Use of Geomatic Techniques to Evaluate Flooding from the February, 1998 Extreme Storm and Sea Level Rise at NASA Ames Research Center

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NH23C-1537

1. Abstract

The NASA Ames Research Center (ARC) campus, located on the southern waterfront of South San Francisco Bay (Figure 1), is vulnerable to projected sea level rise (SLR) given its low elevation. The campus is also vulnerable to flooding during intense precipitation episodes, as was experienced in the February 1998 Extreme Storm which inundated ARC with over 7 cm of rain in a 24 hour period, with the previous two days having also delivered 3.5 cm of rain. The ARC campus and surrounding areas were severely flooded leading to significant damage to the local infrastructure.

To assess the potential impact of future storm events to the ARC campus, the February 1998 Extreme Storm was evaluated using several remote sensing and geomatic techniques. Supervised classification and change detection of multispectral Landsat 5 (TM) imagery from January 17 and February 18, 1998 (the closest dates to the storm for which imagery is available) was performed, to evaluate the extent of flooding after the storm. Both images were recorded at low tide with water levels less than the mean lower low water (MLLW) elevation when referenced to the Coyote Creek tidal station datum. Significantly more area is classified as water in the February image than in the January image. However, change detection analysis underestimates total flood water coverage in other areas due to the time difference between the heart of the Extreme storm and the available Landsat scene image dates.

Ground classification of a publicly available Light Detection and Ranging (LiDAR) point cloud was performed, and a high resolution 1-m digital elevation model (DEM) and 3D building features of the ARC campus were generated to provide a topographic reference for geospatial analysis. The LiDAR DEM was incorporated into FEMA's natural hazard risk assessment and loss estimation software package Hazus-MH 2.1 to generate a flood depth grid. This flood depth grid estimates the extent of flooding due to the Extreme Storm at ARC and is compared to the Hazus generated 100-year and 500-year floodplains. The 3D building features extracted from the LiDAR are combined with the flood depth grid to analyze impact to infrastructure due to such a storm.

In addition to extreme rainstorm events, also sea level rise will pose a significant risk of flooding to the ARC campus requiring updates and maintenance of the protective levees. In the San Francisco Bay area the mean sea-level is projected to rise in the course of this century, with widely varying estimates (Figure 6). To evaluate the potential impact of a 150 cm rise in mean sea level, a second flood depth grid was generated using Hazus. This flood depth grid estimates the potential impact of SLR on floodplain extent and flood volume, and is compared to the Hazus generated 100-year and 500-year floodplains. The 3D building features extracted from the LiDAR are combined with the flood depth grid to analyze impact to infrastructure due to sea level rise.

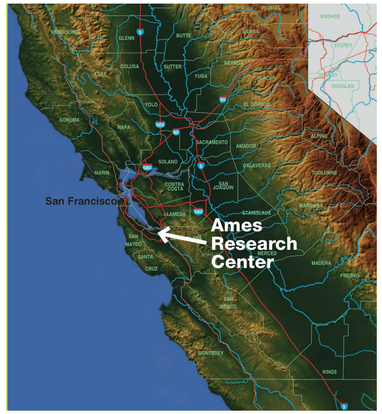

FIGURE 1: The location of NASA Ames Research Center.

2. The Extreme Storm of February 1998

Precipitation Characteristics

The February 1998 Extreme Storm inundated ARC with over 7 cm of rain in a 24 hour period, with the previous two days having also delivered 3.5 cm of rain (Figure 2). The ARC campus and surrounding areas were severely flooded leading to significant damage to the local infrastructure.

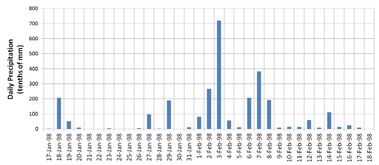

FIGURE 2: Daily precipitation (from midnight to midnight) obtained from the hourly precipitation record for Moffett Field.

3. Impact of the Storm on NASA Ames

Estimation of Flood Extent

High Resolution LiDAR DEM Generation

To evaluate the impact of the 1998 Extreme Storm on ARC, a publicly available LiDAR point cloud from Santa Clara County (2006) was leveraged. High resolution LiDAR digital elevation models (DEMs) are extremely valuable in evaluating floodplain extent and projections of sea level rise. Whereas widely available DEMs for the United States generally fall into the 3 to 30 meter horizontal resolution range with RMSE as high as 2.44 meters, publicly available LiDAR point clouds may yield DEMs with 1 meter or better post-spacing and vertical accuracies in the range of 10 to 50 centimeters or better.

The Santa Clara County LiDAR point cloud was cropped to the area of interest, tiled, and then ground classified. The point spacing of the ground class was just less than 1 meter which supported a high resolution, natural neighbors, 1 meter DEM of ARC and the surrounding areas for geospatial flood analysis.

Delineation of the 1998 Extreme Storm flood extent proved a challenge due to the limited availability of data from the period of January 1998 to February 1998. Landsat, however, provided two vital datasets for this purpose.

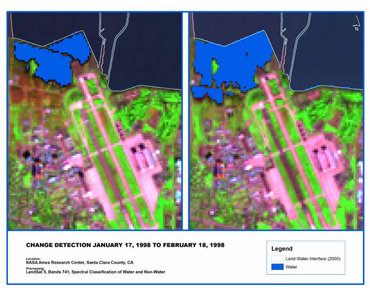

FIGURE 3: Flood coverage delineated from spectral image classification of Landsat TM scenes from January 17, 1998 and February 18, 1998. The February 18th image clearly shows increased water cover in the area of the storm water retention ponds after the Extreme Storm.

Landsat 5 Supervised Image Classification

The Landsat family of satellites provides a relatively high resolution (30 m) multispectral toolset for detection of surficial features. The Landsat 5 Thematic Mapper (TM) senses seven spectral bands of the electromagnetic spectrum. Band 7 (2.08–2.35um) and Band 4 (0.76–0.90um) exhibit strong absorption over water features and may be used for delineation of the boundary between land and water. Band 1 is useful for determining the boundary between bare earth (soils & rock) from vegetation. Band combination 741 was used for delineation of the estimated flood extent.

The 1998 Extreme Storm occurred from February 1st to February 8th. The available cloud-free Landsat 5 imagery for this time period falls on January 17, and February 18. Both images were recorded at low tide with water levels less than the MLLW value when referenced to the Coyote Creek tidal station datum. For each image date, the Landsat bands were made into a 741 composite image, cropped to the ARC campus. Unsupervised classification was performed using a maximum-likelihood algorithm. The training sets were revised, and supervised classification was performed. The January 17th classified image was subtracted from the February 18th classified image. This change detection analysis resulted in significantly more area being classified as water in the February image than the January image (Figure 4) in the area of the storm water retention ponds. However, change detection analysis underestimates total flood water coverage over other areas of the Moffett campus, and no flood water coverage was classified in these images outside of this area. This is due to the nine day lag between the end of the storm (February 8) and the available Landsat scene acquisition date (February 18).

Geo-Located Photographs

Burroughs (2010) presented three geo-located photographs showing significant flooding just after the 1998 extreme storm. The photographs were taken at the pump station that moves water from Moffett Channel into Lockheed Channel, the ordnance bunkers, and Moffett Golf Course adjacent to ARC. The landward-most photograph also corresponds to the highest elevation of the three locations, and thus we can confirm visually that the flooding extended at least to between the 6' and 7' foot contour (NAVD 88) made from the high resolution LiDAR DEM.

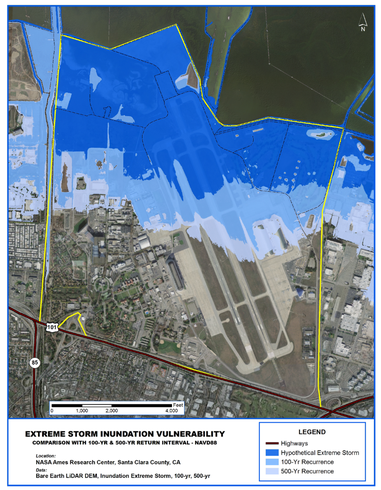

FIGURE 4: Flooding vulnerability compared for an Extreme Storm compared with the 100-year and 500-year recurrence intervals.

NDMI

The Normalized Difference Moisture Index (NDMI), by Gao (1996) provides an indicator of vegetation water content and was calculated for each of the January 17 and February 18 Landsat TM scenes.

NDMI = [Band 4 – Band 5] / [Band4 + Band 5]

NDMI values vary between -1 and 1 with negative values indicating lower water content, and positive values indicating higher water content. The NDMI values for each individual image were classified into either a low moisture (value less than or equal to zero) or high moisture (value greater than zero) category. The January image was then subtracted from the February image to determine the areas of increased moisture between the two time epochs. The Moffett Golf Course contains large areas of increased water content that developed between January and February of 1998.

Based on these three datasets, the flood extent for the 1998 Extreme Storm is estimated to be approximately the 7-ft contour.

Hazus Flood Modleing

Hazus Model of Flood Extent Associated with Hypothetical Inundation from the Bay

The LiDAR DEM described in Section 1 was incorporated into FEMA's natural hazard risk assessment and loss estimation software package Hazus-MH 2.1 to model a storm similar to the 1998 Extreme Storm in extent in a hypothetical scenario in which levees currently protecting the NASA ARC property from flooding were overtopped.

The three possible input parameters for the Hazus coastal flood model include stillwater elevation (SWEL), wave setup, and significant wave height. The SWEL is defined as the mean water level in the absence of waves (FEMA Region III, 2013). The SWEL plus the wave setup is the coastal base flood elevation (BFE). The significant wave height is the average height of the largest third of waves within a given time (NOAA, 2009). For this study we modeled a floodplain only with the stillwater elevation. The wave setup and significant wave height parameters were set to zero.

We generated a flood depth grid for the hypothetical storm that would approximately match the extent of the 1998 Extreme Storm (7 ft contour interval NAVD88). This was achieved by setting the SWEL parameter of the Hazus coastal flood model for the 10-yr return interval to 7 feet. The flood depth grid extent is consistent with the water coverage shown in the Landsat change analysis, the geo-located photographs, and the NDMI change analysis, so as expected, it partially inundates the Moffett Golf Course, the pump station at the Moffet/Lockhead channel intersect, the ordnance bunkers, several roads and other infrastructure. However, the northern-most portion of the runway is also inundated. This would be the case if inundation originated from the Bay (an assumption of Hazus). Though it is anecdotely known that the northern portion of the runway was flooded during the 1998 extreme storm, the available datasets for this study did not show evidence to prove or disprove this notion.

Hazus Model of 100- and 500- Year Floodplain

Figure 4 compares the floodplain of the hypothetical extreme storm to that of the 100-yr and 500-yr floodplains. In order to generate the floodplains for the 100-yr and 500-yr return interval, we input a 100-yr stillwater elevation of 11.7 feet NAVD88. This is the SWEL for the area of Coyote Creek at Guadalupe Slough (Mariza Costa-Cabral, personal communication, October 21, 2013). The Hazus coastal flood model calculated the 500-yr stillwater elevation to be 13.8 feet NAVD88. The 100-yr floodplain extends over a third of the runway, and includes the footprints of at least 20 structures. The 500-yr floodplain covers more than half of the runway, and includes the footprints of at least 30 structures including the Moffett Field hangars.

Sensitivity Analysis of Hazus to Levees in DEM

To determine the influence of the levees in the LiDAR DEM on the Hazus generated flood depth grids, the levees in the area of interest were burned into the DEM at an elevation of 15 ft NAVD88. The 100-yr floodplain was generated with this DEM, and the results are shown in Figure 8. The levees clearly act as barriers to the influx of water modeled by the 100-yr recurrence interval, thus all of the Hazus flood depth grids generated for this study are not full levee failure scenarios.

This analysis also clearly demonstrates the value of the levee infrastructure. The fact that the levee system did not fail during the 1998 extreme storm prevented a much worse flood event. This analysis emphasizes the importance of investing in the update and maintenance of this vital flood protection infrastructure, though nationwide this will be an investment in the billions of dollars.

3D Model of ARC Campus

Feature extraction of buildings from the LiDAR DEM was performed using a custom workflow to generate a high resolution 3D model of the ARC campus. When combined with the flood depth grid, the 3D building features provide a unique way to both visualize and analyze the impact to infrastructure due to an extreme storm, flood, rise in sea level, or combination thereof.

FIGURE 5: Inundation vulnerability with hypothetical 15-ft high levees. The value of the levees is clearly shown as they completely prevent flooding of the ARC campus. If levees were to be breached during a storm event or due to sea-level rise, the extent of flood coverage would likely increase.

4. How Will Future Storms Affect NASA Ames

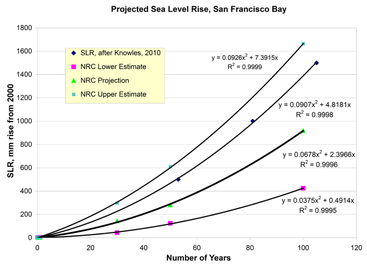

FIGURE 6: SLR projections for San Francisco Bay. All four curves are concave upward and are well described by second-order polynomials. See the list of literature references.

SLR Background and Projections for Next 100 Years

SLR will pose a significant risk of flooding to the ARC campus. In the San Francisco Bay area the mean sea-level (MSL) is projected to rise by 150 cm (Knowles, 2010) in the maximum scenario for the year 2100 (Figure 6). A higher MSL will increase the frequency, extent, and depth of flooding for a given storm event (Burroughs and Iraci, 2010). In order to evaluate the potential impact of future Extreme Storms while incorporating 150 cm of SLR, an additional suite of flood depth grids were generated using Hazus. These flood depth grids estimate the potential impact of SLR on floodplain extent and flood volume for a particular event.

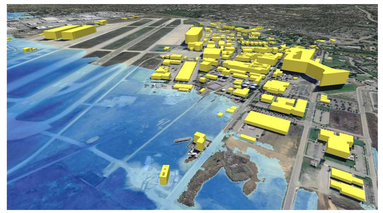

FIGURE 7a: Hazus flood depth grid for the hypothetical Extreme Storm with 40 cm of SLR. The flood extent is approximately equivalent to the current 100-year recurrence interval.

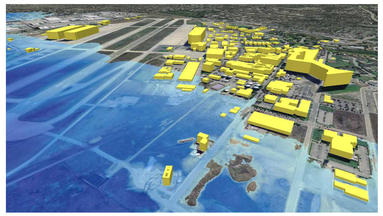

FIGURE 7b: Hazus flood depth grid for the hypothetical Extreme Storm with 150 cm of SLR. The floodplain extends beyond 100-year recurrence interval.

5. Outcomes

Utility of Methodology at Other Facilities

This semi-automated geomatic evaluation of floodplain extent and potential impact to infrastructure can be applied at many facilities for planning purposes. A higher resolution LiDAR-based model (where LiDAR is available) will result in a more accurate estimate of potential economic losses and physical damage, allowing stakeholders to plan more effectively and maximize and prioritize resources for the future.

The Hazus flood model can expand beyond the coastal flood hazard to riverine hazards, or a combination of the two. These tools provide a way for stakeholders and the public in general to not only model and visualize the impact of current flood potential at a particular facility, or even at a particular building, but also to have the ability to visualize and analyze what might happen as the sea level rises throughout the next century and beyond.

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ACKNOWLEDGEMENT: This material is based upon work supported by NASA under award number NNX12AG33G.