context of installation sensitivity curves which reveal response thresholds specific to each installation, pathway and receptor. In the end, our goal is to provide a military-relevant framework for assessment of accelerated SLR vulnerability, and develop the best scientifically-based scenarios of waves, tides and storms and their implications for DoD installations in the southwestern U.S.**

I. INTRODUCTION

Climate change vulnerability is defined by IPCC as "the degree of inability to cope with the consequences of climate change and accelerated sea-level rise" [1]. This concept of vulnerability assessment embraces the assessment of both anticipated impacts and available adaptation options [2,3,4], and encompasses biogeophysical, socio-economic and political factors [5,6]. In this context, adaptive capacity represents the "ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" [7]. In general, climate change vulnerability in coastal areas is magnified by exposure to oceanic forces including increases in sea level, storm surge and wave heights, as well as limitations on adaptive capacity.

Vulnerability analysis of sea-level rise (SLR) for coastal areas has been conducted over varying scales including local area studies, country studies, and global studies [8,9,10]. Larger scale analyses are generally more qualitative and comparative (e.g. which areas of the world are most vulnerable), whereas regional studies are generally more quantitative and focus more on specific planning initiatives [11]. Various frameworks have been proposed and applied for vulnerability assessment over these spatial scales, including the IPCC Common Method [1], the U.S. Country Studies Methodology [12], the UNEP Handbook Methodology [13], and the South Pacific Islands Methodology [14]. While these frameworks bear similarities, they all have recognized limitations and criticisms [10]. While previous assessments have been carried out, there are still significant barriers including: limited understanding of relevant processes affected by sea-level rise; insufficient data on existing conditions; difficulty in developing the local and regional scenarios of future change; and lack of appropriate analytical methodologies for some impacts [15]. Within these frameworks, adaptation is generally considered in terms of retreat (minimize impacts by pulling back from the coast), accommodation (minimize impacts by adjusting human use of the coastal zone), and protection (impacts are controlled by soft or hard engineering) [16,5]. For coastal military bases, these responses must be also weighed in consideration of critical readiness, training and support missions [17].

More recently, climate change assessments have embraced risk assessment paradigms to evaluate sea level rise vulnerability [18,19,20,21,22,23,24]. In these approaches, vulnerability is cast in the risk assessment nomenclature of exposure and effects, with changes in sea level and storminess representing sources or stressors which are manifested through pathways such as shoreline response, erosion, inundation and saltwater intrusion, which in turn result in risk to receptors (or sometimes referred to as sectors such as buildings and structures, natural resources, transportation, etc.; [25]) These risk assessment strategies have generally been applied on regional or smaller scales [19,21,24], and provide a framework for addressing specific vulnerability questions at a relatively quantitative level. In these frameworks, risk is often quantified as the product of the probability of a given scenario with the consequence of the scenario, which includes both the exposure and the vulnerability [22,23]. This reflects the notion that the same sea-level rise scenario will result in different risks in different places because some people and places are more vulnerable than others [21].

II. REVIEW OF EXISTING FRAMEWORKS

A review of existing frameworks was conducted to appraise the state of the science for vulnerability assessment, and to create a credible basis for a DoD-relevant framework that builds on the strategies already developed and utilized in other applications. A cross-section of frameworks and strategies were identified and reviewed, and are briefly described below.

IPCC Common Methodology: The IPCC Common Methodology was developed primarily to assist countries in making first-order assessments of vulnerability to sea-level rise [3]. The methodology incorporates expert judgment and data analysis of socioeconomic and physical characteristics which includes delineation of the case study area, an inventory of study area characteristics, identification of relevant socioeconomic development factors, assessment of physical changes, formulation of response strategies, assessment of the vulnerability profile, and identification of future needs. Adaptation focuses around three generic options: retreat, accommodate or protect. The vulnerability profile defines a range of impacts of sea level rise, such as land loss and associated value and uses and a list of future policy needs to adapt both physically and socio-economically [26].

IPCC Technical Guidelines: These guidelines provide a framework for the assessment of climate impacts and adaptations structured around problem definition, method selection, method testing, scenario selection, assessment of biophysical and socio-economic impacts, assessment of autonomous adjustments, and evaluation of adaptation strategies [27]. The problem definition step identifies the goal of the assessment, the exposure unit, the spatial and temporal scope, and the data requirements. Selection of methods encompasses a range of possible techniques including experimentation, impact projections, empirical studies, and expert judgment. Method testing serves as a precursor to the main evaluation, and encompasses feasibility studies, data acquisition, and model testing. Scenario development relies on the specification of a range of plausible future climate conditions. Assessment of impacts describes the differences between the environmental and socio economic baseline, and the projected conditions under the selected climate change scenarios and incorporates the assessment of both autonomous adjustments and adaptation strategies.

UNEP Handbook Methodology: This method [28] was developed to provide a detailed application strategy for the IPCC Technical Guidelines [27]. It provides a generic framework for conducting assessments of sea-level rise and climate change and the approach is applicable to situations ranging from regional to national level studies, and can be used at both screening and more detailed levels of analysis. General input requirements include physical and socioeconomic characteristics of the coastal zone, and the resulting outputs include potential impacts of sea-level rise and corresponding adaptation strategies according to both socioeconomic and physical characteristics. The methodology has been applied in several countries, including the Cameroon, Antigua and Barbuda, Estonia, Pakistan, and Cuba [26].

US Country Studies Methodology: This methodology was tailored to meet the needs of developing countries in assessing their vulnerability to climate change and identifying opportunities for adaptation [29,12]. The general approach centers on the evaluation of biophysical effects and involves defining the scope of the assessment process, scenario selection, biophysical and economic impact assessments, integration of impact results, analysis of adaptation policies and programs, and documenting and presenting results to decision makers. The method is flexible in that relatively simple methods can be applied when data quality and availability are limited. It has generally been employed when an analysis of biophysical impacts of climate change is the central goal. It is broadly applicable to coastal resources, agriculture, grasslands/livestock, water resources, forestry, human health, fisheries, and wildlife [26].

The South Pacific Island Methodology: This methodology was developed in response to factors that restricted the direct application of the IPCC Common Methodology such as a lack of data, a common constraint in developing countries [30]. The methodology is an index-based approach that applies relative scores to assess a variety of scenarios and take advantage of traditional knowledge and memories of the local people to overcome the shortage of empirical data. The method utilizes six classes of coastal subsystems including natural, human, infrastructural, economic, institutional, and cultural that are further divided into subsystems to which a vulnerability score and a resilience score is assigned based on expert judgment under a range of scenarios. The two values are then combined to produce a sustainable capacity index for each scenario. The method is generally viewed as a screening level analysis for coastal settings [26].

Understanding Vulnerability of Coastal Communities: This approach by [11] presents a framework for assessing adaptive capacity which addresses the inherent susceptibilities of human environment systems exposed to climate variability and change in contrast to typical impact assessments that focus largely on reducing economic impacts. The framework incorporates differential exposures and vulnerabilities based on access and distribution of resources, technology, information and wealth; risk perceptions; social capital and community structure; and institutional frameworks that address climate change hazards. The framework is generally applicable on the local scale as a community-based or bottom-up approach and incorporates short-term exposure to variability as an important source of vulnerability superimposed on long-term change. The framework utilizes community level perceptions and experiences to identify the characteristics that influence response, recovery and adaptation, focusing on locally relevant outcomes that promote more effective planning.

Climate Change and Coastal Zones: The work of [31] presents a conceptual framework for vulnerability assessment, and outlines the steps that are required for the assessment of vulnerability. The framework distinguishes between natural-system vulnerability and socio-economic vulnerability to climate change. They identify the most important biogeophysical effects of sea level rise as: increasing flood-frequency probabilities and enhancement of extreme flood-level risks; erosion and sediment deficits; gradual inundation of low-lying areas and wetlands; rising water tables; saltwater intrusion; and biological effects. Socio-economic vulnerability resulting from these biogeophysical effects is categorized in terms of: direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats; increased flood risk of people, land and infrastructure; and impacts related to water management, salinity and biological activity.

<u>An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments:</u> This risk assessment and management framework for climate change impacts with a focus on individual exposure units that incorporates stakeholder involvement and links key climate variables with impact thresholds is described in [32]. The framework reflects modern risk assessment methodologies while maintaining consistency with the IPCC Technical Guidelines, and introduces the important notion of critical response thresholds in the context of conditional probabilities of exceedence. The framework consists of seven steps with a focus on stakeholder involvement and includes: identification of key climate variables affecting exposure units; creation of scenarios or expected ranges of these variables; a sensitivity analysis of the relationship between climate variables and impacts; identification of impact thresholds through interaction with stakeholders; implementation of the risk analysis; evaluation of risk, feedbacks, and autonomous adaptations; and, consultation with stakeholders, analysis of adaptations, and recommendations.

<u>North Carolina Sea Level Rise Risk Management Study:</u> North Carolina has initiated risk assessment and mitigation strategy demonstration of the potential impacts of sea level rise in that state associated with long-term climate change [19]. The assessment addresses four principal questions including: what changes to coastal flooding hazards will possibly occur between 2009 and 2100 due to storminess and sea level rise?; what built and living systems will be exposed to coastal flooding from increased storminess and sea level rise?; what possible impacts/consequences will occur on the exposed built and living systems?; and, what short-term and long-term strategies will result in efficient and effective prevention and/or alleviation of exposure and consequences from sea level rise and increased storminess? The assessment is scenario-based, utilizing potential sea level rise and demographic conditions for four “time slices” through 2100, and uses a Source-Pathway-Receptor framework model in which “sources” are climate or weather conditions that drive flood hazards, “pathways” are the mechanisms by which sources influence receptors, and “receptors” are the people, industries, infrastructure and natural resources that may be affected by the hazard.

A. *Framework Review Summary*

This cross-section of frameworks reflects different applications and an evolution and refinement in approaches over time. The frameworks share common requirements to define the problem, its scale and boundaries and characterize the biogeophysical and resulting socioeconomic impacts. Overall, sea level rise vulnerability frameworks appear to be evolving from strategies to support large-scale, qualitative screening assessments for specific future conditions, toward strategies that can be applied at regional and local scales to more quantitatively respond to specific vulnerability questions, evaluate a range of possible scenarios, and identify potential responses to vulnerability at the source, pathway and/or receptor level.

III. VULNERABILITY ASSESSMENT FRAMEWORK FOR DOD INSTALLATIONS

The approaches reviewed above can be viewed as complementary, with the traditional approaches such as the Common Methodology providing a flexible procedural strategy for a relatively qualitative assessment, and the emerging risk-based methodologies focusing more on defining and quantifying the conceptual linkages between stressors and receptors. For the purpose at hand, we adopt a hybrid approach which incorporates the risk-based paradigm into the procedural strategies of the IPCC Common Method and the Technical Guidelines to provide a framework that can be generalized to a broad range of potential climate impacts to coastal military installations, while providing sufficient conceptual and quantitative strategies to develop meaningful risk assessments for specific questions at individual installations. This strategy is also consistent with frameworks developed for ecological risk assessment by US EPA [33]. In addition, as emphasized in the US Country Studies Method and the South Pacific Island Method, as well as [32], we recognize the critical importance of local knowledge and expertise in achieving meaningful vulnerability assessments for these installations. Finally, we recognize and incorporate the key concept of sensitivity thresholds in the assessment as a means of quickly focusing the effort on critical characteristics of the installation, rather than simply a range of unrelated scenarios.

The proposed sea level rise vulnerability assessment framework for DoD installations is shown in Figure 1. The framework is quite general, and is consistent with typical systematic planning strategies for risk assessment frameworks that have been applied to human health and ecological risk assessment [33,34], while building on the key elements of traditional vulnerability assessment frameworks. The framework is structured around six primary components including: problem formulation and scoping; conceptual model development; defining and validating data and modeling requirements; conducting the risk assessment; risk communication; and risk management. Below, we outline the common components of the vulnerability assessment framework shown in Figure 1 up to the execution of the risk assessment, but excluding the risk communication and risk management components for the sake of brevity.

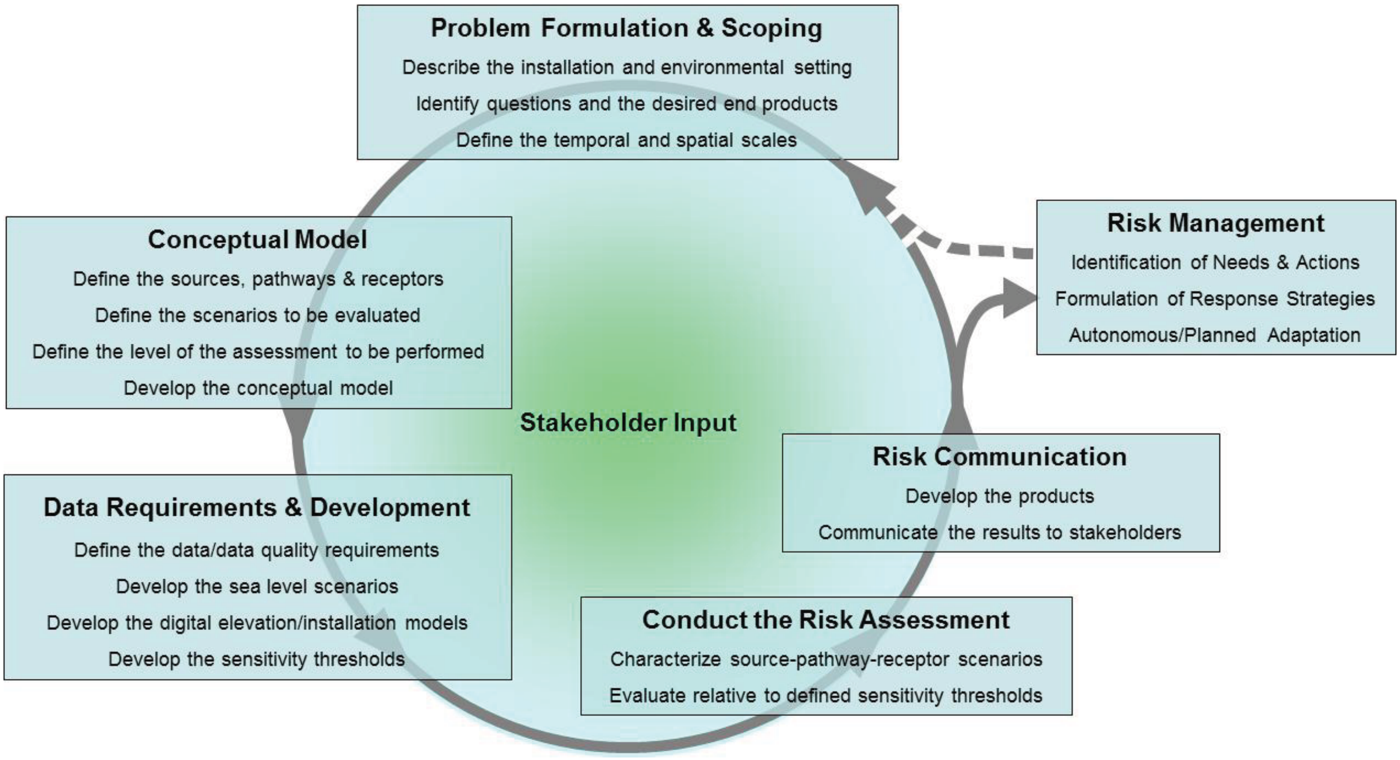

Figure 1. Iterative flow diagram for the vulnerability assessment framework for military installations.

A. Problem Formulation and Scoping

Problem formulation and scoping encompasses a clear development of the installation and environmental setting, the questions to be addressed, identification of the desired end products, and definition of the environmental setting, assessment scale, spatial boundaries, time span and time resolution [33,19,1,27]. Early definition of the problem and scope is critical to the success of the assessment, and provides the basis for development of the conceptual model [33]. Vulnerability assessment for sea level rise is a highly complex and potentially costly proposition, reinforcing the need to focus the study on the critical questions to be addressed, and limiting the analysis to the aspects required to address those questions.

1) Describe the Installation and Environmental Setting: A general understanding of the installation and its environmental setting is critical to the problem formulation for the assessment. The relationship of the installation to its environmental setting provides a context for defining the conditions that will control vulnerability for a given installation. In general, this will include both a historical perspective, a description of current-day conditions, and a projection of future conditions.

2) Identify Questions and the Desired End Products: The development of assessment questions should be structured in a manner consistent with the Source-Pathway-Receptor model. In other words, the question should specify the source of the vulnerability, the receptor that is impacted, and the pathway of impact. Formulation of the questions in this way supports the clear communication of the connections between stressors and impacts, and provides a direct basis for the development of the conceptual model while allowing flexibility to address a broad range of climate change related questions. Specifying the desired assessment products is also a process which should rely strongly on stakeholder interaction. As a general rule, the primary product of most vulnerability assessments is a report and recommendations. In addition, while the media for a typical assessment product may culminate in a report, there are a range of other potential product media such as GIS layers, animations, models, and maps that may be critical tools for the communication and management of risk [35].

3) Define the Temporal and Spatial Scales: Defining the scale and boundaries of the spatial domain requires consideration of the domain that encompasses the land, shoreline, infrastructure and other resources that are the subject of the assessment [36]. A second consideration is the scale of the processes that must be accounted for to conduct the assessment. For a military installation, the legal boundaries of the installation provide one context for defining the boundaries of the assessment. The bulk of the actual vulnerability assessment may focus within these boundaries. However to characterize the relevant biogeophysical processes the boundaries may need to encompass broader scales such as the scale of the coastal littoral cell, or the regional watershed, and the scales of erosion, flooding, inundation and groundwater intrusion may be quite different for a given installation. Also, most military installations are highly interdependent with other regional infrastructure such as roads, power, communications, water, sewer, and many of the installations personnel may reside outside the boundaries of the base itself. Consideration should be given to utilizing existing regional studies or collaborating with other regional programs that may be examining civilian issues in the same general area.

The starting time of the assessment is generally grounded in the best possible delineation of the current or baseline condition. In contrast, selection of the end point of the time span for the assessment should be considered in the balance of the underlying climate drivers, the response, planning and management time scales of the target receptors, and the level of uncertainty associated with long-term projections. For a military installation, the time span must encompass relevant planning projections for mission critical infrastructure and training requirements. In addition to the overall time span, the assessment may also require various levels of time resolution to establish scenarios that incorporate sea level variability at different frequencies, to support modeling analysis of time varying biophysical pathways, and to evaluate receptors at certain time slices along the trajectory [19,37].

B. *Conceptual Model*

The conceptual model serves as a roadmap for the assessment, defining the sources, pathways and receptors, outlining the scenarios to be evaluated, and specifying the level of the assessment to be performed (Figure 2). The conceptual model should follow logically from the problem formulation by characterizing the critical components and linkages required to answer the questions to be addressed.

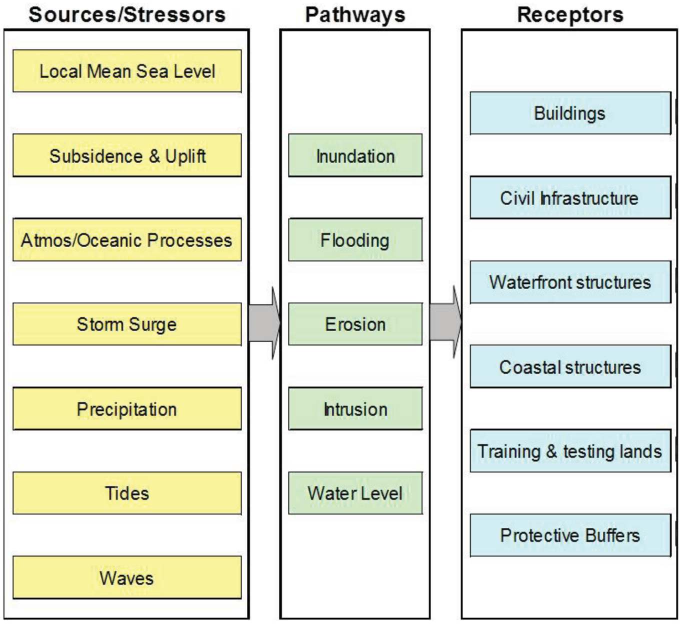

Figure 2. Generic conceptual model for vulnerability assessment of coastal military installations.

1) Define the sources, pathways and receptors: Identification of the relevant sources, pathways and receptors for the assessment should follow directly from the problem formulation if the questions for the study are structured in a manner consistent with the Source-Pathway-Receptor model. The conceptual model is based on the Source-Pathway-Receptor (SPR) framework in which "sources" are climate or weather conditions that drive hazards, "pathways" are the mechanisms by which sources influence receptors, and "receptors" are the people, industries, infrastructure and natural resources that may be affected by the hazard [19].

Sources: Typical sources that should be considered include potential climate related changes and interactions of local mean sea level, uplift and subsidence, atmospheric-oceanic processes such as ENSO, storm surge, precipitation, tides, and waves. Local mean sea level reflects the height of the sea with respect to a land benchmark, averaged over a long enough period of time to remove short-term fluctuations caused by waves and tides, is generally assumed to follow the same general trend as global mean sea level, but may be modified in magnitude in accordance with local tide gauge measurements [38,39]. Subsidence and uplift are caused by localized displacements of the land generally as a result of tectonic motions, consolidation and compaction of sediments, and/or withdrawal of subsurface fluids, in some areas, the local rate of subsidence or uplift may be a source of comparable magnitude to the rate of change of local mean sea level [40,41].

Coupled atmospheric-oceanic processes such as the El Niño-Southern Oscillation (ENSO) or the Pacific Decadal Oscillation are a source of significant inter-annual variability in sea level [42,43]. Storm surge is characterized as a long period wave and associated with the combined effects of storm driven wind and low atmospheric pressure weather, and is generally strongest when storms move onto shallow coastal waters. While the direct influence of precipitation and evaporation cycles plays a role in the large scale water balance and level of the oceans, the localized effects of precipitation and its contribution to runoff, river flow, ground saturation and subsequent flooding and erosion are of principal concern. In most areas, tides are the source of the largest changes in sea level on all time scales of practical interest, short of the millennial time scales associated with glaciations and de-glaciations, and peak tides may be particularly important to flooding and beach erosion, since coastal problems tend to occur when large waves coincide with peak tides and enhanced sea levels due to storm surges and El Niño [44,45,46]. Waves. Wind-generated waves are surface waves that occur on the free surface of oceans, seas, lakes, and rivers as a result of wind blowing over a significant length of fluid surface. Ranging in size from centimeters to tens of meters, waves may be generated locally or may travel as swells for thousands of miles before reaching land.

a) Pathways: Pathways represent the process or mechanism by which sea level rise sources act on receptors to cause impact. Pathways of action for sea level rise generally include inundation, flooding, erosion and intrusion. Often, a given pathway may be governed by the combined action of multiple sources and may influence a range of potential receptors. Primary pathways include innundation, flooding, erosion, intrusion as well as direct effects of changing water levels. Inundation. Inundation is considered as an exposure pathway resulting from a long-term increase in local mean sea level, is primarily linked to the local mean sea level source, and its importance is strongly influenced by the elevation and topography of the coastline. Flooding. Flooding is an exposure pathway that interacts with increases in local mean sea level to increase the frequency and magnitude of short-term impacts to coastal areas. In addition, climate change may also lead directly to increases in storminess relative to current conditions, thus compounding the influence of sea level rise increase. Erosion. Coastlines tend to recede as sea level increases, and this recession occurs partially through erosion, and is generally controlled by transport and a balance of sources and sinks including seacliffs, rivers, gullies, dunes, nourishment and coastal canyons. Intrusion. Salt water intrusion in surface water and groundwater due to increases of local mean sea level can be exacerbated by drought cycles, changes in storminess and precipitation, and increasing demands on water supplies due to population growth. Salinity intrusion into rivers and estuaries can also impact sensitive aquatic plants and animals that do not tolerate high salinity.

b) Receptors: Common receptors for sea level rise vulnerability have been identified in a range of previous assessments [33,47,48,23,19]. In the risk assessment of natural disasters, "High potential loss facilities" such as nuclear reactors, dams and military installations are generally not included unless supplemental studies specific to these facilities are carried out [23]. For purposes of this framework, we have adapted these previous definitions to align with general categories more commonly used by planners, engineers and facilities personnel at military installations including:

- Training and Testing Lands: Encompass the coastal land areas that support training and testing missions which can span many different land forms such as beaches, bays, estuaries, rivers, barrier islands, wetlands, bluffs and lagoons and support many types of missions including amphibious assault training, coastal components of maneuver corridors, amphibious landing beaches, airfields, and beach/bay training areas.
- Buildings: A range of buildings that support operations and missions of the installation that could include buildings for housing, logistics, training, testing, operations, and security.
- Waterfront Structures: Includes a range of structures that support waterfront operations and missions of the installation and encompasses structures such as piers, wharves, quay walls, floating docks and graving docks.
- Coastal Structures: Includes a range of coastal structures whose primary purpose is to protect the shoreline and thus sustain operations and missions of the installation such as jetties, groins and revetments which are used to protect the shoreline and dredged improvements.
- Civil Infrastructure: Describes a broad category of built infrastructure that is critical to the day-to-day operations and mission of the installation and includes receptors ranging from critical utility infrastructure such as buried utilities, fuel transfer/supply, transportation corridors, and storm water conveyance systems.
- Military and Civilian Personnel: Increasing sea level poses the prospect for injury and loss of life at coastal military installations which is predominantly linked to the potential for more frequent and severe flood events that are likely to result from the co-occurrence of storm surge, high waves, high tides and increasing local mean sea level.
- Protective Buffers and Natural Resources: Generally classified as non-engineered coastal areas that provide a natural means of protection for coastal installations from changes in sea level and can include receptors such as beaches, dunes and wetlands that are generally in the first line of exposure to changing sea level.

2) Define the Scenarios to be Evaluated: Sea level rise vulnerability assessments are generally developed based on a limited set of scenarios for both the driving source terms, as well as for the receptors. The magnitude of these adjustments should be consistent with a range of published future predictions. The most commonly used scenarios for global climate change are those described in the IPCC Special Report on Emission Scenarios (SRES; [49]). Scenario development for a coastal military installation should generally incorporate or be consistent with the range of commonly applied SRES scenarios with knowledge of their relation to trends in local mean sea level rise, other sources such as storm surge, El Nino, tides and waves, and should consider which combination of these sources is relevant to the receptors of interest.

3) Define the Level of the Assessment to be Performed: As described in the framework, risk assessment is often an iterative process, and the complexity of sea level rise vulnerability analysis dictates that different levels of assessment may be appropriate depending in the scope of the project and the resources and data available. In many cases, preliminary screening analysis may be important to even framing what the critical questions for a more detailed assessment will be, or which spatial areas may be most sensitive (e.g. [50]). A common construct is to consider at least two levels of analysis, the first often termed a screening level risk assessment, and the subsequent level a baseline assessment. This strategy is commonly applied in ecological risk assessment, and has recently been adopted in climate change vulnerability assessment as well [51].

4) Develop the Conceptual Model: The conceptual model should be viewed as an evolving tool that is updated as the assessment progresses, and in the end captures a simplified yet accurate representation of the vulnerability assessment. A conceptual model for sea level rise must also describe the spatial and temporal context of the assessment, and layout plausible future scenarios for both biophysical and socioeconomic systems. Typical representations include source-pathway-receptor diagrams that illustrate which sources potentially drive risk for a given receptor and though which pathway or pathways. Spatial and temporal models are also useful for illustrating the juxtaposition of sources and receptors in the assessment domain, and to illustrate the hypothesized evolution of the system through time.

C. Data Requirements and Development

Data requirements and development for the vulnerability assessment focuses on defining what data is required, characterizing the quality of the data in the context of uncertainty, and developing these data into the products required to perform the assessment [52,53].

1) Define the data/data quality requirements: Data and data quality requirements can be defined in the context of the source-pathway-receptor conceptual framework. In this context, sea level rise vulnerability assessments will share the same general data requirements for most coastal military installations. Installation-specific requirements will vary to some degree as a function of geographical location, site-specific coastal processes, and the type, character, and mission of the installation. Typical data requirements based on the installations studied in this project are summarized below.

a) Sources: For the southwest US where this project was focused, the primary sea level source terms are mean sea level, tides and waves, along with non-tidal residuals which include effects of storm surge, El Nino, and other large scale oceanographic phenomenon. For establishing mean sea level trends, we followed the approach described in [47] which requires data describing the historical regional trend, the mean sea level for the tidal epoch centered on the starting year, and the sea level at the end year condition. The majority of these inputs are determined from local tide gage data. Future tides are generally predictable from harmonic analysis of historical data, and data sources for these predictions are broadly available. We estimated non-tide residuals and waves using global climate models, in which case an extensive range of data (not described here) is required to parameterize the model. Historical tide gage and wave gage data were used to validate the model preditions.

b) Pathways: Data requirements for the assessment of physical exposure pathways can be extensive. Quantifying these responses often requires a range of historical data and model parameterization. For erosion on exposed shorelines, long-term response models generally require information on the shore profile and substrate, as well as information on the sea level rise trajectory. Additional information for beaches such as sand budgets and transport patterns may also be required. Because episodic events may influence the long-term change, data that reveal the relationship between these events and shoreline response can also be important. For these short-term episodic events, empirical or modeling approaches may be used to estimate the shore response, relying on measured relationships between wave/storm conditions and beach profile change. Modeling approaches generally require information for the starting condition of the shore, time series conditions for the wave and water level forcing, along with historical shoreline and wave data for hindcast and verification.

Flooding and inundation pathways require data to predict the movement of water into upland areas as water levels rise. This generally requires high resolution elevation maps, benchmarks for vertical datum conversions, land cover and shore protection, uplift or subsidence rates, and water level scenarios. For the southwest US where storm surge is a minor component of total water level, static analysis may be sufficient, while in other areas where hurricane impacts are dominant, dynamic analysis of storm surge may be required with additional data requirements. For protected harbor and bay areas, assessment of changes in water levels and currents require data to support hydrodynamic modeling. These data generally include high resolution bathymetric and shoreline elevation data, water levels at the forcing boundaries (e.g. ocean and river), and water level and currents measured within the harbor for validation purposes. General data requirements for the groundwater intrusion pathway include land elevations, lithology of the aquifer, water levels at the ocean and upland boundary, other source and loss terms within the domain, and water levels and salinity data within the domain for model validation. Detailed descriptions of data requirements for the range of exposure pathways assessed in this study are provided in subsequent sections.

c) Receptors: The receptor categories described previously provide a framework for establishing data requirements. Building, civil infrastructure and waterfront structure data for a given installation are often available through the public works officer at the installation or region. In general, this data is represented in GIS layers that may or may not correspond to the categories defined here. Coastal structures and natural buffers may not be described in the GIS, but may be available through natural resource management plans or other regional sources. Often these items can be cataloged from imagery or national wetland inventory data if they are not present in the installation GIS.

2) Develop the sea level scenarios: Sea level scenarios represent future conditions on the basis of the integration of source terms, spatial and time scales as defined in the conceptual model. The scenarios can be constructed in a variety of ways where the emphasis on different source terms may be a function of their importance to a particular installation. In the end, the goal is to produce a cross-section of scenarios that represent the expected range of future conditions. To the extent possible, the scenarios should incorporate estimates of the probability and uncertainty associated with these conditions. The general approach used for this study is shown in Figure 3. Water level sources are determined through a range of modeling and empirical methods, and then integrated to construct a range of scenarios which are exposure dependent. Prescribed mean sea level conditions at 2100 are translated to mean sea level curves for the next century through an empirical model. IPCC future climate scenarios are used to parameterize global climate models, which in turn are used to generate atmospheric and oceanographic conditions. These conditions are applied directly to estimate local non-tidal fluctuations in sea level (non-tide residuals), as well as to drive wave models to predict runup. Finally, empirical harmonic models are used to predict tides, and the various source terms are integrated (in a statistical sense) to create exposure-dependent scenarios for exposed shorelines, protected bays, and groundwater. Detailed examples of this procedure for the MCBCP and NBC installations are presented in subsequent sections.

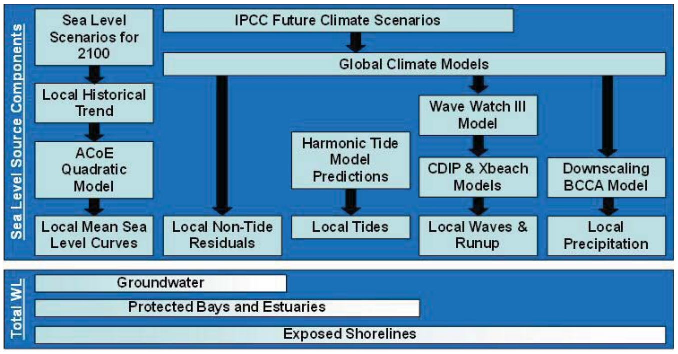

Figure 3. Development strategy for sea level source terms applicable to the Southwestern US.

3) Develop the digital elevation and installation models: A fundamental aspect of conducting the vulnerability assessment is developing an integrated model of the terrain elevation and installation infrastructure. This integrated model serves as the backbone for the analysis, starting with assessment of the physical response of the shoreline, and building toward the analysis of inundation and flooding. This model also provides the basis for understanding the basic sensitivity of the installation receptors to different magnitudes of sea level exposure. Just as in ecological risk assessment, we can define dose-response curves for receptors to physical or chemical stressors, with an integrated terrain and installation model, we can define the dose-response of our installation components to the physical impacts of water level, erosion, intrusion and other exposures associated with sea level rise.

The terrain data is compiled, generally to the best degree possible from available sources (Figure 4). The data are integrated to provide a complete representation of the terrain at the installation for the current day condition. For analysis purposes, the shoreline data must be classified with respect to erodability. In some cases, this may be a distinction between a hardened shoreline and a natural buffer, while in other cases it could be the distinction between a rocky coast and a sandy beach. As a parallel effort, the data describing the built infrastructure of the installation must be compiled. Integration of these data sets then allows for an accurate representation of the vertical elevation of the infrastructure, as well as the lateral location with respect to the shoreline. This vertical and horizontal registration then allows for analysis of exposure with respect to water level, erosion and intrusion pathways. Often it is useful to filter the data at this point to limit the assessment to areas and infrastructure that is within a reasonable range of the expected exposure scenarios.

4) Develop the sensitivity thresholds: Determining sensitivity thresholds for the range of receptors at an installation provides a means of streamlining the vulnerability assessment, and targeting limited resources for adaptation to the most critical risks. Sensitivity thresholds are generally specific to a given installation and represent the exposure to a given stressor that will bring about a rapidly accelerating rate of response. Threshold elevations are a characteristic of most installations where, due for instance to a leveling of the terrain combined with a density of infrastructure, when sea level reaches that level the risk of damage to the installation can increase dramatically. Similarly for saltwater intrusion, increasing sea level may increase salinity levels inland, but a threshold occurs when the allowable level of chloride is exceeded in potable water production wells. Sensitivity curves, developed as described above from the integrated terrain and installation model, provide the means to identify these thresholds and incorporate them into the assessment.

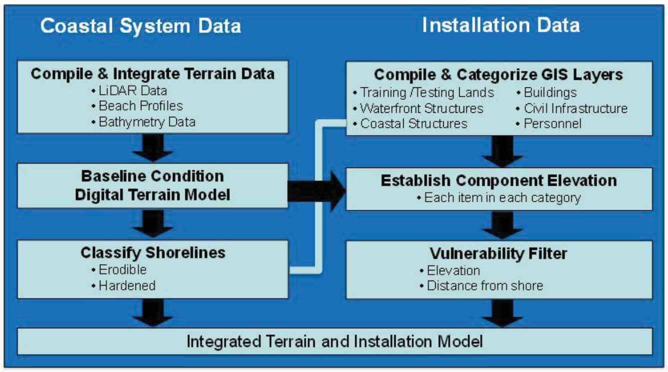

Figure 4. General approach to development of the integrated terrain and installation model.

D. Conducting the Assessment

Conducting the risk assessment requires a characterization of complete source-pathway-receptor scenarios. With the conceptual model as a guide, and defined scenarios and baseline conditions, assessment consists of determining the pathway responses of the system, and quantifying the associated risks in the context of the installation sensitivity.

1) Characterize Source-Pathway-Receptor Scenarios: To assess risk, the response of the system to predicted future conditions must be determined. The specific methods for characterizing various response pathways may vary for different studies and locations, but in general will require the application of a range of response models that provide a simulation of the physical response of the system. These can range from hydrodynamic and morphological models, to groundwater transport and flood routing models and may be theoretically or empirically based. To reduce uncertainty, the response models should be grounded in the context of historical data and be well proven at least under current day conditions. Exposure-specific future sea level scenarios are used to drive a range of pathway-specific models (Figure 5). For exposed shorelines, we examined both long-term response to mean sea level, and short-term response to episodic events. These response models are used to develop modified terrain models that account for erosion and accretion, and quantify the potential for inundation and flooding. Protected harbor areas are assessed under scenarios which exclude wave exposures, but account for sea level rise, tides and non-tide residuals. Hydrodynamic models are applied to evaluate the expected changes in water levels, currents and bottom shear. For groundwater, a cross-sectional transport model was constructed through a critical section of the study area to account for potential responses of the fresh water aquifer to elevated ocean boundary conditions. The scenarios for this exposure utilize monthly average to correspond to the typical time step of the model, and because the long-term groundwater response is highly filtered by the low permeability of the soils. Response is measured in terms of changes in groundwater flow patterns, and landward migration distance of the saltwater front.

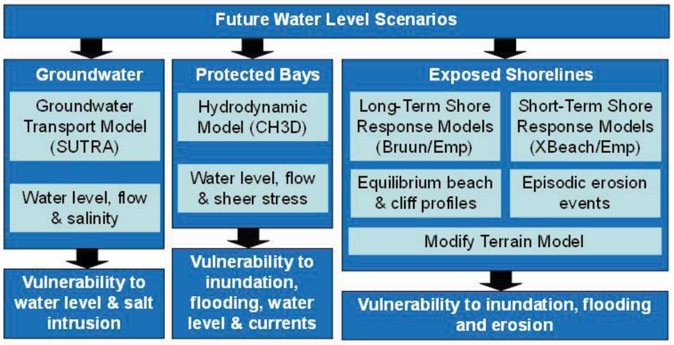

Figure 5. Pathway response modeling approach.

2) Evaluate relative to sensitivity thresholds: The final quantification of risk incorporates the three primary products of scenarios, pathway response assessment, and installation sensitivity. Scenarios associated with a given exposure at the installation provide total water level conditions linked to a given mean sea level and statistical return period. Using the pathway modeling for these scenarios, future conditions at the installation are predicted. These future conditions provide the basis for adjusting the underlying terrain model at the installation, and evaluating risk based on the sensitivity of the installation infrastructure. These risks are quantified using various damage and cost functions that translate the infrastructure sensitivity into specific metrics such as dollars, training days lost, etc. Based on this procedure, an integrated suite of products are generated including installation response curves, sea level vulnerability matrices, and scenario visualizations that provide both quantitative and descriptive assessments of risk.

IV. CONCLUSIONS

Coastal military installations in the U.S. Southwest are potentially vulnerable to sea level rise. The framework developed here builds on previous efforts to provide a consistent approach to addressing risk at these installations in a way that is consistent with risk assessment methodologies that have been applied by the military for other applications. The framework provides strategies for the development of future sea level scenarios that are linked to military–relevant receptors through defined exposure pathways. Future sea level scenarios are considered in the context of installation sensitivity curves which reveal response thresholds specific to each installation, pathway and receptor. Installations infrastructure is indexed to vertical elevations, and depth-damage functions are applied together with cost data to estimate cumulative risk for a range of future sea level scenarios with associated return period probabilities.

REFERENCES

[1] IPCC. 1992. A common methodology for assessing vulnerability to sea level rise, in: IPCC CZMS, 1992. Global Climate Change and the Rising Challenge of the Sea: Report of the CZM Subgroup, Response Strategies Working Group. Ministry of Transport and Public Works, Rijkswaterstaat, Tidal Waters Division, The Hague. 690 pp.

[2] Smith, J.B, N. Bhatti, G.V. Menzhulin, R. Benioff, M. Campos, B. Jallow, F. Rijsberman, M.I. Budyoko, and R.K. Dixon (eds.). 1996. Adapting to Climate Change: An International Perspective. Springer-Verlag, New York.

[3] Tol, R.S.J., S. Fankhauser, and J.B. Smith. 1998. The scope for adaptation to climate change: what can we learn from the impact literature?, Global Environ. Change 8(2): 109-123.

[4] Klein, R.J.T. and R.J. Nicholls. 1999. Assessment of coastal vulnerability to climate change. Ambio 28(2): 182-187.

[5] Bijlsma, L., et al., 1996: Coastal zones and small islands. In: R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds.), Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK and New York. 879 pp.

[6] Turner, B. L. II, R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperson, A. Luers, M.L. Martello, C. Polsky, A. Pulsipher, and A. Schiller. 2003. A framework for vulnerability analysis in sustainability science. Proc. Nat. Acad. Sci. 100(14): 8074-8079.

[7] McCarthy, J.J., O.F. Canziani N.A. Leary, D.J. Dokken, and K.S. White (eds.). 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability - Contribution of Working Group II to the Third Assessment Report of the IPCC.

[8] Nicholls, R.J. and N. Mimura. 1998: Regional issues raised by sea-level rise and their policy implications. Clim. Res. 11(1): 5-18.

[9] Nicholls, R.J. 1995. Synthesis of vulnerability analysis studies. Pp. 181-216 in: Proceedings of WORLD COAST 1993, Ministry of Transport, Public Works and Water Management, the Netherlands.

[10] Nicholls, R.J., and A.C. de la Vega-Leinert. 2008. Implications of sea-level rise for Europe's coasts: An introduction. J. Coast. Res. 24(2): 285-287.

[11] Dolan, A.H., and I.J. Walker. 2006. Understanding vulnerability of coastal communities to climate change related risks. J. Coast. Res. SI 39 (Proceedings of the 8th International Coastal Symposium, Itajaí, SC, Brazil): 1316-1323.

[12] Benioff, T., S. Guill, and J. Lee (eds.). 1996. Vulnerability and Adaptation Assessments: An International Guidebook. Kluwer Academic Publishers, Dordrecht, The Netherlands. 300 pp.

[13] Burton, I. J.B. Smith, and S. Lenhart. 1998. Adaptation to Climate Change: Theory and Assessment. In: J.F. Feenstra, I. Burton, J.B. Smith, and R.S.J. Tol (eds.), Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies, Version 2.0, UNEP/RIVM, Nairobi and Amsterdam. 446 pp.

[14] Yamada K., P.D. Nunn, N. Mimura, S. Machida, and M. Yamamoto. 1995. Methodology for the assessment of vulnerability of South Pacific island countries to sea-level rise and climate change. J. Global Environ. Eng. 1:101–125.

[15] Nicholls, R.J. and R.J.T. Klein, 2000: Adaptation Frameworks for Sea-Level Rise Impacts. First meeting for the Implementation of the Recommendations Arising from the Third Ministerial Conference on Environment and Health, London, 1999, European Centre for

Environment and Health, World Health Organisation, Rome, Italy, 26-28 May 2000, 13 pp.

[16] IPCC, 1990. Strategies for Adaptation to Sea Level Rise: Report of the Coastal Management Subgroup, Response Strategies Working Group. Ministry of Transport and Public Works, Rijkswaterstaat, Tidal Waters Division, The Hague. 131 pp.

[17] Center for Naval Analysis, 2010. National Security and the Threat of Climate Change, Alexandria, VA. http://securityandclimate.cna.org/.

[18] Patz, J.A., P. R. Epstein, T. A. Burke, and J. M. Balbus, 1996. Climate Change and Emerging Infectious Diseases, JAMA. 275(3):217-223.

[19] NC DEM (North Carolina Division of Emergency Management). 2009. North Carolina Sea Level Rise Risk Management Study: Potential Impacts, Risk Assessment and Management Strategies. Office of Geospatial and Technology Management Study Plan 3.1, October 26th, 2009. 32 pp.

[20] Leggett, J., W. Pepper, A. Sankovski, J. Smith, R. Tol, and T. Wigley. 2003. Climate change risk analysis framework (CCRAF) a probabilistic tool for analyzing climate change uncertainties. Geophys. Res. Abstr. 5: 07416.

[21] Cartwright, A., 2008. Global Climate Change and Adaptation – A Sea-Level Rise Risk Assessment. Phase Three: Final Report, A Sea-Level Rise Risk Assessment for the City of Cape Town, Prepared for the Environmental Resource Management Department, City of Cape Town. 65 pp.

[22] Liverman D.M., 2001. Vulnerability to global environmental change. In Kasperson J.X. & Kaspersen R.E. (Eds.), Global Environmental Risk. Tokyo, New York, Paris: United Nations University Press.

[23] van Westen, C.J. and Georgiadou, P.Y. 2001. Spatial data requirements and infrastructure for geologic risk assessment. In: Proceedings Workshop on Natural Disaster Management, ISPRS Technical Committee VII, Ahmedabad, India. 15 pp.

[24] Scheitlin, K. N., J. B. Elsner, S. W. Lewers, J. C. Malmstadt, and T. H. Jagger, 2011. Risk assessment of hurricane winds for Eglin Air Force Base in northwestern Florida, USA, Theoretical and Applied Climatology, DOI: 10.1007/s00704-010-0386-4.

[25] Snover, A.K., L. Whitely Binder, J. Lopez, E. Willmott, J. Kay, D. Howell, and J. Simmonds. 2007. Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments. ICLEI – Local Governments for Sustainability, Oakland, CA. 172 pp.

[26] UNFCCC (Secretariat of the United Nations Framework Convention on Climate Change). 1999. Compendium of Decision Tools to Evaluate Strategies for Adaptation to Climate Change - Final Report. Prepared by Stratus Consulting Inc. 49 pp.

[27] Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. University College London, London. 59 pp.

[28] Feenstra, J.F., I. Burton, J.B. Smith, and R.S.J. Tol (eds.). 1998. Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies, Version 2.0. United Nations Environment Programme, Nairobi, and Institute for Environmental Studies, Vrije Universiteit, Amsterdam. 464 pp.

[29] USCSP (United States Country Studies Program). 1999. Climate Change: Mitigation, Vulnerability, and Adaptation in Developing and Transition Countries. U.S. Country Studies Management Team (PO-6), Washington, D.C. 96 pp.

[30] Mimura. 1999. Vulnerability of island countries in the South Pacific to sea level rise and climate change. Clim. Res. 12(2-3): 137-143.

[31] Sterr H., R.J.T. Klein, and S. Reese. 1999. Climate Change and Coastal Zones: An Overview of the State of the Art on Regional and Local Vulnerability Assessment. In: Climate Change and Mediterranean Coastal Systems: Regional Scenarios and Vulnerability Assessment, International workshop, 9-10 December 1999, Fondazione Eni Enrico Mattei, Venice, Italy, 24 pp.

[32] Jones, R. 2001. An environmental risk assessment/management framework for climate change impact assessments, Natural Hazards 23:197-230.

[33] USEPA (Environmental Protection Agency). 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F, Washington, D.C. 114 pp. + appendices.

[34] Risk Assessment Guidance for Superfund: Volume I - Human Health Evaluation Manual (Part B, Development of Risk-based Preliminary Remediation Goals). OSWER Directive 9285.7-01B.Office of Emergency and Remedial Response, U.S. Environmental Protection Agency, Washington, D.C. 1991.

[35] Titus, J.G. and C. Richman, 2001. Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf coasts, Climate Research: 18: 205–228.

[36] Heberger, M., H. Cooley, P. Herrera, P. H. Gleick, and E. Moore. 2009. The Impacts of Sea Level Rise on the California Coast. California Climate Change Center. CEC ‐ 500 ‐ 2009 ‐ 024 ‐ F.

[37] Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham and R. Flick, 2009. Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, California Climate Change Center, publication #CEC-500-2009-014-F, 64 pp.

[38] Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2006. Projecting Future Sea Level. California Climate Change Center. California Energy Commission, Public Interest Energy Research Program. CEC-500-2005-202-SF. 64 pages.

[39] USACOE, 2009. Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs, Circular No. 1165-2-211, Dept. of the Army, US Army Corps of Engineers, Washington, DC, 31 pp. http://140.194.76.129/publications/eng-circulars/ec1165-2-211/toc.html.

[40] Burkett, V.R., Zilkoski, D.B., and Hart, D.A. 2003. Sea-level rise and subsidence: implications for flooding in New Orleans. IN: Keith R. Prince and Devin L. Galloway (Eds.) U.S. Geological Survey Subsidence Interest Group Conference, Proceedings of the Technical Meeting, Galveston, Texas, November 27–29, 2001. U.S. Geological Survey, Water Resources Division Open File Report 03-308, pp. 63-70. http://pubs.usgs.gov/of/2003/ofr03-308/

[41] Milliman, J.D. and Haq, B.U., 1996. Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies. Kluwer Publ., Amsterdam. 369 p.

[42] Nerem, R. S., “Measuring Very Low Frequency Sea Level Variations Using Satellite Altimeter Data,” Global and Planetary Change, Vol. 20, No. 2-3, pp. 157-171, 1999.

[43] Trenberth, K. and J.W. Hurrell, 1994. Decadal atmosphere-ocean variations in the Pacific, Climate Dynamics 9 (6):303–319.

[44] Flick, R.E. and D.R. Cayan, 1984, "Extreme Sea Levels on the Coast of California," Proc. 19th Int. Conf. Coastal Eng., Amer. Soc. Civil Eng., 886-898.

[45] Flick, R.E., 1986, "A Review of Conditions Associated with High Sea Levels in Southern California," Sci.Total Env., 55, 251-259.

[46] Flick, R.E., 1998. Comparison of California tides, storm surges, and sea level during the El Niño winters of 1982-83 and 1997-98, Shore & Beach, 66(3), 7-11.

[47] Titus, J. G., R. A. Park, S. P. Leatherman, J. R. Weggel, M. S. Greene, P. W. Mausel, M. S. Trehan, S. Brown, C. Grant, and G. W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. Coastal Management 19: 171-204.

[48] FEMA, 1991: Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program (PDF) (70 pp, 690K) October 1991.

[49] IPCC, 2000. IPCC Special Report Emissions Scenarios, Summary for Policymakers, A Special Report of IPCC Working Group III.

[50] Hammar-Klose, and Thieler, E.R., 2001. Coastal Vulnerability to Sea-Level Rise: A Preliminary Database for the U.S. Atlantic, Pacific, and Gulf of Mexico Coasts. U.S. Geological Survey, Digital Data Series DDS-68.

[51] Commonwealth of Australia, 2006. Climate Change Impacts & Risk Management: A Guide for Business and Government, Australian Greenhouse Office, Department of the Environment and Heritage.

[52] Basher, R. E. (1999). "Data Requirements for Developing Adaptations to Climate Variability and Change." Mitigation and Adaptation Strategies for Global Change 4(3): 227-237.

[53] NOAA, 2009. Proceedings from the Sea Level Rise and Inundation Community Workshop, Lansdowne, Virginia, December 3 to 5, 2009.