Modeling Ocean Dynamics at Waikiki Beach

Undergraduate Senior Thesis

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Acknowledgements

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Abstract

This thesis evaluates the ability of the numerical model, XBeach, to reflect the ocean dynamics of Waikiki beaches using both one-dimensional and two-dimensional modeling. First, simple one-dimensional runs (no along-shore variations) were compared to determine if their results could be generalized across a large stretch of beach. Second, the one-dimensional results were compared to results from the two-dimensional model (along-shore variations) to determine if the one and two-dimensional models provided different results. Then, both the one and two-dimensional results were compared to field observations. Finally, the wave parameters were adjusted to optimize the two-dimensional model. It was concluded that the one-dimensional model was unable to fully capture the required physics to sufficiently model Waikiki beaches. The two-dimensional model was more accurate at modeling significant wave height of both wind/swell waves and infragravity waves. Further study of sediment transport parameters is required to determine XBeach's ability to model beach morphology due to a swell at Waikiki.

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Introduction

Waikiki, through tourism, contributed approximately $3.6 billion to Hawaii's state product (*The Economic Contribution of Waikiki* 2002). One of the most important reasons tourists flock to Waikiki is to enjoy the white sandy beaches and playful surf. Unfortunately, erosion plagues Waikiki's beaches, greatly shrinking their size. To combat this problem, millions of dollars have been spent on sand replenishment projects dating back to the 1930s. But these expensive efforts have only managed to increase usable beach area temporarily. They have not halted erosion. This unresolved issue constantly reminds us of how little is known about ocean dynamics that cause erosion at Waikiki beaches. And, as sea levels rise and storms gain power, it becomes increasingly important to understand how beaches will respond.

Numerical modeling is a particularly promising means of studying ocean dynamics. A model of a beach has the ability to provide insights into ocean dynamics that observations cannot duplicate. For example, the model Xbeach has the ability to output data ranging from wave heights and currents to sediment transport at every grid point of an inputed bathymetry, while only requiring wave height at the off-shore boundary, peak period, and tide information to force the model. It would be nearly impossible to gather such a large range of data over such a vast area.

Recently, Austin Barnes, a master's student at the University of Hawaii, Manoa, used XBeach model to predict beach response to a swell event that occurred at Waikiki Beach in August/September 2011. Terrestrial Laser Scanning (TLS) of the shoreline and wave heights from two pressure sensors were used to validate the model. The TLS data at three different zones on the beach revealed accretion during the transition from the highest tide of the day to low tide but no other significant changes in bed level. (Barnes, 2013) Barnes modeled three one-dimensional transects from each of the three zones of the TLS. Although he concluded that the one-dimensional Xbeach model was unable to accurately predict the on-shore accretion observed by TLS, he suggested that a two-dimensional model might produce more accurate results.

Another study attempted to validate the XBeach model over a fringing coral reef in Western Australia. Although XBeach was initially made to model sandy coastlines, they found that it was also capable of modeling over a reef. They utilized both one-dimensional and two-dimensional models, but found that the two-dimensional model produced results more similar to observations than did their one-dimensional model. The one-dimensional model tended to over predict infragravity waves and setup. (Van Dongeren et al, 2013)

This thesis evaluates whether similar results hold true for Waikiki Beach. Thus, a two-dimensional XBeach model of Waikiki Beach has been constructed based on the same August/September 2011 swell used to create the previously mentioned one-dimensional model of the same beach. The one- and two-dimensional models will be compared and the validity of the new two-dimensional model will be evaluated.

Theory

To explain beach morphology at Waikiki Beach, it is imperative to first understand ocean waves. The linear wave theory in fluid dynamics can be used to describe propagating gravity waves. This theory is only appropriate when dealing with deep water waves that only has gravity as an external force. (Holthuijsen, 2007) The surface elevation,η, can be described as a simple harmonic motion. Equating Newton's second law, F = ma, and Hooke's law, F = -kη, sets up a second-order partial differential equation that can be solved to find:

$$\eta(x,t) = a\cos(kx - \omega t)\,,$$

This equation describes the displacement of a simple harmonic oscillator, but is also the foundation of wave mechanics. In this case, Hooke's law represents the restoring force of gravity to level the ocean surface elevation in the absence of motion.

The linear wave theory is based on two equations, a mass balance equation and a momentum balance equation, and the application of boundary conditions.

Mass balance equation:

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho u_x}{\partial x} + \frac{\partial\rho u_y}{\partial y} + \frac{\partial\rho u_z}{\partial z} = S_\rho$$

ρ = the mass density of water, $\vec{u}$ = velocity of water particles, S = the production of fluid

Because the mass density of water is approximately constant and no water is being produced, the mass balance equation can be reduced to the incompressible continuity equation:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

When this equation is combined with the assumption of irrotational motion (typical of non-breaking waves), then Laplace's equation results:

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=0$$

where $\phi(x,y,z,t)$ is the velocity potential function. The velocity potential function can be defined such that $\nabla\phi$ is equal to the velocity of the water particles.

Momentum balance equation (for the x component)

$$\frac{\partial(\rho u_x)}{\partial t}+\frac{\partial u_x(\rho u_x)}{\partial x}+\frac{\partial u_y(\rho u_x)}{\partial y}+\frac{\partial u_z(\rho u_x)}{\partial z}=S_x$$

Here, the momentum balance equation plays the role of Newton's second law for each location in the fluid. S_x is the production of momentum in the x-direction from a force, like gravity, pressure gradients, or friction, acting on a volume of water. Newton's second law can show that force is the rate of change of momentum, so S_x is also equal to the force in the x-direction per unit volume. For small amplitudes of forcing, a linear theory is appropriate, reducing the equation to:

$$\frac{\partial(\rho u_x)}{\partial t}=F_x$$

Assuming negligible friction and linearising the equations of motion for small amplitudes, the remaining forces and accelerations are: gravity, pressure gradients, and local rate of change of velocity. This assumption leads to the linearised momentum balance equations, where p is the pressure and g is the gravitational acceleration.

$$\frac{\partial u_x}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$
$$\frac{\partial u_y}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$
$$\frac{\partial u_z}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

From these momentum balance equations, the linearised Bernoulli equation can be derived (Holthuijsen, 2007):

$$\frac{\partial \phi}{\partial t} + \frac{p}{\rho} + gz = 0$$

The appearance of gravity in this equation is the essence of why Hooke's law can be applied to waves. This second linearisation builds on the previous assumptions, also linearising the surface pressure boundary condition, which must match the local atmospheric pressure, which is assumed constant for simplicity.

Applying boundary conditions to these equations provides information about the propagation speed of wave energy and wave dynamics. There are two important types of boundary conditions to think about: kinematic and dynamic conditions. The kinematic boundary condition at the surface is that particles are not able to leave the surface. Mathematically, that can be represented (in linearised form) as $\frac{\partial \phi}{\partial z} = \frac{\partial \eta}{\partial t}$ at z = 0. The bottom kinematic boundary condition is that water particles are not able to penetrate to seafloor. This condition can be represented (in linearised form) as $\frac{\partial \phi}{\partial z} = 0$ at z =-d. The dynamic boundary condition at the surface states that the atmospheric pressure at the surface is constant. Applying this condition (in linearised form and neglecting atmospheric pressure variations) to the Bernoulli equation when z = 0 gives $\frac{\partial\phi}{\partial t} + g\eta = 0$.

After applying the kinematic boundary conditions to the Laplace equation, shows that the velocity potential function is:

$$\phi = \hat{\phi}\cos(\omega t - kx)$$
$$\hat{\phi} = \frac{\omega a}{k}\frac{\cosh[k(d+z)]}{\sinh(kd)}$$

Solving Laplace's equation using the velocity potential function and Bernoulli's equation as a boundary condition results in the dispersion relationship:

$$\omega^2 = gk\ \tanh(kd)\,,$$

which relates frequency to wave number. (Holthuijsen, 2007) Dispersion is the separation of waves caused by waves of different wavelengths propagating at different speeds. In terms of phase speed of waves, c, the dispersion relationship can be written:

$$c = \frac{g}{\omega}\tanh(kd) = \sqrt{\frac{g}{k}\tanh(kd)}\,.$$

In deep water, tanh(kd) approaches one as kd approaches infinity, so the propagation speed is dependent on the wavelength or frequency ($c = (g/k)^{1/2}$). (Mei, 1989) Long waves travel faster than short waves. (Holthuijsen, 2007) These waves are called dispersive waves because they disperse based on their frequencies and follow the linear wave theory. (Holthuijsen, 2007) The phase speed of a wave is the speed of propagation of individual crests (c_p=omega/k) and the group speed is the speed of propagation of wave energy and the speed of propagation of a “packet” of waves (c_g=domega/dk). It is clear from the dispersion relation above that the phase and group speeds of surface gravity waves differ. As different waves interact, they can develop into wave groups. These wave groups travel through the ocean at the group speed until they eventually approach a coastline. (Holthuijsen, 2007)

These waves, as derived, are nearly linear. Thus, different frequencies and wavelengths do not interact, and the dispersion relation above describes the rate of propagation of each size of wave. In reality, weak nonlinear interactions among the waves of different frequency and wavelength leads to the evolution of a spectrum of waves. In these nonlinear interactions, energy is not lost, but rather transferred between waves of different frequencies. (Brown et al. 1989) The JONSWAP spectrum (Hasselmann et al.) is a classic empirical waveform that has been repeatedly observed and is believed to be a near-solution to the nonlinear problem of propagation of waves in deep water and can be expressed as :

$$E_{JONSWAP}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right] \gamma^{\exp\left[-\frac{1}{2}\left(\frac{f/f_{peak}-1}{\sigma}\right)^2\right]}.$$

Webb & Fox-Kemper (2011) contrast the JONSWAP spectrum against other empirical and modeled wave spectra.

As waves approach shallower waters, they begin to interact with the ocean bottom. First, the *kd* argument of the tanh function in the dispersion relation above begins to achieve finite values, and *tanh(kd)=kd.* (Mei, 1989) This reduction in wave speed causes shallow water waves to behave in a different manner than previously described, because linearization of the equations of motion begins to break down. The phase speed is now equal to $\sqrt{gd}$ and does not depend on the wave length or frequency. (Holthuijsen, 2007) Shoaling occurs when the group velocity changes as a result of the wave and ocean bottom interaction. This causes an increase in wave height until the wave eventually breaks, implying leading order nonlinearity. The wave will eventually break when the wave height divided by the depth approaches .75.

Waves transport energy and momentum, which may produce currents when the waves break and deposit their energy and momentum in the ambient fluid. This breaking along with wave interaction can also produce much lower frequency (infragravity) waves and zero-frequency setup. These low frequency waves play a major roll in erosion. (Raubenheimer and Guza 1996) Additionally, wave breaking produces a change in water level called the setup. The details of these nonlinear interactions are highly complex, and depend on local topographic features such as reefs and headlands. For this reason, it is standard practice to use a fully nonlinear numerical model to try to simulate these near-shore complex interactions (Mei, 1989) Mei (1989) describes the best method of determining currents induced by breaking of waves in a surf zone by examining the relationship between the radiation stresses and mean-flow in the surf zone. For this thesis, setup between an off-shore and on-shore location was measured by calculating the difference between the onshore and offshore mean water levels.

Away from shore, where linear, irrotational equations apply, the velocity potential can also be used to find the particle velocities.

$$u_x = \hat{u}_x \sin(\omega t - kx) \qquad \hat{u}_x = \omega a \frac{\cosh[k(d+z)]}{\sinh(kd)}$$

$$u_z = \hat{u}_z \sin(\omega t - kx) \qquad \hat{u}_z = \omega a \frac{\sinh[k(d+z)]}{\sinh(kd)}$$

As waves propagate through fluids, the particles travel in circular or elliptical orbits with velocities called orbital velocities. The velocities can be found from the potentials with the equations stated above.

To analyze waves, and because of the complexity of the nonlinear interactions and near-solutions like the JONSWAP spectrum, it is helpful to look at wave statistics. The wave height is the vertical distance from the crest to the trough of a wave. When analyzing waves, it is best to look at wave height averages. There are two main methods for averaging waves. The first is the calculation of the significant wave height, H_s. It is an approximation of the highest one-third of waves in a record. It can also be found using the sea level elevation. This statistic best represents the wave height an observer would visualize. The other relevant wave statistic is the root-mean-square wave height, H_{rms}. This is the square root of the average wave heights squared. The root-mean-square wave height is often useful when looking at energy as the wave height squared is proportional to wave energy. Multiplying the H_{rms} by a factor of root two results in the H_s. This relatively obscure factor is introduced to match modern observations, where the measurement of H_s is similar to the traditional “eyeball” measurements of sailors. The “eyeball” estimates of “wave height” tend to reliably match the significant wave height H_s, and overestimate the root-mean-squared surface height variations, H_{rms}.

To predict these types of wave statistics, many models, XBeach included, solve the wave action balance equation. (XBeach Manual) The wave action balance equation is capable of predicting the sea state if it is known for a specific time. Wave action is the conserved quantity that propagates along with wave groups as they evolve in wavenumber through nonlinear interactions. (Mei, Andrews & McIntyre 1978) The statistical properties of a sea state can be represented by the wave spectrum. Slowly evolving this and applying different forcings like wind and nonlinear interactions results in the wave action balance equation.

Model Design

As hurricanes continue to devastate coastlines, it has become more and more evident that something has to be done to minimize damage. XBeach was developed to predict coastal response during time-varying storm conditions with the ability to model "wave breaking, surf and swash zone processes, dune erosion, overwashing and breaching." (Roelvink et. al, 2009) Previous models were capable of accurately predicting coastal response to storms if the alongshore had minimal variability. (XBeach Manual) Unfortunately, this is not the case for many coastlines. The XBeach model sets itself apart by being able to accurately model coastlines that have alongshore variability. For example, XBeach is capable to modeling coastlines with sea walls, which are very important to understand when trying to study coastline protection.

The XBeach model determines the wave forcing by solving the wave action balance equation,

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D_w}{\sigma}$$

$$A(x,y,t,\theta) = \frac{S_w(x,y,t,\theta)}{\sigma(x,y,t)}$$

at every bin in a given grid. Wave action, A(x,y,t,θ), is the amount of energy in a wave of a particular frequency and direction. This quantity is particularly useful to consider when looking at coastal waters because unlike wave energy, wave action is conserved in the presence of currents. (Holthuijsen, 2007) S_w is the wave energy density in each bin and σ is the intrinsic wave frequency. The wave action propagation speeds (c_x and c_y) ithe x and y direction is the sum of the group velocity speed and depth averaged Lagrangian velocities. (XBeach Manual) The group velocity is found using linear wave theory, where $c_x = \frac{\partial \omega}{\partial k_x}, c_y = \frac{\partial \omega}{\partial k_y}$. Additionally through linear wave theory, the model is able to determine the wave number and intrinsic frequency. The model calculates total wave energy dissipation, D_w , from wave breaking based on Roelvink's (1993a) methods.

$$\overline{D}_w = 2\frac{\alpha}{T_{rep}} Q_b E_w$$

Waves will begin breaking when the wave height exceeds gamma*depth. One of the many parameters that the user can adjust in XBeach is this gamma value. A larger gamma value allows waves to become taller before breaking.

To solve for currents, the action balance equation is coupled with a roller energy equation solver and a shallow water equation solver. When waves break, waves transfer momentum into currents. The action balance equation is capable of determining the wave-induced radiation stress, but additional roller energy equations are needed to determine the contribution of roller radiation stress. Radiation stress is the excess flow of momentum due to the presence of waves. (Longuet-Higgins and Stewart 1964) A force is generated as a result of cross-shore variation of radiation stress.

$$F_x(x,y,t) = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}$$

$$F_y(x,y,t) = -\frac{\partial S_{yy}}{\partial y} - \frac{\partial S_{yx}}{\partial x}$$

The radiation stress is the sum of both the wave induced and roller radiation stresses. S_{xx} and S_{yy} are radiation normal stresses, while S_{xy} and S_{yx} are radiation shear stresses. This force generates currents and changes in the mean water level.

There are a variety of offshore boundary conditions that can be selected. To determine the wave energy at the offshore boundary, XBeach must be forced with significant wave height and peak period. Each data point is taken to be a summation of wave components around a spectral peak where the energy density is higher. (XBeach manual) Additionally, each data point has a frequency, phase, amplitude, and direction associated with it. The wave phase is selected randomly using the random phase model. The direction of the wave is also determined randomly using the Cumulative Distribution Function based on wave frequencies. The wave number is determined by using the dispersion relation. It is important to select an offshore boundary in deep enough water that the waves do not interact with the bottom. The model uses the equation,

$$\eta(0,y,t) = \sum_{i=1}^{K} B_i \cos(k_i \sin(\theta_i) - 2\pi f_i t + \varphi_i)$$

to find the surface elevation at the offshore boundary. The wave energy at the boundary can be expressed as:

$$E_{\theta_i}(y,t) = \frac{1}{2}\rho g A_{\theta_i}(y,t)$$

Infragravity waves are generated by interacting two waves of different frequencies and wave numbers.

Field Observations

During a swell in August/September 2011, two Sea-Bird pressure recorders were placed at an off-shore and on-shore location at Waikiki beach. The off-shore sensor was placed near the break point at the latitude/longitude of 21.2699/-157.831883 in approximately 6.9 meters of water. During the wave event, the sensor was slightly displaced, settling at a different depth. The data was corrected for the small depth change. The on-shore sensor was placed at a latitude/longitude of 21.275447/ -157.826181 in approximately 1.5 meters of water.

The Sea-Birds recorded time, pressure, and temperature at the frequency of 1 Hz with 20 second gaps every 12 hours when the data was being recorded to the memory. The pressure is recorded in pounds per square inch absolute. This data was then converted to surface elevation, η. Running a fast Fourier transform converts the surface elevation into an estimate of the energy at a particular frequency. Both low frequency (0.001 to .033 Hz) and high frequency (0.033 to 0.303 Hz) bands were captured. The low frequency band represents the infragravity waves, and the high frequency band represents the wind/swell waves. The wind/swell waves have an average period of 15.1 seconds, while the infragravity waves have an average period of over twice that. The surface elevations of the high and low frequency bands were used to find the significant wave height of both wind/swell waves and infragravity waves.

$$H_s = 4 * std(\eta)$$

These records of significant wave height were then used to force the XBeach model and used to validate the results.

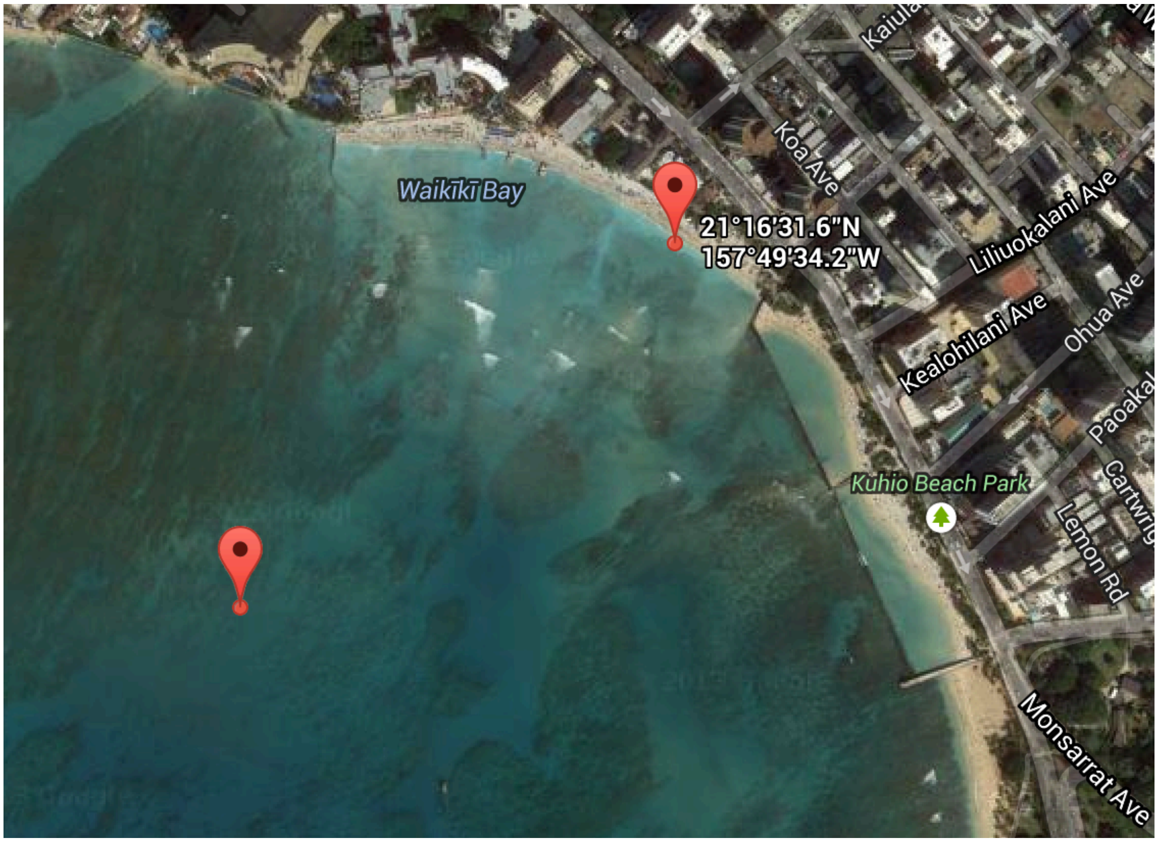


Figure 1: Google Earth image of Waikiki beach with pressure sensor locations marked.

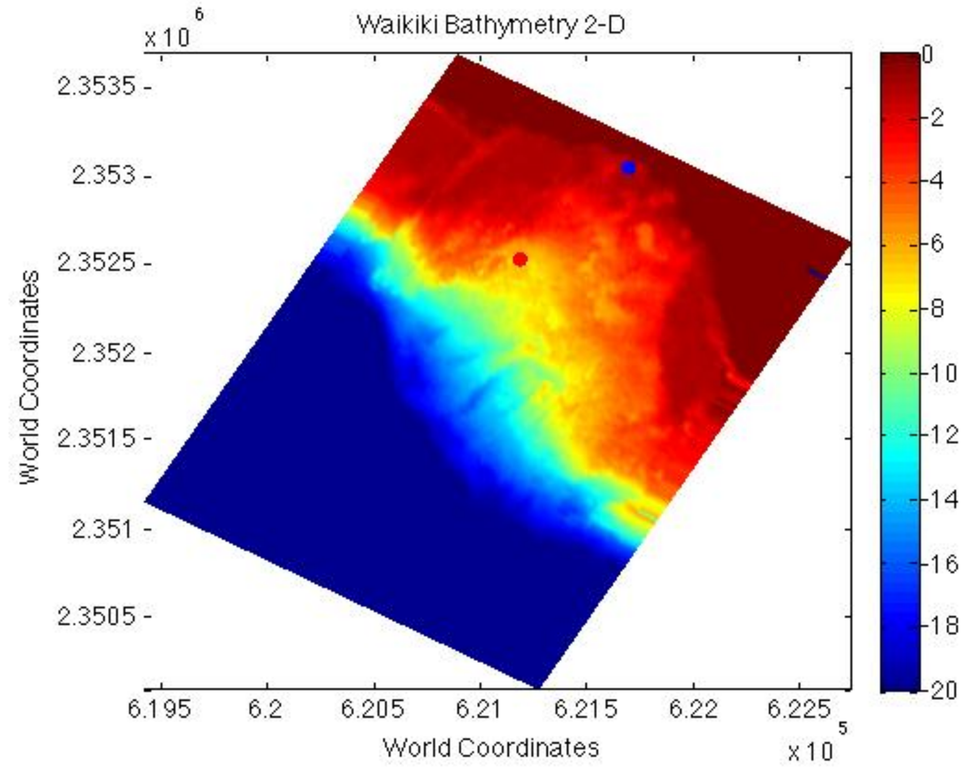


Figure 2: Two-dimensional bathymetry after optimized by XBeach, marked with pressure sensor locations.

In addition to the Sea-Birds, the University of Hawaii set up TLS to measure coastal morphology during a large summer swell at three zones on the beach. These scans revealed accretion occurred when the tide fell from highest to low tide. But showed no other bed level changes during different times of the day.

During the sand replenishment project from January through May 2012, a video camera was placed on the top of the Sheraton Hotel to observe the progress. The project caused a lot of excess sand to run into the water. This sand acted as a tracer showing a huge rip current running off shore. The video footage collected from this project provided new insight on currents at Waikiki beach, and valuable qualitative data to compare model results to.

Figure 3: Image from video footage of sand replenishment project. The circle marks the location of the rip current highlighted by the sand.

Model Validation

Before computers were powerful enough to run models, scientists had to rely solely on observations. However, in the late 1970s, an increase in computing power allowed scientists to develop high-resolution numerical models that showed significant promise at reflecting observations. (Siedler et al., 2001) The development of these high-resolution numerical models opened doors to new information about the earth's oceans and climate that simple observations could not provide. (Siedler et al., 2001)

Technological advances have resulted in instruments capable of collecting accurate, unbiased data, but there are still many limitations with these observations. First, it is very difficult to collect accurate results over large areas. This obstacle can be seen when studying ocean and climate interactions. Instruments transported by boat are capable of collecting a wide range of data, but are unable to collect data over large areas. On the other hand, satellites can measure data over large areas, but only have the ability to observe surface data. (Siedler et al., 2001) Second, collecting data over long periods of time can be complicated. This issue could be a result of instrument limitations, like battery power, or accessibility to locations where the desired data would come from. Third, observations only give information about the moment the data was taken. This makes predicting future changes and impacts of changes difficult.

On the other hand, many numerical models, like XBeach, do not have such limitations. Many models have the ability to take observations from a small area and apply them over large areas. Additionally, models can be executed for long periods of time, and over a time period of the users choice. This allows modelers to gather data from the past and future. Parameters can also be changed in a model giving modelers insight on hypothetical situations. For example, in climate modeling, the parameter of CO_2 emission can be manipulated to assess different possible scenarios for the earth's future climate. Finally, models can output types of data that would be impossible to gather through observations.

To be sure, numerical models also have some drawbacks. One of the most concerning issues is that numerical models must make many approximations in the equations of motion. For example, XBeach assumes linearised waves and a constant density even though coastal processes are more complex than that. Only crude approximations can be made to determine wave breaking and wave-wave nonlinear interactions. Although there have been major advances in computing power, it is still a limitation on how precise the model can be. A lot of models, XBeach included, produce different results based on the resolution of the grid. How can a model that produces different results be trusted? Additionally, models cannot stand alone without observations. Models require certain data inputs that must come through observations if they are to be applied to the real world. For example, XBeach requires bathymetry data and wave forcing data. These drawbacks lead to the question: how can a model be validated?

Model validation requires observations from the field. The data available to validate the XBeach model at Waikiki Beach included the measurements from the two pressure sensors, the Terrestrial Laser Scanning (TLS) data, and observations from above the beach. The first step to validating the model was looking at the modeled wave heights at the locations of the pressure sensors. Pressure sensors are only capable of recording data at the location where they are mounted to the sea floor. As a result, the data must only be compared to the model data at that given location. Similarities between wave height and water level trends reveal the model has promising results. Next, the setup measured from the pressure sensor data was compared to the setup from the modeled data. Although the model is capable of determining the setup throughout the entire input bathymetry, the focus was only on the setup between the location of the off-shore and on-shore pressure sensor, since that is where data is available. If the observed and modeled setups provide similar results, it can be concluded that the model was able to accurately determine the setup between the off-shore and on-shore pressure sensor. Another crucial characteristic of Waikiki Beach is the rip current that was observed. To claim that the model accurately reflected the water circulation, the results needed to show the strong rip current running through the channel at the beach. Finally, the information from the TLS was compared to the bed level change. Ideally, the model would need to reflect the same beach response to the swell as the TLS showed.

To match the model results to the observed data, adjustments had to be made to the forcings and the parameters. The wave forcing from the off-shore pressure sensor, which was located at a depth of 6.9 m, had to be back refracted to the depth of the off-shore boundary, 150 m. Comparing the model with this wave forcing to observations gave insight into the parameters that needed to be adjusted, zeroing in on “gamma” and the “bed friction factor.” Gamma is the breaker parameter representing the ratio between the wave height and depth allowed before the wave will break. (Roelvink, 1993) This was an important parameter to adjust because the data used to validate the model was wave height data at two specific points. Wave height at a given point on the grid is greatly influenced by the gamma value. The bed friction factor was important to modify because Waikiki Beach has a mixture of reef and sand bottom. Reef causes friction as waves travel above, slowing the bottom of waves down more rapidly than a sandy bottom would. XBeach was initially developed for sandy bottom beaches. (Van Dongeren et al, 2013) However, increasing the bed friction factor would increase the friction between the bed and the water as if it were reef.

To ensure that the offshore wave forcing was correct, the back-refracted pressure sensor data was compared to the JONSWAP spectrum. The energy spectrum of the pressure sensor data followed the same trend as the true JONSWAP spectrum. Therefore, having the model generate wave groups based on the JONSWAP spectrum seemed accurate.

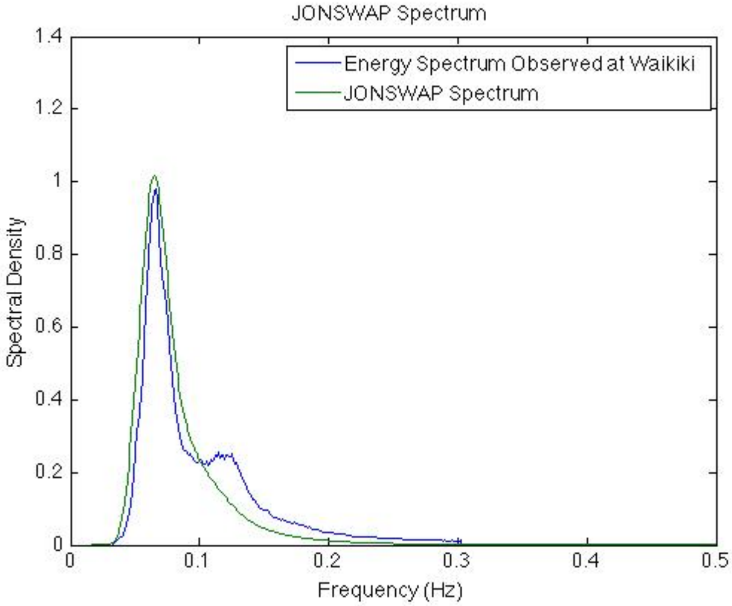


Figure 4: The JONSWAP spectrum compared to the energy spectrum observed at Waikiki beach.

Results

One-Dimensional Model

To evaluate the ability of a one-dimensional XBeach model to accurately reflect observations at Waikiki Beach, a variety of transects from the two-dimensional bathymetry were selected to run through the model. Transect 13 and transect 75 were located on either sides of the channel, and transect 47 was located in the center of the channel where the onshore pressure sensor was located. One additional transect was run through the one-dimensional model that was generated by finding the average depth across the two-dimensional bathymetry.

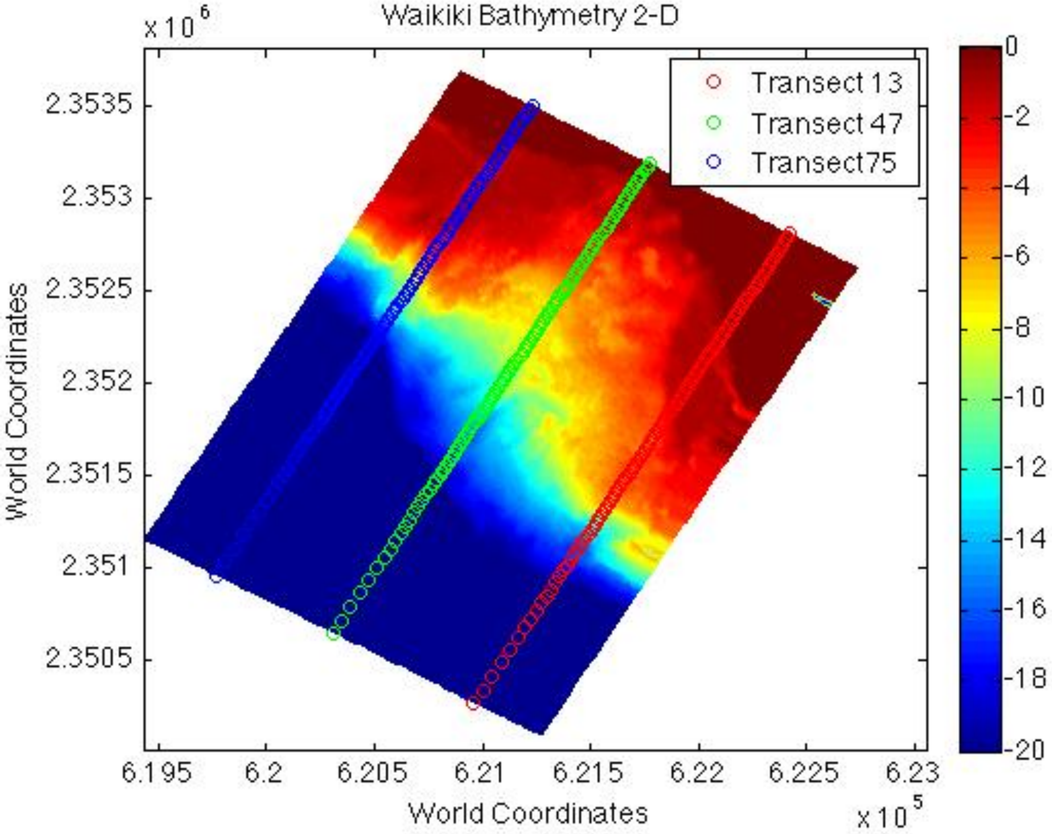


Figure 5(a): Locations of the three transects run through the one-dimensional model.

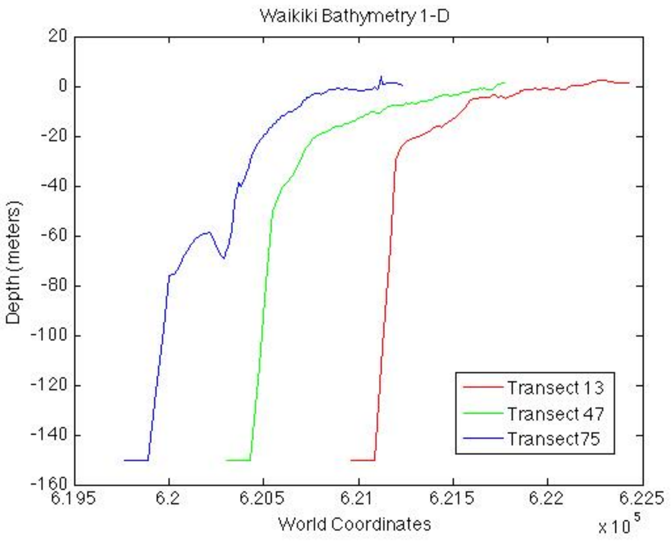


Figure 5 (b): Profiles of the three transects from the 2-D optimized grid.

The model results from the four different transects greatly differs. The mean of the significant wave height reveals that waves develop and travel differently along all four transects (Figure 6). Additionally, the setup from the four different transects are different. It is not surprising that the setups vary from each other. Setup is very sensitive to wave-wave interactions, which is limited in the one-dimensional model. Another concern with the one-dimensional model is that it is incapable of modeling variations in longshore current. Observations show that longshore currents are very prevalent at Waikiki Beach and produce a rip current where the longshore currents converge. Instead, the one-dimensional model just reflects cross-shore currents rushing away from the beach.

The different results from modeling the four different transects reveals that model handles every transect differently depending on its bathymetry. This is not surprising because wave breaking is very dependent on water depth. Since these four runs all have different bathymetries, they all have different hydrodynamic results. As a result, a one-dimensional model cannot be generalized across a large stretch of beach with highly variable depth like Waikiki.

One-Dimensional Model vs. Two-Dimensional Model

After conceptually determining the one-dimensional model was insufficient to fully model the ocean dynamics of Waikiki Beach, the two-dimensional model was compared to one-dimensional results and observational data to quantitatively show the insufficiencies of the one-dimensional model. The two-dimensional model was performed in 24-hour increments due to computing power limitations. The first 24-hour period was focused on to compare against the first 24-hours of the one-dimensional model. The model parameters, gamma and bed friction coefficient, were tweaked based on the first 24-hour window. The parameters were set to be the same for both the one-dimensional and two-dimensional runs to ensure consistency. When comparing the data from each one-dimensional transect with the data from the identical one-dimensional transect within the two-dimensional model, it was found that the two-dimensional results greatly differed from the one-dimensional results.

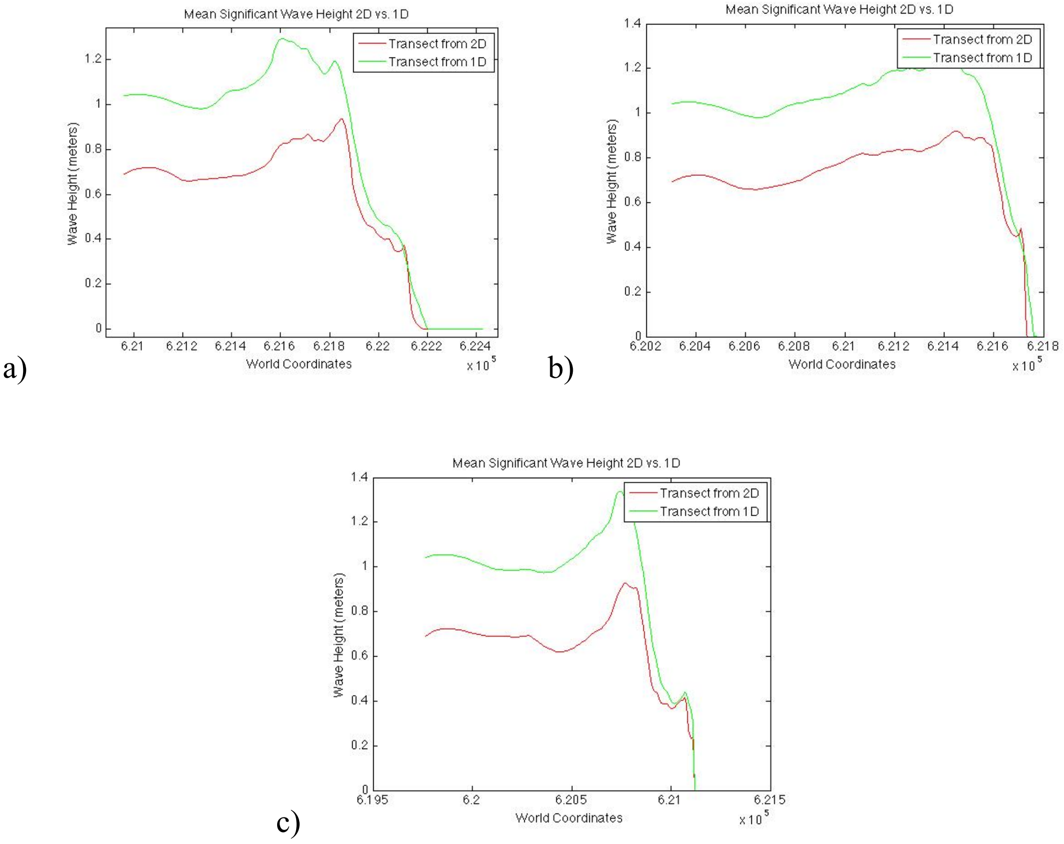


Figure 6 a,b,c: Mean significant wave height comparisons between 1-D and 2-D runs. Reveals 1-D model consistently predicts larger significant wave height than 2-D model.

Figure 6 a, b, and c are the mean significant wave heights from the one-dimensional and two-dimensional model at every grid point over transect 13, 47, and 75 respectively. It is clear from these figures that not only do the one-dimensional significant wave heights differ from the two-dimensional significant wave heights along the same transect, but also the one-dimensional mean significant wave heights differ from each other. Although the wave heights follow similar trends, the one-dimensional model continually predicts a larger significant wave height.

The differences between the one-dimensional model and the two-dimensional model do not stop at the significant wave height. These same inconsistencies are also clear when examining the on-shore infragravity wave heights.

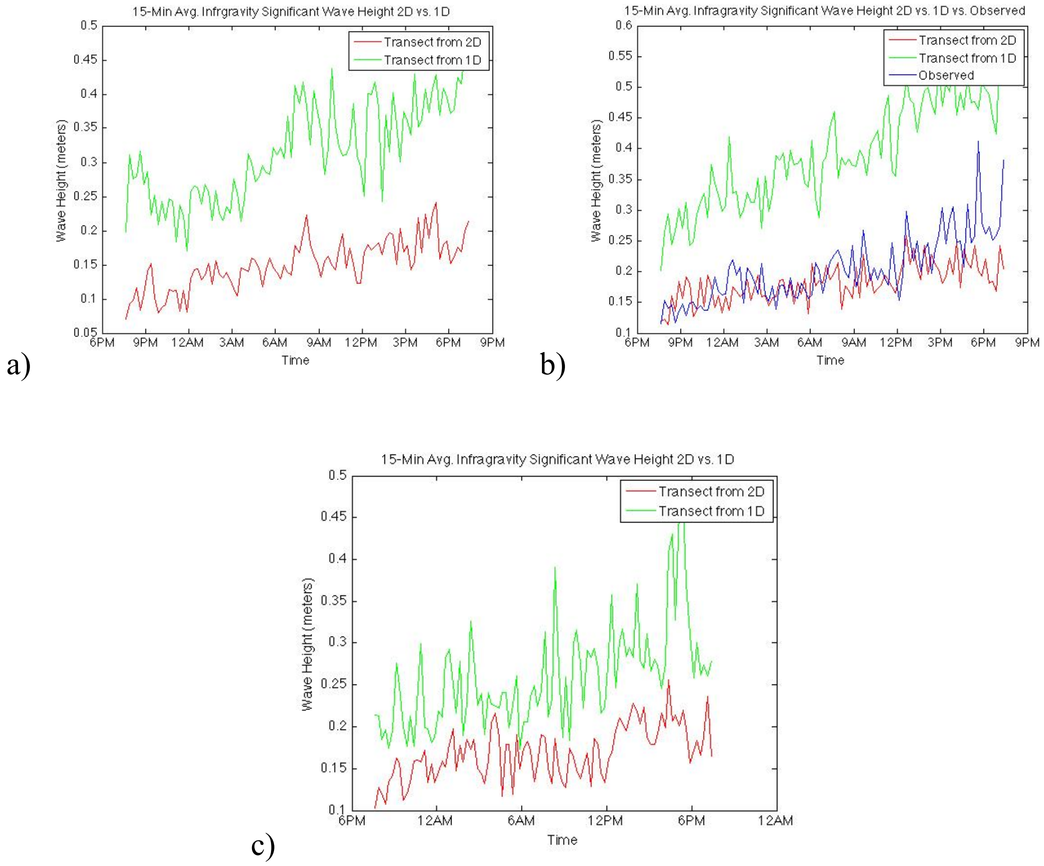


Figure 7 (a,b,c): Time series of infragravity waves at approximately 1.5 m depth along each transect. Figure 7b is also contains time series of infragravity waves from the on-shore pressure sensor.

At all transects, the one-dimensional model predicts a much larger infragravity band than the two-dimensional model predicts. Transect 47 can also be compared to the on-shore pressure sensor data as the pressure sensor was located along this transect. Clearly, the two-dimensional model produces results more similar to the observed results than the one-dimensional model.

Comparing the measurement of setup from the one-dimensional and two-dimensional results does not show as clear of a trending difference between both types of models.

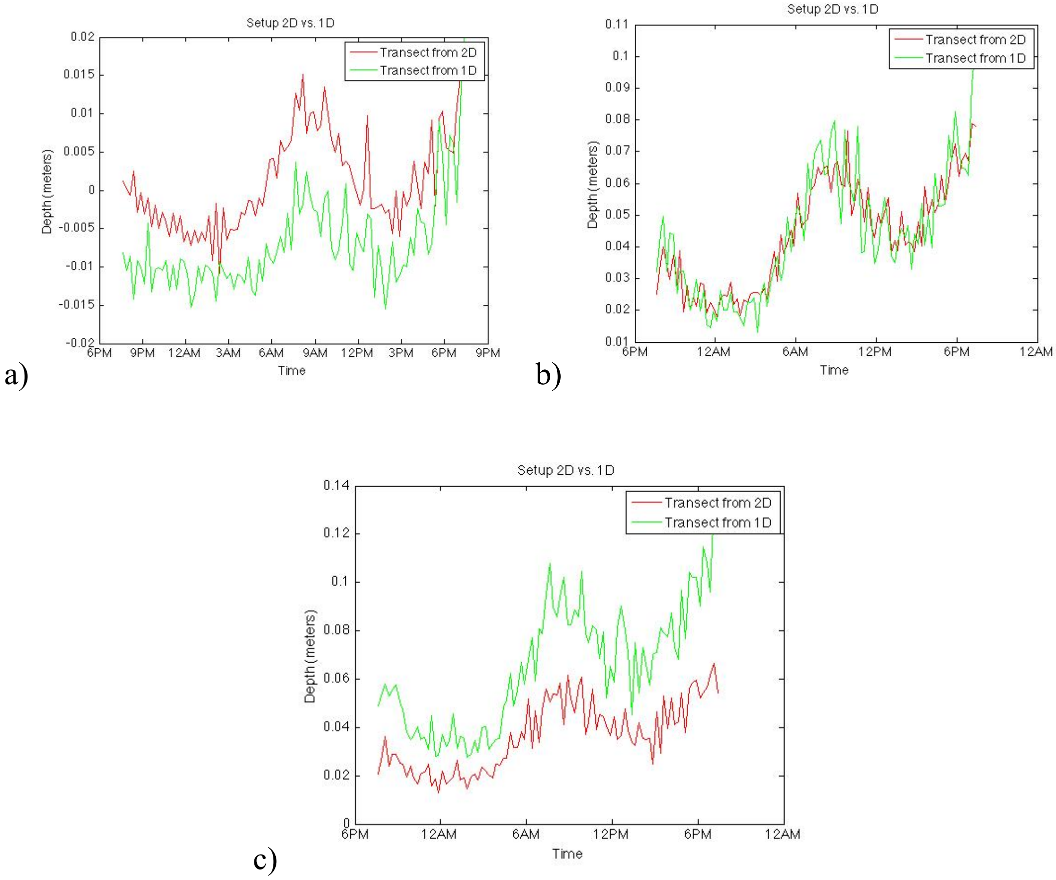


Figure 8 (a,b,c): Time series comparison of setup from 2-D and 1-D transects.

For transect 13 (figure 8a), the two-dimensional run predicts a higher setup than the two-dimensional model, while the one-dimensional results from transect 75 (figure 8c) predicts a slightly higher setup than the two-dimensional model. The one-dimensional and two-dimensional results match up very well for transect 47 (figure 8b). These results cannot be compared to the observed setup because the offshore pressure sensor is not located along transect 47 like the on-shore pressure sensor.

The largest difference between the one-dimensional and the two-dimensional results was found in the current results. The total current is the sum between the Lagrangian and Eulerian velocities.

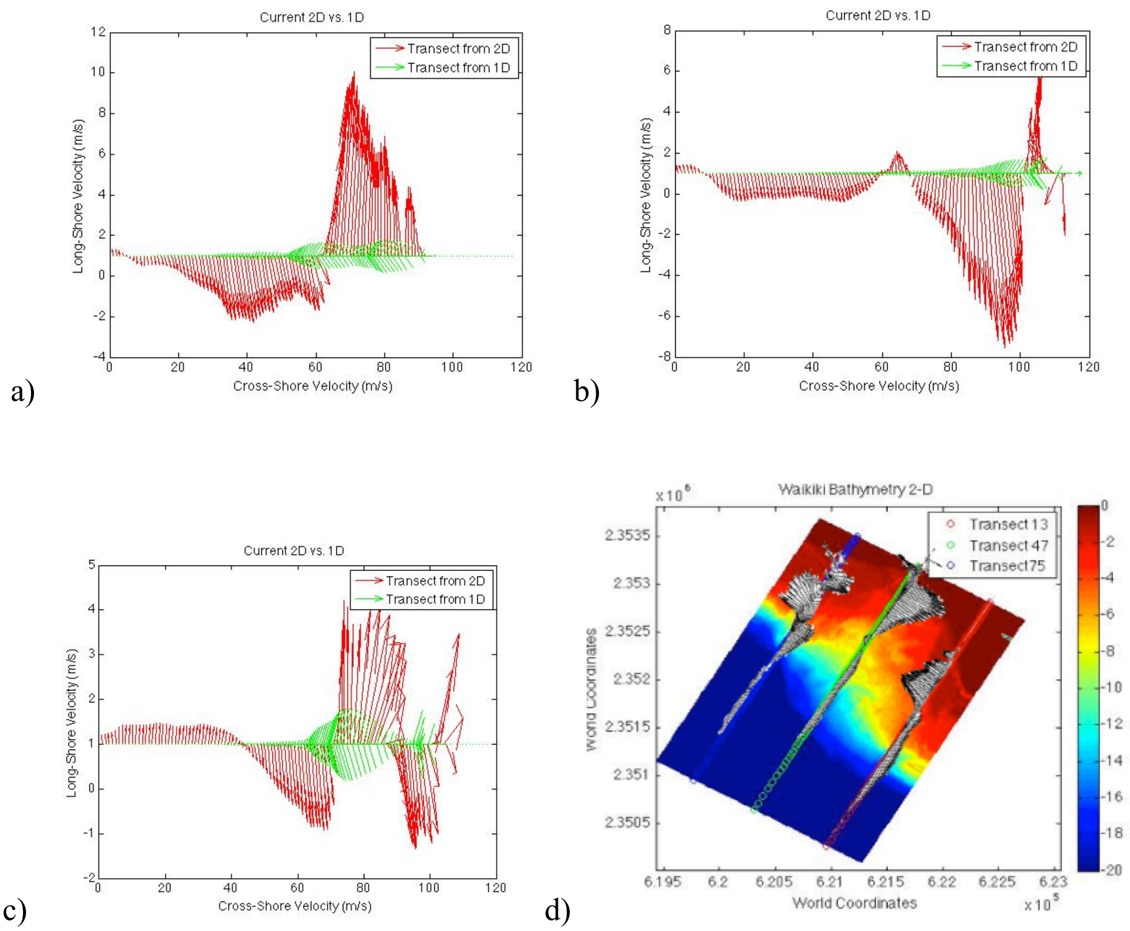


Figure 9(a,b,c): Comparison of current vector maps for 2-D and 1-D runs.
Figure 9 (d): Bathymetry with current vector map along appropriate transects.

Obviously, the one-dimensional model is unable to measure long-shore currents, while the two-dimensional current modeling is more complex and takes both cross-shore and long-shore currents into account. According to the one-dimensional model, all three transects have currents pointing offshore. However, observing the sand flowing through Waikiki, highlighting the rip current, it was obvious that the currents are much more complicated than a simple one-dimensional model could reflect. Transects from the two-dimensional model show currents run both cross-shore and long-shore.

After thorough comparison of the one-dimensional and two-dimensional models, it is clear that they produce different results. As previously mentioned, attempts at modeling Waikiki Beach using the one-dimensional XBeach model have failed to produce satisfying results. Additionally, studies have found more promising results over reefs with a two-dimensional XBeach model. (Dongeren et al., 2013) As a result, pursuing a two-dimensional model of Waikiki Beach appeared to be appropriate. Two-dimensional modeling is very complex and can be difficult to validate, as much of the data produced would be impossible to observe over a long period of time. A significant amount of time had to be spent on fine tuning the two-dimensional model to make sure the grid and parameters were appropriate.

Two-Dimensional Model

The first obstacle of the two-dimensional model was finding a grid that was not only accurate, but also small enough to run on a single computer. This required a lot of tinkering with the grid boundaries and XBeach optimization parameters. The offshore boundary proved to be the most important boundary to provide accurate results. If the offshore boundary was located at too shallow of a depth, the wave forcings would already interacte with the bottom producing unstable results. The selected grid began at a depth of approximately 150 m to avoid this issue. Once the most appropriate grid was found, runs were performed repeatedly to ensure results could be reproduced. Once runs were reproduced, fine-tuning the model began.

As previously mentioned, the most interesting parameters were gamma and the bed friction factor. Gamma would control when the waves would break, which greatly impacted the wave height across the entire grid. When gamma was set to a high value, waves would be allowed to get very tall without breaking. Since wave breaking is dependent on depth, it is also highly dependent on tide. During low tide, beaches become far shallower causing waves to approach gamma further from shore than at high tide resulting in a break point further from shore. The Waikiki data agreed best with a low gamma value of .4 compared to the default of .55. The friction factor can imitate the effects of a reef bottom causing more wave energy dissipation. This was important to our results because Waikiki has a primarily reef and sand bottom. When a friction factor was not applied, the waves did not dissipate enough, and the significant wave height onshore was too high. These two parameters were critical because they greatly impact wave height throughout the grid. Since the data used to validate the model focused around wave height data at two specific locations, it was very important to tune the model based on the wave height comparisons.

In the two figures below, the significant wave height of wind/swell waves (figure 11) and the significant wave height of infragravity (figure 12) from XBeach is compared to the observations at the locations of both the onshore and offshore pressure sensor. The model slightly over predicted the onshore significant wave height of the wind/swell waves. However, the model was very accurate at predicting the offshore significant wave height of these waves. The model was also successful at producing accurate results for the infragravity waves at both locations. There was just a slight under prediction at both the onshore and offshore locations. XBeach also has the ability to show snapshots of infragravity wave height. This feature allows users to observe infragravity waves propagating towards shore. Observing the propagation makes it clear that modeling Waikiki is a two-dimensional issue. Infragravity waves can be seen traveling through the grid, but not restricted to one transect. Waves can be seen reflecting and refracting, which would be difficult to accurately represent in a one-dimensional model. Figure 12 below shows a snapshot of infragravity wave propagation.

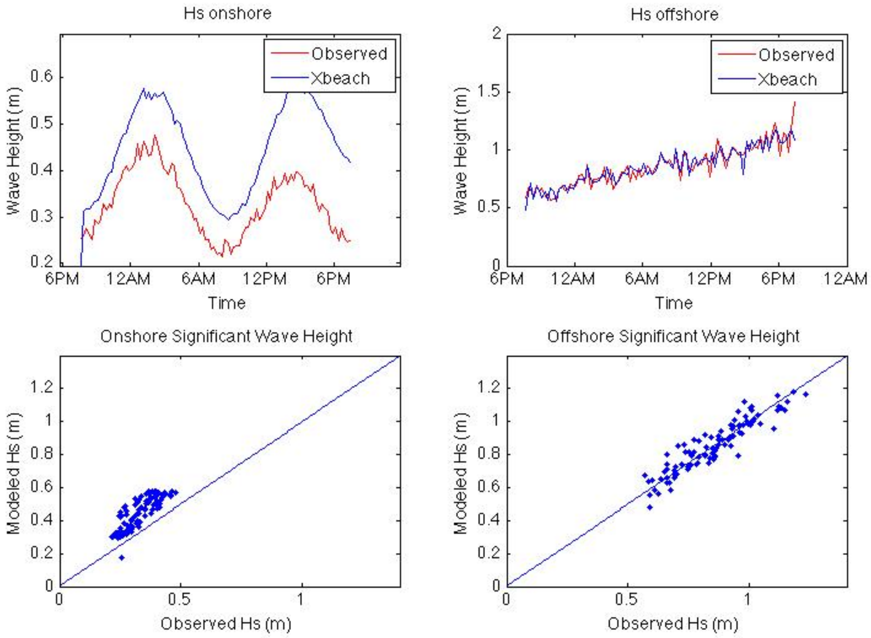


Figure 10 (Top): Time series comparisons of the observed significant wave height and modeled significant wave height.
Figure 10 (bottom): Modeled significant wave height vs. observed significant wave height.

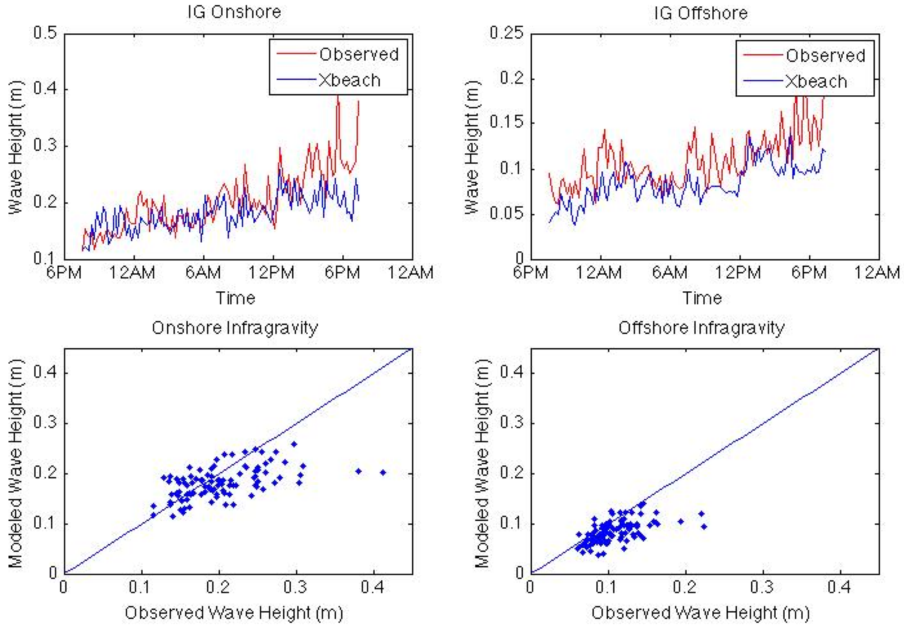


Figure 11 (Top): Time series comparisons of the observed infragravity wave height and modeled infragravity wave height.

Figure 11 (bottom): Modeled infragravity wave height vs. observed infragravity wave height.

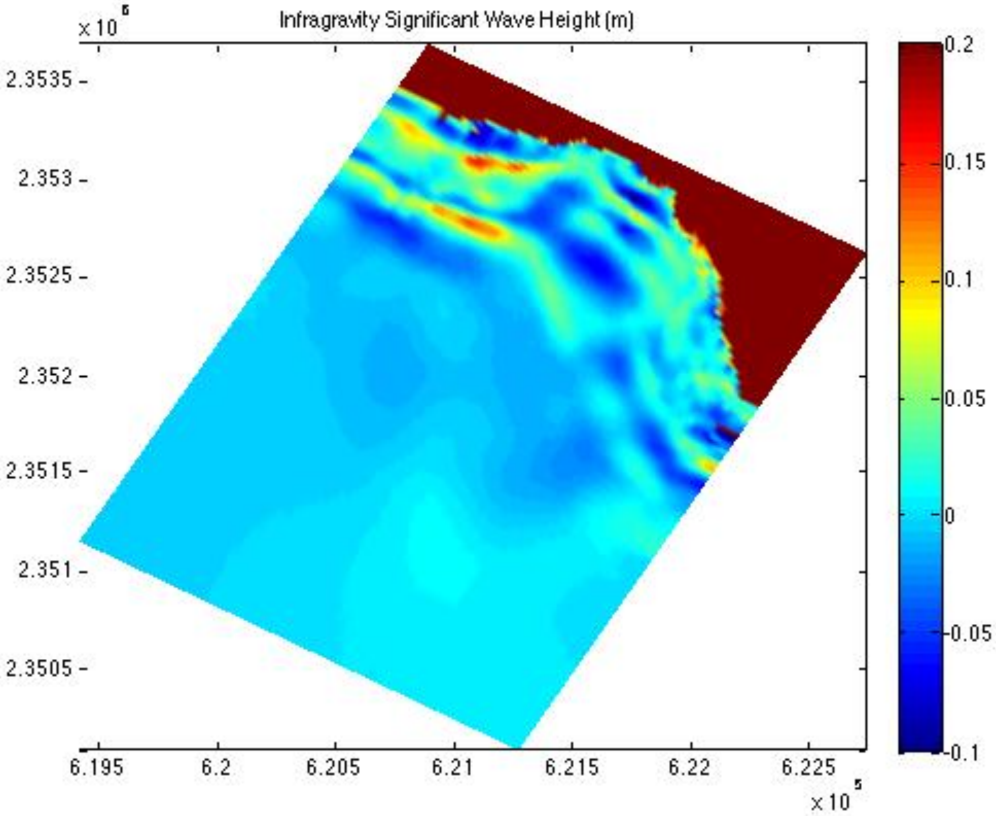


Figure 12: Snapshot of infragravity wave propagating towards shore.

The two-dimensional model is capable of measuring the setup through the entire surf zone (figure 13). However, it would be nearly impossible to gather this sort of data to validate these results. From the pressure sensor data, the setup can be measured between those two locations. To compare these results against those of the model, the setup between just the two locations was also calculated (figure 14). The setup from the XBeach model and the pressure sensors follow a very similar trend; however, XBeach slightly over predicts the results.

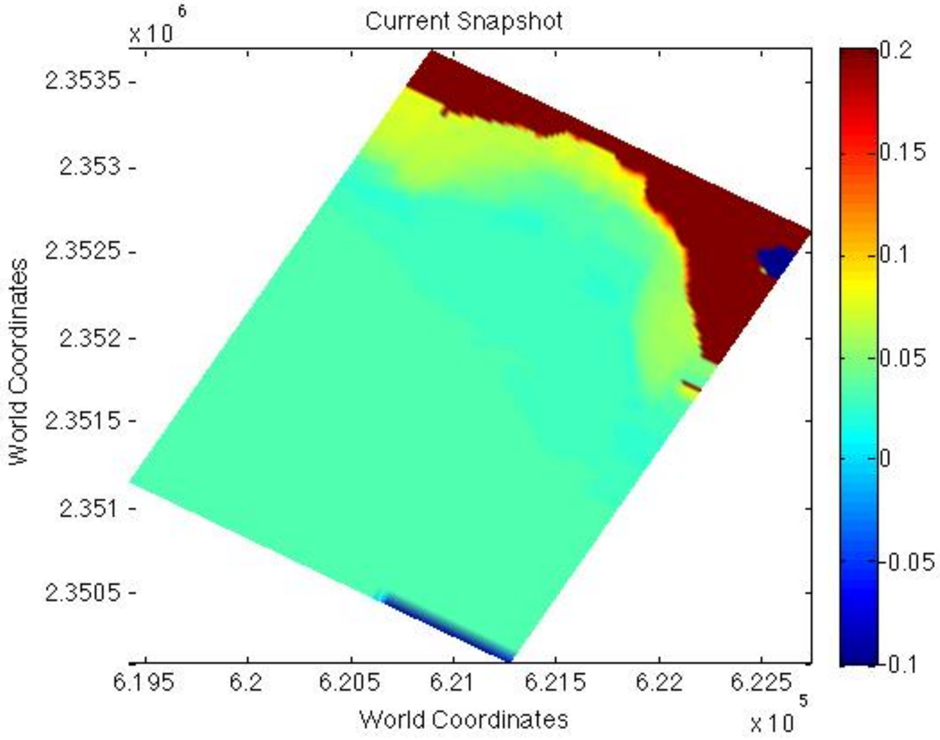


Figure 13: Average setup across entire 2-d grid.

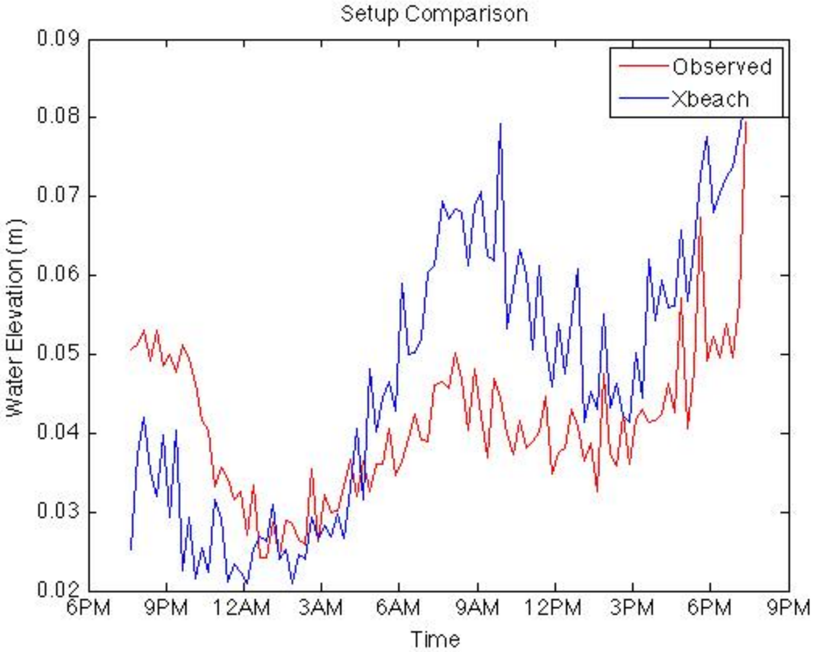


Figure 14: Comparison of setup between pressure sensors from observations and model.

An important feature that the one-dimensional model could not reproduce was the rip current that was observed. However, the two-dimensional model produced a rip current in the channel. Although we do not have truly observed velocity data values to compare against the modeled results, it is very promising that the model produced currents displaying a rip current. Figure 14a shows a snapshot of currents throughout the grid, and figure 14b is a zoomed in view of the rip current.

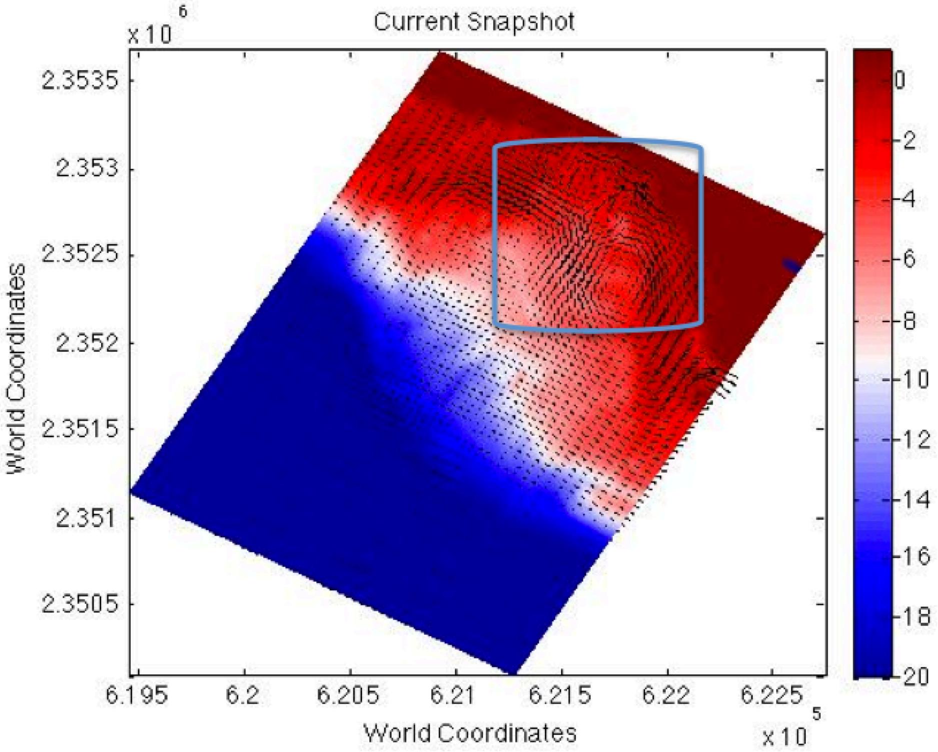


Figure 14 (a): Current snapshot of entire grid. Boxed portion can be seen enlarged in figure 14b.

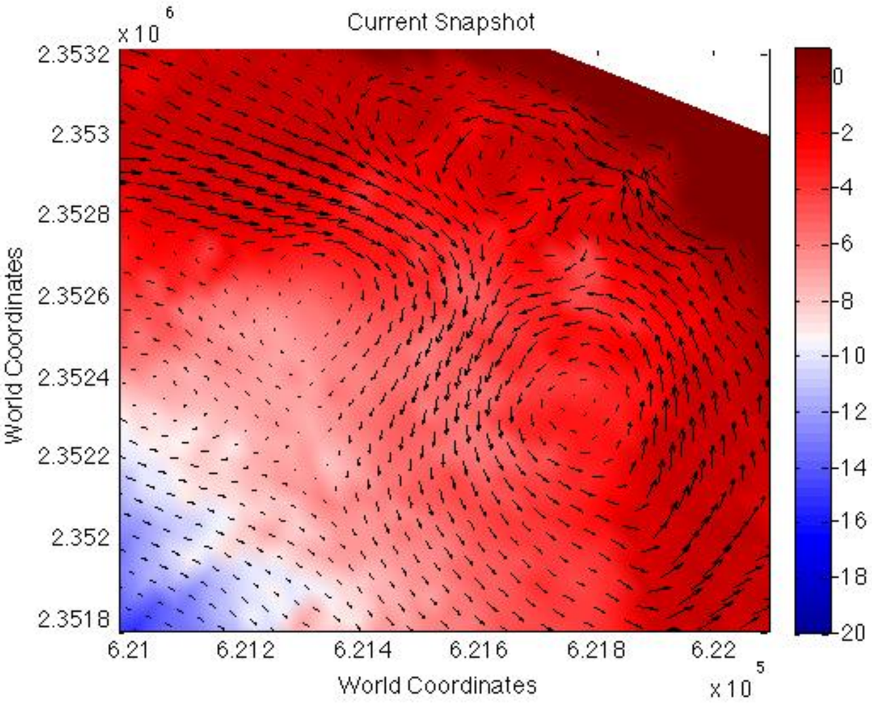
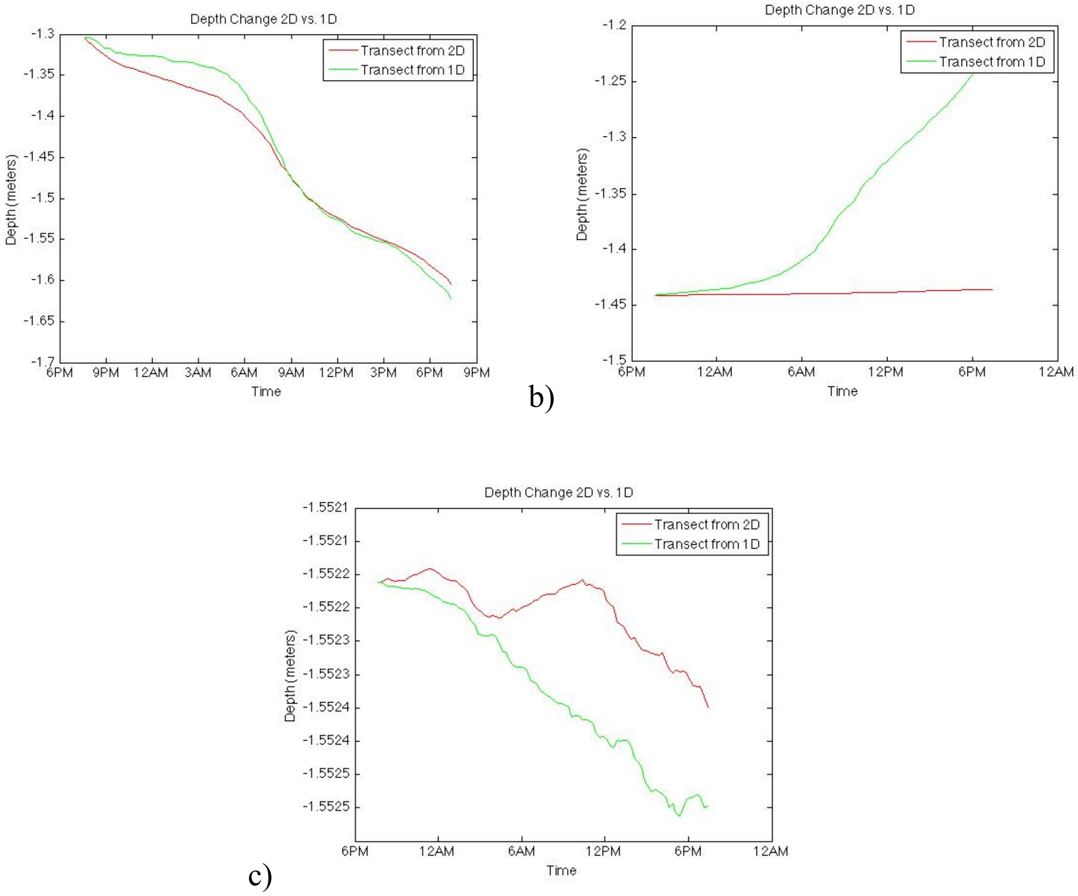


Figure 14 (b): Enlarged view of rip current

Future Work

Ideally, after fine-tuning the model to reflect the hydrodynamic aspects of Waikiki beach, the two-dimensional model would have produced the same beach response that was witnessed in Barnes' thesis. (2013) Unfortunately, this was not the case. None of the transects showed accretion that was dependent on tide (Figure 15). However, this is not entirely unexpected. Sediment transport is a very complicated process that not only requires highly accurate hydrodynamic results, but also a strong understanding of how the ocean interacts with the sediment on the beach. The majority of this thesis was spent on manipulating the parameters that dealt with the hydrodynamic aspects of the model. There are several sediment transport parameters that have yet to be adjusted in the two-dimensional model of Waikiki. If XBeach's sensitivity to changes in its wave parameters is any indication of how it would respond to changes in its sediment transport parameters, small adjustments could lead to big changes. Modeling in two-dimensions is very complicated and requires a very high level of precision. Moving forward, the sediment transport parameters should be manipulated to determine the ability of XBeach to model the coastal response to waves.



a) b) c)

Figure 15 (a,b,c): Bed level change of 2-D model compared to 1-D model

Conclusion

Clearly, the results from the one-dimensional and two-dimensional models greatly vary. The main reason for this can be explained by the numerical differences in the one and two-dimensional model. If a one-dimensional bathymetry is used, the wave action only forces the cross-shore radiation stress causing infragravity wave energy to be over predicted compared to a two-dimensional case where directional spreading occurs. (Dongeren et al., 2013) The high infragravity wave height for the one-dimensional runs is consistent with these claims.

While the one-dimensional model produced some interesting results, a two-dimensional model is the only way to gain a full understanding of coastal dynamics at Waikiki Beach. The inability of the one-dimensional model to produce long-shore currents cannot be neglected, as strong long-shore currents and rip currents have been observed. Not only do long-shore currents impact water circulation, setup, and infragravity waves, they also play a major role in beach morphology. Additionally, the two-dimensional model is capable of showing infragravity waves traveling through the grid. Figure 12 is just a snapshot of that motion, but a series of snapshots reveals infragravity energy travels throughout the grid and is not limited to a one-dimensional transect.

Although the two-dimensional results showed a lot of promise in many hydrodynamic aspects like wave heights and currents, there are many ways to potentially improve the results. First, it would be interesting to see how the model would handle a larger, more expensive grid. This would need to be run on a more powerful computer than used for these runs. This not only provides the chance to produce more accurate results, but also another opportunity to validate the less expensive grid. If both grids provide similar results, it is more likely the model is accurate. Thus far, XBeach appeared to be very sensitive to grid size changes, which makes the model difficult to trust. Second, the off-shore wave boundary forcing data could be improved. Back refracting from a pressure sensor located at a depth of 6.9 m to a depth of 150 m is an imperfect science. Getting more accurate wave data at the depth of the off-shore boundary could produce more accurate results. Finally, there are hundreds of parameters in this model that can be manipulated. These parameters can greatly affect the model results, and therefore are critical to obtain the most accurate model. Until the sediment transport parameters are thoroughly examined, a conclusion cannot be made about its ability to model beach morphology.

Additional data would be very useful to validate the model. The biggest gap in observations is with the current data. The only current data available at Waikiki Beach is based on observations. These observations provide a very general understanding of the water circulation, but do not provide specific velocities to validate against a numerical model. While it was very promising to see the two-dimensional model producing long-shore currents and rip currents, quantitative data is required to truly validate the water circulation. Additionally, it may be helpful to place more pressure sensors in the water. More pressure sensor data from a variety of locations provides more grid locations the model can be validated against.

Although Waikiki is one of the most popular beaches in the world, very little is known about the local water dynamics and its impact on beach morphology. As sea levels rise, it will only become more important to understand these concepts. This study shows that numerical modeling has the power to shed light on many issues that simple observations cannot. However, it also emphasizes the importance of observations to truly understand both a numerical model and complicated coastal issues.

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