One Size Does Not Fit All
(new perspectives on Sea Level Rise)
by
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Presentation Objectives

Provide summary on the coastal flood levels due to varying coastal processes experienced in studies for Pacific to Atlantic to Gulf regions.

Presentation intended to help make study contractors aware of how coastal processes contribute to the Total Water Levels.

Provide examples and comparisons on the degree of influence each coastal TWL component can have on the BFE determination.

Share the study findings on contributing coastal process and sea level rise study coastal hazard analyses.
One Size Does Not Fit All

- **Ocean Swell**
- **Wind Waves**
- **Shoreline Change**
- **Extratropical Storms**
- **Tropical Storms**
- **Tsunami**
- **Pineapple Express**
- **La Nina**
- **El Nino**
- **PDO**
- **Stillwater Level**
- **King Tides**
- **Storm Surge**

*Images of various weather phenomena and graphs representing ENSO indices.*
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In the Pacific Ocean region,

- The primary coastal hazard is due to wave runup during storm events driven by extratropical storm fronts and extreme wave conditions along the coast which are long duration events (occurring over multiple tide cycles) – which is best captured in a response-based study methodology and technical approach.
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In the Pacific Ocean region,

- The hindcasts of deepwater and nearshore wave transformation is viable due to wave buoy data and forecasting tools, which allow for use of recorded data to validate the modeling efforts to extend the hindcast period as far back as possible (e.g., data to support a 50-year hindcast of 1960 to 2010 for entire coast of CA).
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In the Pacific Ocean region:

- Response-based analysis refers to the procedure of conducting statistical analyses on the response variable of interest, such as the total water level at the shoreline, as opposed to an event-based procedure of pre-selecting a particular set of storm conditions, such as a 1-percent water level combined with a 10-percent wave event.
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In the Pacific Ocean region:

- This type of analysis is considered to be more robust than event-based analyses (applied in Atlantic Ocean and Gulf of Mexico regions), especially in coastal regions such as the Pacific coast, where the 1-percent total water level can be realized through many different combinations of water level and wave conditions.
Key components of the Pacific region flood levels in FEMA coastal studies include contributions to the TWL from:

- Sea level rise (e.g., long-term tide gage data),
- Tide differences (large astronomical ranges and extreme tides like, “King Tides”),
- Seasonal effects (e.g., El Nino and La Nina),
- Storm surge (residual of wind setup effects captured in tide records),
- Wave setup (radiation stress from extreme wave climatology), and
- Wave runup (swash zone flooding due to wave action)
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By comparison in the Atlantic Ocean & Gulf of Mexico region:

- The primary coastal hazard is due to storm surge and overland wave flooding in the southern reaches of Gulf and SE-mid-Atlantic coastal regions, and storm surge and wave runup in NE coastal areas.
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By comparison in the Atlantic Ocean & Gulf of Mexico region:

- These processes are driven by specific hurricane events of short duration but high impact – which is best captured in an event-based study methodology and technical approach.
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By comparison in the Atlantic Ocean & Gulf of Mexico region:

- The spatial variability of data along the coast for landfalling hurricanes requires use of known storm parameters to create a synthetic database of potential storms based on local vulnerability and historical records.
Key components of the Atlantic-Gulf region flood levels in FEMA coastal studies include contributions to the TWL from:

- Sea level rise (e.g., long-term tide gage data),
- Tide differences (important if hurricane landfall corresponds to high tide),
- Seasonal effects (e.g., summer heating of Gulf water),
- Storm surge (influence of wind setup and pressure fields due to hurricane landfall),
Key components of the Atlantic-Gulf region flood levels in FEMA coastal studies include contributions to the TWL from:

- Wave setup (episodic and short duration radiation stress influence during hurricane landfall), and
- Wave height or runup (breaking wave heights above the static surge level (stillwater elevation) or swash zone flooding above the Stillwater elevation due to wave action on steep slopes)
What are the Pacific Region components of the total water level (TWL)?

- Astronomical tide (predicted tide): 5-7 ft
- Surge components: atmospheric pressure, wind setup, El Niño sea level effects: 1-3 ft
- Wave components: wave setup + runup: 10-30 ft

- **SWL** = Tide + surge (no wave effects)
- **TWL** = SWL + setup + runup
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• While there is similarity in the coastal processes:
  ▪ About 60% of the contribution to the TWL is from wave setup and wave runup in the Pacific regions, and
  ▪ Only 10% from storm surge so the TWL results will vary more as sea level rise is increased in the coming years.

• By comparison in the Atlantic-Gulf regions:
  ▪ The storm surge alone is about 50% of the TWL, and
  ▪ When surge is combined with wave effects (wave height or runup) they account for 70-80% of TWL and are less sensitive to modeling changes due to sea level rise.
  ▪ For Atlantic Ocean, results are different again due to the surge being much lower than Gulf (and proximity of continental shelf to shore).
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Pacific Region with open coast wave setup & runup:

Tide = 5-7 ft
Surge = 1-3 ft
Setup = 4-6 ft
Runup = 7-10 ft
TWL = 17-26 ft

• SWL = Tide + surge (no wave effects)
• TWL = SWL + setup + runup

[Diagram showing the relationship between different water levels and wave effects]
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Gulf Region with open coast surge & wave runup:

<table>
<thead>
<tr>
<th>Component</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>1-2 ft</td>
</tr>
<tr>
<td>Surge</td>
<td>8-14 ft</td>
</tr>
<tr>
<td>Setup</td>
<td>1-3 ft</td>
</tr>
<tr>
<td>Runup</td>
<td>4-8 ft</td>
</tr>
<tr>
<td>Total Water Level (TWL)</td>
<td>14-27 ft</td>
</tr>
</tbody>
</table>

- SWL = Tide + surge (no wave effects)
- TWL = SWL + setup + runup

![Diagram showing water levels and their components](image-url)
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Atlantic Region with open coast surge & wave runup:
Tide = 2-4 ft
Surge = 7-10 ft
Setup = 1-3 ft
Runup = 6-8 ft
TWL = 14-25 ft

- SWL = Tide + surge (no wave effects)
- TWL = SWL + setup + runup

Wave Runup Dynamic Water Level (DWL)
Stillwater Level (SWL)
Tide Level
Datum
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Gulf Region with open coast surge & wave height:

Tide = 1-2 ft
Surge = 8-14 ft
Setup = 1-3 ft
Height = 6-10 ft
TWL = 16-29 ft

- SWL = Tide + surge (no wave effects)
- TWL = SWL + setup + height (varies with depth)
Atlantic Region with open coast surge & wave height:

- Tide = 2-4 ft
- Surge = 6-8 ft
- Setup = 1-3 ft
- Height = 4-8 ft
- TWL = 13-23 ft

SWL = Tide + surge (no wave effects)

TWL = SWL + setup + height (varies with depth)

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- So what does this mean for sea level rise (SLR) studies?
- For the event-based analyses on Atlantic and Gulf coasts, the proof of concept study on SLR scenarios for 2050 and 2100 demonstrated that linear superposition method of adding SLR to the final TWL was acceptable.
  - This is due to analyses that also came up with similar results when SLR was added to modeling to create TWLs (mapping BFEs).
- Additional SLR pilot studies are underway now for Pacific region in San Francisco City/County (CA) and Gulf of Mexico in Hillsborough County (FL).
- The following slides show preliminary results of SLR study in San Francisco and how a linear superposition approach (SLR added to final TWL) compares to a direct analysis approach (SLR included in detailed coastal modeling (i.e., Direct Analysis)).
Summary:
- Pacific Region flood processes dominated by wave setup and wave runup, not storm surge and wave heights.
- Recommended technical approach follows FEMA’s *Pacific Guidelines* and implementation of a response-based analysis.
- Requires reconstructing a 50-year hindcast of hourly wave and water level conditions
- 1% TWL elevations (SWL + wave setup + wave effects) determined for each transect reach throughout the open coast study area
- Existing conditions results currently being used in floodplain mapping task with no sea level rise projections in TWL.

How sensitive is the TWL to sea level rise when introduced to coastal study process?
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Linear Superposition

- Offshore Zone
- Shoaling Zone
  - Wave Transformations
    - Nearshore Waves
      - Wave Setup
        - Wave Runup
          - Overtopping
        - Overland Wave Propagation
          - (if necessary)
        - TWL
          - + SLR
          - Flood Hazard Mapping
      - Water Levels
  - Erosion
    - Coastal Structures
  - Surf Zone and Backshore
- TWL_{SLR} = TWL + SLR

Direct Analysis

- Offshore Waves
  - Wave Transformations
    - Nearshore Waves
      - Wave Setup
        - Wave Runup
          - Overtopping
        - Overland Wave Propagation
          - (if necessary)
        - TWL
          - + SLR
          - Flood Hazard Mapping
      - Water Levels
  - Erosion
    - Coastal Structures
  - Shoreline Change & Profile Adjustment
- TWL_{SLR} > TWL + SLR

Assume: Effect of SLR on nearshore waves negligible
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Pacific Study Outline

- Offshore Zone
- Shoaling Zone
- Nearshore Waves
- Wave Transformations
- Water Levels
- Wave Setup
- Wave Runup
- Overtopping
- Surf Zone
- Overland Wave Propagation
- (if necessary)
- TWL
- Flood Hazard Mapping
- Coastal Structures
- Erosion
- Wave Heights
- Wave Runup
- Wave Overtopping
- Flood Hazard Mapping

Atlantic-Gulf Study Outline

- Offshore Waves
- Stillwater Levels
- Wave Transformation
- Wave Setup
- Coastal Structures
- Erosion
- Wave Heights
- Wave Runup
- Wave Overtopping
- Flood Hazard Mapping

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SLR will increase flood hazard areas at the shoreline through three key mechanisms:

1. **Linear increase** in TWL due to increase in mean sea level. \( \text{TWL}_{\text{SLR}} = \text{TWL} + \text{SLR} \) (linear superposition). The increase in TWL is equal to the increase in MSL.

2. **Non-linear increase** in TWL due to feedback processes in wave runup. The increase in TWL is greater than the increase in MSL. \( \text{TWL}_{\text{SLR}} > \text{TWL} + \text{SLR} \)

3. Increase in **landward extent** of inundation by TWL due to *shoreline retreat*. 
**Mechanism 1: Linear increase in TWL**

- Increase in 1% TWL is equal to increase in MSL
- Linear superposition does not capture the wave runup feedback processes at the toe of structures, bluffs, etc
- This is especially true for non-erodible bluffs and armored slopes

\[ 1\% \text{ TWL}_{\text{SLR}} = 1\% \text{ TWL} + \text{SLR} \]
Mechanism 2: Non-linear increase in TWL:

- SWL is increased by SLR and analysis is re-run
- Larger waves impact toe of backshore feature, resulting in increased runup and overtopping
- Increase in BFE may be greater than SLR (non-linear)

\[ \text{TWL}_{SLR} > \text{TWL} + \text{SLR} \]
Mechanism 3: Increase in landward extent due to shoreline retreat

- Shoreline retreats due to ongoing historical erosion and SLR-induced retreat
- Landward recession of the shoreline increases landward extent of inundation zone
- New hazard zone due increase in TWL elevation and landward extent due to shoreline retreat

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Example: San Francisco at Sloat Blvd – Armored Low Bluff

• City/County of San Francisco

• CA Open Pacific Coast Study Areas
Coastal Analysis Results (Existing Conditions)
1% SWEL = 9.0 ft NAVD
0.2% SWEL = 9.7 ft NAVD
1% Runup (TWL) = 26 ft NAVD
0.2% Runup (TWL) = 27 ft NAVD
No overtopping under existing conditions

Crest at 30-31 ft NAVD
**TWL response to SLR (ex. cond./24”/66”)**

- **Existing conditions:** peak TWL is ~5 ft below crest
- **24” SLR:** peak TWL is ~1-2 ft below crest
- **66” SLR:** many TWL events exceed crest
- **TWL results exhibit non-linear response to SLR**

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Example: San Francisco at Sloat Blvd – Armored Low Bluff
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Example: San Francisco at Sloat Blvd – Armored Low Bluff

- BFE increase greatly exceeds the linear superposition rate (by a factor of ~2)
- Wave runup feedback important at this transect
- Overtopping occurs at much lower SLR under direct analysis vs. linear superposition method

<table>
<thead>
<tr>
<th>SLR (in)</th>
<th>ΔBFE (ft)</th>
<th>BFE (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>25.6</td>
</tr>
<tr>
<td>12</td>
<td>2.2</td>
<td>27.8</td>
</tr>
<tr>
<td>24</td>
<td>4.3</td>
<td>29.9</td>
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<tr>
<td>36</td>
<td>6.3</td>
<td>31.9</td>
</tr>
<tr>
<td>48</td>
<td>9.6</td>
<td>35.2</td>
</tr>
<tr>
<td>66</td>
<td>12.9</td>
<td>38.5</td>
</tr>
</tbody>
</table>
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• Tsunami
• King Tides

• El Nino
• King Tides

Multivariate ENSO Index

Stillwater Level

• Tsunami

01/27
01/27
01/27
01/27
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01/27
01/27
01/28
00:00
04:00
08:00
12:00
16:00
20:00
00:00
Date/Time (LST)
Summary Points

Contributing factors in Total Water Level (TWL) determinations vary with each regional methodology and vary with each type of dominate coastal process.

It is good to understand the degree of influence each component of the regional coastal processes will have on final BFE determination along coast.

Study contractors should be aware that the results change significantly depending upon when sea level rise is introduced into the study process (begin or end point).

In addition, the understanding of the contributing coastal processes of wave height, wave runup, wave setup, surge, and tides can determine best study approach – direct analysis or linear superposition.
## CCAMP OPC/SLR Pilot Study
### Points of Contact

<table>
<thead>
<tr>
<th>Role</th>
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Thank You

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