Modeling Normal and Extreme Wave Conditions in Callao Bay, Peru using Reanalysis Data

Rafael Pimentel[a], Emanuel Guzman[b] and Carmela Ramos[c]
Facultad y Escuela de Ingeniería Civil, Universidad Peruana de Ciencias Aplicadas, Av. Prolongación Primavera 2390, Santiago de Surco, Lima, Peru

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Abstract: Numerical simulations of wave conditions in Callao bay in normal and extreme conditions were carried out to characterize the wave dynamics in the bay. Bathymetry data from the navigation charts to represent bottom depth were used. Waves in deep waters from numerical reanalysis were calibrated with satellite data that have allowed define scenarios of wave propagation to shallow water in normal and extreme conditions. Model results were compared with in situ wave data obtaining good approximation between modeling and observed waves. Results indicates that waves coming from Southwest and South-Southwest, which is the most predominant waves in deep waters, due to the diffraction effects caused by San Lorenzo Island generate two areas with different wave height conditions, in this way in the area affected by diffraction wave reach height between 0.5 to 1m, while area unaffected by diffraction effects wave reach heigh between 2 to 5m. Waves coming from Northwest has more influence in the bay, due to diffraction effects are neglected and in general terms all the bay increase the wave height around to 2 to 5m.

1 INTRODUCTION

The study and knowledge of waves in coastal areas are important due to the impacts that can occur in them, such as coastal flooding and the erosion and sedimentation processes in coastlines. Some numerical Simulation Investigations performed Along the North Coast of the United States projected an increase in wave height (Erikson et.al, 2015), which may have an impact on the increase in sea level on flooded shores (Ruggiero, 2013). Numerical simulations of coastal flooding carried out in California and other coastal areas of the USA indicate that there would be a loss of 150 billion dollars due to coastal inundation by waves an sea level (Barnard et.al, 2019), Gainza et.al 2018 applied ~~a~~ numerical modeling of tidal and wave factors to predict the advance of the sea in the territory of Gold Coast, Australia.

The study area is located in central part of Peru in the Constitutional Province of Callao (Figure 1), and currently is the third most populated province in Peru with an annual growth population rate of 1.3%, (INEI, 2018).

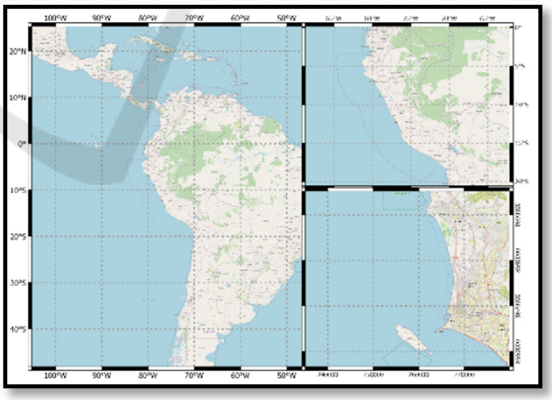

Figure 1: Location of the study area.

Likewise, the study area is considered as a tourist place due to its beaches like Chucuito, and Cantolao beaches, gastronomy, and architecture like Real Felipe Castle. Another important aspect is that Callao Port,

[a] https://orcid.org/0000-0002-4155-3563
[b] https://orcid.org/0000-0001-8381-4509
[c] https://orcid.org/0000-0002-4269-2944

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which is the most important Peruvian port and carries out industrial trade activities (Guzman et al, 2020).

In some seasons, especially in summer (January February and March), Callao bay is affected by irregular or unusual wave dynamics, for example in 2015, the bay was affected by irregular wave events that affect the coast and alert to population, due to the probability of flooding (Lainez, 2015). Similar situation occurred in 2016, in which wave attack was so aggressive that it could drag large stones to the squares (Figure 2) (Perú21, 2016).

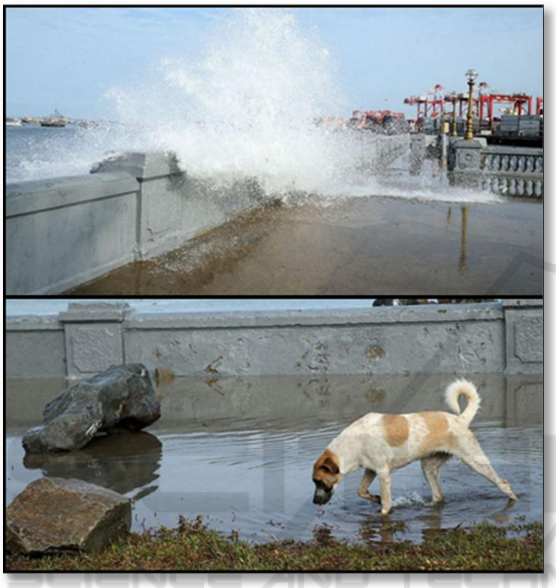

Figure 2: Flooding due to waves in the Callao bay. Source: Peru21, 2016.

The last event similar to the events of 2015 and 2016 occurred in January 2011, when there was a rise in the tide and anomalous waves coming from the Northwest (Figure 3), causing serious damage to infrastructures, flooding and again putting in danger to the population, because the force of the waves was so great that they knocked down in Plaza Grau (Figure 4) and dragged a large amount of stones, likewise, the waves caused damage to a museum that was below ground level.

Although Callao Bay has many coastal structures such as protection walls and breakwaters of 1.3 km long to prevent the waves from exceeding and reaching the population, these were not enough to stop the advance of the waves. Therefore, analyzing the conditions of normal and extreme waves is of great importance, since depending on the characteristics of the waves, it could flood the coastal strip and damage nearby infrastructures and even against the life of those who live in the area.

Figure 3: Aggressive waves coming from the northwest. Source: The photograph was taken by the authors in January 8, 2021.

Figure 4: Collapse of the walls of Plaza Grau and stones washed away by the waves. Source: The photograph was taken by the authors in January 24, 2021.

2 METHODOLOGY

2.1 Data Used

To make numerical simulation oceanographic data were used from global databases and in situ data. Bathymetric data were used from available navigation charts for Callao Bay, sea level data available from University Hawaii Sea Level Center (UHSLC) (Cadwell et al, 2015) has been used, which collects the sea level data from tide-gauge stations in the world and for our case, data from Callao station recorded from 1970 to 2019 was used. In the case of waves in deep waters, the wave reanalysis data from the NOAA (National Oceanic Atmospheric Administration) from 1979 to 2019 with 3 hours of temporal resolution. These data were complemented with satellite data for a point located on 78°W and 12.5°S. Data has also been collected in shallow waters off the Callao bay at a depth of 10m (Figure 5), to validate the results obtained in the numerical wave modeling.

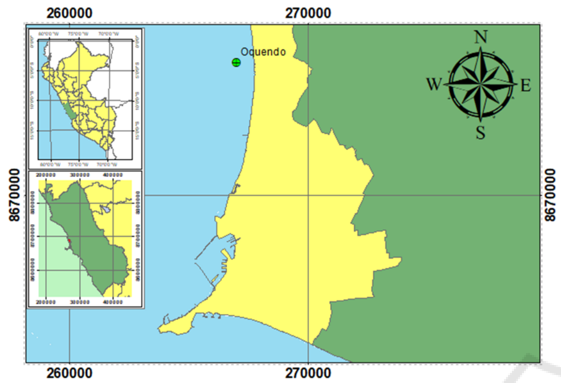

Figure 5: Location of wave data collection in shallow water.

2.2 Wave Climate in Deep Waters

Wave reanalysis data in deep waters have been compared with the satellite data to calibrate numerical reanalysis. The uncalibrated reanalysis data shows good trend and correlation between the wave height of the model and the satellite (Figure 6 and 7) obtaining acceptable statistical indicators between the data of the uncalibrated model and satellite. (Table 1). When model was calibrated, the indicators regarding the data observed by the satellite improve significantly (Table 1).

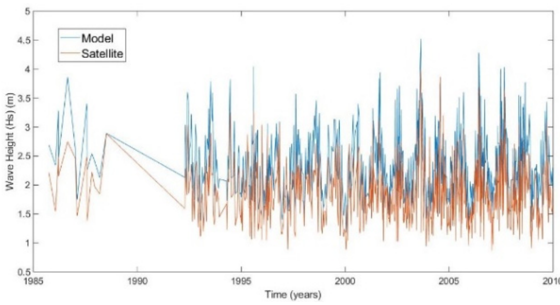

Figure 6: Time series of wave height comparison between Waves reanalysis and Satellite data at location 78°W, 12.5°S.

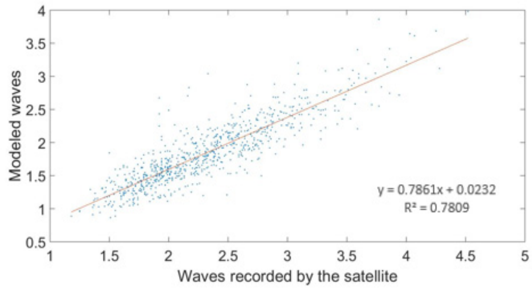

Figure 7: Waves satellite data and wave reanalysis dispersion at point 78°W, 12.5°S.

Table 1: Wave model calibration.

Indices	Uncalibrated model	Calibrated model
BIAS	0.4732	0.1732
RMSE	0.5423	0.3164
SI	0.2934	0.1712
IOA	0.7268	0.907

With the calibrated deep water model, the general characteristics in deep water are established, and wave height (Figure 8) and wave period (Figure 9), observing that there is a predominant swell from the southwest with wave height between 2 to 3m, reaching maximum heights of 4m (Figure 8) and predominant periods of 12 to 14s, with maximum periods of 22s (Figure 9).

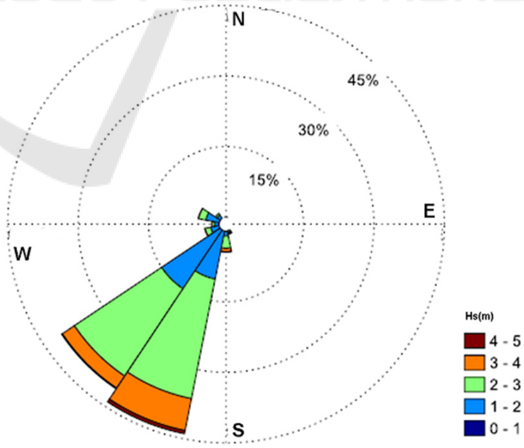

Figure 8: wave height rose in deep waters (78°W, 12.5°S).

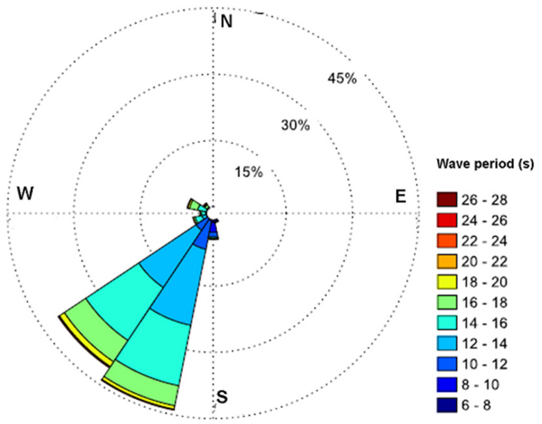

Figure 9: wave period rose in deep waters (78°W, 12.5°S).

After calibrating the model in deep waters, a table has been prepared with the main cases of wave propagation (Table 2), where the average, 90 percentile and maximum are shown in each wave direction.

Table 2: Mean regime cases for each wave direction in deep waters.

Case	Dir	Hs (m)	Tp (s)	Case	Dir	Hs (m)	Tp (s)
1		2.9	7.7	13		2	14.6
2	SSE	3.7	8.7	14	WSW	2.4	16.5
3		4.9	9.9	15		3.8	20.2
4		2.5	10	16		1.9	15.2
5	S	3.3	13.2	17	W	2.4	16.7
6		4.9	20	18		3.4	20.3
7		2.4	13.9	19		1.9	16.3
8	SSW	3.3	13.2	20	WNW	2.4	18.7
9		5.3	23.2	21		3.3	21.9
10		2.2	14.4	22		1.9	17.6
11	SW	2.9	16.9	23	NW	2.3	20.2
12		4.8	23.5	24		2.8	24.9

The extreme regimes consist in establish the most unusual wave cases that have occurred in deep water close to study area (Kim & Suh, 2018). The LogNormal and Gumbell criteria will be used (Frihy et al, 2010) to calculate wave height over 10, 30 and 50-year return period (Figure 10 and Table 3). Table 3 shows in general terms that wave coming from SW and SSW have the greatest heights comparing with other directions.

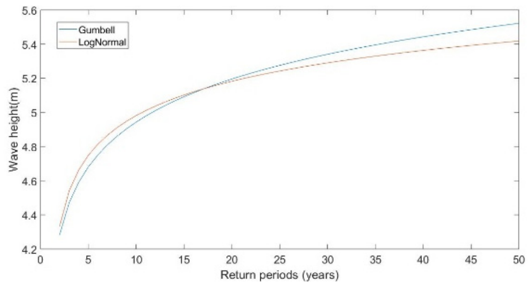

Figure 10: Extreme wave height regime in deep waters (78°W, 12.5°S).

Table 3: Extreme regime cases obtained in deep waters.

Return Period (years)	Case	Dir	Hs (m)	Tp (s)	Case	Dir	Hs (m)	Tp (s)
10	1		4.3	8.7	13		3.2	16.5
30	2	SSE	4.7	8.7	14	WSW	3.5	16.5
50	3		5.2	8.7	15		3.7	16.5
10	4		4.4	13.2	16		3.0	16.8
30	5	S	4.9	13.2	17	W	3.3	16.8
50	6		5.1	13.2	18		3.4	16.8
10	7		4.9	13.2	19		2.9	18.7
30	8	SSW	5.3	13.2	20	WNW	3.2	18.7
50	9		5.5	13.2	21		3.3	18.7
10	10		4.6	16.9	22		2.5	20.2
30	11	SW	5.0	16.9	23	NW	2.7	20.2
50	12		5.1	16.9	24		2.9	20.2

3 SEA LEVEL

Data from UHSLC sea level were grouped in 5 decades to calculated mean sea level (MSL) over each decade (Table 4) and shows an oscillatory trends of MSL from 1970 to 2019.

Table 4: Mean sea level in Callao Bay station calculated by decade.

Decade	Mean sea level
1970 – 1979	1097 mm
1980 – 1989	1125 mm
1990 – 1999	1110 mm
2000 – 2009	1071 mm
2010 - 2019	1096 mm

4 NUMERICAL MODELING

Numerical modeling consists of performing the wave propagation method from deep waters to several locations in shallow water of study area to stablish the climate wave (Yuk, Park & Joh, 2018).

A nested grid to propagate deep water waves were used (Figure 11), with a coarse grid with 30° rotation for coarse grid while for shallow water a grid oriented with x-axis were defined. The main characteristics of each grid is showed in Table 5.

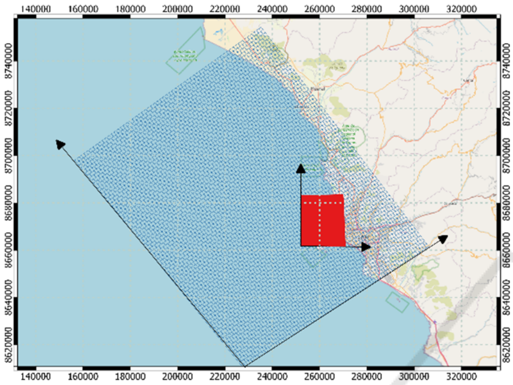

Figure 11: Wave grid in intermediate and shallow waters.

Table 5: Characteristics of the grids used in numerical wave modeling.

Grid	Deep water	Shallow waters
Long	93km	18.3km
Width	113km	21.7km
dx	1158m	77m
dy	1398m	91m
Orientation	30°	0°

The Delft3D-wave model (DELTARES, 2014) were used to propagate each scenario defined in deep water to shallow waters. Model was configurated to propagate waves in stationary mode.

5 RESULTS AND DISCUSSIONS

5.1 Modeling of the Medium Regime

Results of wave modeling of mean regime shows that waves coming from the south-southeast direction does not affect La Punta and La Perla districts, because the maximum wave height reached is less than 0.5m (Figure 12). For waves coming from southwest (Figure 13) wave heights in the northern area of the bay reach 3 to 3.5 m, but in the La Punta the wave heights are around 1m and in La Perla near the coast the heights are around 0.5m.

Finally waves coming from northwest are presented in Figure 14, where the highest wave heights are 2.5m and are mostly throughout the northern part of the study area, and the district of La Punta has nearby waves of heights close to 2 m, but the district of La Perla has waves less than or equal to 1 m.

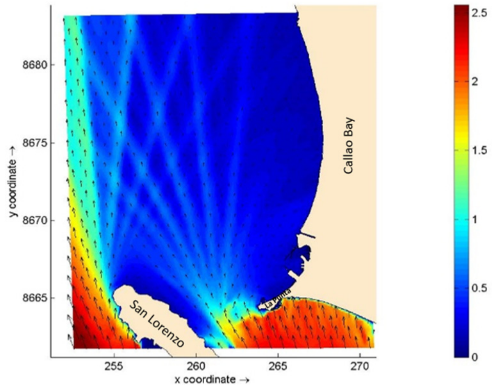

Figure 12: Wave modeling for SSE direction. Case 01: Wave period: 7.7 s, wave height: 4.3 m.

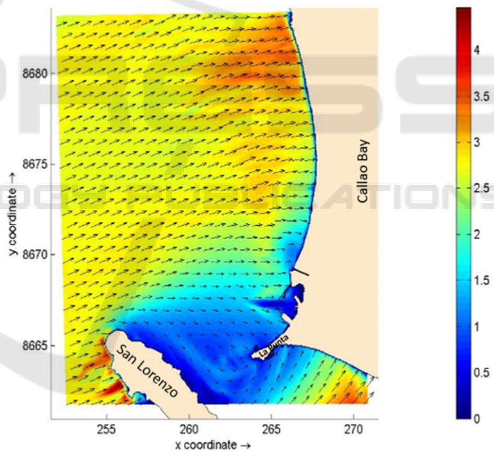

Figure 13: Wave modeling for WSW direction. Case 15: Wave period: 20.2 s, wave height: 3.8 m.

5.2 Modeling of the Extreme Regime

In general terms, waves coming from Northwest (Figure 15) shows wave height between 1.5 to 2m in all the study area, and the northern part of study area is most affected by waves. Figure 16 shows that wave coming from Southwest generate two defined wave areas. The first area correspond to northern part of the bay, which wave heights reach values between 2 and 5m, and the second area is protected by San Lorenzo Island which cause the diffraction and wave heights reached is less than 2m.

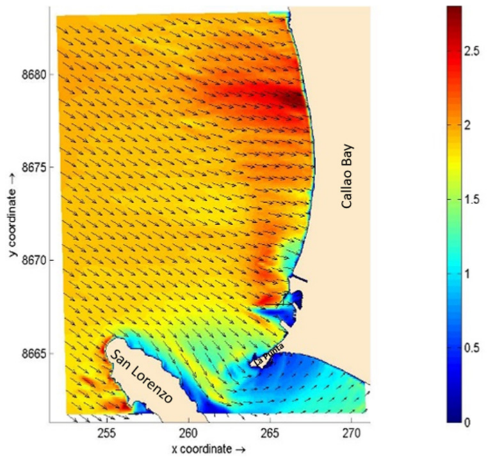

Figure 14: Wave modeling for WNW direction. Case 21: Wave period: 21.9 s, wave height: 3.3 m.

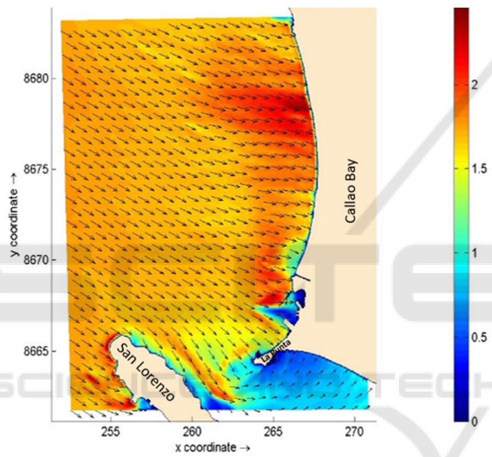

Figure 15: Wave modeling for NW direction. Case 22: Return Period: 10 years, Wave period: 20.2 s, wave height: 2.5 m.

6 MODEL VALIDATION IN STUDY AREA

Likewise, Figure 17 shows the comparison of percentiles of uncalibrated modeled waves, calibrated model with in situ data. It is observed that uncalibrated model has the same trends with in situ date, however model is overestimate 0.20m approximately, for this reason modeled wave were calibrated to obtain better index of comparison (Table 6). Consequently, the numerical modeling with Delft3D program is acceptable for the purposes of this research.

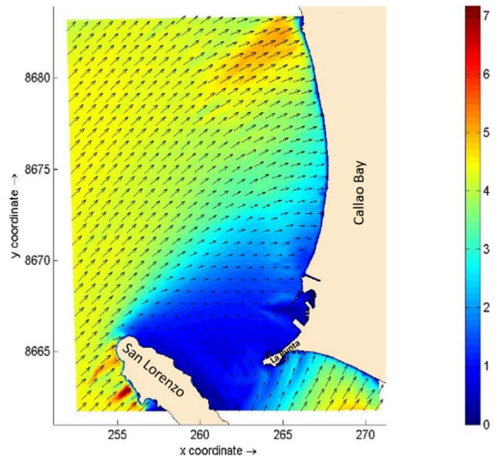

Figure 16: Wave modeling for SW direction. Case 11: Return Period: 30 years, Wave period: 16.9 s, wave height: 5 m.

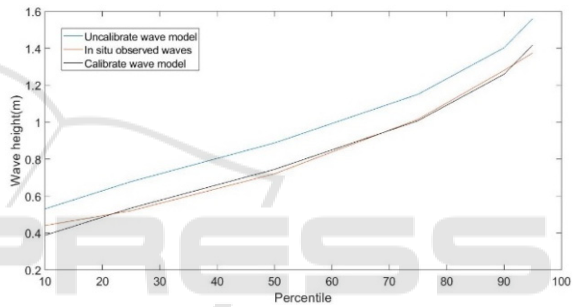

Figure 17: Trend of the percentiles of registered and modeled wave heights.

Table 6: Wave modelling validation in shallow waters.

Indices	Uncalibrated Model	Calibrated Model
BIAS	0.043	0
RMSE	0.053	0.031
SI	0.060	0.035
IOA	0.995	0.998

The events that affected to the bay during January 2021 (Figure 18 and 19) were represented in numerical modeling as wave from Northwest (Figure 15), in this case ins observed how the wave inside directly to Callao bay without influence of diffraction effects from San Lorenzo Island.

Figure 18: Waves that were presented in Plaza Grau and La Punta. Source: Martínez, 2021.

Figure 19: Waves that were stopped by the La Arenilla breakwater. The photograph was taken by the authors in January 8, 2021.

7 CONCLUSIONS

The numerical modeling presents the possible wave scenarios in the study area in specific wave situations, but these scenarios must be validated with data dispersion criteria. The direction of the waves is an important variable since it serves as an indicator of the areas where the waves will be aggressive and would cause damage to structures and put the population on alert. Usually, the waves between the south and southeast directions generate waves less than 0.5m close to the southern zone of the La Punta district and the La Perla district. However waves coming from northwest directions generate waves with 2m of height close to the north of Callao bay. In the case of extreme wave events, the lowest wave height that can occur on the coast has a magnitude of around 2m, which may vary due to the shape of the coastline and coastal structures. Likewise, the most dangerous wave direction is the West-Northwest since the modeled scenarios show that both in the medium and extreme regime the wave heights are significant. In normal conditions the waves coming from the west southwest can reach heights of around 2m near the coast, but in extreme conditions these could reach 3m or more. It has been observed that San Lorenzo Island protect to study area from waves especially when it is coming from South and South-west directions.

Finally, the porpoise of this paper was characterizing the mean and extreme regime of wave in Callao bay to provide a tools of decision makers to prevent future events of flooding by waves.

REFERENCES

Erikson, L., Hegermiller, C., Ruggiero, P., & VanOrmondt. (2015). Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. Ocean Modelling, 171-185. doi:http://dx.doi.org/10.1016/j.ocemod.2015.07.004.

Ruggiero, P. (2013). Is the intensifying wave climate of the US Pacific Northwest increasing flooding and erosion risk faster than sealevel rise? Journal of Waterway Port Coastal and Ocean Engineering, 88-97. doi:10.1061/(Asce)Ww.1943-5460.0000172.

Barnard, P. L., Erikson, L. H., Foxgrover, A. C., Hart, J. A. F., Limber, P., O'Neill, A. C., … Jones, J. M. (2019). Dynamic flood modeling essential to assess the coastal impacts of climate change. Scientific Reports, 9(1), 1–13. https://doi.org/10.1038/s41598-019-40742-z

Gainza, J., Rueda, A., Camus, P., Tomás, A., Méndez, F. J., Sano, M., & Tomlinson, R. (2018). A Meta-Modelling Approach for Estimating Long-Term Wave Run-Up and Total Water Level on Beaches. Journal of Coastal Research, 342(2), 475–489. https://doi.org/10.2112/jcoastres-d-16-00198.1

INEI (2018) Población del Perú totalizó 31 millones 237 mil 385 personas al 2017.INEI Instituto Nacional de Estadística e Informática. Recuperado de: https://www.inei.gob.pe/

Guzman, E., Ramos, C., & Dastgheib, A. (2020). Influence of the el nino phenomenon on shoreline evolution. Case study: Callao bay, Peru. Journal of Marine Science and Engineering, 8(2). https://doi.org/10.3390/jmse8020090

Lainez Yonce, A. (1 de Mayo del 2015) Oleaje: alerta en el Callao y Costa Verde por inundaciones. Crónica Viva. Recuperado de: http://www.cronicaviva.com.pe/oleaje-alerta-en-el-callao-y-costa-verde-por-inundaciones/

Perú 21 (4 de Febrero del 2016) Callao sigue afectado por fuerte oleaje [Fotos y video]. Perú 21. Recuperado de: https://peru21.pe/lima/callao-sigue-afectado-fuerte-oleaje-fotos-video-210087-noticia/?ref=p21r

Caldwell, P. C., M. A. Merrifield, P. R. Thompson (2015), Sea level measured by tide gauges from global oceans — the Joint Archive for Sea Level holdings (NCEI Accession 0019568), Version 5.5, *NOAA National Centers for Environmental Information*, Dataset, doi:10.7289/V5V40S7W.

National Oceanic and Atmospheric Administration (w.d.) Wavewatch III Hindcast and reanalysis archives. Environmental Modeling Center NOAA NWS National Centers FOR Environmental Prediction. Recuperado el 27 de Agosto del 2020. https://polar.ncep.noaa.gov/waves/hindcasts/

Chen, Y., Xie, D., Zhang, C., & Qian, X. (2013). Estimation of long-term wave statistics in the East China Sea. Journal of Coastal Research, 65, 177–182. https://doi.org/10.2112/si65-031.1

Kim, I. C., & Suh, K. D. (2018). Effect of Sea Level Rise and Offshore Wave Height Change on Nearshore Waves and Coastal Structures. Journal of Marine Science and Application, 17(2), 192–207. https://doi.org/10.1007/s11804-018-0022-8

Frihy, O. E., Deabes, E. A., & El Gindy, A. A. (2010). Wave climate and nearshore processes on the mediterranean coast of Egypt. Journal of Coastal Research, 26(1), 103–112. https://doi.org/10.2112/08-1020.1

Yuk, J.-H., Park, J., & Joh, M. (2018). Modelling of Storm-induced Seawater Flooding in the Suyeong River Area, South Korea: A Case Study due to the Storm Surge and Waves during Typhoon Sanba. Journal of Coastal Research, 85, 746–750. https://doi.org/10.2112/si85-150.1

DELTARES (2014) Delft3D-WAVE, User Manual. The Netherlands. Deltares.

Hamza, W., Lusito, L., Ligorio, F., Tomasicchio, G. R., & D'Alessandro, F. (2018). Wave climate at shallowwaters along the Abu Dhabi coast. Water (Switzerland), 10(8), 1–19. https://doi.org/10.3390/w10080985

Martínez Moreno, Xenia (23 de Enero del 2021) Callao: Oleaje anómalo se registra en Callao. RPP Noticias. Recuperado de: https://rpp.pe/peru/callao/callao-oleaje-anomalo-se-registra-en-la-punta-video-noticia-1316800?ref=rpp