Use of unstructured meshes for wave height and particles horizontal displacement analysis in central zone Veracruz, Mexico

Utilización de mallas no estructuradas para el análisis de altura de ola y desplazamiento horizontal de partículas en la zona central de Veracruz, México

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Abstract

The objective research is the calculation of free-floating particle displacement trajectory using the Simulating Waves Nearshore (SWAN) software having as base unstructured meshes to get the diagram of the study area. Third-party tools and data were used, such as bathymetry, wave and tide data from the Global Ensemble Forecast System-Wave (GEFS-Wave) and data processing using SWAN. The modelling software and some local developments were used to generate valid Delaunay diagrams for the central zone of the Veracruz state, Mexico. For the configuration of the experiments, we worked with physics variables of the modelling software until achieving one that resembled the real conditions of the area; once the similarity was achieved, it was possible to run the experiments to obtain the wave height and frequency and replace the values in the horizontal displacement equation until obtaining the spaghetti diagrams that indicate the possible paths of the particles.

Wave height, Particles displacement, unstructured mesh

Resumen

El objetivo de la investigación es el cálculo de la trayectoria de desplazamiento de partículas de libre flotación utilizando el software Simulating Waves Nearshore (SWAN) teniendo como base mallas no estructuradas para obtener el diagrama del área de estudio. Se utilizaron herramientas y datos de terceros, como lo fueron la batimetría, datos de olas y mareas del Global Ensemble Forecast System-Wave (GEFS-Wave) y el procesamiento de los datos utilizando SWAN. El software de modelación y algunos desarrollos locales fueron utilizados para generar los diagramas de Delaunay válidos para la zona central del estado de Veracruz, México. Para la configuración de los experimentos se trabajó con variables de física del software de modelación hasta lograr una que asemejara las condiciones reales de la zona; una vez que se logró la similitud, fue posible ejecutar los experimentos para la obtención de altura y frecuencia de la ola y reemplazar los valores en la ecuación de desplazamiento horizontal hasta obtener los diagramas de espagueti que indican las posibles rutas de las partículas.

Altura de ola, Movimiento partículas, Mallas no estructuradas

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Introduction

The study that was developed bases its postulates on the theory of waves and their formation. It would be impossible to understand the wave's height without considering the action exerted by the wind on the sea. This study does not consider the height of the waves generated by extraordinary phenomena such as hurricanes and earthquakes; whose generation and propagation consider different formulas in addition to values of variables such as salinity, density, seabed, etc. and that due to their propagation speed, they are more complicated to predict (Musinguzi et al., 2019).

A wave is considered to be the sinusoidal variation in elevation of the sea surface and can be defined as a height, **H**, which is the vertical distance from the crest to the trough of the wave in feet or meters, with wavelength, **λ**, which is the distance in feet or meters between two similar points on the wave and the wave period, **T**, which is the time in seconds or minutes it takes for the wave to repeat itself.

From **Figure 1**, several additional variables are obtained that helps to represent the wave movement, among them:

Wave frequency, $\omega = 2\pi/T$

Wave number, $k = 2\pi/\lambda$

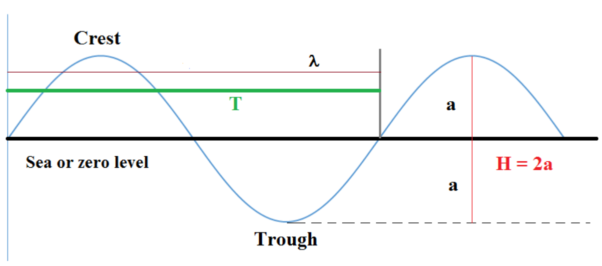

Figure 1 Wave parts and measurements identification
Source: Own elaboration

A wave on the ocean surface is considered to be the result of the combination of different disturbing and restoring forces that are in dynamic equilibrium. Consequently, the tides could be considered as waves of very long period. It is considered that a wave generated by the force of gravity has a period of between 1 and 30 seconds in duration; and the tides have a period of between 12 - 24 hours (Pecher & Kofoed, 2017).

The waves always start as small waves that increase in size due to the constant supply of energy provided by the wind. As long as the wind continues to blow, the waves reach their limit, beyond which they do not grow due to the balance caused by the loss of energy. This loss of energy should not be understood as the sea entering a static moment since when the wind stops blowing, the waves will continue to exist with the ability to travel great distances while conserving practically the same amount of energy (Friedman & Tillich, 2004; Ringler et al., 2013). In this study, we will separate the waves into two groups: wind waves created by local winds and tidal waves, created by winds that do not blow in the area. Although, all waves are both created by the effect of the previous wind and are affected by the local wind; it is the local wind that generates waves that are out of the ordinary. Although the separation of the waves generated by local winds and swell waves is a way that facilitates the description of the conditions in a particular point of the ocean and, until now, it must be considered one of the main pieces when carrying out trajectory forecasts of free-floating objects on the surface of the oceans (Johns et al., 2020).

The elevation of the water surface ζ is understood to be given by the following equation:

$$\zeta = \frac{H}{2} \cos\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right] \quad (1)$$

This change in ocean surface elevation is the result of an elliptical motion of water particles, which extends below the surface; and the amplitude of the motion decreases exponentially with depth. So it is obtained that for the vertical displacement of the water particles **ζ(z)** is given by the formula, where ***d*** depends on the depth of the seabed. That measure generally is taken from bathymetry

$$\zeta(z) = \frac{H}{2} \cos\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right] \frac{\sinh[2\pi(z+d)/\lambda]}{\sinh[2\pi d\lambda]} \quad (2)$$

And the horizontal displacement **ξ(z)**:

$$\xi(z) = \frac{H}{2} \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right] \frac{\cosh[2\pi(z+d)/\lambda]}{\sinh[2\pi d\lambda]} \quad (3)$$

Once the equations to determine the movement of the particles are available, it is important to have the bathymetry of the area and generate its mesh to run the corresponding simulations. For our analysis, we will work with an unstructured mesh based on Delaunay triangles; that in areas where there are sudden changes in depth as the seashore, as well as intense meteorological changes, analyzes with unstructured meshes have been more accurate than analyzes with structured meshes (Aguilera-Méndez, Juárez-Toledo, Martínez-Carrillo, & Vera-Popoca, 2021; Weatherill, 1992). Together with the bathymetry, the friction factor with the seabed should be considered; JONSWAP is widely used but RIPPLES will be used in the experiment since it has shown that in this coordinates with the spaces close to the coast its results on the wave cycle in unusual conditions are more accurate.

Although the experiment seeks to obtain the waves total height on the beach, the effect that the lunar cycles have on the tide must be considered; This is because the simulation software performs the calculations for the waves height caused by the wind and does not contemplate a dynamic generation of the tide with the lunar cycles, so it must be entered manually. There are some oceanographic models from which the initial tidal data is taken. For this experiment we will use the data set of the Global Ensemble Forecast System-Wave (GEFS-Wave) (Toth & Kalnay, 1997), which is an assemble of the GFS and WW3 models administrated by National Oceanic and Atmospheric Administration (NOAA); This model has the peculiarity that 1) the data is verified and 2) it takes the 6 hours of the last forecast generated in order to obtain continuity of the forecasts and discard the 00 or start time.

By definition the forecasts wave heights are the "Significant Wave Height"; this is the average wave height (trough to crest) of the highest 1/3 of the forecast waves. So working only with the output from the model misses the general rule: the largest individual wave one can find will be a little less than twice the significant wave height. It does not mean that all waves encountered will be within the forecasted significant wave height; some will be less and some will be more because the measurement uses the Rayleigh statistical distribution model (García et al., 2009).

Consequently, the results produced by the SWAN model for the variables Hsig (significant wave height) and Hswell (significant swell height) will be used to calculate the seas variable; this variable is used to describe the combination of wave and swell heights when superimposed on one another, whose formula is:

$$seas = \sqrt{(Hsig^2 + Hswell^2)} \qquad (4)$$

Statistically, it is possible to generate a wave twice the size indicated by the Hsig every 8,000 seconds or 2.2 hours (Ainsworth, 2006); therefore we will use the seas result for the study.

To facilitate the results analysis, it was decided to use the lunar calendar as a basis due to its effects on the tide and on the earth's cycle of seasons. A fundamental part for the results validation will be the evidence in buoys and tide gauges; but it is the records on beaches and ports that stand out in importance, since there the wave height observed will give us a precise measure of what happened that can be contrasted with the simulations data. For the experiments that were carried out, the use of random numbers within the displacement formulas was not considered necessary because calculations of wave direction and height use them.

Development

The study area is located between (18.9°, 19.4°) north latitude and (-96.4°, -95.8°) west longitude, which includes the port and city of Veracruz, Boca del Rio and Antón Lizardo, among other sites of interest as indicated in Figure 2. The grid bathymetry has a 15 arc seconds resolution, or one point every 0.004° (GEBCO Compilation Group, 2021) which generates a mesh of 144 x 120 or 17,280 points that represent the study area and is showed in Figure 3; it should be noted that the bathymetry of the coastal zone (in blue) that suffers little alteration up to the land zone (in green). On the part of the unstructured mesh generated with Delaunay triangles, 1,715 vertices were obtained for the sea area with the generation conditions of internal angles of at least 30° and areas smaller than 100 m^2. 3,196 cells were generated, yielding 4,909 faces that were evaluated to obtain the height forecast. The simulation software is expected to provide data showing the variation in wave height near the beach, so it is necessary to confirm that the unstructured mesh has a higher density of triangles in coastal areas, as shown in Figure 4.

The next step was to obtain the 10 meters above sea level wind speed and speed direction as well as sea current speed and direction for the observed coordinates. The GEFS-Wave has both data, so the information extraction routines were programmed. For wind and tidal information, the data was entered for the point located at north latitude 19.15° and west longitude -96.0°; due to the area size and their availability because the GEFS-Wave outputs has 0.25° resolution.

Each execution was carried out at 00, 03, 06, 09, 12, 15, 18 and 21 hours for each day, for a cycle of 3 months of temporary. The marine physics variables were considered with the default model values, as well as the GEN3 calculations offered by SWAN and the RIPPLES quotient was used for friction. For the tide calculations, the lunar calendars were used with the predicted height values for the different dates that were established for the experiment, those is published by Mexico's Secretary of Navy in the web page https://oceanografia.semar.gob.mx/mapa_estaciones.html.

Figure 2 Location study area. Secretary of Tourism, Veracruz, México

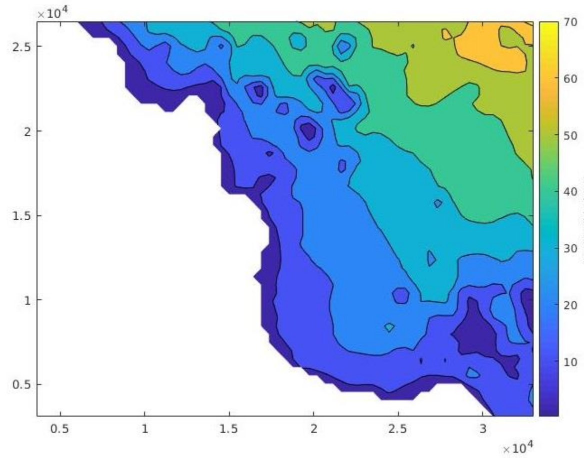

Figure 3 Area bathymetry, the land area is indicated in white and the ocean depth in blue to yellow scale
Source: Own elaboration

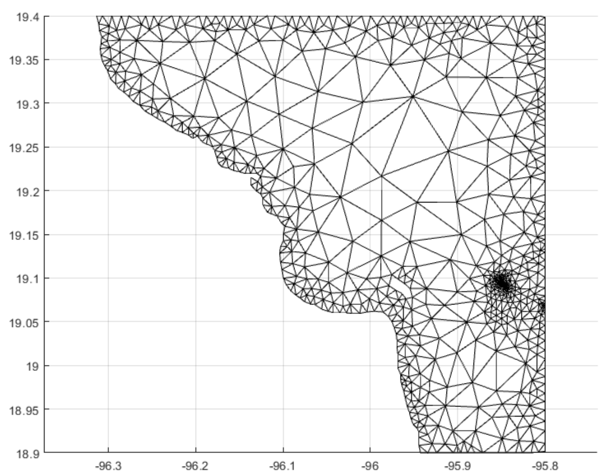

Figure 4 Study area map generated with Delaunay triangles
Source: Own elaboration

Once the input data (Delaunay diagram, bathymetry, waves and wind) had been obtained and the physics of the experiment had been configured, the next step was the recognition and validation of the information by the simulation software; the software output is shown in **Figure 5** and it was validated that they were consistent and it was possible to start the simulations cycle.

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CGRID UNSTRUCTURED CIRCLE 36 0.0521 1.0 31
Resolution in sigma-space: df/f =  0.1000

READ UNSTRUCTURED TRIANGLE 'veracruz'

The unstructured grid contains solely triangles generated by Triangle

Number of vertices          =    1715

Number of cells             =    3196
   Number of internal cells =    2970
   Number of boundary cells =     226

Number of faces             =    4909
   Number of internal faces =    4679
   Number of boundary faces =     230

The minimum gridsize =     0.00001
The maximum gridsize =     0.06978


INPGRID BOTTOM -96.40 18.9 0 143 119 0.004166 0.004166

$>INPGRID BOTTOM UNSTRUCTURED

READINP BOTTOM -1 'veracruz.bot' 2 6
**  Heading lines file veracruz.bot **
-> ncols        144
-> nrows        120
-> xllcorner    -96.400000000000
-> yllcorner    18.900000000000
-> cellsize     0.004166666667
-> NODATA_value -32767
```

Figure 5 Information from the SWAN software indicating the recognition of the input data to perform the simulation
Source: Own elaboration

To establish a reference, the data recorded by the buoys and the tide gauges placed in the port of Veracruz were taken. The variable that was compared was the height of the wave, since with it the possibility of the sea exceeding the height of the natural or artificial barriers and invading the land was determined. In this project it was determined not to use the variable of wind direction or construction plans and it is assumed that the bordering areas of the beach area are considered in the altimetry, due to the lack of reports of constructions or artificial barriers that stop the straight ahead of the waves. The experiments to adjust the physics parameters of the model were applied for the year 2021. The most observed variables were those related to the friction and density of the water (because it is a deep-water port with oil contamination). As shown in Table 1 for a control point located at north latitude 19.21° west longitude -96.12° which is the closest point to the Ver2 buoy. The data shown is illustrative and indicates how the data from the different runs was compared against the buoy reading.

Table: control01, SWAN version:41.31				
Friction/date	**Xp (deg)**	**Yp (deg)**	**Hsig (m)**	**Tm01 (s)**
(03/31)				
JONSWAP	-96.12	19.21	1.473	12.018
RIPPLES	-96.12	19.21	1.588	13.155
BUOY	Ver2		1.541	12.868
(06/30)				
JONSWAP	-96.12	19.21	1.488	12.787
RIPPLES	-96.12	19.21	1.396	12.644
BUOY	Ver2		1.432	11.873
(09/30)				
JONSWAP	-96.12	19.21	2.837	14.982
RIPPLES	-96.12	19.21	3.573	13.872
BUOY	Ver2		3.143	12.832
(12/31)				
JONSWAP	-96.12	19.21	0.929	11.193
RIPPLES	-96.12	19.21	1.388	11.627
BUOY	Ver2		1.113	11.521

Table 1 Result comparison of the SWAN software executions against the records in buoys
Source: Own elaboration

Due to the differences, it was found that the RIPPLES friction was the closest for the wave height measurements under the conditions that were established.

Some of the problems reported were the interpretation of the data produced by the SWAN simulator as well as the way in which it needs the input data to make the calculations on the wave's height considering the tide and the wind waves. One of the errors that appeared in the diagrams was the effect of wave tidal continuity. This is due to the fact that the data entered as a start has greater relevance in the final results than the calculations per se; so it was necessary to consider the results of the first execution as start results prepared for the rest of the executions. Figure 6 and 7 shows some errors clearly.

Once the outputs of the simulations were accepted, the value of H was replaced in equations 2 and 3 by the results obtained for seas to perform the calculation for the particles movement.

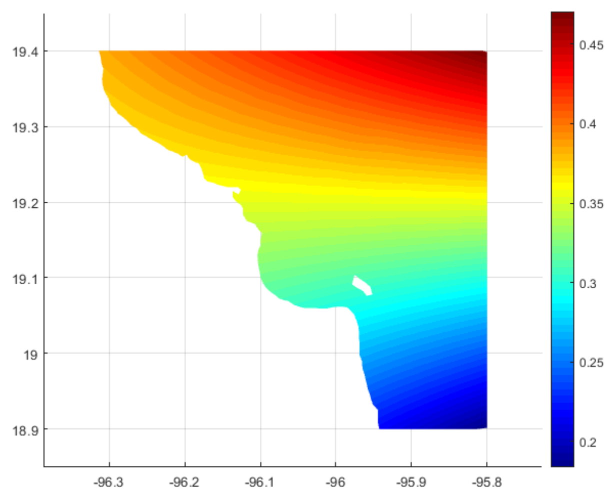

Figure 6 Tidal wave high diagram generated considering a uniform value for the area. The label bar has the same colour scheme as the map
Source: Own elaboration

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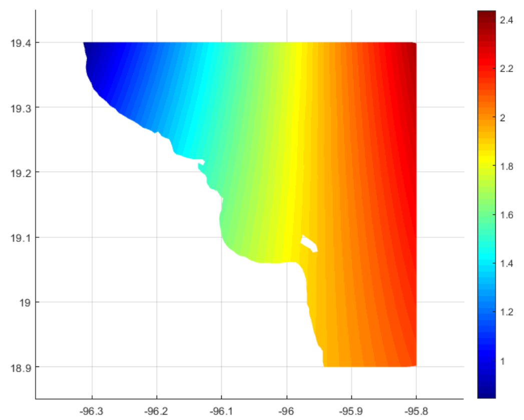

Figure 7 Tidal wave high diagram generated using a non-constant swell input values with different grid scales
Source: Own elaboration

Results

With the results obtained for Hsig and Hswel variables at the time of adjusting the simulation physics and data grid input and was validated against equation 1, it only remained to apply the formula for obtaining seas variable value, equation 4, for the different control points. The Ver2 buoy checkpoint results are shown below in Table 2:

Table: Results01, SWAN version:41.31AB				
Date	**Hsig**	**Hswel**	**seas**	**buoy**
01/10	1.5893	0.1976	1.6015	2.089
01/11	1.9837	0.2467	1.9989	2.108
01/12	1.6832	0.2093	1.6961	1.967
01/13	2.1233	0.2640	2.1396	2.472
01/14	2.4428	0.3038	2.4616	2.278
02/20	0.73153	0.09126	0.7372	0.8367
02/21	0.32296	0.04014	0.3254	0.4921
02/22	0.66603	0.07802	0.6705	0.6252
02/23	0.13386	0.01923	0.1352	0.1593

Table 2 The data obtained for wave height and seas variable calculation are shown. The buoy height presented is the maximum height reached in the same observation period that was from 12:00 to 14:59 (12Z). Data in meters (m)
Source: Own elaboration

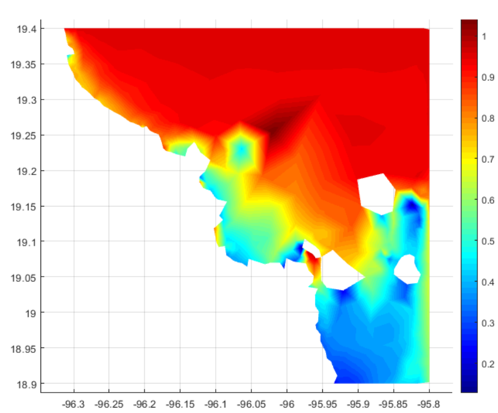

Figure 8 The seas variable behavior is shown as the probable maximum wave height with north originated winds
Source: Own elaboration

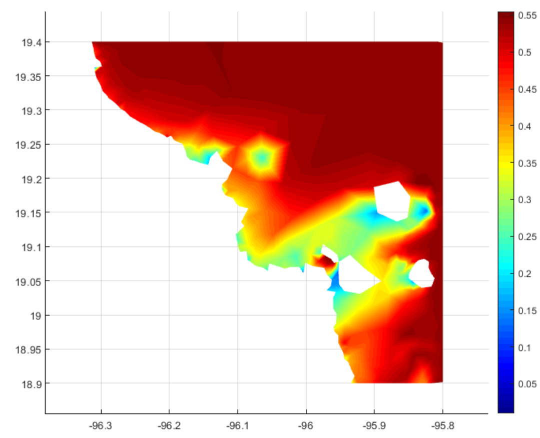

Figure 9 The seas variable behavior is shown as the probable maximum wave height with west originated winds
Source: Own elaboration

With the data obtained for wave height, proceeded to verify, in the same tabulated way, the information on the wave frequency showed in **Table 3**.

Table: Results02, SWAN version:41.31AB		
Date	**Tm01 (s)**	**Buoy (s)**
01/10	8.45	8.56
01/11	7.98	8.23
01/12	8.24	7.64
01/13	8.42	7.32
01/14	7.78	7.84
02/20	6.25	6.03
02/21	5.99	6.21
02/22	6.14	5.93
02/23	5.20	5.31

Table 3 Wave frequency as result of the simulation against the data buoy recorded
Source: Own elaboration

With which it was possible to generate the wave frequency maps as Figure 10

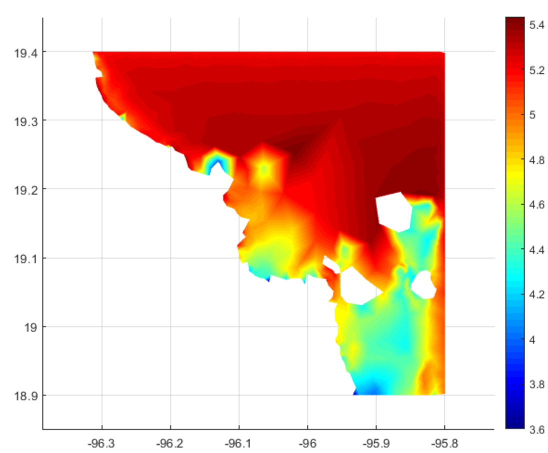

Figure 10 Wave period
Source: Own elaboration

Once the data were obtained, it was possible to substitute the values in the horizontal particle displacement equation and perform the analysis on free-floating bodies, such as some types of algae, as well as floating debris (garbage). The accumulated data allowed us to construct spaghetti-type diagrams that allow us to make an approximate calculation of the movement of objects on the ocean surface. An accumulation of data is mentioned since a spaghetti diagram reflects the possible change in the path of a body, and this change cannot be reflected only in time t; a sequence of t, t+1, t+2… t+n is required to indicate the expected change.

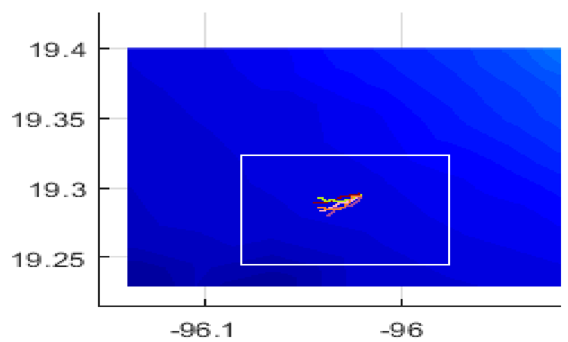

Figure 11 Spaghetti diagram showing possible particle displacements for a specific point for times t, t+1, t+2...t+24
Source: Own elaboration

Conclusions

The results showed a high percentage of acceptance with respect to the values recorded by the tide gauges and buoys, showing a variation within 20%. As also explained, in some cases the size of the wave doubled the predicted size; but for the data that was available, it was only possible on occasions where the presence of hurricanes or tropical storms drastically affected the results.

The particles horizontal displacement showed great consistency with the movement of floating objects that were in the area, but it was not possible to validate them mainly due to the lack of information from the authorities; although laboratory results with satellite images indicated a good correlation.

Just as the software considers variables for the experiment physics, it would also be advisable to have several data sources that could be introduced into the experiment, thus not only having data from SEMAR and NOAA.

Likewise, for further research, the use of non-hydrostatic, free-surface, rotational flow and transport phenomena in coastal waters models is suggested; such as SWASH, XB and ADCIR, among others.

The experiment showed consistency with the available data and scales; It would be advisable to have more sensitive bathymetry data and a smaller area (less than 100 km^2) if the objective was to analyze the waves height and their approach or invasion of beach or inland areas. It is recommended to use Artificial Intelligence tools like Artificial Neural Network that allow the learning of images (Aguilera-Méndez, Juárez-Toledo, Martínez-Carrillo, & Flores-Vázquez, 2021) to be used in research or civil protection areas in the event of rising waves in beach areas.

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