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NORTHERN NEW ENGLAND COASTAL FLOODING

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1. INTRODUCTION

1.1 *Coastal Flood Forecasting Challenges*

Storm surge and coastal flood prediction raise challenging issues along the Maine and New Hampshire coastline. Complex bathymetry and the irregular configuration of the northern New England coast (Fig. 1) allow for a large range of atmospheric and tidal conditions through localized channeling effects of wind and water. Availability of real-time tide data traditionally has been limited to the Portland Harbor tide gage, which is problematic when forecasting over a large, data-sparse coastline. The benchmark for the onset of flooding for this gage is 12 feet (3.7 m).

To complicate this issue, significant damage can occur with water levels below flood stage during splash-over events. Splash-over can be described as damage driven by large waves "over-toping" obstacles resulting in beach erosion, whereas coastal flooding is the "inundation of land areas adjacent to bodies of salt water" (NWS 2006). These challenges are becoming increasingly magnified as the population swells near vulnerable beaches and epoch surveys show steady sea level rises (NOS 2006). Coastal storms significantly

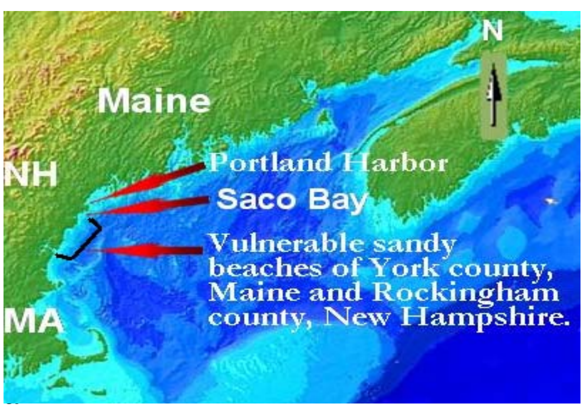

Figure 1: Bathymetry and topography within and surrounding the Gulf of Maine.

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impact the marine community and pose a risk of billions of dollars in personal property damage (NOAA 1998).

The relative infrequency of these events increases forecaster reliance on storm surge models. Statistical and dynamical guidance is readily available, but can have large numerical and temporal errors and is only available in select locations. Therefore, in an effort to better understand and depict the wide range of tide levels and environmental conditions associated with coastal flooding, a coastal flood climatology was created for forecasters and emergency managers. Although not directly calculated as part of the climatology, an introduction into the Ekman Spiral, the role of wave set-up, wave run-up and the effects of atmospheric pressure were also introduced. When coupled together, these environmental conditions can create large storm tides in northern New England.

1.2 The Paradox of Splash-over Versus Coastal Inundation

Splash-over can cause significant damage especially along sandy beaches, yet in the absence of tidal inundation, it is not considered a warnable event by National Weather Service (NWS) standards. Many locations along the East coast experience this phenomenon as wave action interacts with man-made obstacles. In Saco, Maine for example, the community of Camp Ellis is particularly vulnerable to splash-over, in part due to the construction of nineteenth century summer homes on eroding, sandy beachheads (Scontras 1993). Computer generated wave simulations show beach erosion in this region may also be locally enhanced by the refraction and super-positioning of focused wave energy along a nearby jetty (U.S. Army Corps of Engineers 2006).

2. DATA/METHODOLOGY

A catalog of coastal flood episodes was established. All events which produced flood damage along coastal Maine and New Hampshire were extracted from Storm Data Publication (NCDC 2007) for the period 1914-2007. This was challenging as minor versus moderate and severe coastal flood events are also not well defined or easily distinguishable when querying Storm Data Publication. Resolving which tide cycle caused flooding was also occasionally unclear.

A local research archive of the top ten tides and tidal surges ever recorded in Portland Harbor (Budd 1980) was then appended to this list to produce a robust catalogue of 96 events. The list was almost exclusively comprised of non-tropical systems, except for hurricane Carol (1954). A data worksheet was compiled for each event and contained available buoy wind and wave information, predicted versus observed tides, storm track and severity as well as surge guidance. In 37 modern events (1980-2007), the precise time of observed high tide was available for comparison with the predicted high tide (NOS 2007). High temporal resolution (six minute) tide data became available in 1996.

Observed tide levels from Portland Harbor were compared with storm tracks (NOAA 2007) to identify synoptic conditions during coastal flood events. Predicted versus observed storm surges were then reviewed. Finally, storm surge guidance was examined to produce a model forecast bias.

A recent study found a positive correlation between coastal flooding and wave action in southern New England (Nocera 2005). Therefore, wind and wave data available from the National Data Buoy Center (NDBC 2007) and the Gulf of Maine Ocean Observing System (GoMOOS 2007) were examined (1986-2007) to determine conditions at buoy locations nearest the coastal flooding. This included all marine observations adjacent to coastal Maine and New Hampshire (Fig. 2). An empirical relationship was then created from this data using a "best fit" analysis of wave height versus storm tide.

A series of bar graphs will be presented to aid in conceptualizing the coastal flood climatology. Much of the modern day atmospheric and analysis of wave height versus storm tide oceanographic information can also be reproduced and plotted at www.gomoos.org. This web site employs an interactive visualization tool which allows the user to graph numerous environmental variables simultaneously.

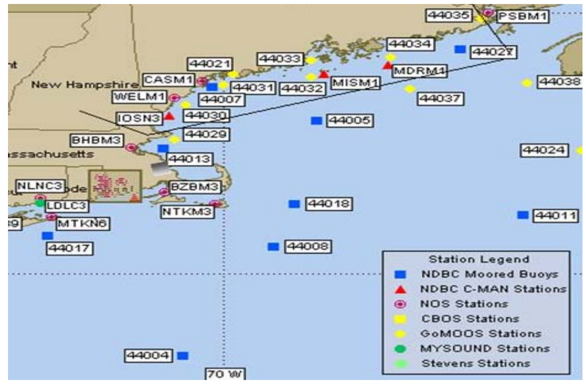

Figure 2: Near-shore marine observations used in this study are outlined along the Maine and New Hampshire coasts.

3. RESULTS: THE COASTAL FLOOD CLIMATOLOGY

3.1 The Seasonal Coastal Flood Distribution

A series of bar graphs depicting all 96 events was produced to better visualize the coastal flood climatology. The Portland Harbor data showed Northern New England coastal flooding dominated in the fall and particularly the winter seasons in 83 out of 96 (86%) events (not shown). The monthly distribution indicates the majority of events (83%) occurred during the typically active cold season period for intense coastal storms, October through March (Fig. 3).

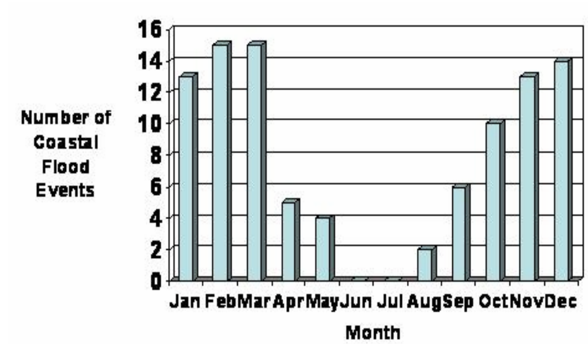

Figure 3: A distribution of coastal flood events by month for coastal Maine and New Hampshire (1914-2007).

Tidal flooding tended to occur in clusters with two or more events in a single year relatively common, especially during the active meteorological decades of 1960's and 1970's. The majority of coastal flood events occurred along the vulnerable beaches south of Portland, while extremely large astronomical tidal ranges routinely occurred along the rocky coast northeast of Portland without problems.

3.2 *Historical Return Periods and Tide Statistics*

A local historical archive (1914-2007) suggested coastal Maine and New Hampshire were overdue for a significant coastal flood event. The return period for the Portland Harbor tide gage reaching 13.0 feet (3.96 m) is approximately once every 10 years (Budd 1980). The last time this stage was reached was during the Patriot's Day storm (16 April, 2007), when the gage topped out at 13.28 feet (4.05 m). The highest tide ever recorded was 14.17 feet (4.32 m) during the Blizzard of 1978 (7 February, 1978). A tidal surge of 3.5 feet (1.07 m) averages about once every 10 years as well. The last storm to produce a surge of this magnitude was the "Perfect Storm" (30 October, 1991).

The onset of flooding occurs in Portland, Maine when the harbor tide gage exceeds a benchmark of 12 feet. This coastal flood reference can often be accurately extrapolated to predict coastal flood conditions along nearby shorelines. However, localized wind and wave conditions have produced flooding in the Portland area despite water levels below the 12 foot tidal reference point.

The average observed height of the tide during coastal flood events in this study was 12.31 feet (3.75 m), however seven flood events (19%) occurred at water elevations below the 12 foot benchmark in Portland Harbor (1980-2007) (Fig. 4a).

Predicted astronomical tides were then compared to observed water levels during coastal flood events. This subset revealed astronomical water levels between 11.0 and 11.5 feet (3.35 – 3.50 m) were initially anticipated prior to many flood events (38%) (Fig. 4b).

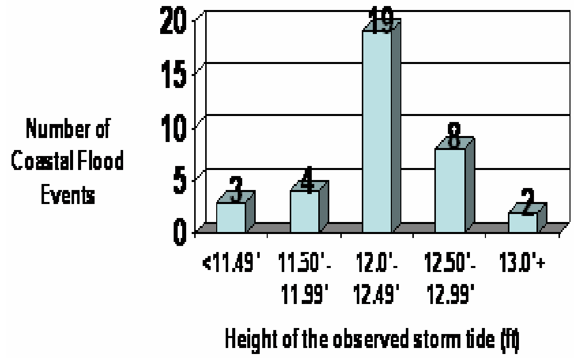

Figure 4a: Height of the observed storm tide during coastal flood events in Portland Harbor (1980-2007). Note seven flood events occurred below the Portland Harbor 12 foot flood stage.

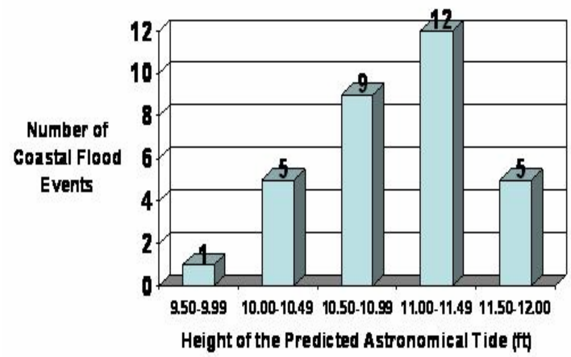

Figure 4b: Same as figure 4a, except the graph depicts height of the predicted (not observed) astronomical tide during coastal flood events in Portland Harbor (1980-2007).

3.3 *The Role of Wind and the Effect of the Ekman Spiral*

Wind direction from near shore buoys were examined for each coastal flood event. A northeast wind direction accompanied 53 (55%) events (Fig. 5). This wind direction is parallel to topographical and bathymetrical features within and surrounding the Gulf of Maine (Fig. 1).

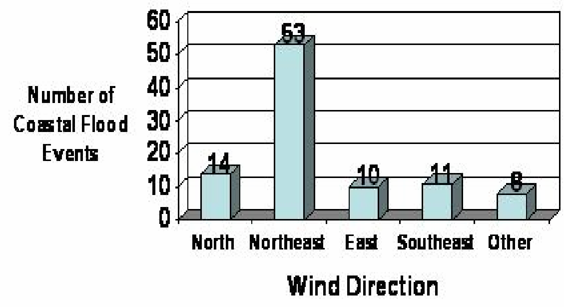

Figure 5: Prevailing wind direction during coastal flood event by category along the Maine and New Hampshire coastline (1914-2007). A northeast wind direction is mainly parallel to the Maine and New Hampshire coasts.

Some experts have correlated wind direction and tidal surge with the Ekman Spiral (Sobien and Paxton 1998). During long-lived, large scale "northeasters" located off the Eastern seaboard, water is forcibly piled up along the Maine and New Hampshire coastline as the Coriolis effect deflects shallow water to the right (towards the coast). Normally this water would evacuate in a deep ocean circulation. However, in shallow water, the introduction of bathymetrical features interrupts this circulation, resulting in an increased surge of water near the shoreline. This effect requires time to develop and is not applicable to fast moving systems such as accelerating, small diameter, tropical cyclones (Sobien and Paxton 1998). This team found the Ekman Spiral can have a pronounced effect of twice the magnitude due to onshore winds. This is counterintuitive to meteorologists who have been trained to expect onshore winds to produce the greatest contribution of storm surge.

Surge produced by the Ekman Spiral was not calculated for this study. However, the frequency of northeast flow events during coastal flooding (Fig. 5) suggests this phenomenon may play an important role in Maine and New Hampshire coastal flooding and future research is recommended.

3.4 *The Relationship of Tide Cycles and Tidal Piling*

The precise onset time of the peak storm tides that produced flooding was available for 26 events (1996-2007). In 19 cases (73%), the peak storm tide occurred prior or nearly coincident with the predicted high tide (Fig. 6). This is not surprising as a "sloshing effect" of an incoming tide often causes maximum storm surge at high tide (Wei 2007). In the remaining seven events (27%), the observed storm tide occurred after the predicted high tide.

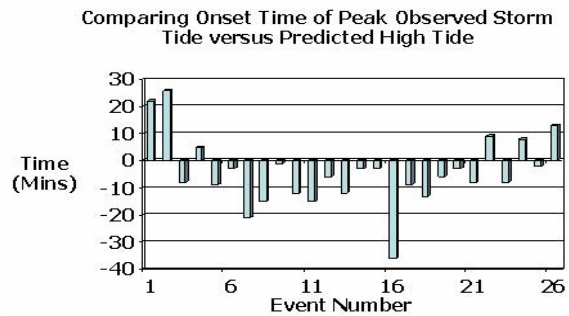

Figure 6: Difference in time of peak observed versus predicted high tide (1980-2007). Negative values denote an earlier then expected peak tide.

The cumulative affect of increasing water levels over successive tides (tidal piling), may have contributed to coastal flooding during several events. Tidal cycles exhibiting back-to-back coastal flooding were noted in five (14%) modern events where high temporal resolution tide data was available.

The relationship between steady state atmospheric conditions and storm surge (the difference between storm tide and astronomical tide) may aid meteorologists in the predictability of coastal flooding. To determine whether storm surge could be successfully extrapolated sequentially from tide to tide, the surge at peak storm tide versus the preceding low tide cycle was compared. In nine cases (35%), the greatest storm surge varied considerably leading up to coastal flood events (Fig. 7). However, 17 events (65%) depicted storm

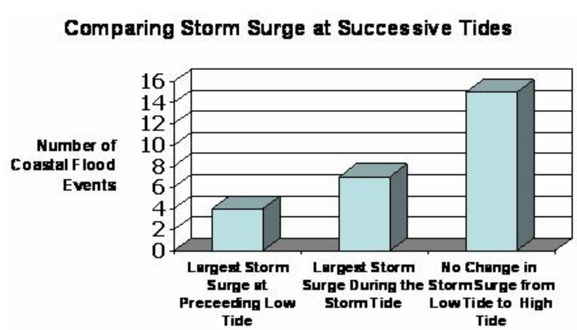

Figure 7: A comparison of storm surge at low tide versus the following high tide (1996-2007).

surges during flooding to be similar to the previous tidal cycle.

3.5 *The Role of Large Waves, Wave Run-up and Wave Set-up during Coastal Flooding*

Wave characteristics can affect coastal damage. Large, long period waves contain a disproportionately greater amount of energy when compared to smaller waves. Also, within a wave spectrum, the largest of breaking waves cause significant wave run-up along the beaches, thereby increasing the threat of coastal damage. In addition, wave setup can allow for splash-over or coastal flooding despite the absence of a wind driven surge. Wave setup is the transfer of potential energy of waves within the shoaling zone as it is converted to kinetic energy released by the breakers. This focused energy can increase near-shore water levels by a magnitude of 10-15 percent of the shoaling breaker height (NOAA 2006).

An empirical relationship between storm tide and large ocean waves was created for the climatology (Fig. 8).

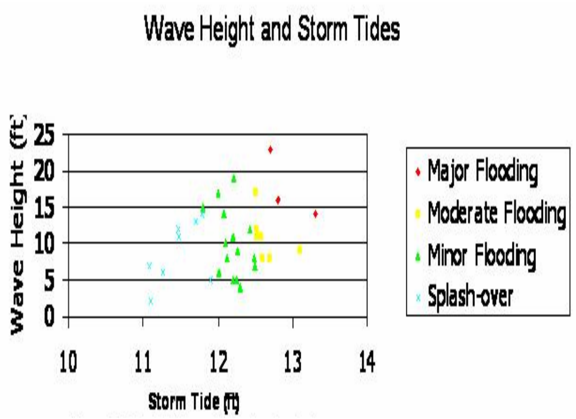

Figure 8: A plot of all coastal flood and splash-over events (1980-2007). Major flooding was associated with large ocean waves and significant storm tides.

Wave heights from marine observations nearest the coastal flooding or splash-over along the Maine and New Hampshire coasts were examined (Fig. 2). As wave heights increased, there was a greater risk of localized splash-over or coastal flood conditions despite tide heights below the 12 foot flood stage in Portland Harbor (1980-2007).

3.6 *The Secondary Role of Atmospheric Pressure*

Storm surge is predominantly driven by wind with a secondary influence of atmospheric pressure (Harris 1963). However, atmospheric pressure accounts for a one foot (0.3 m) response (rise) in ocean level for every 30 mb of surface pressure drop. This magnitude of pressure drop may be used as an initial approximation during intense northern latitude cyclogenesis, however cold, dense water can offset (dampen) this variable (Sobien and Paxton 1998).

Deep, long-lived cyclones accompanied all three modern day severe coastal flood cases including the "Perfect Storm" (1980-2007), however the effects of pressure on water levels were not explicitly calculated in this study. Faster moving systems either did not coincide with peak astronomical tides or did not create the necessary wave height and Ekman Spiral contributions to cause significant flooding.

3.7 *Unusual Coastal Damage Situations Including the Effects of Extreme Rainfall*

There were a host of special situations which led to coastal damage, but may not have caused inundation and were therefore not included in the coastal flood climatology. Hurricanes well offshore can produce splash-over problems from powerful ocean waves, such as Hurricane Juan in 2003. Fourteen foot (4.3 m) swells reached the southwest coast of Maine, causing significant splash-over damage in Saco, Maine on 29 September. An unusual gravity wave occurred during the 4 January, 1994 coastal storm (Bosart 1998). This allowed for a surge of seawater to produce coastal flooding during half tide as the rapidly rising water damaged boats moored in river-mouths. Damage during the infamous blizzard of February, 1978 was preceded by a major northeaster. This precursor northeaster was included in the coastal flood climatology, but is unique. The storm exacerbated conditions by destroying protective dunes and seawalls in advance of the February storm throughout coastal Maine and New Hampshire. It was the second highest tide ever recorded in Portland Harbor at 13.98 feet (4.3 m).

Another unusual coastal flood event may occur with tide gage readings significantly below the standard Portland Harbor flood stage during extreme rainfall events. This phenomenon coincided with the extraordinary rainfall events of October 1996 and 1998. In these cases, rainfall in excess of a foot caused localized, severe flooding in the vicinity of Portland, Maine (Fig. 1). As recently as May, 2006, extreme rainfall produced isolated, yet severe coastal flooding in York County, Maine. During these rare events, fresh water runoff near estuaries and the mouths of rivers can interact with the incoming tide (EPA 2006). Water in the estuary or river may back up and enhance flooding in low lying areas.

4 STORM SURGE GUIDANCE

4.1 *The MRPECS and MRPSSE Products*

There are two surge models used operationally in the NWS. First, the Nested Grid Model (NGM) produces statistical Marine Product-East Coast Storm Surge guidance (MRPECS) (NCEP 2005). Storm surge is forecast using sea-level pressures at NGM grid points. Therefore tidal surges are indirectly resolved through this model as wind forecasts are not explicitly used as predictors. Also available are Marine Product Storm Surge East (MRPSSE) guidance derived from the Global Forecast System (GFS) model. This dynamical storm surge guidance employs shallow water equations similar to the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model with high-resolution bathymetry and coastal topography (Eberwine 2005). The model's accuracy in forecasting storm surge is highly dependent on the lowest winds from the lowest sigma-level (30 m).

Storm surge guidance was examined, despite very limited archived information. The two operational model runs (00 UTC and 12 UTC) immediately prior to each flood event were averaged and compared to the actual storm surge. All of the events revealed nearly identical back to back storm surge forecasts from run to run. This individual model consistency offers operational utility to forecasting storm surges.

4.2 *Model Bias*

In a limited dataset of 16 events, (MRPECS; NGM based) guidance consistently over-forecast tidal surge in fourteen cases, while in two events the guidance matched observed surge. On average, the guidance over-forecast storm surge by 0.4 feet (0.12 m) (Fig. 9a).

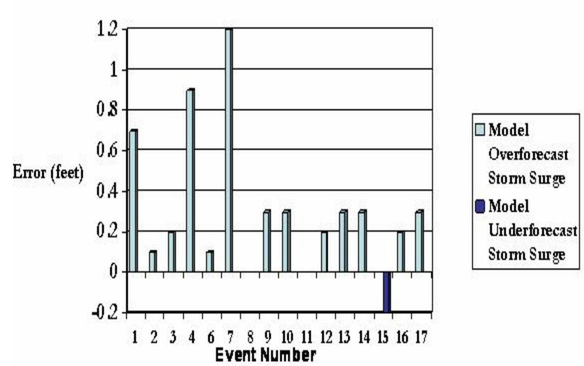

Figure 9a: Error (in feet) of the NGM storm surge guidance (MRPECS) during coastal flood events in Portland Harbor (1996-2007).

This error is large, considering the average storm surge predicted during these events was 1.2 feet (0.4 m). The opposite was true for the Marine Product Storm Surge East (MRPSEE; GFS based), product which under-forecast all events and showed an equal and opposite forecast surge bias of 0.4 feet (Fig. 9b).

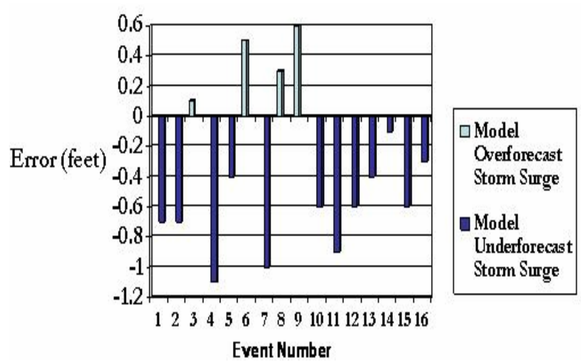

Figure 9b: The same as figure 9a, except graph depicts GFS based storm surge guidance (MRPSSE).

This suggests a blend of surge guidance may be appropriate at times during "steady-state" synoptic situations, where large scale wind patterns are consistently captured by numerical models during long-lived events. Forecasters should proceed with caution however, as the most accurate surge forecast will be highly dependent upon an individual models ability to accurately predict storm track and intensity.

5. CONCLUSION

The 12 foot tidal benchmark in Portland Harbor has provided an initial approximation for the onset of coastal flooding for adjacent coastal regions. However, the climatology and conceptual models present additional insight into the broad range of varying environmental conditions necessary for coastal flooding. There are a number of unusual and extreme cases which can cause damage within this spectrum. This includes the more common phenomena of splash-over, which is treated separately from coastal inundation.

Forecaster and emergency management experience with coastal flooding may be limited due to the relatively infrequent nature of coastal flood events. These findings can serve to increase meteorologist's confidence during the warning process and assist emergency managers in preparedness. A storm tide-wave height relationship has been incorporated into a decision aid for guidance purposes in local operations.

Future work will focus on the creation of a web based, coastal flood nomogram. This nomogram will display computed storm tides by coupling astronomical tides with a storm surge ensemble prediction from the MRPSSE and MRPECS products. Predicted wave heights will then be calculated for near-shore buoys from the Wave Watch III model and plotted at hourly intervals (Fig. 10).

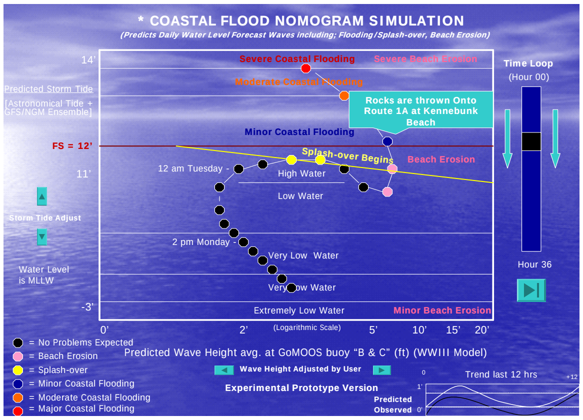

Figure 10: Experimental Coastal Flood Nomogram depicting predicted storm tide versus predicted wave height.

With this methodology, the synergistic effects of extreme tides and large battering waves could be better visualized by users. The plot would incorporate the relationship between coastal flooding, splash-over and beach erosion based on the coastal flood climatology and a splash-over database. A prototype for this interactive, experimental tool has been created by GoMOOS.

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