Using LIDAR to Identify EL Niño Related Erosion Scarps in Coastal Washington and Oregon

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Abstract

The 2015-2016 El Niño was one of the strongest El Niño's to occur in the last 33 years, after only the 1983 and 1997 event. All three events were associated with elevated water levels along the northwest Oregon and southwest Washington coast resulting in increased erosion and scarping. In this study LIDAR data collected by NOAA's Ocean Service for July 2014 and April 2016 are used to identify beaches that actually experienced scarping during the 2014-2016 El Niño. To accomplish this I developed several GIS based models to extract scarps from the LIDAR data. An "erosion risk analysis" was then conducted using site specific mid-beach slopes extracted from the 2016 LIDAR data for every 100 meters along the open ocean coast.

Results

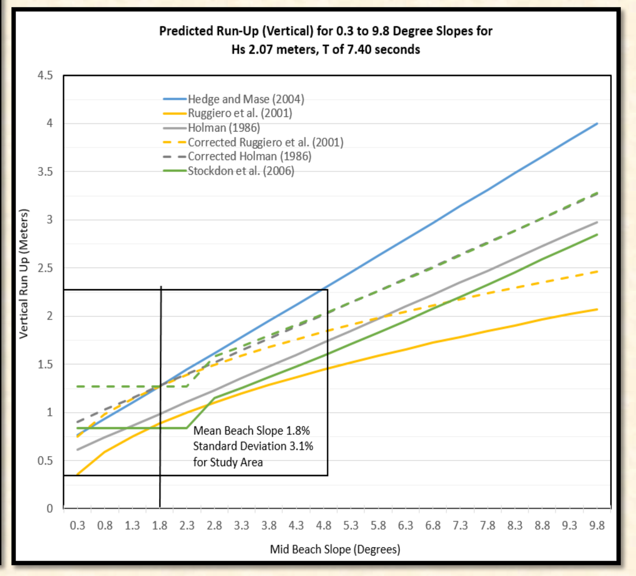
Run-up models based on Regional average parameters provide a first order estimate of risk, but under predicted the actual number of transects that were subject to erosion from the 2015-2016 El Niño. The under prediction was primarily due to: (1) the use of a mean mid-beach slope of 3% vs. the generally lower site specific slopes derived from the LIDAR data, (2) not including a measured +0.093 m tide anomaly in the run-up calculations, and (3) an improved estimate off the deepwater significant wave height of 2.07 vs. 1.97 m. The new analysis obtained run-ups that were 10 to 30 m higher on transects with mid-beach slopes < 3% and run-ups that were lower than originally predicted when mid-beach slopes were > 3%.

Run-Up Model Selection

Most empirically derived wave run-up models developed over the past 50 years require beach slope (*B*), deepwater significant wave height (Hs), and deepwater wave period (Lo) or wave Period (T) (Shand et al. 2011). Four commonly used run-up equations were compared in this study: Holman (1986), Hedges and Mase (2004), Ruggiero et al. (2001), and Stockdon et al. (2006). The horizontal run-up calculations from these models were corrected based on a factor (K) derived by Shand et al. (2011). The K factor applies when the "upper beach slope of the backshore" is used for ***B***, or as defined here, the mid-beach slope.

Model	Equation	Correction Factor (K1)* Shand et al. (2011)	Adjustment Factor (K2)* this Study
Holman (1986)	$R_{2\%} = (5.2 \tan\beta + 0.2) H_S$	1.31	+0.29 m
Ruggiero et al. (2001)	$R_{2\%} = 0.27(\tan\beta H_0 L_0)^{0.5}$	1.39	+0.39 m
Hedges and Mase (2004)	$R_{2\%} = (0.34 + 1.49\xi_0) H_S$, $\xi_0 = \frac{\tan\beta}{\sqrt{H_0/L_0}}$	0.95	---
Stockdon et al. (2006)	$R_{2\%} = 0.043(H_0 L_0)^{0.5}$ for $\xi_0 < 0.3$; $R_{2\%} = 1.1\left(0.35\tan\beta_f (H_0 L_0)^{0.5} + \left(\frac{[H_0 L_0 (0.563\tan\beta_f^2 + 0.004)]^{0.5}}{2}\right)\right)$ for $\xi_0 \geq 0.3$	1.47	+0.43 m

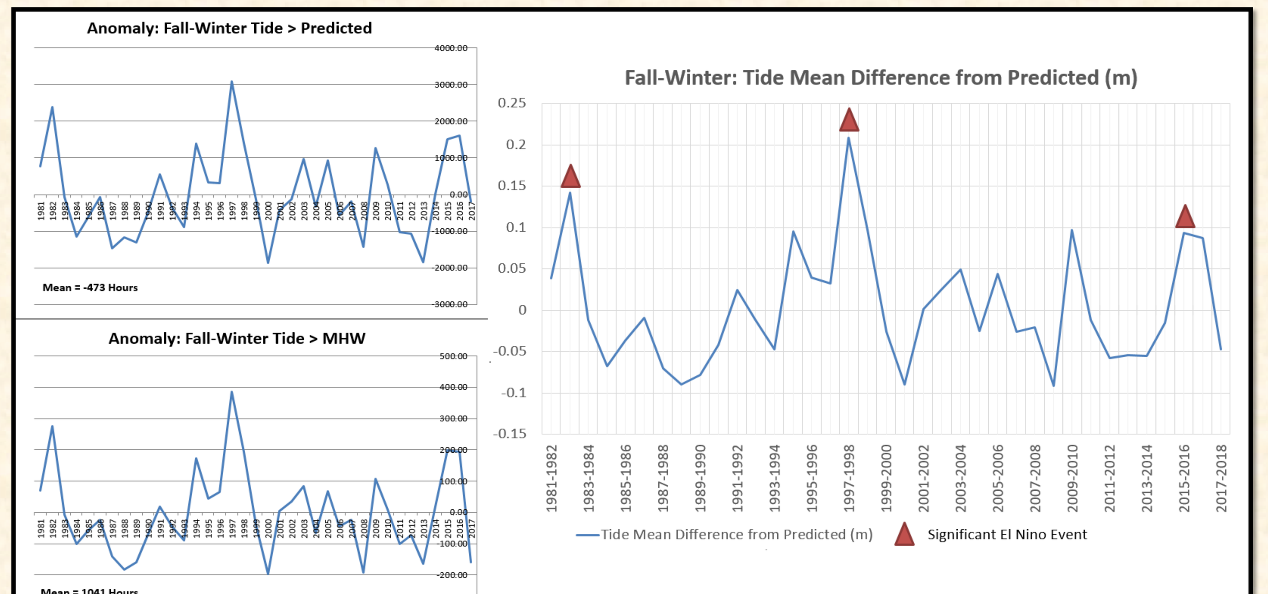
K1 is for a beach slope of 1.9% with mean sediment diameter of 0.16 mm.
K2 is for a beach slope of 1.8% with a mean sediment size of 0.2 mm.
H_o and H_s is deepwater significant wave height; L_o is the deepwater waver period; ξ_0 is the deepwater Iribarren number; and tan ***B*** is the beach slope.



Correlation analysis of the Hedges and Mase (2004) equation with three other popular models obtained a R^2 of 0.91 or better for beaches with slopes of 0.3% to 9.8%. This indicates that with a appropriate site-specific correction factor (e.g., K2 for this study area) these models will produce similar results. Shand et al. (2011) found Hedges and Mase (2004) to be the most accurate model overall for low slope beaches; because of this the Hedges and Mase (2004) equation was selected for use in this erosion risk analysis.

Tides and Water Levels

Hourly Tide elevation data from NOAAs National Ocean Services Station 9440910 Toke Point, WA were analyzed for the period 1981 to 2018. This station was selected because of its long period of continues record and its located at the approximate center of the study area. Missing data points in the stations record were estimated based on linear correlation equations derived with two adjacent gauges (9439040 Astoria, OR and 9439011 Hammond, OR).



Based on an analysis of hourly tide gage data NOAA's Toke Point, WA I found that during the 2015-2016 winter season (October 1 to March 31) the measured tide heights averaged +0.093 m above predicted; resulting in the beach being impact by an additional 1,239 hours (51 days) with water levels above predicted levels. Prior to calculating the horizontal run-up for each transect the El Nino induced elevation anomaly was added to the vertical run-up derived by the model for each transect.

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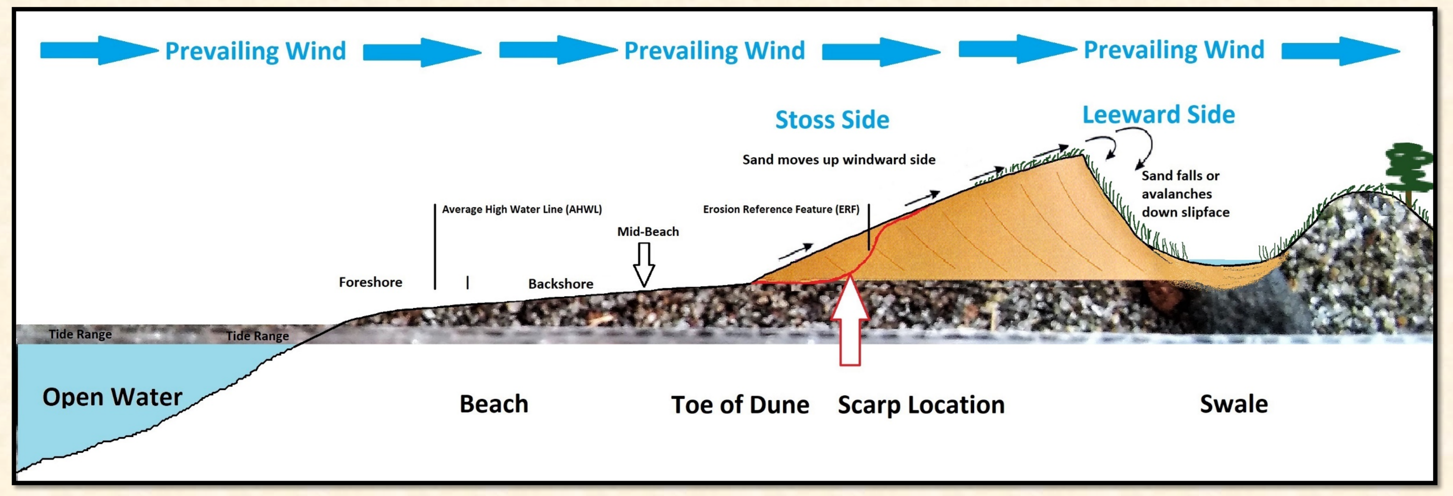


Beach Width

Beach widths were derived from National Agriculture Imagery Program (NAIP) orthophotography flown on August 16, 2015 for Washington and June 22, 2014 for Oregon. The average high water line (AHWL) and erosion reference feature (ERF), represented by the transition zone where vegetation no longer covers more than 50% of the ground (in areas where the vegetation line is not visible the ERF will be the top edge of the cliff, bluff/scarp, or top center of the seaward most dune), were digitized and used to create an envelope or polygon. This envelope was used to clip the transects created in DSAS. The length attribute for each of the resulting transects was now the approximate width of the backshore –that portion of the beach only affected by waves during exceptional high tides or severe storms.

Mid-Beach Slopes and Scarps

The 1 x 1 meter bare earth LIDAR DEM's used for this study was obtained from NOAA's Coastal Zone Mapping and Imaging Lidar (CZMIL) system. Horizontal accuracy is 1 m and vertical accuracy is 0.196 m or +/- 0.098 m at the 95% confidence level. LIDAR data for 2014 was collected between July 30-August 13, 2014 and data for 2016 was collected between April 28-May 28, 2016.

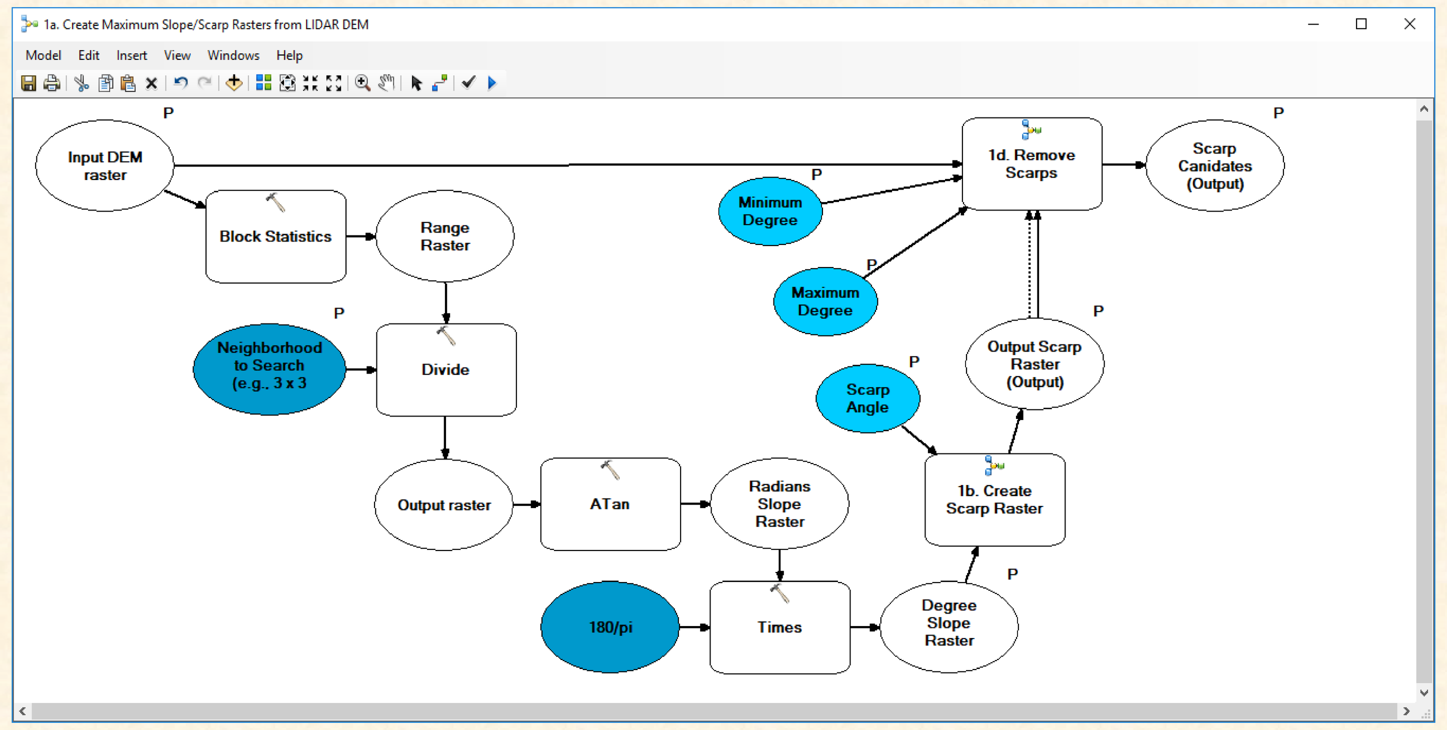
I derived scarp locations for 2014 and 2016 from the LIDAR DEM's. Maximum Slope expressed in degrees was calculated for each cell as follows: the Range of Slope values was determined within a roving 3 x 3-cell window (i.e., 3 x 3 m). The Range was then divided by 3 meters to obtain the maximum slope found within each 3 x 3 m neighborhood. To determine if a specific cell represented the located at a scarp I used the concept of the lower Angel of Repose (AoR) and foredune formation. In the beach environment the seaward side of the foredune will be flattened by on-shore winds forming a ramp with an angle of about ½ the AofR (17 Degrees) for 0.2 mm sand (average sand size for the study area) in the dry condition. Based on this I have taken the presence of ocean facing slopes >= 20 Degrees that are present in 2016, but not in 2014, to indicate the presence of a "New" Scarp.

An area search was then run that compared the "New Scarp" locations with the clipped transects (note - the transects were clipped by the average high water line and erosion reference feature in 2015, so the transect length approximated the width of the backshore); the search distance used was 49 m or about 1/2 the transect spacing. If a "New" scarp is located within 49 m of a transect it can be said that significant scarping and foredune erosion occurred near the transect in the period between Summer 2014 and Spring 2016 (i.e., large enough that it was not repaired by onshore sediment transport between the end-of-winter in 2015 and spring 2016).

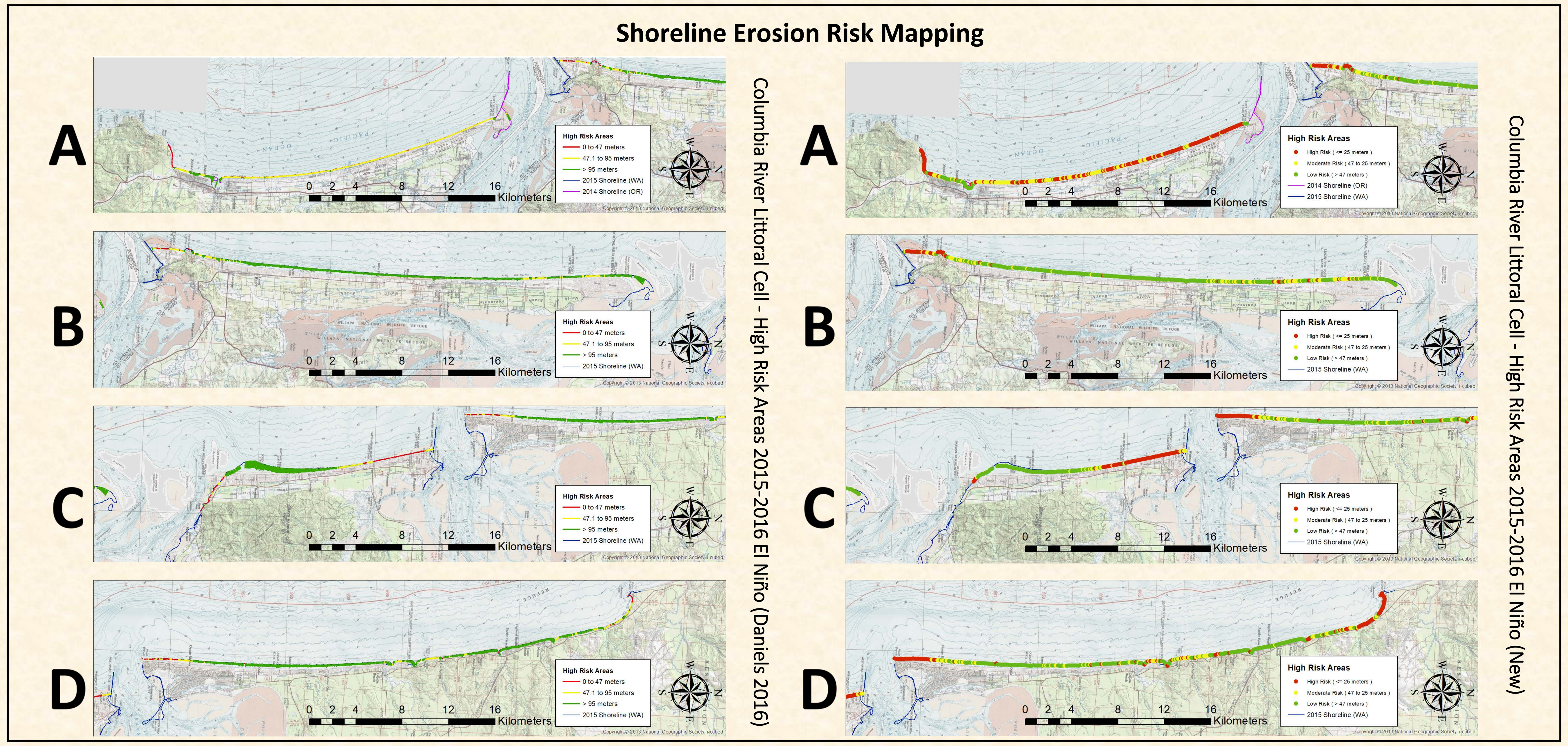
Scarp Recovery after five days with Sun, no rain, and onshore winds (10-15 mph) in Ocean Shores, WA
(Photo location 1 mile north of Grays Harbor North Jetty; scarps 1.8 to 2 m high)

Derive Scarps from LiDAR Raster's

I calculated the Maximum degree slope for each cell using a Majority Filter within a 3 x 3 window using the RANGE option. This allowed me to calculate a MAXIMUM Slope for each cell. The cells were then resampled to 3 x 3 meters. This despeckled the resulting Scarp Raster, remove scarps less then 3 cells long, and reduced the cell resolution to approximate that of the Horizontal accuracy of the underlying LiDAR data (i.e., +/- 1 meter). The Scarp Raster was then modified by removing scarps that are facing the 'wrong direction' (i.e., not facing toward the coast) and whose angle was less than the specified angle of repose (20 Degrees in this case). The result is a binary raster (1=scarp, 0= no scarp). The 2016 result was was subtracted from the 2014 result to obtain the binary El Nino "New" scarp dataset.



Shoreline Erosion Risk Mapping

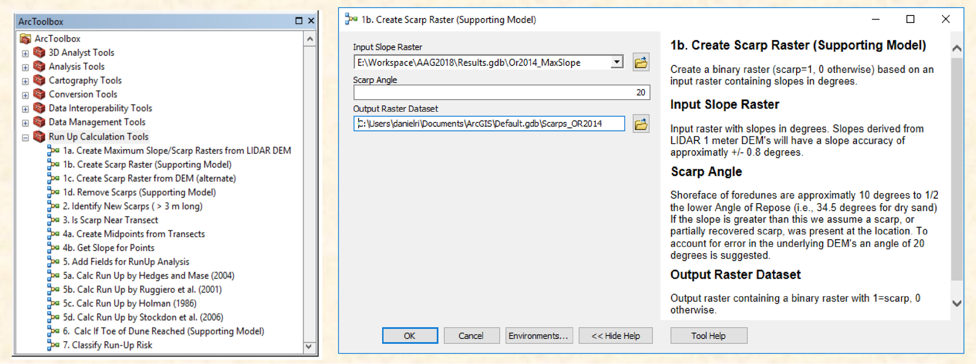


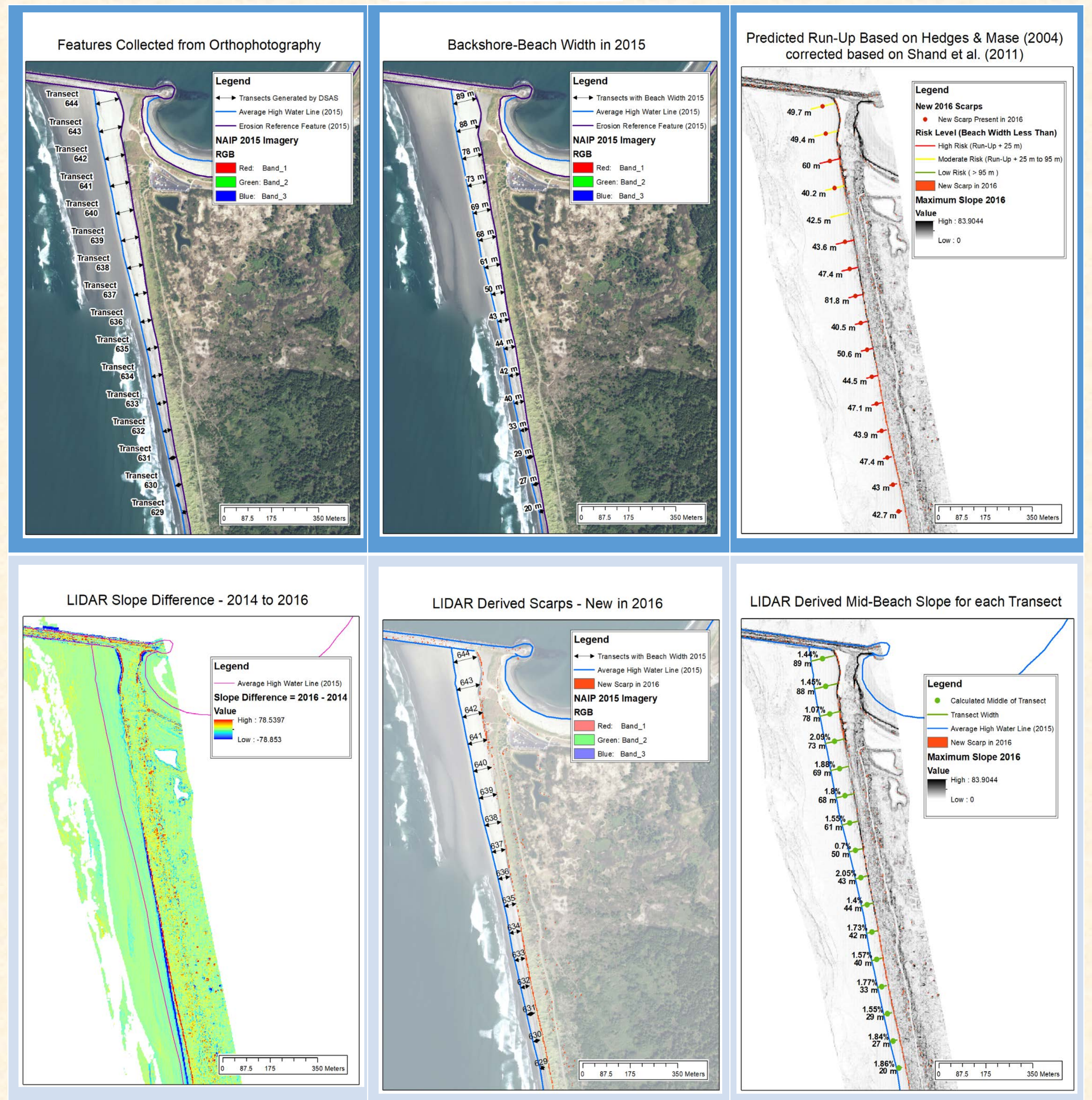
Run-Up Calculation Models and Scarp Identification Tool Box

The Run-Up Calculation Toolbox is implemented in ArcGIS Desktop 10.5.1. The toolbox automates:

1. four commonly used Wave Run-Up Models,
2. the calculation of beach slopes,
3. Identification of scarp locations, and
4. The extraction of mid-beach slopes for shoreline transects

from LIDAR data.





Accuracy Assessment: Risk vs. Scarp Locations

New Analysis	High Risk	Moderate Risk	Low Risk
Number of Transects	398	287	694
Number with Scarps	253	94	113
% of Transects with Scarps	64%	33%	16%
Daniels (2016) Analysis	**High Risk**	**Moderate Risk**	**Low Risk**
Number of Transects	134	462	797
Number with Scarps	107	312	476
% of Transects with Scarps	80%	68%	60%

Conclusions

This analysis found that empirical run-up models such as Hedges and Mase (2004) can be used to predict the site of 'future' erosion when appropriate site specific values are available and that these models produce comparable results when correction factors are used. In the United States LIDAR derived 1 x 1 m DEMs are now available for most of our Nations open coast. As such the use of "Regional Average" beach slopes should be discouraged and actual slope measurements derived from LIDAR used. This enhancement resulted in significantly improved erosion risk mapping for our study area (e.g., only 16% of the transects identified as being at 'Low Risk' in the new analysis showed evidence of scarping, down from 60% for the 'Low Risk' category in the previous analysis).

Results

The vulnerability of the northwest Oregon and southwest Washington ocean coast to coastal erosion was calculated for 1,420 shore perpendicular transects located 100 m apart for the 2015-2016 Niño event. The transects were created using the USGS Digital Shoreline Analysis System (Thieler et al. 2009). In this region major El Niño events are associated with region-wide beach recession, dune scarping, and episodic coastal flooding during the weeks leading up to and after the Winter Solstice.

- During Fall-Winter of the 2015-2016 El Niño the number of hours were the observed tide exceeded the predicted tide and mean high water was 197 hours (276 hours 1982-1983;387 hours 1996-1997); the mean tide elevation was +0.093 m above predicted.
- Analysis of Wave Height and Period data for 2009-2017 from the Grays Harbor, WA and Astoria, OR CDIP Buoy obtained a Significant Wave Height (Hs) of 2.07 m and Deep Water period of 7.40 sec. This is higher than the previously accepted Regional average of 1.97 m and 7.44 sec. (Daniels 2016).
- The mean beach slope for the study area, derived from the 2016 LIDAR slope raster, was 1.8% with a standard deviation of 3.12%. This is lower than the previously used Regional average of 3%.
- Analysis of the 2014 and 2016 LIDAR data derived a location dataset of "New Scarps", where "New" means a scarp was present in 2016 but not in 2014. Of the 1420 transects in the study area 905 (64%) had identifiable "New" scarping.

Using LIDER derived site specific information resulted in improved run-up calculations. On average, this resulted in horizontal run-up's that were higher than were predicted (when the Regional average slope was used). Transects with mid-beach slopes < 3% had run-ups 10-20 m higher than previously predicted while transects with mid-beach slopes > 3% had run-ups ~10 m lower than predicted.

DSAS DIGITAL SHORELINE ANALYSIS SYSTEM GIS @ WSDOT