

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**EVALUATION OF EXISTING PARAMETRIZATION OF WAVE
DISSIPATION IN SPECTRAL WAVE MODEL SWAN**

FATİH BAHİR AYDIN
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING

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YÜKSEK LİSANS JÜRİ ONAY FORMU

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SUMMARY

Waves dissipate most of their energy as they break, transforming it into heat and turbulence. This energy is crucial for sediment transport, beach profile and the design of coastal structures. Nonetheless, wave breaking calculations are mostly based on empirical formulas. There is limited knowledge concerning the mechanism of wave breaking and is still not fully understood. However, thanks to various numerical models, these processes can be simulated.

Various wave models to calculate wave breaking energy were developed in the past. One of the leading wave models is Simulating Waves Nearshore (SWAN). This study examined the parameters in the wave breaking process using SWAN models. Datasets of a field experiment in Duck Beach, North Carolina which is named DUCK94 are used to calibrate and evaluate the models. These datasets occur bottom profiles, tidal surges, and spectrums of waves. In this study different types of breaking process implemented in the runs including constant breaker index and the variable breaker index. The optimum values of the coefficients in the wave breaking parameters were determined and evaluated. This study also covers the effect of triad wave-wave interaction and bottom friction in the calibrated models.

As a result of running SWAN models, two different types of models with different values of the coefficient are proposed. Models with a variable breaker index and models that calculate the dispersion of breaking waves with a constant breaker index are compared. The performances of the models in deep and shallow water conditions were evaluated separately.

Key Words: Wave breaking, energy dissipation of waves, SWAN, triad wave-wave interactions, wave hindcasting.

ÖZET

Dalgalar kırılırken enerjilerinin çoğunu ısıya ve türbülansa dönüştürürler. Bu enerji, sediment taşınımı, plaj profili ve kıyı yapılarının tasarımı açısından önemlidir. Bununla birlikte, dalga kırılması hesaplamaları çoğunlukla ampirik formüllere dayanmaktadır. Dalga kırılması mekanizması hala tam olarak anlaşılamamıştır. Ancak çeşitli sayısal modeller sayesinde bu süreçler simüle edilebilmektedir.

Geçmişte dalga kırılma enerjisini hesaplamak için çeşitli dalga modelleri geliştirilmiştir. Önde gelen dalga modellerinden birisi SWAN'dır (Simulating Waves Nearshore). Bu çalışmada SWAN modelleri kullanılarak dalga kırılma sürecindeki parametreler incelenmiştir. Modelleri kalibre etmek ve değerlendirmek için DUCK94 olarak adlandırılan Duck plajında yapılan bir saha deneyinin veri setleri kullanılmıştır. Bu veri setleri taban profilleri, gelgit yükselmeleri ve spektral dalga verilerinden oluşmaktadır. Bu çalışmada, sabit kırıcı indeksi ve değişken kırıcı indeksi de dahil olmak üzere farklı kırma süreçleri modellenmiştir. Dalga kırılma parametrelerindeki katsayıların optimum değerleri belirlenmiş ve değerlendirilmiştir. Bu çalışma aynı zamanda kalibre edilen modellerde üçlü dalga-dalga etkileşimi ve dip sürtünmesinin etkisini de kapsamaktadır.

SWAN modellerinin çalıştırılması sonucunda, farklı katsayı değerlerine sahip iki farklı model türü önerilmiştir. Değişken kırılma indisine sahip modeller ile sabit kırılma indisine sahip kırılan dalgaların dağılımını hesaplayan modeller karşılaştırılmıştır. Modellerin derin ve sığ su koşullarındaki performansları ayrı ayrı değerlendirilmiştir.

Anahtar Kelimeler: Dalga kırılması, dalgaların enerji yayılımı, SWAN, üçlü dalga-dalga etkileşimi, dalga tahmini.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
γ	: Breaker index, ratio of maximum individual wave height over depth
α	: Proportionality coefficient of the rate of dissipation
ζ	: Autocorrelation function of a specific stochastic time series
1D	: One dimensional
H	: Wave height
H _d	: Breaking wave height
H _m or H _{max}	: Maximum individual wave height
H _{rms}	: Root-mean-square wave height
H _s	: Significant wave height
k	: Wave number
L	: Wavelength
Q _b	: Fraction of breaking waves
QUAD	: Four wave-wave interactions
TRIAD	: Three wave-wave interactions
CHL	: Coastal & Hydraulics Laboratory
DCTA	: Distributed Collinear Triad Approximation
DEF	: Default parameters recommended by SWAN
DTA	: Discrete Triad Approximation
DUCK94	: Duck Nearshore Experiment, 1994
FFT	: Fast Fourier Transform
FRF	: Field Research Facility
LTA	: Lumped Triad Approximation
NOAA	: National Oceanic and Atmospheric Administration
Pdf	: Probability density function
RTC	: Recommended Tuneable Coefficients

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1. INTRODUCTION

1.1. Aim and Content of The Study

The design of coastal structures is based on the most extreme wave conditions during the lifetime of the structure. These conditions often require long-term observations or high accurate predictions of waves propagating to the shore. The effects of waves on coastal structures depend on many parameters such as wave breaking, wave period, and wave height. The examination of these parameters has been the subject of many studies in the past and today. However, the irregularity of the waves reaching the shore has led researchers to develop various methods and formulas.

The best method for studying irregular waves is long-term statistical solutions. However, this method brings with it high labour and cost. Therefore, more economical analysis methods have been investigated by using the data of previous experimental studies. In the study of Booij et al., (1999). A third-generation numerical wave model known as Simulating WAVes Nearshore (SWAN) is a wave model developed by Delft University of Technology. This model has aimed to compute random, short-crested waves in shallow water coastal regions with ambient currents. The model is based on an Eulerian formulation of the discrete spectral balance of action density and can be driven by boundary conditions and local winds. This model is similar to other third-generation wave models as it explicitly represents the processes of wind generation, whitecapping, quadruplet wave-wave interactions, and bottom dissipation. However, SWAN also includes triad wave-wave interactions and depth-induced wave breaking, which are not accounted for in other models of this generation.

Furthermore, unlike other third-generation wave models, SWAN utilizes an implicit numerical propagation scheme, which provides a more cost-effective computational solution in shallow water. The model's accuracy has been confirmed through comparisons with analytical solutions, laboratory observations, and generalized field observations. The goals of the SWAN model are to solve the spectral action balance equation without any a priori restrictions on the spectrum for the evolution of wave growth. This equation represents the effects of spatial propagation, refraction, shoaling, generation, dissipation, and nonlinear wave-wave interactions [SWAN Team, 2023a].

One of the fundamental issues in wave models is the complex wave breaking processes. As waves move towards the shoreline, their height increase and break when they reach a critical point. Wave breaking not only generates energy acting on coastal structures, but also plays a crucial role in the formation of complex processes such as turbulence. Waves dissipate their energies while breaking. That energy mostly transforms to heat and turbulence. This energy effect many conditions in the water like sediment transport and beach profile.

Energy dissipation calculations are mostly based on empirical formulas. This study contains energy dissipation by wave breaking, bottom friction and triple wave-wave interaction calculations with SWAN model. It describes spectral wave, SWAN technical background and compares results of different wave models according to existing experiment data. The results show how the wave parameters effect energy dissipation. Following the default parameters and coefficients recommended by SWAN in the models, the parameters calibrated according to the model conditions were tested and the results were compared. Thus, the model parameters and the effect on the result were tried to be described.

The main aim of this study is to evaluate the simulation of the wave breaking dissipation process in the SWAN wave model using data from the Duck Nearshore Experiment, 1994 (DUCK94) field experiments conducted on the Duck beach in North Carolina in 1994 by United States Army Corps of Engineers (USACE). In addition, the effect of triad wave-wave interaction process, which is one of the SWAN model parameters, to waves was also evaluated and compared with the models without using this process.

In chapter 1, firstly, information about the past and present developments of wave models is given and then the spectral representation of waves is given. SWAN wave model, which is also one of these wave models, is briefly explained and especially the formulas for the calculation of wave breaking energy distribution are provided. The triad wave-wave interaction processes are also briefly described in this section. Finally, previous studies on these topics in the literature are given.

In the 2nd chapter, the experiments carried out within the scope of the DUCK94 project are described and the data obtained as a result of these experiments and the operations performed on these data are explained. In addition, the sources of other data used in this study are also presented.

Chapter 3 explains the general concept about the application of the SWAN model. It contains information about the parameters used in the models. In addition, it defines the statistical values used to compare the models.

In 4th chapter of this thesis, the results of several models created within the scope of this study are discussed and the calibration process is explained.

Finally, in chapter 5 the conclusions obtained from the comparisons of these results are listed and suggestions and recommendations for the future studies are provided.

1.2. Wave Models

First wind wave models have been primarily developed and applied to deep water conditions. The use of these models in coastal areas required the finite depth effects to be considered. In addition, changes in the surf zone also affect the model. These changes are sediment transport, which causes erosion and deposition, and bottom friction, which is the resistance experienced by the wave.

Historically, predictions of wave conditions for Normandy landings (June 1944) are considered the first attempt at operational wave forecasting. Study of Sverdrup and Munk (1947) was the first form of wave prediction models. Their model was also first in describing simple wave parameters involving the wind speed, fetch, duration, wave height and period. In [Gelci et al., 1957], introduced the concept of spectral firstly to the numeric wave modelling literature. The development of the wave spectrum concept by Pierson et al., (1955) Pierson, Neumann, and James (PNJ) and Darbyshire (1952) represented a significant advancement in forecasting methods by introducing a variable that could effectively describe the markedly irregular appearance of waves at the ocean surface. The method of PNJ was unable to achieve the desired level of success in wave forecasting. This lack of achievement in both approaches were primarily attributed to their subjective nature, which limited their ability to make practical predictions. Furthermore, these methods attempted to solve exceedingly complex problems through the use of relatively simplistic procedures. The Sea Wave Modelling Project [SWAMP group, 1982] study was intended to elucidate the fundamental physical concept of surface waves and their numerical representation. Additionally, this model provides a clear means of quantitatively predicting the spatiotemporal evolution of a two-dimensional wave spectrum given a particular wind

input. Up to the late 1980's many models developed, using simple nonlinear interaction approximations and/or assumptions on spectral shape. Those models named as first and second-generation models [Web 1, 2010]. The main result of the intercomparison studies performed is that the prediction results still strongly depend on the specific wave model used [Graber, 1984]. Currently, three state-of-the art numerical wave models are widely used. They are WaveModel (WAM), [Komen et al.,1994], SWAN [Booij et al.,1999] and WAVEWATCH III® (WW3) [Tolman, 2002]. These models share a common characteristic of utilizing the action balance equation to model waves with sources and sinks. However, they exhibit variations in numerical implementation and parameterization of physical processes. WAM model employs a single set of source terms, while SWAN and WW3 offer a diverse range of source terms and parameterizations for users to choose from. Originally, WAM and WW3 were developed as large-scale models, whereas SWAN was designed explicitly for simulating nearshore waves. Nonetheless, both WAM and WW3 have since incorporated new source terms and parameterizations to account for nearshore processes and advanced numerical techniques. Presently, all three models have the capability to simulate waves in coastal areas [Björkqvist et al., 2020]. In section 1.2.2 the SWAN model will be explained in detail.

1.2.1. Spectral Description of Waves

To understand energy dissipations of waves, it is necessary to know the generation of waves. As fluids, the ocean and atmosphere inherently constitute a thermodynamically coupled system, perpetually exchanging heat, mass, and momentum. Frequently, these alterations result in a modification of the boundary conditions separating the fluid media [Massel 2013]. Due to these alterations, wind waves emerge on the surface of the ocean. The predominant mechanism generating wind waves is the wind flow impinging on the ocean surface. However, winds are not the only factor causing changes in the ocean surface. Concurrently, factors such as planetary waves and eddies may also elicit modifications to the ocean surface in tandem with wind waves. The frequency of oceanic waves is influenced by a confluence of external factors governing wave generation conditions, including wind

speed, wind fetch, duration, water depth, presence of swells, and stage of storms. Additionally, internal mechanisms within the wave field, such as nonlinear interaction between wave components and energy dissipation caused by wave breaking or bottom friction impact wave frequency. Given the multiplicity of sources involved, a deterministic approach is unfeasible for the study of the sea, necessitating instead a stochastic approach. A tool for the analysis of stochastic variables is the investigation of the energy spectrum of the associated random variable [Silva, 2015].

The forecasting of wave parameters necessitates the utilization of stochastic analysis exclusively. Such analysis can be formulated within two fundamental domains, namely the frequency domain and the probability domain [Massel, 2007]. In the time domain, the autocorrelation function of a given stochastic time series $\zeta(t)$ can be expressed as:

$$K(\tau) = \int_{-\infty}^{\infty} \zeta(t)\zeta(t - \tau)dt = E[\zeta(t)\zeta(t - \tau)] \quad (1.1)$$

where the autocorrelation of a signal can be construed as the degree of similarity between observations separated by a time lag (τ). The spectral analysis of waves can be carried out using Fourier transforms, which separate a waveform into its constituent sinusoids and represent them as a plot of amplitude against frequency. The continuous Fourier transform is commonly employed to analyse signals that extend over an infinite interval. In contrast, the discrete Fourier transform is better suited for analysing experimental signals with finite duration. Similarly, two distinct techniques can be employed to analyse the spectrum of a stochastic variable: the Fast Fourier Transform applied to the random signal $\zeta(t)$ or the Fourier Transform applied to the autocorrelation function, yielding the spectral density function $S(\omega)$, as illustrated by the equation below:

$$S(\omega) = \int_{-\infty}^{\infty} K(\tau) e^{j\omega\tau} d\tau \quad (1.2)$$

Spectral moments assume a significant role in spectral analysis. The r-moment of a spectrum is typically expressed by Equation 1.3.

$$m_r = \int_0^{\infty} \omega^r S(\omega) d\omega \quad (1.3)$$

As per the definition, the variance of a random variable, such as the surface elevation zeta, is denoted by σ_ζ^2 and represents the zero-moment. The spectral moments play a crucial role in deducing several important spectral features, including the mean wave frequency, mean wave period, and the significant wave height. The equations of these features shown below:

$$\bar{\omega} = \frac{m_1}{m_0}, \quad \bar{T} = \frac{2\pi}{\bar{\omega}} = 2\pi \frac{m_0}{m_1} \quad (1.4)$$

$$\bar{\omega}_0 = \sqrt{\frac{m_2}{m_0}} \quad \bar{T}_0 = \frac{2\pi}{\bar{\omega}_0} = 2\pi \sqrt{\frac{m_0}{m_2}} \quad (1.5)$$

$$H_s = H_{1/3} = 4 \sqrt{\sigma_\zeta^2} \quad (1.6)$$

The significant wave height is defined as the average height of the highest one-third of waves in a given wave record. There is an alternative formula to estimate mean frequency and mean period. It is called the average frequency of up-crossing of the mean level ($\bar{\omega}_0$) and average period ($\bar{T}_0$) :

$$\bar{\omega}_0 = \sqrt{\frac{m_2}{m_0}} \quad (1.7)$$

$$\bar{T}_0 = \frac{2\pi}{\bar{\omega}_0} = 2\pi \sqrt{\frac{m_0}{m_2}}$$

the central spectral moments ($\tilde{m}_n$) are defined as:

$$\tilde{m}_n = \int_0^\infty (\omega - \bar{\omega})^n S(\omega) d\omega \quad (1.8)$$

$$\tilde{m}_0 = m_0, \quad \tilde{m}_1 = m_1 - \bar{\omega}m_0 = 0, \quad \tilde{m}_2 = m_2 - \frac{m_1^2}{m_0}$$

The central moment $\tilde{m}_2$ is a measure of concentration of the spectral wave energy around frequency $\bar{\omega}$. If $\tilde{m}_2$ is normalized by product $\bar{\omega}^2 \tilde{m}_0$, non-dimensional v^2 parameter is obtained as:

$$v^2 = \frac{\tilde{m}_2}{\bar{\omega}^2 \tilde{m}_0} = \frac{m_0 m_2}{m_1^2} - 1 \quad (1.9)$$

Parameter v^2 is acceptable, lower-order quantity which is a measure of the spectral width. When the energy of all waves is concentrated in a single frequency, $\omega = \bar{\omega}$ and $v^2 \rightarrow 0$ as can be seen in the above equation. If the wave energy is widely distributed between the frequencies, parameter v^2 increases. Under typical storm conditions, the spectral width parameter v exhibits an approximate value of 0.3.

[Massel, 2007] explained 4 different types of spectral forms. Only Pierson–Moskowitz spectrum [Pierson and Moskowitz, 1964] and Joint North Sea Wave Project (JONSWAP) spectrum [Hasselmann et al., 1973] will be explained in this section.

To encompass the high-energy portion of the spectrum when frequency is lower than the peak frequency ($\omega < \omega_p$), several proposals have been made to employ power functions multiplied by exponential functions. According to [Pierson-Moskowitz, 1964], a general expression for the spectral density function and the spectral moments have been proposed as:

$$S(\omega) = A\omega^{-p} \exp[-B\omega^{-q}] \quad (1.10)$$

$$m_r = AB^{(r-p+1)/q} \left(\frac{1}{q}\right) \Gamma\left(\frac{p-r-1}{q}\right)$$

where A, B, r and q are free parameters, $\Gamma(x)$ is a gamma function. The spectrum defined by Pierson-Moskowitz is the most popular spectrum form. They used field data and theoretical studies of [Phillips, 1958] and [Kitaigorodskii, 1962] and defined the spectral density function for fully developed sea, when phase speed is approximately equal to wind speed:

$$S(\omega) = \beta g^2 \omega^{-5} \exp \left[-B \left(\frac{g}{\omega V_{19.5}} \right)^4 \right] \quad (1.11)$$

in which $\beta = 8.1 \times 10^{-3}$, $B = 0.74$ and g is gravity acceleration. Here $V_{19.5}$ is the wind speed at 19.5 m elevation above the sea surface level. As seen in equation (1.11) the shape of the Pierson-Moskowitz spectrum is controlled by single parameter wind speed ($V_{19.5}$). According to Pierson-Moskowitz also defined the following constants:

$$\frac{V_{19.5} \omega_p}{g} = 0.879 \text{ and } \frac{V_{19.5} \omega_p}{2\pi g} = 0.13 \quad (1.12)$$

When substituting in Equation (1.11), the result is:

$$S(\omega) = \beta g^2 \omega^{-5} \exp \left[-\frac{5}{4} \left(\frac{\omega}{\omega_p} \right)^{-4} \right] \quad (1.13)$$

Certain mathematical challenges arise when computing the spectral fourth moment utilizing this equation. To remedy this shortcoming, PM suggested applying a cut-off frequency:

$$m_4 = \int_0^{\omega_c} \omega^4 S(\omega) d\omega \quad (1.14)$$

in which $\omega_c = n\omega_p$ and $n > 3$.

An alternative spectral formulation, known as the JONSWAP spectrum, originates from an extensive wave measurement project known as the Joint North Sea

Wave Project. This initiative was conducted during the years 1968 and 1969 in the North Sea, as documented by [Hasselmann et al., 1973]. Just like Pierson-Moskowitz, JONSWAP is a wave spectrum model using the [Kitaigorodskii, 1962] approach and [Phillips, 1958] saturation range. JONSWAP spectrum considered a limited fetch instead of an infinitely large fetch. In addition, the number of coefficients were increased according to PM model. The JONSWAP spectrum as a function of non-dimensional frequency $\hat{\omega} = \frac{\omega}{\omega_p}$ takes the form:

$$S(\hat{\omega}) = \frac{\beta g^2}{\omega_p^4} \hat{\omega}^{-5} \exp\left(-\frac{5}{4} \hat{\omega}^{-4}\right) \gamma^r \quad (1.15)$$

where γ is the peak enhancement factor of the standard value and r is defined as:

$$r = \exp\left[-\frac{1}{2} \frac{(\hat{\omega} - 1)^2}{\sigma_0^2}\right] \quad (1.16)$$

in which

$$\sigma_0 = \begin{cases} 0.07 & \text{when } \omega < \omega_p \\ 0.09 & \text{when } \omega \geq \omega_p \end{cases} \quad (1.17)$$

The Phillips constant β in equation (1.15) and peak frequency ω_p is defined in Hasselmann et al., (1973) as:

$$\beta = 0.076 \left(\frac{gX}{V_{10}^2}\right)^{-0.22} \quad (1.18)$$

and

$$\omega_p = 7\pi \left(\frac{g}{V_{10}} \right) \left(\frac{gX}{V_{10}^2} \right)^{-0.33} \quad (1.19)$$

The Pierson-Moskowitz spectrum can be made as an example of the JONSWAP spectrum by setting the peak enhancement factor (γ) to 1 in equation (1.15).

1.2.2. SWAN 3rd Generation Wave Model

SWAN is the most common third generation wave model that computes all the energy loss processes as a result of wind-induced wave generation, wave propagation, wave-wave interactions, depth-interaction breaking and bottom friction in coastal regions and inland waters. SWAN uses to calculate irregular wave motions near shore based on deep water wave conditions, wind, base topography, currents, and tides (in deep and shallow waters). It was developed by Delft University of Technology in the Netherlands [Kutupoğlu, 2018] [Swan Team, 2023a].

The primary objective of the SWAN model is to solve the spectral action balance equation, enabling the evolution of wave growth without imposing any prior limitations on the spectrum. This equation encompasses the combined impacts of spatial propagation, refraction, shoaling, generation, dissipation, and nonlinear wave-wave interactions. The SWAN model shares the same scientific philosophy as WAM cycle 3 and employs similar formulations for the source terms [SWAN Team, 2023b].

1.2.2.1. Governing Equation

The SWAN model uses action balance equation to simulate waves. In the presence of ambient current, the action density $N(\sigma)$ which defined as $N = E/\sigma$ is conserved during wave propagation along its characteristic, but the energy density E is not [SWAN Team, 2023b]. In this equation, σ represents relative wave frequency. The following equation governs the rate of change of the action density N at a single location in space ($\vec{x}; \sigma, \theta$):

$$\frac{\partial N}{\partial t} + \frac{\partial(c_x N)}{\partial x} + \frac{\partial(c_y N)}{\partial y} + \frac{\partial(c_\theta N)}{\partial \theta} + \frac{\partial(c_\sigma N)}{\partial \sigma} = \frac{S_{tot}}{\sigma} \quad (1.20)$$

where t is time, x and y are planes in the cartesian coordinate system. θ term in the equation represents wave direction taken counterclockwise from geographic east. The non-conservative source/sink word S_{tot} is used to describe any physical processes that generate, dissipate, or redistribute wave energy at a given location. If ambient current is not available at deep water this equation transforms as:

$$\frac{\partial E}{\partial t} + \nabla_{\vec{x}} \cdot (\vec{c}_g E) = S_{tot} \quad (1.21)$$

In the left-hand side second term represents the propagation of wave energy in two-dimensional geographical $\vec{x}$ -space and $\vec{c}_g$ is group velocity. SWAN can calculate wave growth by wind. A resonance mechanism [Phillips, 1957] and a feed-back mechanism [Miles, 1957] are used to explain how wind energy is transferred to the waves. But this study doesn't cover wave growth by wind. According to [SWAN Team, 2023b], six basic processes contribute to S_{tot} in shallow water:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (1.22)$$

in which S_{in} is wave input, S_{nl3} and S_{nl4} nonlinear transfer of wave energy through three-wave and four-wave interactions, $S_{ds,w}$, $S_{ds,b}$, $S_{ds,br}$ are wave dissipation due to white capping, bottom friction and wave breaking respectively. This study deals with wave breaking, bottom friction dissipation and triad wave-wave interactions, therefore these terms are detailed in next sections.

1.2.2.2. Wave Breaking Dissipation

Shoaling causes waves to become higher as they advance towards the shore. Waves start to break and quickly dissipate energy when the ratio of wave height over water depth passes a specific threshold. Waves start to break and quickly dissipate energy when the ratio of wave height over water depth passes a specific threshold ($H_{max}/d \approx 0.75$). This mechanism takes control over all other processes in the surf zone.

There is still a lack of knowledge regarding the depth-induced wave breaking process and associated spectral modelling. In contrast, Battjes and Janssen (1978) and Thornton and Guza (1983) found that the overall dissipation resulting from wave breaking could be accurately approximated using the dissipation of a bore applied to the breaking waves in a random field. Eldeberky and Battjes (1995) developed a spectral adaptation of Battjes and Janssen's (1978) bore model that maintains the spectral shape. The expression is expanded to encompass directions as follows:

$$S_{ds,br}(\sigma, \theta) = \frac{D_{tot}}{E_{tot}} E(\sigma, \theta) \quad (1.23)$$

where E_{tot} is the total wave energy and D_{tot} is the rate of dissipation of the total wave due to wave breaking according to Battjes and Janssen (1978) and $D_{tot} < 0$. The value critically influencing the value of D_{tot} is the breaker parameter $\gamma = H_{max}/d$ where H_{max} is maximum individual wave height and d is water depth in that location. SWAN can simulate wave breaking with both a constant and a variable value of breaker parameter. Variable breaker parameter expressed as BKD in SWAN. BKD indicates that the breaker index (γ) scales with both the dimensionless depth (kd) and the bottom profile slope (β). This study covers both value types of breaker parameter and implementation details are described in chapter 3. SWAN uses 0.73 as default constant breaker parameter according to Battjes and Stive (1985) and 0.54 as the default variable value of the breaker index.

SWAN used the bore-based model of Battjes and Janssen (1978) (BJ78) to simulate the energy dissipation due to depth-induced random wave breaking.

According to BJ78 the mean rate of energy dissipation per unit horizontal area D_{tot} shown as:

$$D_{tot} = -\frac{1}{4}\alpha_{BJ}Q_b\left(\frac{\tilde{\sigma}}{2\pi}\right)H_{max}^2 = -\alpha_{BJ}Q_b\tilde{\sigma}\left(\frac{H_{max}^2}{8\pi}\right) \quad (1.24)$$

where α_{BJ} is proportionality coefficient of the rate of dissipation and taken 1 in SWAN as default and Q_b is the fraction of breaking waves, $\tilde{\sigma}$ is the mean frequency defined as:

$$\tilde{\sigma} = E_{tot}^{-1} \int_0^{2\pi} \int_0^\infty \sigma E(\sigma, \theta) d\sigma d\theta \quad (1.25)$$

And the fraction of breaking waves Q_b expressed in SWAN as:

$$Q_b = \begin{cases} 0, & \text{for } \beta \leq 0.2 \\ Q_0 - \beta^2 \frac{Q_0 - \exp(Q_0 - 1)/\beta^2}{\beta^2 - \exp(Q_0 - 1)/\beta^2}, & \text{for } 0.2 < \beta < 1 \\ 1, & \text{for } \beta \geq 1 \end{cases} \quad (1.26)$$

in which $\beta = H_{rms}/H_{max}$. In addition, for $\beta \leq 0.5$, $Q_0 = 0$ and for $0.5 < \beta \leq 1$, $Q_0 = (2\beta - 1)^2$. If the defined above D_{tot} and E_{tot} are written in the equation of Eldeberky and Battjes (1995):

$$S_{ds,br}(\sigma, \theta) = \frac{-\alpha_{BJ} Q_b \tilde{\sigma}}{\beta^2 \pi} E(\sigma, \theta) \quad (1.27)$$

The equation defines the dissipation for a spectral component per unit time in SWAN.

Thornton and Guza (1983) suggest an alternative to the bore-based model of Battjes and Janssen (1978). Regarding the description of the wave height probability density function, this model can be seen as a modification of Battjes and Janssen. The total dissipation due to breaking caused by depth is expressed as:

$$D_{tot} = -\frac{B \tilde{\sigma}}{8\pi d} \int_0^\infty H^3 p_b(H) dH \quad (1.28)$$

where B is a proportionality coefficient and $p_b(H)$ is the probability density function of breaking waves times the fraction of breakers (Q_b). The total dissipation is expressed as follows when the Rayleigh distribution and integral are used:

$$D_{tot} = -\frac{3B^3 \tilde{\sigma}}{32\sqrt{\pi}d} Q_b H_{rms}^3 \quad (1.29)$$

1.2.2.3. Triad Wave-Wave Interaction

SWAN computes nonlinear interactions in shallow water. Uses two distinct triad nonlinear wave-wave interactions: the Distributed Collinear Triad Approximation (DCTA) and the Lumped Triad Approximation (LTA) method which is based on Boussinesq theory. SWAN employs the LTA of Eldeberky (1996), an only slightly modified version of the Discrete Triad Approximation (DTA) of Eldeberky and Battjes (1995):

$$S_{n13}(\sigma) = S_{nl3}^-(\sigma) + S_{nl3}^+(\sigma) \quad (1.30)$$

where:

$$S_{nl3}^+(\sigma) = \max[0, \alpha c_\sigma c_{g,\sigma} J^2 \sin(-\beta) \{E^2(\sigma/2) - 2E(\sigma/2)E(\sigma)\}] \quad (1.31)$$

and

$$S_{nl3}^-(\sigma) = -2S_{nl3}^+(2\sigma) \quad (1.32)$$

in which c_σ and $c_{g,\sigma}$ respectively, are the phase and group velocity and at σ , β is the biphase of self-self-interaction and J is the interaction coefficient and according to Madsen and Sørensen's (1993) Boussinesq theory defined as:

$$J = \frac{k_{\sigma/2}^2 (gd + 2c_{\sigma/2}^2)}{k_\sigma d \left(gd + \frac{2}{15} gd^3 k_\sigma^2 - \frac{2}{5} \sigma^2 d^2 \right)} \quad (1.33)$$

[Eldeberky, 1996] suggested that the biphase is roughly represented by:

$$\beta = -\frac{\pi}{2} + \frac{\pi}{2} \tanh\left(\frac{m}{Ur}\right) \quad (1.34)$$

where Ur is the Ursell number and expressed as:

$$Ur = \frac{gH_{m0}}{8\sqrt{2}} \left(\frac{T_{m01}}{\pi d} \right)^2 \quad (1.35)$$

and m in equation (1.34) is a tuneable coefficient. SWAN uses $m = 0.63$ according to [Doering and Bowen, 1995]. Triad wave-wave interactions due to both LTA or DCTA can be calculated only for $Ur \geq 0.1$ in SWAN.

DCTA is another approach of triad wave-wave interaction in SWAN. In DCTA, a heuristic triad formulation was put up by [Booij et al., 2009] that takes into consideration both the emergence of all super harmonics and the change to a universal tail of $k^{-4/3}$. Formulation of DCTA given by:

$$S_{nl3}(\sigma_1) = \lambda \frac{\sin(-\beta) \tilde{k}^{1-p}}{d^2} \int_0^\infty \frac{\tanh \bar{k} d}{\bar{k} d} N(\sigma_3) [\sigma_2 c_{g,2} k_2^p N(\sigma_2) - \sigma_1 c_{g,1} k_1^p N(\sigma_1)] d\sigma_2 \quad (1.36)$$

where λ is a calibration coefficient that regulates the magnitude of triad interactions, $\tilde{k} = \tilde{\sigma}/\sqrt{gd}$ in which $\tilde{\sigma}$ expressed in equation (1.25), $p = 4/3$ is a shape coefficient that forces the high frequency tail, and $\bar{k} = (k_1 + k_2 + k_3)/3$ which is a characteristic wave number of the triad wave-wave interaction.

1.2.2.4. Bottom Friction

When wave shoaling reaches a water depth/wavelength (d/L) ratio of 1/2, the effect of dissipation due to bottom interaction becomes much greater than other processes. Neglecting this dissipation leads to overestimation of wave height values. A loss of energy occurs as a result of bottom friction when wave energy interacts with the seafloor.

Different formulas have been developed for bottom friction calculations. The SWAN model can calculate the energy loss due to bottom friction with 4 different formulas. On the other hand, two of these formulae are analysed in this study. These

are the “JONSWAP” [Hasselmann et al., 1973] and “Ripples” [Smith et al., 2011] methods. Semi-empirical JONSWAP bottom friction is calculated as shown in equation (1.37):

$$S_{ds,b}(f, \theta) = -C_b E(f, \theta) \sigma^2 / (g^2 \sinh^2 kd) \quad (1.37)$$

where d is water depth, k the wave number and C_b is bottom friction coefficient which is found $0.038 \text{ m}^2\text{s}^{-3}$ according to the observations of JONSWAP experiment. Different values for this coefficient have been suggested in the past. Nevertheless, the value of $0.038 \text{ m}^2\text{s}^{-3}$ has been strongly recommended and accepted as the default value in SWAN wave model [van Vledder et al., 2012].

In the second formulation, friction depends on the formation of bottom ripples and sediment size. The criticism of the JONSWAP model in their study is that it assumes that friction remains constant with respect to time. In his work [Jonsson, 1966], he developed the following formula for C_b :

$$C_b = f_w \frac{g}{\sqrt{2}} U_{rms} \quad (1.38)$$

in which f_w is non-dimensional friction factor and it is estimated by using the formulation below:

$$\frac{1}{4\sqrt{f_w}} + \log_{10} \left(\frac{1}{4\sqrt{f_w}} \right) = -0.08 + \log_{10} \left(\frac{A_b}{K_N} \right) \quad (1.39)$$

in which A_b is near-bottom excursion amplitude and K_N represents Nikuradse Roughness. So, [Smith et al., 2011] developed a new bottom friction calculation method by relating sediment size and specific gravity to the K_N value and validated the model by testing in 2 different cases in lake conditions. They improved the results in the estimation of wave heights under both test conditions.

1.3. Literature Review

This study targeted to explain the depth-induced breaking, energy dissipation and triad wave-wave interaction processes of the waves in nearshore by modelling them with SWAN. Datasets of the project “Duck Nearshore Experiment, 1994” (hereafter referred to as DUCK94) are used in these models.

Many scientific studies, field and laboratory experiments have been carried out to explain wave parameters in surf zone including energy dissipation, breaking, shoaling. However, due to the difficulty of the wave breaking mechanism, the energy distribution models are solved based on empirical and semi-empirical formulas. To make an empirical formula reliable, it must be calibrated or verified with a wide range of experimental conditions. [Rattanapitikon, 2007] This study contains the SWAN model calibration and verification with DUCK94 datasets.

One of the applications related to energy dissipated by wave breaking was made by [Collings, 1970]. However, this study is limited to regular waves and shallow water situations. The breaking criterion for regular waves identified by [Miche, 1944]. According to this study, the limiting steepness of stable periodic waves in water of constant depth is:

$$\left(\frac{H}{L}\right)_{max} = 0.14 \tanh \frac{2\pi d}{L} \quad (1.40)$$

which in shallow water approximates to:

$$\left(\frac{H}{d}\right)_{max} = 0.28 \pi \approx 0.88 \quad (1.41)$$

where H is the wave height, L is the wavelength and d is the depth of water.

[Battjes 1972] used a model based on the breaking criterion, which should be valid in deep water as well as shallow water. In the study, it is assumed that only the energy corresponding to the height of the local breaker height is dissipated and

expected to develop a more realistic model that used by Collins. The main purpose of those studies to explain the wave breaking process is to determine the critical wave height at which the breaking occurs. [Battjes, 1972] clarified all waves are breaking or have already broken which have heights equal to H_b :

$$\frac{H_b}{L} = 0.14 \tanh\left(\frac{\gamma}{0.88} \frac{2\pi d}{L}\right) \quad (1.42)$$

where γ is an adjustable coefficient. In shallow water this formula can simply:

$$H_b = \gamma h \quad (1.43)$$

As seen in equation (1.43) the determination of the breaking wave height is directly related to the determination of the value of γ coefficient. The value of γ varies with beach slope and the steepness of the incident waves. Many studies have been done and models have been developed to determine this value. Some of these studies detailed below.

[Battjes and Janssen 1978] led many theoretical and experimental studies. They explained non-broken wave heights as a Rayleigh-type distribution, calculated fraction of breaking waves (Q_b) as a function of H_{rms}/H_m (equation (1.44)) in their study.

$$\frac{1 - Q_b}{-\ln Q_b} = \left(\frac{H_{rms}}{H_m}\right)^2 \quad (1.44)$$

where H_{rms} is root-mean-square wave height and H_m is maximum wave height in a specific water depth (h). This equation forms the basis of the BJ78 model. H_{rms}/H_m fraction denotes the rate of broken waves. The Q_b value was expected to be equal to 1 when all the waves approaching the shore were broken. Model used Miche's breaker

height formula which is mentioned before. The energy balance is explained, and energy flux (P) integrated from energy balance equation as:

$$P = Ec_g = \frac{1}{8} \rho g H_{rms}^2 c_g \quad (1.45)$$

According to the BJ78 model, the depth profile $h(x)$ can be integrated with respect to the given incident wave parameters and a suitable selection of model parameters α and γ in order to determine the corresponding $H_{rms}(x)$.

In experimental studies of BJ78, they developed an energy dissipation prediction model for breaking irregular waves. This model was constructed so that the energy dissipation rate due to breaking is independently while previous models' prediction of wave energy density is based on variation of local depth on the beach. Battjes and Janssen's model is based on integrating the energy flux balance equation with wave height dependent on the shoaling processes along the integral path starting in deep water. They used an 1m height, 45m length and 0.88 width flume to test the model. A random-wave generator was placed on one side of the waterway. On the other side, 7 parallel gauges and the created beach profile were placed. This profile was created from two beaches with different slopes. Two sections with a slope of 1:20 are connected by a straight section of 1:40. They run models with parameters $\alpha = 1$ and $\gamma = 0.8$ in 15 different conditions and compare the experimental results with the theoretical model. When the initial α value was 0.5 and the γ value was 0.8, the calculated decay rate is low. Accordingly, the optimum values for 0.8 γ for α were determined as 1. Thus, the calculation results matched the experimental data. The Battjes and Janssen model's flaw is that, despite being theoretically straightforward, the wave height distribution does not accurately reflect the reported wave height pdf due to the delta function and truncation at H_b . As Battjes and Janssen pointed out, "The similarity between estimated and observed H_{rms} does not imply that the underlying probability density function's are identical [Thornton and Guza, 1983].

The wave height distribution model published by [Thornton and Guza, 1983] explain the concept of the wave model, similar to the work of [Battjes and Janssen, 1978]. However, their model has been expanded to offer a more realistic explication

of the transformation of the root-mean-square wave height, as well as probability density functions of wave height. Furthermore, their model incorporates bottom friction as a factor in the distribution function. Some of their field experiments have shown that even within the surf zone, the wave height data are explained quite well in the Rayleigh distribution. The model explains the dissipation caused by wave breaking and bottom friction.

They considered energy dissipation as the conversion of potential wave energy to turbulent kinetic energy in their article. They calculated the rate of wave breaking energy dissipation per unit area:

$$P\langle\varepsilon_b\rangle = \frac{f}{4}\rho g \frac{(BH)^3}{h} \quad (1.46)$$

where H is a single broken wave of height, f the frequency, h the water depth, ρ the water's mass density and B a coefficient. To determine the average rate of energy dissipation, it is necessary to sum the dissipation of every wave that has broken, as computed by equation (1.47) and then divide the result by the total number of waves, encompassing both broken and unbroken ones.

$$\langle\varepsilon_b\rangle = \frac{f}{4}\rho g \frac{B^3}{h} \int_0^\infty H^3 P_b(H) dH \quad (1.47)$$

where $P_b(H)$ is a function which is describing breaking wave distributions. Thornton and Guza's [1983] study have showed that the H_{rms} value was approximately $\sqrt{8m_0}$ as a result of their measurements where m_0 is the variance of sea surface elevation and calculated 0.995 correlation between these two variables. The empirical findings presented in their study lend robust support to the employment of the Rayleigh distribution as a suitable model for the probability distribution function of wave height. On the other hand, it is imperative to identify breaking waves to enable the computation of the required dissipation for integrating the energy balance equation.

As the result of the study, the Rayleigh distribution is shown to give good estimates of wave height statistics $H_{\max}$ for the spilling breakers measured in the field. They calculated the mean errors over the measured values compared with the Rayleigh statistics of $H_{1/3}$, $H_{1/10}$ and $H_{\max}$ they were -0.2, -1.8, and -6.8% respectively. Their study results showed the number of waves in the tail of the distribution slightly overpredicted by Rayleigh distribution however it is still able to predict the central statistics of $H_{1/3}$ and $H_{1/10}$ well. Wave heights, which are random in nature, can be explained everywhere using the Rayleigh distribution. The data used in the study also confirmed this. They used 2 different numerical energy flux balance models to compare. The considerations that set apart these models from each other are the depth limiting condition $H = \gamma h$ and the analytical solution of the transformation of H_{rms} wave height in shallow water. These models were compared with laboratory data like [Battjes and Janssen, 1978] and field data. With laboratory data the coefficient $B=0.8$ fits to model, while field data fits $B=1.5$ with 8.6% error rate. The model used in this study successfully predicted the shoaling of the H_{rms} wave height up to very close to the surf zone. This study also showed that the accuracy of the model strongly depends on the value of the B coefficient, but how the $P_b(H)$ function is defined is less important.

[Battjes and Stive, 1985] proposed a model to explain the average rate of dissipation caused by random wave breaking. This model was derived from the BJ78 study and was extensively calibrated and verified using a diverse range of laboratory and field datasets. These datasets were collected from beaches with almost plane slope as well as barred beaches and encompassed a wide range of wave and bottom conditions. The model aimed to predict an optimal value of breaking wave height coefficient.

Their dataset consisted of 20 different beach and environmental conditions. Half of them were concrete beach and half were sand beach. They had 16 laboratory and 4 field experiments. Root-mean-square wave height (H_{rms}) vary from 0.096 to 2.78 m, peak frequency (f_p) vary from 0.128 to 0.633 Hertz (Hz) in their sources of dataset. [Battjes and Stive, 1985] examined for different values of this γ parameter for these experiments in different conditions. They detected that the theoretical model has effectively one adjustable parameter and determined based on a comparison of calculated and measured variations of rms wave height (H_{rms}) in areas of wave breaking, optimal values of this coefficient. According to [Battjes and Stive, 1985]

integrations expressing breaking gives two functions, $\eta(x)$ (function which expresses the wave-induced set-up) $H_{rms}(x)$ (function which expresses the root-mean-square of all wave heights) shoreward of a reference point, which can be compared with the measurements of each experiment conditions. Repeating the integration for several choices of (α, γ) , optimal values of these coefficients can be estimated. They stated that α controls the level of energy dissipation and γ controls the fraction of breaking waves. Battjes and Stive calibrated the models using γ as a value ranging from 0.60 to 0.83 while keeping α constant ($\alpha = 1$).

By contrasting the estimated and observed fluctuations in root-mean-square wave heights in wave breaking zones, they were able to identify the ideal values of coefficients. They provided a parameterization of this reliance and used this parameterization to assess the overall effectiveness of the model. According to the study's findings, the correlation between the anticipated and actual H_{rms} levels was 0.98. Additionally, the rms relative error was 0.06 and the model bias was nearly negligible. The study makes a significant contribution since, based on their findings, they set the default value of the gamma (γ) parameter in SWAN at 0.73.

They determined the optimal values of coefficients by comparing the calculated and measured variations of rms wave heights in areas of wave breaking. They presented a parameterization of this dependence and evaluated the overall performance of the model using this parameterization. The results of the study showed that they achieved a coefficient of correlation of 0.98 between predicted and observed H_{rms} values. Additionally, the model bias was close to zero, and the rms relative error was 0.06. The contribution of the study is of significance since it establishes the default value of the constant gamma (γ) parameter in SWAN based on their findings.

To calculate the height of short-wave bores incident on the shoreline, [Baldock et al., 1998] updated the parametric wave transformation model based on the BJ78.

[Baldock et al., 1998] used a Rayleigh distribution to explain the wave heights in the surf zone in their theoretical research:

$$p\left(\frac{H}{H_{rms}}\right) = 2\frac{H}{H_{rms}} \exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right] \quad (1.48)$$

which is assumed to be valid for broken and unbroken waves. They described a breaking criterion as:

$$\frac{H}{H_{rms}} \geq \frac{H_b}{H_{rms}} = 0.6 \quad (1.49)$$

and explained fraction of breaking waves (Q_b) as integration of the Rayleigh distribution over all waves for which for that meet the breaking criterion. The result of this integration shows the fraction of breaking waves as:

$$Q_b = \exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right] \quad (1.50)$$

where $\frac{H_b}{H_{rms}} \rightarrow 1$, $Q_b \rightarrow 0$ and $\frac{H_b}{H_{rms}} \rightarrow 0$, $Q_b \rightarrow 1$. Q_b getting closer to 1 means all waves are broken. Baldock defined energy dissipation rate as:

$$\langle \varepsilon_b \rangle = \frac{1}{4} \rho g f_p B \exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right] (H_b^2 + H_{rms}^2) \quad (1.51)$$

where B is a constant of order one.

[Rattanapitikon and Shibayama, 1998] developed and implemented energy dissipation models for regular and random breaking waves to calculate wave heights.

638 wave profiles from 13 published experimental sources were taken from data from earlier investigations, which were utilised. Previous models were applied to compute and analyse energy dissipation for regular breaking waves. For irregular breaking waves, a new model applied based on the regular breaking wave model on the local fraction of breaking waves. The model was validated using small- and large-scale laboratory data under regular wave conditions. Their model's computed wave height yields better results than the one from the previous model. The current model's average rms relative error dropped from 17.8% to 15.8%. The model was able to simulate a wide range of wave conditions and different beach profile shapes for irregular wave conditions, including the increase in rms wave height due to shoaling and the subsequent decrease due to wave breaking. Laboratory and field data collected on a small- and large-scale were used to validate the model. The model's average rms relative error is 10.0%. Additionally, the fact that previous studies used a wave-by-wave approach to simulate the transformation of irregular waves means that D_b is proportional to the difference between the local energy flux of a breaking wave and stable energy flux. The wave-by-wave approach requires a lot of computation time, which is substandard. As a result, it might not be appropriate to use in a beach deformation model. The study demonstrated that increasing the accuracy of the model and coefficients that are predicted by using many laboratory results when computing the average rate of energy dissipation in regular and irregular breaking waves.

The investigation conducted by [Rattanapitikon et al., 2003] examined six selected dissipation models in the context of regular wave breaking. In order to test the applicability, equivalent regular waves based on the rms wave height were used to directly apply the chosen dissipation models of regular waves breaking to the irregular waves. To calibrate and evaluate the models, a total of 395 examples from 12 sources of published experimental results were used. The investigations, which include small-scale, large-scale, and field studies, cover a wide range of wave and bottom topography conditions. Additionally, in the study it was discovered that the representative wave technique could be utilized to compute the rms wave height transformation with very accurate predictions if the appropriate dissipation model was used. Their model was valid only in the nearshore zone (excluding the swash zone) and open coastal waters. Their model's simplicity and usefulness are its main advantages; for instance, it only needs one equation to calculate the nearshore zone's rms wave height transformation. Their work was not intended to displace more sophisticated models, but rather to offer

a simple estimation methodology for the cross-shore beach deformation model. It is possible to compare straightforward model of [Rattanapitikon et al., 2003] to a more complex one by using it as a benchmark.

One of the most extensive studies in this field is summarized in [Rattanapitikon, 2007]. In the study, data from 1723 cases and 13 experimental tests, including DUCK94 datasets, were used to verify the existing 8 wave dissipation models. He computed the transformation of H_{rms} from the energy flux conservation law. Accordingly, the energy dissipation ratio of the breaking waves is calculated with the following formula:

$$\frac{\rho g}{8} \frac{\partial(H_{rms}^2 c_g \cos\theta)}{\partial x} = -D_B \quad (1.52)$$

where c_g is the group velocity and θ is the mean wave angle. This formula comes from Snell's law and the linear wave theory. As a result of the study, parameter coefficients were determined, and 42 different models were created and compared with the calibrated formulas. These models consisted with different rate of dissipation (D_b) and the fraction of breaking waves (Q_b). This fraction is derived under the premise that the probability density function (pdf) characterizing the elevation of waves could be represented by a truncated Rayleigh distribution at the breaking wave height (H_b), whereupon all broken waves a height equivalent to the breaking wave height. Rattanapitikon described this ratio as similar to the model of BJ78:

$$\frac{1 - Q_b}{-\ln Q_b} = \left(\frac{H_{rms}}{H_b}\right)^2 \quad (1.53)$$

Error rates of these models at different scales were determined and the models were calibrated. The most suitable models were figured out in each scale. In result of this study, the breaker height (H_b) formula determined as:

$$H_b = K_1 L \tanh[(K_2 kh + K_3)kh] \quad (1.54)$$

This formula based on the model of [Ruessink et al., 2003]. In the equation (1.54) there are 3 coefficients. These coefficients K_1 - K_3 are published as 0.14, 0.86 and 0.33 by [Ruessink et al., 2003] and calibrated as 0.047, 0.44 and 0.78 by Rattanapitikon respectively. The rate of dissipation for irregular waves by [Rattanapitikon et al., 2003] and computed as:

$$D_b = K_4 \frac{\rho g c_g}{8h} [H_{rms}^2 - (K_5 H_b)^2] \quad (1.55)$$

where K_4 and K_5 are coefficients. Published coefficients are 0.12 and 0.42. In the study of 2007, Rattanapitikon calibrated these coefficients 0.07 and 0.047 respectively. This calibration decreased error rates of model from 9.9 to 8.6. This model referred as M41 in the study, and it became the base model for the DUCK94 datasets.

[Battjes and Stive, 1985] defined a formula to calculate the optimal value of γ as:

$$\gamma = 0.5 + 0.4 \tanh(33s_0) \quad (1.56)$$

where s_0 is deep-water steepness. In another study [Nairn, 1990] modified this equation as:

$$\gamma = 0.39 + 0.57 \tanh(33s_0) \quad (1.57)$$

After the calibrations for many beach conditions and wide scale, [Rattanapitikon, 2007] defined the equation as:

$$\gamma = 0.63kh + 0.21\tanh(39s_0) \quad (1.58)$$

According to DUCK94 data Rattanapitikon denoted that Ruessink's formula works with the highest accuracy.

In a similar study [Alsina and Baldock, 2007] improved a formulation to describe breaking wave energy dissipation. The new formulation accounts for a term in the bore dissipation equation neglected in some previous modelling, but which is shown to be important in the inner surf zone. The only free model parameter remains the choice of γ , the ratio of wave height to water depth at initial breaking. The new formulation is an important improvement in predicting wave height condition close to the shoreline in surf zone conditions.

$$D = A \frac{H_{mss}^3}{h} \left[\left(\left(\frac{H_b}{H_{rms}} \right)^3 + \frac{3}{2} \frac{H_b}{H_{rms}} \right) \cdot \exp \left(- \left(\frac{H_b}{H_{rms}} \right)^2 \right) + \frac{3}{4} \sqrt{\pi} \left(1 - erf \left(\frac{H_b}{H_{rms}} \right) \right) \right] \quad (1.59)$$

and where:

$$D = erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (1.60)$$

in which erf is the Gauss error function.

In dissipative conditions an improvement is also noticeable. The new model which created by them gives the smallest error between predicted and measured wave heights for all three data sets presented when compared other 4 models.

In addition to the studies described so far, one of the recent studies, [Saprykina et al., 2022] investigated wave energy dissipation with plunging and spilling breaking waves and nonlinear processes with Boussinesq and SWAN models. This study

revealed that modelling the dissipation of wave energy caused by wave breaking should be carried out taking into account the compensation of nonlinear changes arising from the use of different nonlinear source terms.

Some values of coefficients for breaking wave calculating such as alpha and gamma (α, γ), have been proposed in many studies. In this study, while the α value took various values between 0.4 and 1.3, the γ value was kept between 0.2 and 1.2. The details of this study are explained in Chapter 3.

As seen in all these studies, many research studies are continuing the energy dissipation of wave breaking. As in some previous studies, this study includes simulating the energy dissipation processes of wave breaking in the SWAN program and comparing the results with the existing experimental results. This study also obtained results using data from a large-scale field experiment called DUCK94. The spectral parameters were examined, and the results obtained by creating different models by changing the wave parameters were compared with the DUCK94 data. However, thanks to the developing computational methods, in this study, a large number of different coefficient values are analysed to explain the wave breaking process.

2. EXPLAINING THE DUCK94 FIELD EXPERIMENT

2.1. DUCK94 Experiment

The DUCK94 project, carried out in August, September, and October 1994 at the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck Beach, North Carolina, USA. It was an intense, large-scale multi-agency study that investigated surf zone winds, waves, currents, sediment transport, and morphology within a 1 x 0.5 km region. DUCK94 included 31 investigations of varying complexity, using a variety of instruments. The study area of DUCK94 Project is shown in Figure 2.1. The experiments were place under remarkably various circumstances, and the findings represent one of the most thorough collections of nearshore dynamics measurements ever made. The data had enormous promise for significantly enhancing nearshore research and comprehending the processes that occur in the surf and swash zone, such as shoaling and wave breaking. For each experiment, scientists gathered the data. Since 1998 there has been public access to the data [Web 2, 2023].

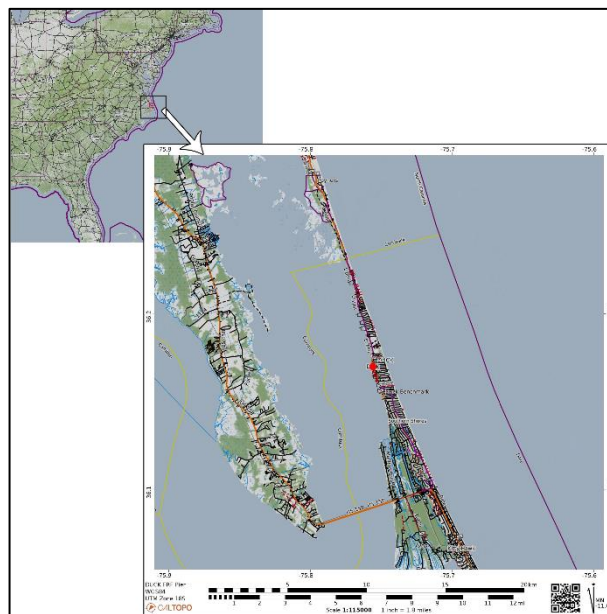


Figure 2.1: Map of the DUCK94 Project's study area as it looks today.

The DUCK94 data are a collection of various types of data that were collected by the individual researchers and stored in a variety of formats on a network of widely dispersed computers and media. Some data sets are of wide general interest, some are

not. The primary investigators extensively explained and checked the quality of certain data, but not many. These data continue to be used today and have been the focus of numerous studies in the past. The experiment "Surface gravity waves and nearshore circulation" carried out by Elgar, Herbers, Guza, and O'Reilly provided the data utilized in this study. Their datasets are available online in PV-Lab (pv-lab.org) data portal. These data sets were collected between July and November 1994 using a nearshore cross-shore "SPUVT" array of Sonar altimeters (S), Pressure gages (P), bi-directional current meters (UV), and Thermistors (T) in 8m water depth. By measuring the amount of time, sonar altimeters take an acoustic pulse to reach the bottom and return and translating that measurement to a distance using the theoretical sound speed, they may be used to determine the position of the seafloor. In the past, near-shore bedforms have been investigated using sonar altimeters mounted on fixed frames [Gallagher et al., 1996]. A bidirectional current meter is a specialized type of current meter used to measure the flow of current in both directions. The thermistor is a resistor whose resistance is dependent on temperature. Bottom-mounted pressure gauges are used to measure waves in coastal inlets. The pressure gauges in the experiment captured the waves in a spectrum. The significant wave heights corresponding to the spectrum data on 10 October 1994 10:00 according to Eastern Standard Time Zone (EST) and the bedform of the Duck beach are shown in Figure 2.2

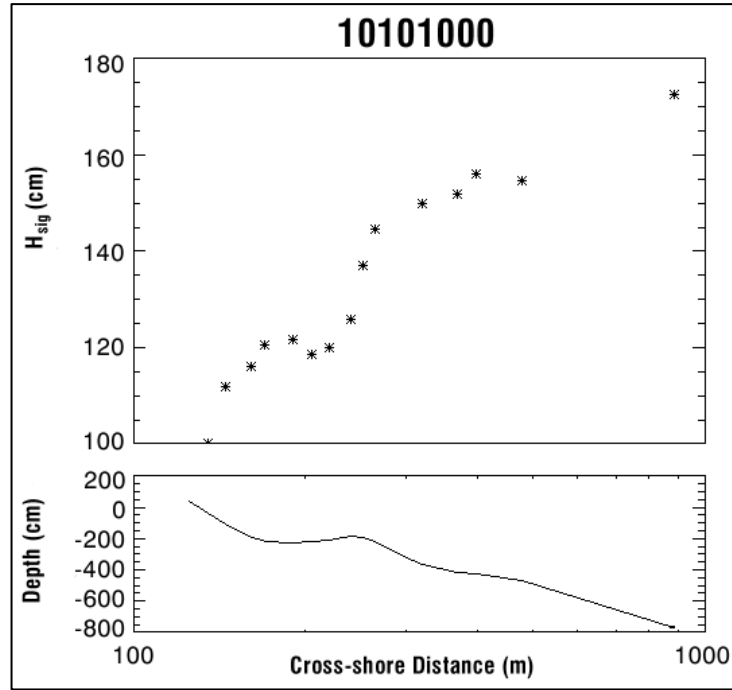


Figure 2.2: Significant wave heights and bottom profile of DUCK94 Experiment on 10-10-1994 10:00 (EST).

2.2. DUCK94 Datasets

In order to simulate the wave condition for a date in the SWAN model, wave information, bed form, tide, simulation parameters and boundary conditions should be specified for that date. In this study, this information was obtained from various reliable sources.

2.2.1. Spectrum Data of The Waves

The SPUVT dataset included data from seventeen pressure gauges. Spectral readings were acquired when the sensors were positioned at various intervals along the cross-shore axis. A total of 8691 spectrum files are available. These contain spectrum data from different dates and with different gauges. Each pressure gauge is labelled with the letter "p" and a number (i.e., p01, p02, p03, p87 etc.). The analysis of the results of the SWAN model is also based on these points. Date and pressure gauge names appear in the names of these spectrum files. For instance, spectral measurements of pressure gauge p02 on 09.06.1994 16:00 (EST) called as 09061600.ppp02. Those files include all spectrum data where measurement is existed.

However, there are some days and hours when measurements cannot be taken by the sensors. In order to prevent this from causing problems in the SWAN model, the first studies were carried out on specific days when measurements were taken from 15 points. The cross-shore distances of the measurement points, the names of the pressure gauges located at these points and the naming of these points in this study are given in Table 2.1. At each of the pressure gages along the cross-shore transect, power spectra of bottom pressure and sea-surface elevation are recorded in the datasets.

Table 2.1: Cross-shore distances of measurement and estimation points and naming of these points within the scope of the study.

Pressure Gauges	Cross-Shore Distance (m)	Name of Location
p01	124,94	LOCATION 0
p02	135,01	LOCATION 1
p03	145,42	LOCATION 2
p04	160,77	LOCATION 3
p05	169,5	LOCATION 4
p23	190,2	LOCATION 5
p26	190,2	LOCATION 5
p12	205,34	LOCATION 6
p13	220,23	LOCATION 7
p14	240,55	LOCATION 8
p16	252,03	LOCATION 9
p15	264,7	LOCATION 10
p17	320,37	LOCATION 11
p45	370,08	LOCATION 12
p18	398,39	LOCATION 13
p19	480,34	LOCATION 14
p87	884,11	LOCATION 15

Each spectrum files have 4 columns, and these columns has 204 data rows. The first column is number of rows which is titled as “BAND”. The second column is "FREQ" which represent frequency of the midpoint of that band in Hertz. The third and fourth columns are the power spectral density as cm^2/Hz according to bottom pressure and sea-surface pressure respectively. As seen in Table 2.1, gauges p23 and p26 are located at the same point in cross-shore and longshore axes. Although the gauges' altitudes might vary, for the sake of this study, they were treated as a single

point. Again, as seen in Table 2.1 pressure gauge p01 named as “LOCATION 0” because in most of cases shoreline starts in after 130th m of cross-shore distance. In these circumstances, the p01 gauge does not record data since it is not in touch with water.

After a range between 0.3 Hz and 0.4 Hz, the spectral density data display ridiculous values. These ridiculous values were also adjusted during data correction in order to get them closer to zero. Detailed information about this process is provided in subsection 2.3.1

2.2.2. Bathymetry Data of Duck Beach

Bathymetry data for Duck beach was provided by USACE. The bottom profile data received by FRF were presented in 2 different data portals of USACE. One of them is stored by Coastal & Hydraulics Laboratory (CHL)¹ and the other one is stored by FRF Data Portal². Since the first of these provides more detailed data, it is taken as bathymetry data in this study. This data is in csv format and consists of 14 columns such as profile number, cross-shore distance, longshore distance, elevation, latitude, longitude, date, and time. According to the longshore axis of the FRF coordinate system, the profile number column represents the profile's mean position. The pressure gauges from which the spectral wave data were taken are located at approximately 929 metres in longshore axis. Bathymetry data were not taken at this distance on some days. Interpolation was performed to determine the profile at this distance. These procedures and other data error corrections are detailed in subsection 2.3.2

2.2.3. Tidal Data of Duck Beach

Tides are a frequent phenomenon affecting many processes in the oceans. As the sun rises in the east and the stars come out at night, the ocean waters regularly rise and fall along shores. These changes in water level also affect the waves. In order to simulate this effect more appropriately in SWAN, tidal data which were obtained from the National Oceanic and Atmospheric Administration (NOAA) data portal were used. Tidal rise/fall information was taken at hourly intervals for the days when DUCK94

¹ CHL Web page: https://chldata.erdc.dren.mil/thredds/catalog/frf/survey_temp/catalog.html

² FRF Data Portal: <https://frf.usace.army.mil/pub/Experiments/DUCK94/FRF/survey/>

experiments were conducted, and spectral wave data were available. These data consist of 2 columns: date-time and tidal elevation (in metres). Unlike the other data, date-time information is based on Greenwich Mean Time Zone (GMT), not EST. This mismatch must be corrected in order to avoid misinterpretation of the data.

The DUCK94 experiment was conducted by the USACE in 1994 with sensors installed at Duck Beach in the Atlantic Ocean. The investigators recorded the measurements of the sensors for about 2 months. The data contains wave condition for a total of 799 different times collected in 114 different days. These wave conditions have a wave height of 0.21m to 3.88m. Duck beach is a sandy beach and covers a range of deepwater wave steepness (H_{rms}/L_o) from 0.0009 to 0.0290 in 799 cases. The data obtained from these measurements have been the subject of many studies in the past as in this study.

2.3. Correction of DUCK94 Datasets

As mentioned in the previous section, there are some errors and omissions in the datasets due to the way the sensors work. These incorrect data should be corrected, and missing data should be completed. In this chapter these processes of correction and completing will be explained.

2.3.1. Correction of Spectral Wave Data

In the simulations performed within the scope of this study, SWAN spectral wave data were used. Therefore, the correctness of the spectral wave data is critically important. However, in the spectrum files, it was observed that the sensors did not work properly and recorded ridiculous values in wave conditions where the frequency value was greater than 0.4 Hz. Therefore, it was necessary to correct the wave data with a frequency above 0.4 Hz. The correcting process was performed by using Python. Winsorizing was preferred as a statistical method. The Winsorizing method was developed by Charles P. Winsor (1895-1951) and is used in statistics to remove extreme data from the data. This method compresses the data between certain percentages. By replacing outliers and extreme values with limit values, it makes the erroneous data more plausible [Dalén, 1987] [Tambay, 1988]. However, in this study, some special modifications were made to the Winsorizing method. For each spectrum

file, the point at which the spectral power density value corresponding to the frequency between 0.3 and 0.4 Hz where starts to give ridiculous values was chosen as the limit value. In order to reduce the repetition of the determined limit value, the spectral power density value was decreased between 1% and 10%. Thus, extreme values are eliminated. and from the limit value onward, the spectral power density values are reduced as if it were a real and natural wave spectrum.

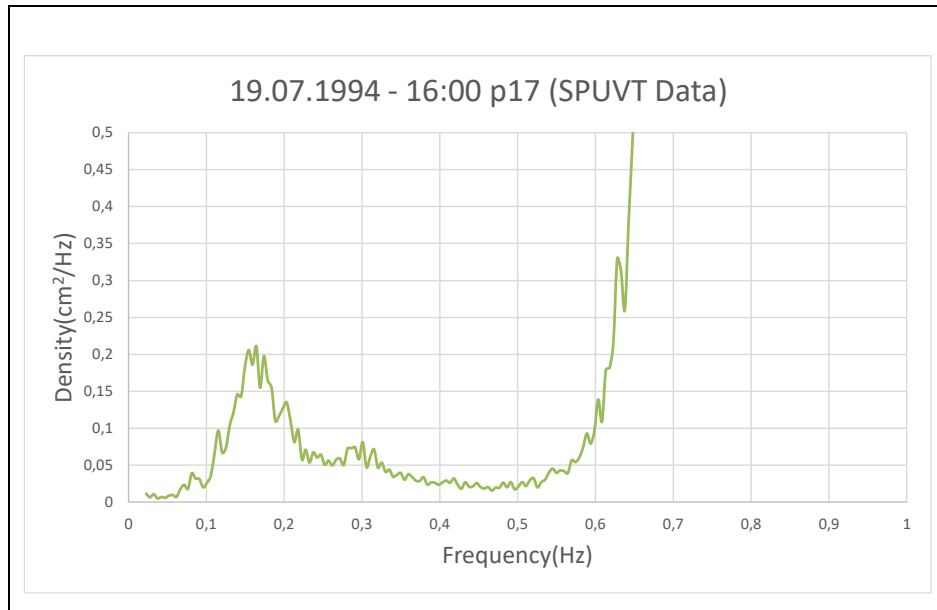


Figure 2.3: Spectral wave data given by DUCK94 sensor p17 date 19.07.1994 – 16:00 (EST).

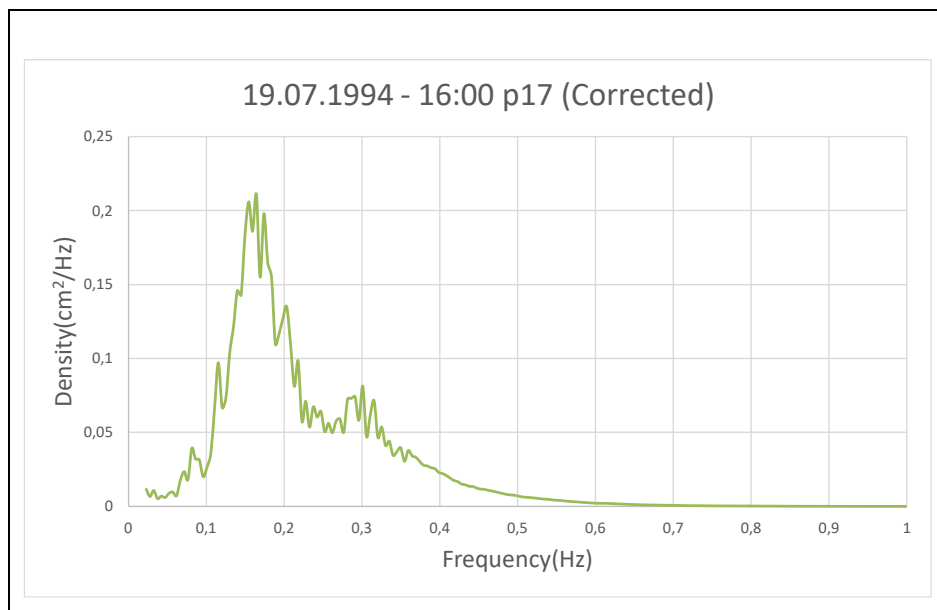


Figure 2.4: Spectral wave data corrected with Python date 19.07.1994 – 16:00 (EST).

Figure 2.3 is the plot drawn by the wave data in the original spectrum files. On the other hand, Figure 2.4 shows wave spectrum data which is corrected by Python with using Winsorizing method. The axis limit in Figure 2.3 has been set at $0.5 \text{ cm}^2/\text{Hz}$ to allow the details to appear properly. The maximum spectral power density at that point is around $3610000 \text{ cm}^2/\text{Hz}$, which is ridiculous. This value increases with distance from the coastline. Figure 2.5 shows the difference between corrected and raw data without correction in offshore measurement location (p87). As can be seen the corrected data follows the original data up to a certain point, after which the frequency approaches one and the intensity approaches zero. The maximum spectral power density in that location is $3.24 \times 10^{22} \text{ cm}^2/\text{Hz}$.

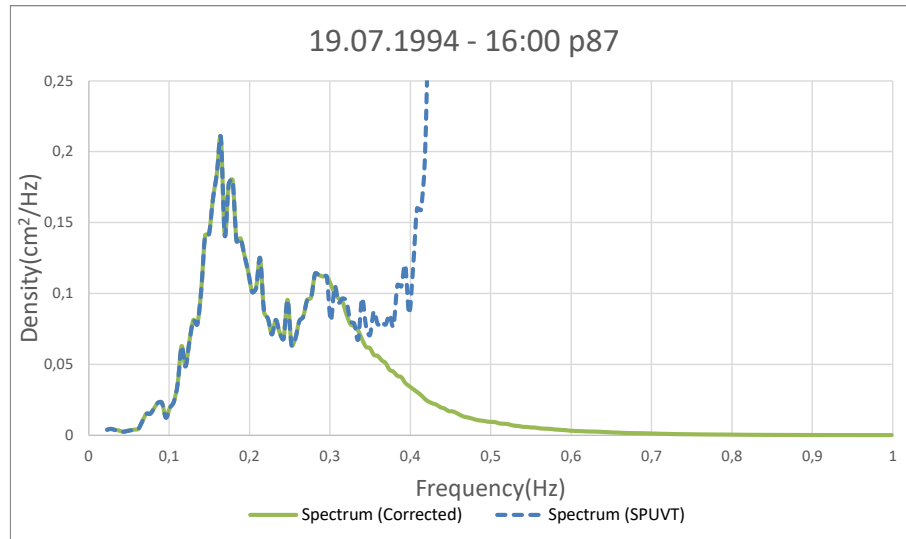


Figure 2.5: Spectral wave data corrected with Python date 19.07.1994 – 16:00 (EST).

The spectral wave datasets are ready for use in SWAN after this correction procedure. SWAN models often employ the offshore site p87 as boundary conditions. If this sensor doesn't have any wave measurements, measurements from other places are used. Since the 1D model was used, the directional information of the wave data was not used in this study.

2.3.2. Correction of Bathymetry Data

The bathymetry data provided by USACE in CHL contains elevation measurements in different locations. The region where the spectrum measurements were taken is located at 929 metres on the longshore axis according to the FRF

coordinate system. However, most of the USACE bathymetry data do not contain data for this point. Bathymetry measurements are available for profiles close to this location (e.g., 860 and 1029). In addition, some profiles do not reach the last measurement point where 885th m on the cross-shore axis. This situation is clearly seen in Figure 2.6. Only profile 1240 reaches 885 metres, while the other profiles are not long enough.

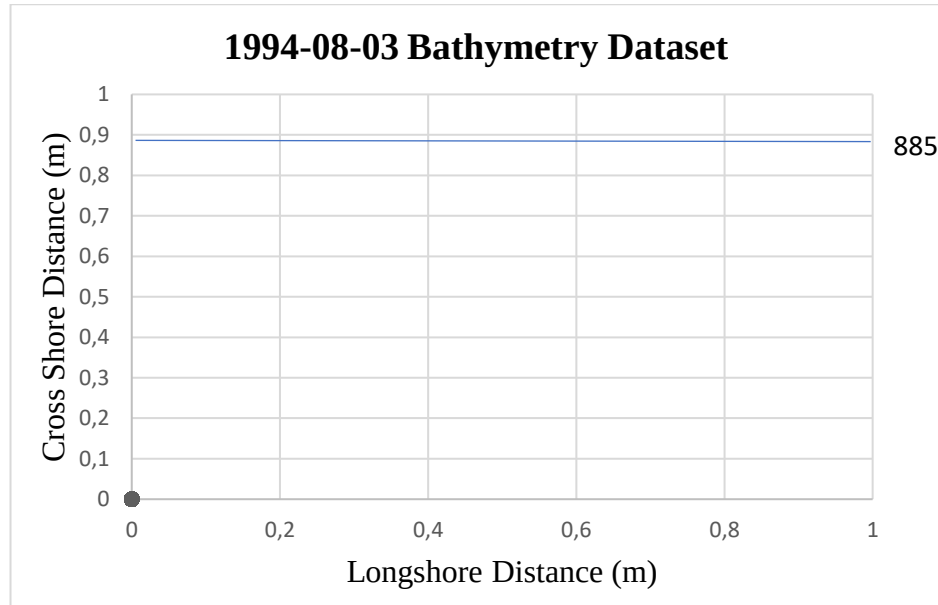


Figure 2.6: Bathymetry data of Duck Beach in 08.03.1994.

In the correction process, firstly the bottom profile in 929th m was determined by interpolation and then this profile was extended to 885 metres in the cross-shore axis. The interpolation method of SciPy, one of the Python libraries, was used for interpolation. This method requires parameters such as an x array, y array, and interpolation type (kind). Linear interpolation was applied as the kind of interpolation to find the profile at the point where the sensors are located. The elevation values of these profiles were determined on the x-axis corresponding to one-meter intervals. The purpose of this operation was to get rid of the differences due to the distances on the x-axis. Thus, python calculated the bottom profile to be used in SWAN at one metre intervals on the x-axis.

Figure 2.7 shows two profiles which located 860 and 1029m in longshore axis dated 03.08.1994. Accordingly, the profile at 929th m should be between these two profiles and should be 69 metres higher than the profile at 860th m and 100 metres lower than the profile at 1029th m. Additionally, at places farther than 433 meters in

cross-shore axis, neither of these two profiles exhibits the bedform. However, the 884th m is the location of the measuring point that is the furthest from the coast which named LOCATION 15 in Table 2.1. In order to extend the profile in the measured and simulated area up to 884 metres, the location information of the pressure gauge at that point (p87) was taken into account.

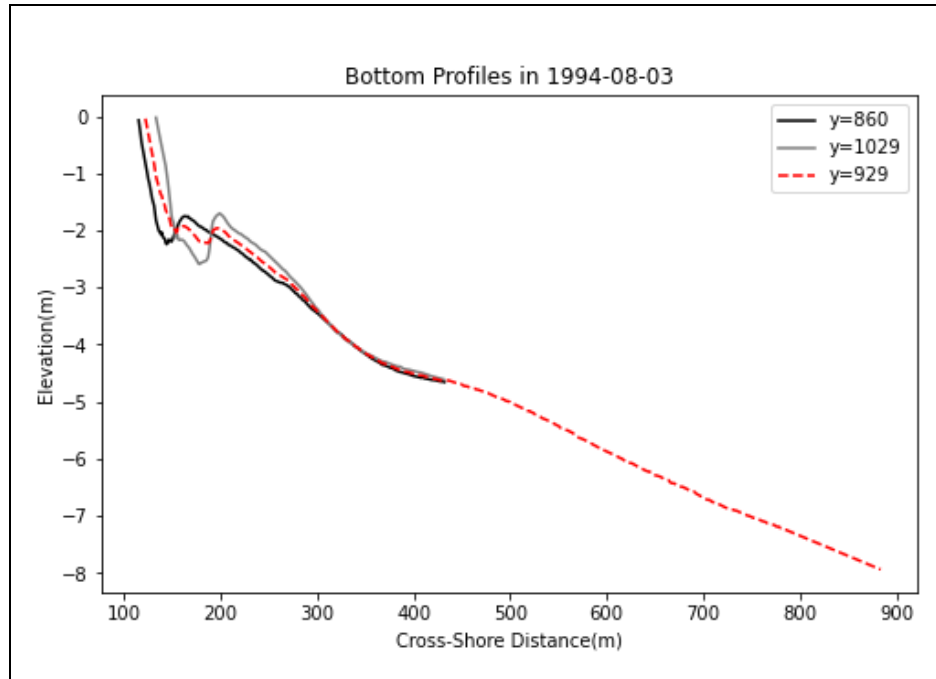


Figure 2.7: Bathymetry data of Duck Beach in 03.08.1994 in different longshore locations and extended profile of the measurement area (dashed).

The bottom profile at Duck Beach varies from day to day according to the wave and tidal conditions. Figure 2.8 shows the variation of 5 bottom profiles of different days. In order to create a simulation as close as possible to the realised conditions, a bottom profile close to the profile at that date should be entered into SWAN. On the other hand, the bathymetry dataset contains bottom profile measurements for 38 different days whereas spectral wave data covers 104 different days. Therefore, in SWAN, the profile of the date with the closest measurement date to the date of the relevant spectrum wave data is used.

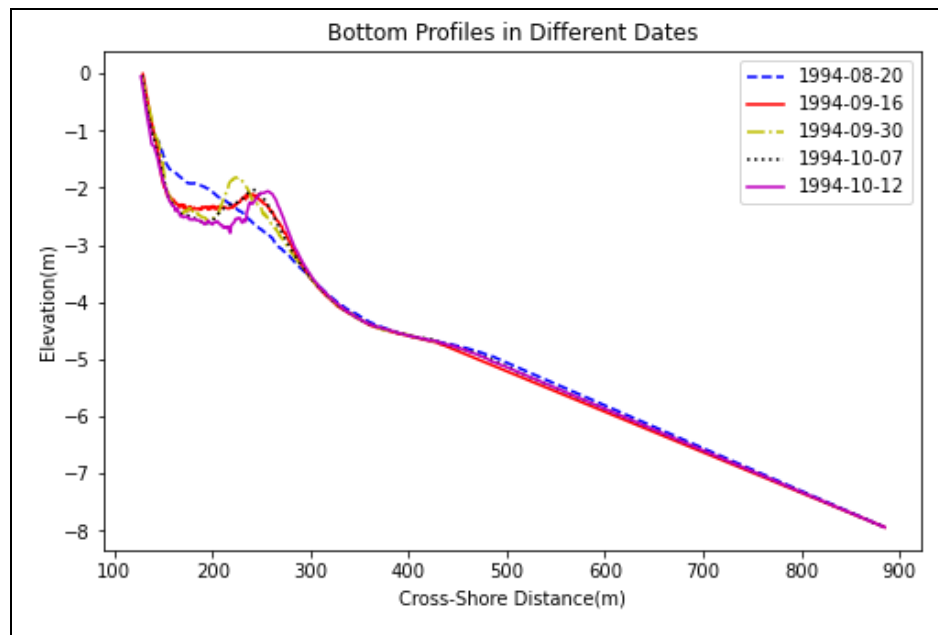


Figure 2.8: Changes in bottom profile on 5 different days at Duck Beach.

3. IMPLEMENTATION OF SWAN MODELS

SWAN is a 3rd generation numerical wave model which uses for estimating the waves accurately. SWAN model can be run in any scale for wind-generated surface gravity waves or with the spectral data of waves. This study is focused on depth-induced wave breaking and nonlinear wave-wave interaction processes in SWAN. Therefore wind-generated wave growth is not used in this study. Instead, the spectral data of the waves were used as boundary conditions and the simulation was performed in this way. In this study all models were run on SWAN version 41.31A. Since SWAN is a numerical modelling tool, it contains some features and requirements that all numerical models contain. In this section, firstly the basic principles of numerical models will be mentioned and then the implementation of SWAN models will be presented. Finally, model comparison parameters used in calibration and verification processes will be explained.

3.1. Basic Principles of Numerical Modelling

The basic principles behind the phenomenon are expressed using numerical wave models. The effectiveness of the numerical wave model depends on how well the phenomena are modelled numerically, allowing for accurate prediction of the wave parameters. The energy balance equation served as the foundation for the SWAN numerical wave models, which took varied inputs from the source function [Thomas and Dwarakish, 2015]. Several choices and assumptions must be made in order to create a spectral wave model in SWAN. This model, for instance, needs to be appropriate for both nearshore and oceanic applications. Because SWAN takes both deep and shallow sea wave mechanisms into account. The other assumption in numerical models is the discretisation of the balance of action equation is that it must be simple, robust, and accurate for calculations in coastal areas. Therefore, in SWAN, a finite difference approach is employed based on the so-called method of lines. This indicates that the decision regarding time integration is unrelated to the decision about spatial discretization. Furthermore, in order to achieve accurate wave shoaling, the finite difference schemes also need to conform to the law of constant energy flux along

the wave ray. This is essential, especially when bathymetry is changing quickly [SWAN Team, 2023b].

3.2. General Model Parameters in SWAN

In SWAN, 5 different model types were created. In these models, different wave parameters are active or passive. These are named as Default, Default + TRIAD, No Dissipation, No Dissipation + TRIAD and Default + Fric. The first model (Default) was used for the calibration of the wave breaking parameter. These Default named models were initially run using the default parameters recommended by SWAN. The results obtained by SWAN were compared with the DUCK94 measurement data and calibration was performed. Detailed descriptions of the various named models are given in Table 3.1.

Table 3.1: Different model types according to SWAN parameters run within the scope of this study.

Model Name	Parameters			
	Breaking	White-Capping	Bottom Friction	TRIAD
Default	Active	Active	Inactive	Inactive
Default + TRIAD	Active	Active	Inactive	Active
No Dissipation	Inactive	Inactive	Inactive	Inactive
No Dissipation + TRIAD	Inactive	Inactive	Inactive	Active
Default + Fric	Active	Active	Active	Inactive

Each model type was run based on wave data at 799 different times. All other parameters not shown in the Table 3.1, such as grid, boundary conditions, bottom profile, etc. are common to each model. The calibration process was performed according to the Default model and the optimum coefficients obtained were applied to all 5 types of models.

As mentioned above, when numerical modelling is performed in SWAN, various parameters of the implemented model are available. These parameters are computational grids, spectral grids, boundary conditions, output requests which will be explained in this section.

3.2.1. Defining the Grids

Grids can be either structured or unstructured in SWAN. Rectilinear and uniform or curvilinear can be used to create structured grids. They are always composed of quadrilaterals with four grid cells meeting at each internal grid point. This number can vary arbitrarily (often between 4 and 10) in unstructured grids. As a result of this, unstructured grids provide a far greater level of flexibility in terms of the distribution of grid points than structured grids. Triangles or a combination of triangles and quadrilaterals, referred to as hybrid grids, may be present in unstructured grids.

Unstructured grids are a good alternative to nested models in SWAN, both in terms of the simplicity with which the mesh resolution may be adjusted optimally and in terms of the work required to produce grids regarding complex geometries, such as islands and irregular shorelines. In coastal areas with wide variations in water depth, these flexible meshes can be very helpful. Therefore, the greatest resolution is provided where it is most required by this variable spatial meshing. With far fewer grid points compared with regular grids, the usage of unstructured grids makes it easier to resolve the model area.

It is necessary to specify two categories of grids and time windows. These are spectral grid, spatial (geographic) grid (time windows in case of nonstationary computations). The user-defined spectral grid is a computational spectral grid on which SWAN runs its calculations. The user-defined spatial grids used in SWAN in this study are as follows:

- A geographic computing grid on which SWAN runs its calculations,
- A spatial output grid needed for the SWAN output [SWAN Team, 2023b].

In this study all SWAN models are run in 1D ($\partial/\partial y \equiv 0$), uniform and rectangular grids. These models meshed $n - 1$ times in which n is the length of bed profile in cross-shore axis as input and output grids. Applying this formula means that each mesh has a length of 1 metre in one dimension. These models do not have a time window, as they do not take into account factors such as currents, wind growth which is time-dependent variables. For investigations of coastal regions, SWAN suggests a spatial resolution (Δx) in the range of 50–1000 m. This survey covers a spatial resolution of 750–765 m. The resolution value may vary for each case.

3.2.2. Defining the Boundaries

SWAN's computational spatial grid has either land or ocean as its boundaries. Land does not produce waves, and in SWAN, it completely absorbs all incoming wave energy. But in the case of an ocean boundaries, as it is frequently unknown what the wave conditions would be along such a boundary, SWAN assumes that no waves will enter the region and that waves will be able to exit it freely. These presumptions have flaws, which are carried over into the model. Therefore, in order to avoid affecting the computations there, these boundaries must be selected to be sufficiently far from the area where accurate calculations are required. There are instances when a reliable estimate of the waves at these boundaries can be made. This is the case if observations (DUCK94 observation data in the present study) or the output of another model run are available [SWAN Team, 2023b].

In this research, the water boundary is implemented. If measurement is available, Location 15 (where the pressure gauge p87 located) is suitable to be used as a boundary condition. This is because this point is far from the other measurement points and outside the surf zone where the wave breaking processes are located. However, in some datasets the sensor at this point did not give data. In these cases, the data of the sensor furthest from the shore was used as the boundary condition.

3.2.3. Defining the Spectral Grid

The computational spectral grid for SWAN must be supplied by the user. Simple minimum and maximum frequencies as well as a frequency resolution proportionate to the frequency are information that are needed to define the frequency domain. Four different ways to define the frequency space are possible. The first option is to select the lowest frequency, the highest frequency, and the number of frequencies. In the second option only the lowest frequency and the number of frequencies are specified. The highest frequency will be calculated by SWAN. In the third option only the highest frequency and the number of frequencies are entered. The lowest frequency will be calculated by SWAN. The last option is to select only the lowest frequency and the highest frequency. SWAN will calculate the number of frequencies.

The lowest frequency must be less than 0.7 times the lowest projected peak frequency, according to the SWAN user manual. The value of highest frequency must

be at least 2.5 to 3 times the highest peak frequency expected. Additionally, SWAN advises selecting a value of less than or equal to 1 Hz.

Within the scope of this project, spectral direction did not consider because all models are run in 1D. A frequency range between 0.04 and 1.4961 was adapted and formulated as exponential as in equation (3.1):

$$\Delta f = 0,01f \quad (3.1)$$

Where Δf is the difference between f_i and f_{i+1} which are the elements of the frequency range. This formula represents an exponentially rising curve. In this study, f_0 (the lowest frequency) is equal to 0.04 Hz and f_{38} is equal to 1.4961 Hz as the highest frequency.

3.2.4. Defining Output Requests

Apart from specifying the physical and spectral domains and their boundaries, output options must be entered into the SWAN model. As output, firstly the points where the results of the calculations are to be seen should be entered into SWAN. These points are the measurement locations given in Table 2.1. SWAN should calculate the spectral wave information at these points so that a comparison with the DUCK94 measurements can be made. With these spectrum energy density information, mean wave height (H_s), mean wave periods (T_{m01}, T_{m02}) can be calculated. These parameters can be calculated with the help of the integration given in equation (1.4).

Requests for the output were given to SWAN and all 799 models were run. These operations were prepared quickly with Python files created during the work of this thesis. An example command file where all this information is given to SWAN is presented in the APPENDICES.

3.3. Statistical Parameters Used in This Study

Different statistical analysis methods were used in this study to evaluate and compare the performance of the models. In this section, the meanings and mathematical explanations of these parameters are given. The values of these parameters will lead to the calibration of the models by comparing the predicted values calculated by SWAN with the measured values within the DUCK94 project. The statistical performance parameters determined are concepts used in previous studies about numerical model such as accuracy, bias, and error rates.

One of them is accuracy. The degree to which a prediction or computation provides a result that conforms to the intended value is known as accuracy. It offers a way to see how well the observation series and predicted series line up. A close match between the predicted and observed values is referred to as high accuracy. Low accuracy, on the other hand, denotes a large disparity between those series and a lack of correlation between the parameters. A high accuracy value is desirable in studies. Pearson's Correlation Coefficient (CC) was used in this study.

Bias refers to the continuous and systematic deviation of the estimate or calculation value. Bias indicates that the difference (negative or positive) between observed values and predicted values is consistent. In other words, it means that the predicted values consistently deviate in the same direction. Low bias values are preferable.

The difference between observational values and predicted values is represented by the other parameter, error rates. Error rates like Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) demonstrate the distance the predictions are from the real-world information. By proportioning these variations using different expressions, some error rates give these differences greater meaning. Low error rates are always desirable.

3.3.1. Pearson's Correlation Coefficient

The Pearson correlation coefficient [Pearson, 1895] is one of the most common ways of measuring a linear correlation in statistics. Correlation coefficient can be a number between -1 and 1 that measures the strength and direction of the relationship between two variables which can be seen in Figure 3.1. 1 refers full correlation

between predicted and measured series. 0 refers no correlation and -1 means negative full correlation.

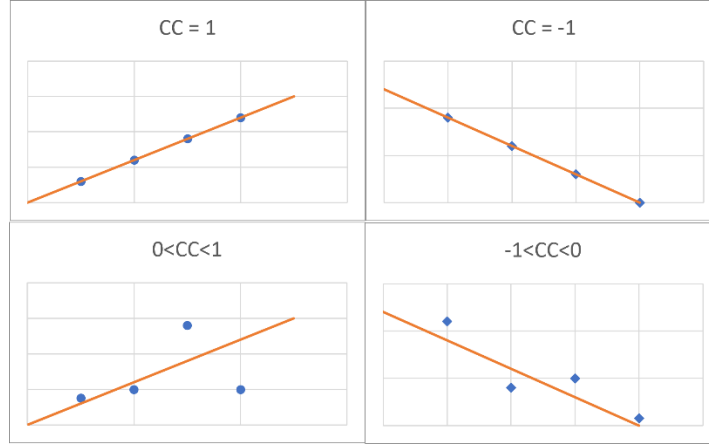


Figure 3.1: Examples of scatter plots with various correlation coefficient values

The Pierson's correlation coefficient can be calculated with the equation below:

$$CC = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (3.2)$$

in which n is the number of measurements, x_i and y_i are values of i^{th} observations. In the equation, $\bar{x}$ and $\bar{y}$ represents the mean of the x and y series respectively. The CC close to +1 indicates the accuracy of the models.

3.3.2. Mean Absolute Error

Mean Absolute Error is the most basic and widely using statistical method that shows the error rate of the models. MAE calculates difference between predicted values and observed values. Formulation of MAE for the n predicted and observed values is given in the equation (3.3).

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (3.3)$$

where y_i is observed value and $\hat{y}_i$ is predicted value. Lower MAE in the models is desirable.

3.3.3. Root Mean Square Error and Normalised RMSE

Root Mean Square Error is the most common statistical method to define accuracy and compare errors between two series. A lower RMSE value indicates that the accuracy of the model is better. RMSE is expressed as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (3.4)$$

where n represents total number of observations or predictions and y_i , $\hat{y}_i$ are individual observed and predicted values respectively. The normalised RMSE (NRMSE) is often used together with the RMSE. Normalisation is usually done by dividing by the range or mean value of the observation values. Here, NRMSE is calculated similarly to RMSE but is divided by the sum of squares of the observation values to normalise the error rate.

$$N - RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i)^2}} \quad (3.5)$$

Where n is total number of observation and y_i , $\hat{y}_i$ are observed and predicted values respectively.

3.3.4. Scatter Index

The scatter index (SI) represents variability, and is used to detect random, non-systematic errors. The SI value describes the precision of the model. A low SI value

means that the models run with high accuracy. The formula for SI is given in the equation below:

$$SI = \sqrt{\frac{\sum_{i=1}^n [(O_i - \tilde{O}) - (P_i - \tilde{P})]^2}{\sum_{i=1}^n (O_i)^2}} \quad (3.6)$$

where O_i is observation value, P_i is predicted value, $\tilde{O}$ and $\tilde{P}$ represent mean of observation series and mean of prediction series respectively.

3.3.5. Bias and Normalised Bias

The difference between a population mean of the measurements or estimated results is known as bias in statistics. The overestimation or underestimate of prediction values in comparison to observation values can also be identified as bias. Negative bias results in overestimation, whereas positive bias results in underestimate. Formulation of bias and normalised bias (N-Bias) is given the equations as follows:

$$Bias = \frac{1}{n} \sum_{i=1}^n y_i - \hat{y}_i \quad (3.7)$$

$$N - Bias = \frac{\sum_{i=1}^n y_i - \hat{y}_i}{\sum_{i=1}^n y_i} \quad (3.8)$$

in which n represent total number of observation data and y_i , $\hat{y}_i$ are actual and predicted values respectively.

In statistics, there are numerous ways for evaluating performance. The approaches listed above, together with their formulations and descriptions, are the ones that are most frequently employed. In other studies, various situations can be addressed using various methodologies. These techniques serve as the foundation for the comparison, calibration, and evaluation of the models in this work.

4. RESULTS AND DISCUSSIONS

In this section, firstly, running the models with the default parameters suggested by SWAN is explained. In these runs, a subset of the wave data from the DUCK94 experiment was used. The results of these runs are presented in the subsequent subsections. These results are compared with measurements using the statistical methods described in the previous sections. The calibration process based on these results is then described. The next subsection is about running SWAN models using the calibrated parameters. In the last subsection, the results of these models are compared with measurements and with the results of running with the default parameters which is recommended by SWAN.

4.1. Running the Models with SWAN Recommended Parameters

SWAN suggests specific default parameters and coefficients to its users. These parameters and values were established in accordance with the findings of many experiments and previous scientific studies.

SWAN considers wave breaking by default unless the user indicates specifically that it is not a breakage calculation. Section 1.2.2.2 contains the parameters α and γ used in SWAN for the calculation of wave breaking energy dissipation where γ is breaker index and α proportionality coefficient of the rate of dissipation. SWAN has set α as 1 and γ as 0.73 as default value.

Since wind wave growth is not used in the models in this study, wind parameters are entered as 0 in terms of speed (m/s) and direction (in degrees).

White capping calculations are included in the calculation by default unless SWAN is switched off by the user. Bottom friction is switched off by default. Therefore, bottom friction is not taken into account in these models.

4.1.1. Default Model Results

For faster calibration and other operations, 207 of the 799 DUCK94 wave conditions were selected and run using the parameters recommended by SWAN. These 207 wave conditions are all September wave conditions. Because the sensors provided

96% of the data this month, the amount of incomplete and erroneous data remained at a minimal. In addition, the highest recorded wave height was 3.88 m and the maximum wave peak period was 10.58 s in this month. In this respect, the waves in September represent the wave conditions taken as basis in the calibration process.

Table 4.1: Statistical results of 207 “Default” wave models with the parameters recommended by SWAN in 15 different locations.

N=207	CC	MAE	RMSE	N-RMSE	SI	Bias	N-Bias
LOCATION 1	0,6650	0,1753	0,2328	0,3656	0,1086	0,011	0,060
LOCATION 2	0,8745	0,0842	0,1440	0,1805	0,0291	-0,016	0,004
LOCATION 3	0,8759	0,1240	0,1799	0,2225	0,0278	-0,109	-0,127
LOCATION 4	0,8906	0,1161	0,1744	0,2136	0,0267	-0,100	-0,118
LOCATION 5	0,9076	0,0983	0,1614	0,1946	0,0260	-0,073	-0,085
LOCATION 6	0,9260	0,1014	0,1595	0,1898	0,0223	-0,084	-0,098
LOCATION 7	0,9315	0,0935	0,1530	0,1789	0,0215	-0,069	-0,079
LOCATION 8	0,9597	0,0705	0,1228	0,1410	0,0145	-0,042	-0,047
LOCATION 9	0,9751	0,0895	0,1539	0,1748	0,0252	-0,007	-0,008
LOCATION 10	0,9814	0,0515	0,0860	0,0964	0,0073	-0,010	-0,012
LOCATION 11	0,9914	0,0386	0,0681	0,0760	0,0042	-0,012	-0,016
LOCATION 12	0,9952	0,0405	0,0601	0,0669	0,0026	-0,028	-0,033
LOCATION 13	0,9945	0,0490	0,1104	0,1226	0,0105	-0,031	-0,037
LOCATION 14	0,9959	0,0522	0,1109	0,1224	0,0109	-0,030	-0,035
LOCATION 15	1,0000	0,0028	0,0037	0,0038	0,0000	0,003	0,003

Table 4.1 shows the result of those 207 models. In shallow water close to the shore (location 1) the correlation is approximately 66% with a normalised root mean square error of just over 36%. In the second location, these rates were calculated as 87% and 18%, respectively. It is obvious that these ratios can be enhanced with a calibrated model given that the majority of wave breaking takes place at these locations. The correlation at location 15, which is given to SWAN as a boundary condition, should typically be close to 1. Since there is no breaking in deep water conditions, SWAN predictions and measurements are close to each other. This situation showed that calibration of the parameters and coefficients of the breaking should be performed.

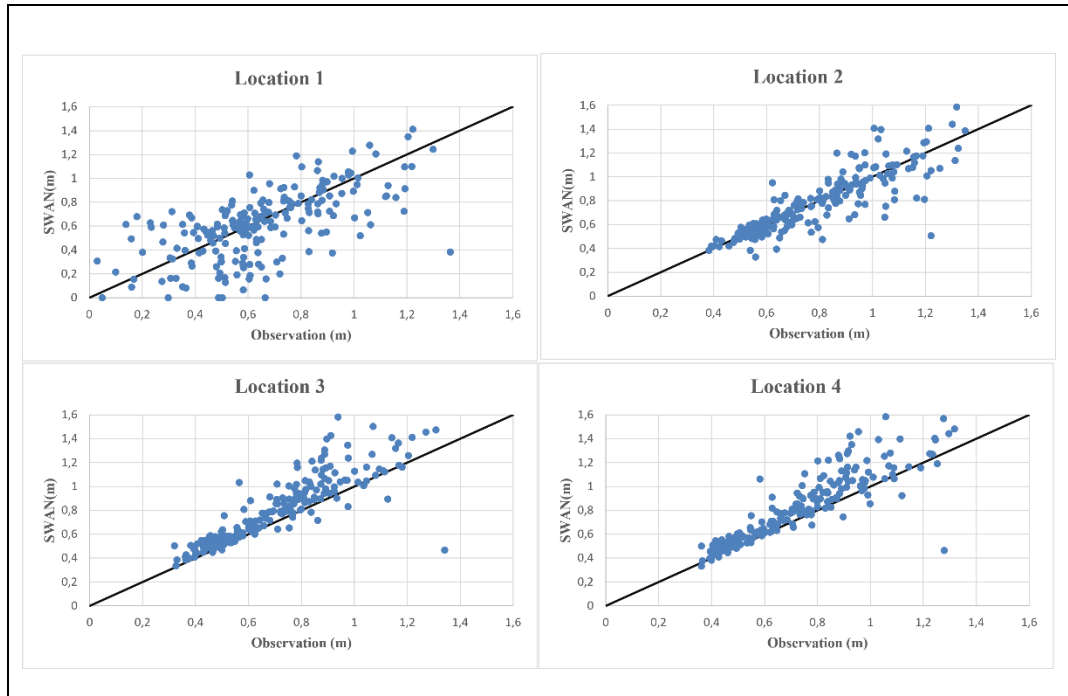


Figure 4.1: Comparison of significant wave heights of 4 locations in the shallowest water in “Default Model” with observations (N=207).

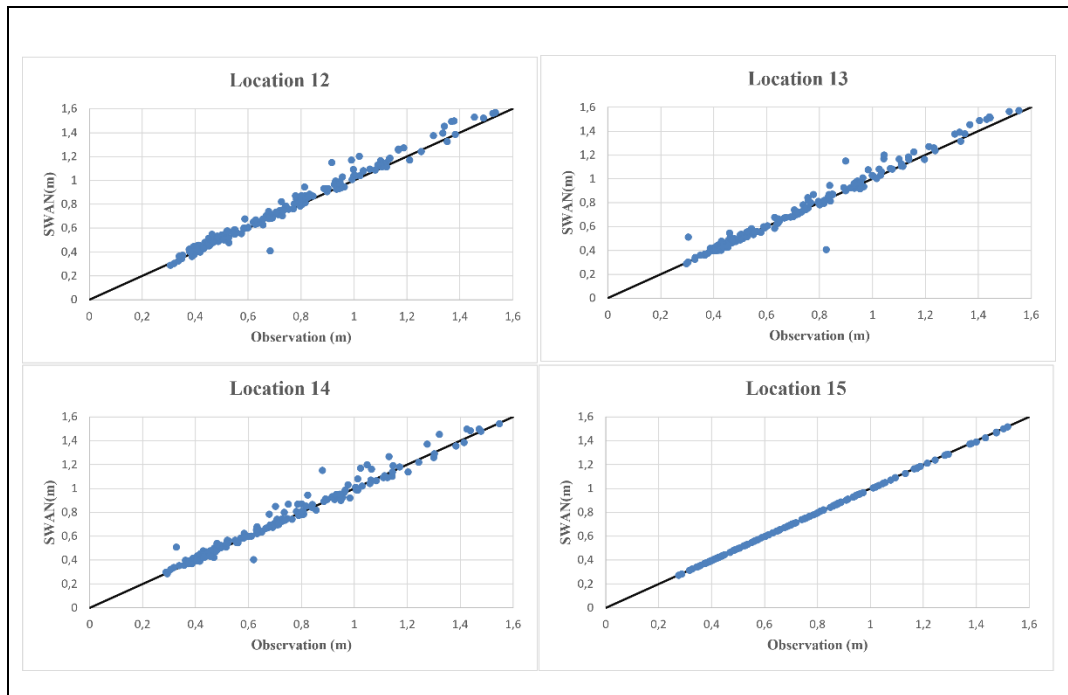


Figure 4.2: Comparison of significant wave heights of 4 locations in the deepest water in “Default Model” with observations (N=207).

Figure 4.1 shows high deviations between the significant wave heights calculated by SWAN and measured by the sensors in shallow water conditions. Predicted wave heights are important for the planning of coastal structures. Therefore,

high deviations in wave heights may cause critical problems in the design of coastal structures. In addition, waves dissipate most of their energy at the moment of breaking. Therefore, the accuracy of wave height predictions in the surf zone, where wave breaking occurs intensively, is of critical importance. On the other hand, outside the surf zone of Figure 4.2 (i.e. between locations 12-15) the accuracy of the predictions is close to 100%.



Figure 4.3: Comparison of significant wave heights of 3 locations in the shallowest water as time-series in “Default Model” with observations (N=207).

In Figure 4.3, wave heights are given as time series for the 3 shallowest locations. At these 3 points SWAN overestimated the wave height. This is an expected result. According to studies in the past, SWAN overestimates the wave height and underestimates the periods [Amarouche, Khalid, et al., 2019]. Figure 4.3 shows that

on 1994-09-18, a single model showed unexpectedly high wave height. These and similar outliers are analysed in subsection 4.3.

4.1.2. Other Model Results

In this subsection, the models modified with wave breaking and triad wave-wave interaction parameters which are named as “Default + TRIAD”, “No Dissipation” and “No Dissipation + TRIAD” are examined and compared their results with the “Default Model”. Explanations of these naming schemes are given in Table 3.1.

The exchange of energy between resonant sets of wave components, which redistributes energy over the spectrum, is the physical meaning of wave-wave interactions. Three-wave interactions, or TRIAD in SWAN, are significant in shallow water, but four-wave interactions, or QUAD in SWAN, are significant in deep and intermediate water. In shallow water, triad wave-wave interactions transfer energy from low frequency waves to high frequency waves [SWAN Team, 2023b].

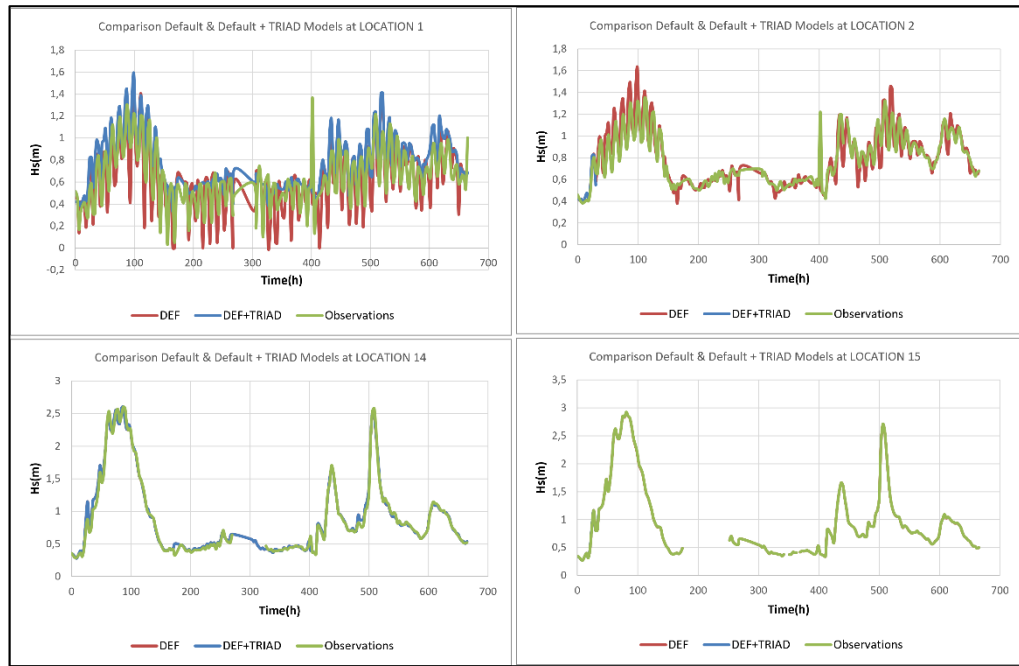


Figure 4.4: Comparison of significant wave heights of 4 locations in shallow and deep water of the 207 different “Default Model”, “Default + TRIAD Model” and observations.

As clearly seen in Figure 4.4, The triple wave-wave interaction did not cause any change in significant wave height in deep water (locations 14 and 15), while significant

wave heights in shallow water (locations 1 and 2) decreased according to the "Default Model". This shows that the triad has no effect in deep water.

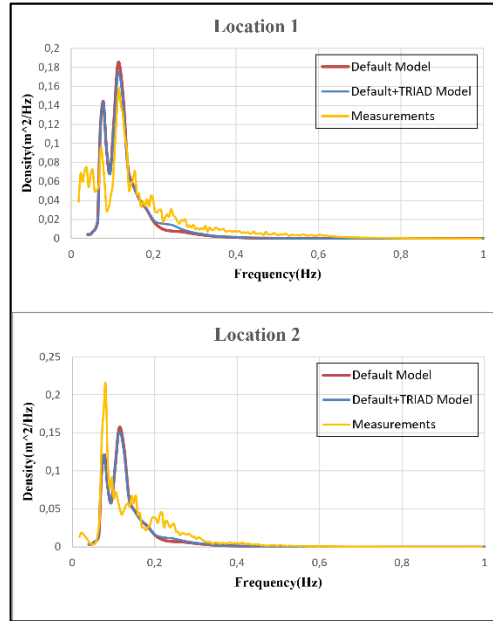


Figure 4.5: Model #09010100 - Comparison of frequency and energy density of 2 locations in shallow water of the “Default Model” and “Default + TRIAD Model”.

Figure 4.5. shows the energy transfer from low frequency to high frequency with triad effect. In the Figure 4.5, the energy density at a frequency of 0.1141 Hz is reduced by the triad effect in SWAN. On the other hand, at the point where the frequency is around 0.2 Hz, the energy density increased in the model where the triad effect is taken into account. The triad effect is solely responsible for the shift in energy at these places. Because the addition of the "TRIAD" command in SWAN is the only distinction between the two variants.

Again, the change due to breaking in shallow water is shown in Figure 4.6 (on the left side). Wave breaking at Location 1 and Location 2 reduced the spectrum energy density. The "No Dissipation" model without breaking dissipation has a higher energy than the "Default Model". The Figure 4.6 demonstrated that SWAN takes into account the breaking energy dissipation in the current model.

The spectrum charts on the right side of Figure 4.6 show the "No Dissipation + TRIAD Model" where no dissipation is taken into account, but triad wave-wave interactions are taken into account. The triad effect is also realised in the same way, transferring energy from low to high frequency.

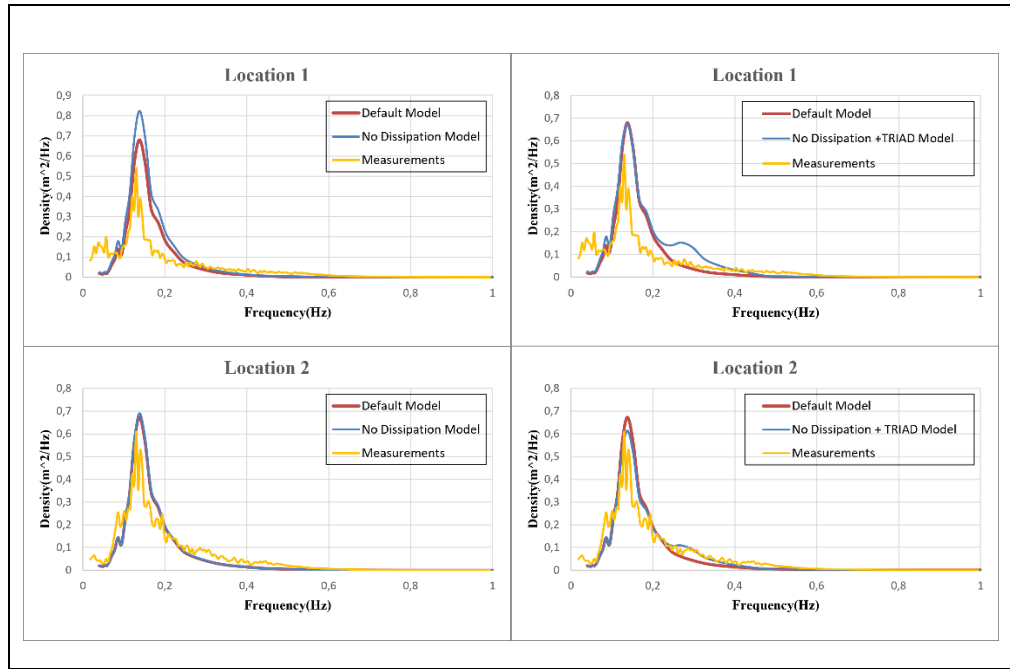


Figure 4.6: Model #09200400 - Comparison of frequency and energy density of 2 locations in shallow water of the “Default Model”, “No Dissipation Model” and “No Dissipation + TRIAD Model”.

The statistical comparison of "Default + TRIAD Model" with DUCK94 measurements is given in Table 4.2. Although the correlation and root mean square error values are similar to the "Default Model", the increase in the scatter index value indicates an increase in the random error rate. It is not correct to say that the triad effect brings the current model, run with the values recommended by SWAN, closer to the observation values. On the contrary, it increased the error rate of the model. Nevertheless, this comparison will be repeated after calibration process.

In “No Dissipation” models, in addition to neglecting the breaking effect, the white capping effect is included in the models. However, it is seen that white capping dissipation is not effective without including wind data.

It was mentioned in subsection 1.2.2.2 that in SWAN, breaking can be modelled with constant or variable parameters. In SWAN, the BKD variable breaking parameter uses 3 tuneable coefficients (a_1 , a_2 , a_3) in addition to the alpha (α) and gamma (γ) coefficients as in the constant parameter. While the default value of alpha does not change when calculating with BKD, however the default value of gamma is 0.54. Default values of tuneable parameters are 7.59, -8.06 and 8.09 respectively. 207 The model was also run with the default values of the BKD parameter and the statistical results in Table 4.3 were obtained.

As seen in the Table 4.2 and Table 4.3, the correlation values of the Default + TRIAD and BKD models, which are among the uncalibrated models, slightly decreased compared to the Default model. However, no significant changes were observed in RMSE, MAE and SI values.

Table 4.2: Statistical results of 207 “Default + TRIAD” wave models with the parameters recommended by SWAN in 15 different locations.

DEFAULT + TRIAD (CONSTANT)					
	CC	MAE	RMSE	SI	Bias
LOCATION 1	0,6416	0,1752	0,2326	0,1159	0,037
LOCATION 2	0,8591	0,0856	0,1436	0,0309	0,003
LOCATION 3	0,8761	0,1196	0,1714	0,0261	-0,102
LOCATION 4	0,8914	0,1131	0,1670	0,0251	-0,096
LOCATION 5	0,9074	0,0973	0,1565	0,0248	-0,070
LOCATION 6	0,9244	0,1017	0,1563	0,0217	-0,082
LOCATION 7	0,9290	0,0941	0,1515	0,0214	-0,067
LOCATION 8	0,9581	0,0714	0,1225	0,0146	-0,041
LOCATION 9	0,9712	0,0942	0,1608	0,0275	-0,007
LOCATION 10	0,9804	0,0529	0,0880	0,0077	-0,010
LOCATION 11	0,9911	0,0401	0,0699	0,0044	-0,014
LOCATION 12	0,9953	0,0418	0,0613	0,0026	-0,030
LOCATION 13	0,9946	0,0497	0,1108	0,0104	-0,033
LOCATION 14	0,9960	0,0520	0,1108	0,0107	-0,032
LOCATION 15	1,0000	0,0028	0,0037	0,0000	0,003

Table 4.3: Statistical results of 207 BKD wave models with the parameters recommended by SWAN in 15 different locations.

DEFAULT BKD					
	CC	MAE	RMSE	SI	Bias
LOCATION 1	0,6374	0,1917	0,2481	0,1201	0,005
LOCATION 2	0,8855	0,0736	0,1261	0,0249	0,013
LOCATION 3	0,8573	0,0794	0,1187	0,0260	-0,007
LOCATION 4	0,8754	0,0778	0,1160	0,0242	0,000
LOCATION 5	0,8786	0,0759	0,1254	0,0258	0,028
LOCATION 6	0,8922	0,0830	0,1297	0,0275	0,017

Table 4.3: Statistical results of 207 BKD wave models with the parameters recommended by SWAN in 15 different locations. (Continue)

LOCATION 7	0,8925	0,0830	0,1473	0,0327	0,029
LOCATION 8	0,9387	0,0696	0,1325	0,0229	0,032
LOCATION 9	0,9397	0,1325	0,2353	0,0667	0,038
LOCATION 10	0,9774	0,0565	0,0941	0,0089	-0,012
LOCATION 11	0,9787	0,0597	0,1264	0,0164	0,027
LOCATION 12	0,9807	0,0638	0,1263	0,0168	0,018
LOCATION 13	0,9816	0,0717	0,1551	0,0255	0,010
LOCATION 14	0,9883	0,0746	0,1487	0,0225	-0,001
LOCATION 15	1,0000	0,0028	0,0038	0,0000	0,003

4.2. Calibration of Breaking Parameter

In order for the significant wave heights estimated by SWAN to give results closer to the observations, the breaking parameter was tested by trial-and-error method with various values as constant (hereinafter abbreviated CON) and variable breaker index scales with both the bottom slope (β) and the dimensionless depth (kd) (hereinafter abbreviated BKD).

Models with the CON parameter have 2 calibrated values. These are the alpha and gamma values described in the previous section. A value between 0.45 and 1.5 was selected for the alpha coefficient, while various values between 0.2 and 1.05 were selected for the gamma coefficient and the models were run. Values between 0.5 and 2.0 for the alpha coefficient and between 0.25 and 1.0 for the gamma coefficient were selected and evaluated for the BKD models. In addition, the BKD models also contain 3 different tuneable coefficients, the alpha and gamma values were first calibrated in these models, and after, the other coefficients were calibrated including the values recommended by SWAN to define the most appropriate coefficients for the observation values.

4.2.1. Results of CON Models

Since the main objective of this study is to estimate the energy dissipated by the wave breaking mechanism, which occurs mostly in shallow water, among the

calibrated models, the models that provide high accuracy and low error rates for Location 1 and Location 2, where the breaking is the most frequent, were preferred.

Statistical results for different CON models are given in between Table 4.4 and Table 4.11. These results belong to 207 models selected as examples. When the statistical values in the tables between Table 4.4 and Table 4.11 are examined, the correlation coefficient of 0.65 in the model using the values recommended by SWAN increased to approximately 0.66 in the calibrated models in location 1. Since the correlation values are approximately the same, the most optimal model can be determined by looking at the MAE and RMSE error values. According to the MAE and RMSE error values, the best calibrated model is the CON 0.82 0.65 model shown in Table 4.9. While the MAE value was 0.17 and the RMSE value was 0.24 in DUCK94 wave conditions according to default model, RMSE value decreased to 0.23, in the calibrated model. In addition, the SI value of the calibrated model is 0.12, which shows that the increase in model accuracy is not random.

Although many models were developed with different alpha and gamma values in CON models, 7 models with the highest accuracy were presented in the tables below.

Table 4.4: Statistical result of 207 sample models with recommended alpha and gamma value and CON parameter.

CON 1.0 0.73 (DEF)	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6504	0,8745	0,8759	0,8906	0,9076	0,9260	0,9315	0,9597	0,9751	0,9814	0,9914	0,9952	0,9945	0,9959	1,0000
	MAE	0,1753	0,0842	0,1240	0,1161	0,0983	0,1014	0,0935	0,0705	0,0895	0,0515	0,0386	0,0405	0,0490	0,0522	0,0028
	RMSE	0,2382	0,1440	0,1799	0,1744	0,1614	0,1595	0,1530	0,1228	0,1539	0,0860	0,0681	0,0601	0,1104	0,1109	0,0037
	SI	0,1086	0,0291	0,0278	0,0267	0,0260	0,0223	0,0215	0,0145	0,0252	0,0073	0,0042	0,0026	0,0105	0,0109	0,0000
	Bias	0,011	-0,016	-0,109	-0,100	-0,073	-0,084	-0,069	-0,042	-0,007	-0,010	-0,012	-0,028	-0,031	-0,030	0,003

Table 4.5: Statistical result of 207 sample models with CON 0.5 0.65 parameter.

CON 0.5 0.65	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6825	0,8960	0,8788	0,8949	0,9112	0,9308	0,9348	0,9635	0,9738	0,9834	0,9923	0,9948	0,9941	0,9953	1,0000
	MAE	0,1919	0,0831	0,1130	0,1042	0,0868	0,0901	0,0811	0,0618	0,1006	0,0494	0,0351	0,0365	0,0474	0,0537	0,0028
	RMSE	0,2519	0,1503	0,1683	0,1593	0,1443	0,1395	0,1328	0,1062	0,1634	0,0827	0,0638	0,0570	0,1096	0,1129	0,0037
	SI	0,1154	0,0267	0,0260	0,0238	0,0225	0,0186	0,0182	0,0116	0,0288	0,0064	0,0038	0,0027	0,0110	0,0118	0,0000
	Bias	-0,009	-0,048	-0,098	-0,089	-0,060	-0,069	-0,052	-0,032	-0,006	-0,019	-0,006	-0,018	-0,023	-0,024	0,003

Table 4.6: Statistical result of 207 sample models with CON 0.5 0.75 parameter.

CON 0.5 0.75	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6936	0,8875	0,8693	0,8857	0,9087	0,9320	0,9403	0,9650	0,9856	0,9838	0,9931	0,9955	0,9946	0,9961	1,0000
	MAE	0,2219	0,1242	0,1583	0,1479	0,1246	0,1235	0,1085	0,0864	0,0809	0,0670	0,0451	0,0482	0,0563	0,0535	0,0028
	RMSE	0,2862	0,2094	0,2339	0,2242	0,2035	0,1952	0,1785	0,1503	0,1259	0,1180	0,0857	0,0811	0,1208	0,1124	0,0037
	SI	0,1165	0,0370	0,0391	0,0367	0,0342	0,0280	0,0246	0,0175	0,0136	0,0099	0,0055	0,0043	0,0112	0,0102	0,0000
	Bias	-0,069	-0,104	-0,148	-0,138	-0,106	-0,113	-0,094	-0,071	-0,042	-0,052	-0,031	-0,040	-0,043	-0,039	0,003

Table 4.7: Statistical result of 207 sample models with CON 1.0 0.65 parameter.

CON 1.0 0.65	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6492	0,8823	0,8755	0,8917	0,9019	0,9174	0,9159	0,9487	0,9456	0,9732	0,9874	0,9909	0,9904	0,9928	1,0000
	MAE	0,1746	0,0758	0,0873	0,0803	0,0729	0,0774	0,0749	0,0621	0,1293	0,0602	0,0442	0,0447	0,0550	0,0635	0,0028
	RMSE	0,2355	0,1303	0,1296	0,1225	0,1168	0,1169	0,1264	0,1140	0,2261	0,1101	0,0902	0,0784	0,1228	0,1269	0,0038
	SI	0,1215	0,0263	0,0219	0,0200	0,0198	0,0186	0,0220	0,0166	0,0609	0,0132	0,0081	0,0061	0,0151	0,0159	0,0000
	Bias	0,062	0,015	-0,055	-0,047	-0,019	-0,028	-0,011	0,008	0,032	0,014	0,012	-0,002	-0,008	-0,012	0,003

Table 4.8: Statistical result of 207 sample models with CON 0.7 0.65 parameter.

CON 0.7 0.65	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6673	0,8932	0,8784	0,8946	0,9079	0,9253	0,9265	0,9574	0,9615	0,9795	0,9904	0,9933	0,9926	0,9943	1,0000
	MAE	0,1799	0,0737	0,0980	0,0899	0,0773	0,0818	0,0760	0,0591	0,1148	0,0526	0,0378	0,0391	0,0498	0,0578	0,0028
	RMSE	0,2389	0,1332	0,1461	0,1377	0,1266	0,1239	0,1249	0,1038	0,1936	0,0902	0,0738	0,0644	0,1141	0,1185	0,0037
	SI	0,1155	0,0250	0,0231	0,0210	0,0202	0,0176	0,0190	0,0128	0,0427	0,0085	0,0053	0,0039	0,0125	0,0135	0,0000
	Bias	0,023	-0,017	-0,077	-0,068	-0,040	-0,049	-0,031	-0,012	0,013	-0,003	0,003	-0,010	-0,016	-0,018	0,003

Table 4.9: Statistical result of 207 sample models with CON 0.82 0.65 parameter.

CON 0.82 0.65	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6574	0,8884	0,8773	0,8935	0,9050	0,9213	0,9209	0,9530	0,9533	0,9764	0,9889	0,9921	0,9916	0,9936	1,0000
	MAE	0,1759	0,0737	0,0916	0,0842	0,0745	0,0787	0,0749	0,0598	0,1228	0,0561	0,0409	0,0419	0,0523	0,0607	0,0028
	RMSE	0,2338	0,1297	0,1362	0,1284	0,1201	0,1189	0,1246	0,1080	0,2112	0,0999	0,0820	0,0713	0,1182	0,1226	0,0038
	SI	0,1181	0,0253	0,0222	0,0202	0,0197	0,0179	0,0204	0,0145	0,0521	0,0107	0,0067	0,0049	0,0137	0,0146	0,0000
	Bias	0,044	0,000	-0,065	-0,056	-0,028	-0,037	-0,020	-0,001	0,024	0,006	0,008	-0,006	-0,012	-0,015	0,003

Table 4.10: Statistical result of 207 sample models with CON 1.35 0.65 parameter.

CON 1.35 0.65	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6363	0,8665	0,8714	0,8875	0,8952	0,9089	0,9053	0,9392	0,9296	0,9656	0,9839	0,9881	0,9878	0,9910	1,0000
	MAE	0,1785	0,0836	0,0817	0,0769	0,0723	0,0782	0,0774	0,0689	0,1414	0,0696	0,0510	0,0506	0,0608	0,0688	0,0028
	RMSE	0,2403	0,1386	0,1212	0,1157	0,1153	0,1181	0,1339	0,1294	0,2533	0,1326	0,1072	0,0941	0,1334	0,1366	0,0038
	SI	0,1298	0,0297	0,0222	0,0205	0,0209	0,0210	0,0262	0,0219	0,0791	0,0195	0,0116	0,0090	0,0183	0,0187	0,0000
	Bias	0,097	0,041	-0,038	-0,030	-0,003	-0,012	0,006	0,025	0,049	0,028	0,020	0,005	-0,001	-0,006	0,003

Table 4.11: Statistical result of 207 sample models with CON 1.5 1.0 parameter.

CON 1.5 1.0	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6707	0,8843	0,8633	0,8805	0,9064	0,9314	0,9401	0,9618	0,9845	0,9809	0,9897	0,9929	0,9924	0,9950	1,0000
	MAE	0,2023	0,1307	0,1944	0,1827	0,1570	0,1535	0,1334	0,1077	0,0891	0,0870	0,0689	0,0684	0,0736	0,0639	0,0027
	RMSE	0,2593	0,2184	0,2825	0,2722	0,2485	0,2368	0,2148	0,1847	0,1317	0,1576	0,1434	0,1335	0,1543	0,1277	0,0037
	SI	0,1085	0,0395	0,0493	0,0468	0,0438	0,0360	0,0311	0,0237	0,0122	0,0161	0,0138	0,0112	0,0161	0,0118	0,0000
	Bias	-0,046	-0,109	-0,185	-0,173	-0,139	-0,143	-0,121	-0,094	-0,063	-0,074	-0,055	-0,061	-0,062	-0,051	0,003

4.1.2. Results of BKD Models

Following the calibration of the CON models, the calibration of the BKD type models, which are shown by SWAN as an alternative in the wave breaking process, was carried out. Tables between 12 and 19 shows 8 different model type with using BKD breaking parameter.

Table 4.12 shows BKD model with recommended values of alpha, gamma, a1, a2 and a3. SWAN user manual recommends alpha 1.0 gamma 0.54. The values of a1, a2 and a3, which are the first, second and third tuneable coefficients for breaker index, are 7.59, -8.06, 8.09, respectively. The models are named with the alpha, gamma and tuneable parameter values they take next to the BKD prefix. +RTC is the abbreviation for recommended tuneable coefficient and indicates that tuneable parameters are used as default values.

Table 4.13 shows the results for models calibrated with alpha and gamma values of 0.5. In this model, the calibration coefficient was 0.67 but the RMSE value increased to 0.26. While the scatter index value was 0.12 in the model created using the default coefficients in SWAN, it decreased to 0.11 in this model.

Table 4.14, Table 4.15, Table 4.16 and Table 4.17 show the models calibrated with different values of gamma, where the alpha value is kept as 1. Accordingly, the calibration coefficient value decreased when the gamma value was less than 0.5. In the model with a gamma value of 0.6, the calibration coefficient was 0.66, while in the model with a gamma value of 1.5, the calibration coefficient approached 0.7. However, it is seen that RMSE and MAE values are high in the model where gamma is 1.5.

In Table 4.18 and Table 4.19, the models where the alpha value of the variable breaking parameter is 1.1 and the gamma value is taken as 0.45 and 0.46 can be compared. When these models were compared with the default model, it was observed that the RMSE and MAE values decreased in the calibrated models. On the other hand, calibration coefficient and scatter index values decreased.

The following tables show the results of the default model and 7 calibrated models. These values are the results of the models that give the highest accuracy among 28 different BKD calibration models in total. However, it is not clear which of these 7 models is closest to the observed values. Therefore, these models will be shown in Taylor diagrams and the model closest to the observation values will be preferred.

Table 4.12: Statistical result of 207 sample models with recommended alpha and gamma value in BKD parameter. (#12)

BKD DEF (1 0.54) + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6374	0,8855	0,8573	0,8754	0,8786	0,8922	0,8925	0,9387	0,9397	0,9774	0,9787	0,9807	0,9816	0,9883	1,0000
	MAE	0,1917	0,0736	0,0794	0,0778	0,0759	0,0830	0,0830	0,0696	0,1325	0,0565	0,0597	0,0638	0,0717	0,0746	0,0028
	RMSE	0,2481	0,1261	0,1187	0,1160	0,1254	0,1297	0,1473	0,1325	0,2353	0,0941	0,1264	0,1263	0,1551	0,1487	0,0038
	SI	0,1201	0,0249	0,0260	0,0242	0,0258	0,0275	0,0327	0,0229	0,0667	0,0089	0,0164	0,0168	0,0255	0,0225	0,0000
	Bias	0,005	0,013	-0,007	0,000	0,028	0,017	0,029	0,032	0,038	-0,012	0,027	0,018	0,010	-0,001	0,003

Table 4.13: Statistical result of 207 sample models with BKD 0.5 and 0.5 parameters. (#14)

BKD 0.5 0.5 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6737	0,8973	0,8722	0,8893	0,8981	0,9157	0,9202	0,9590	0,9669	0,9824	0,9831	0,9847	0,9852	0,9900	1,0000
	MAE	0,2042	0,0715	0,0780	0,0736	0,0706	0,0747	0,0709	0,0546	0,1099	0,0519	0,0545	0,0589	0,0670	0,0719	0,0028
	RMSE	0,2639	0,1292	0,1194	0,1141	0,1143	0,1139	0,1227	0,1010	0,1867	0,0853	0,1128	0,1127	0,1449	0,1421	0,0038
	SI	0,1125	0,0231	0,0226	0,0206	0,0207	0,0195	0,0215	0,0128	0,0396	0,0068	0,0129	0,0132	0,0220	0,0205	0,0000
	Bias	-0,043	-0,022	-0,032	-0,025	0,002	-0,010	0,000	0,002	0,013	-0,021	0,024	0,014	0,006	-0,003	0,003

Table 4.14: Statistical result of 207 sample models with BKD 1.0 and 0.4 parameters. (#22)

BKD 1.0 0.4 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,5901	0,8308	0,7769	0,7988	0,7951	0,8108	0,8209	0,8934	0,8809	0,9459	0,9235	0,9231	0,9278	0,9483	1,0000
	MAE	0,1799	0,1431	0,1280	0,1308	0,1442	0,1386	0,1404	0,1350	0,1864	0,0899	0,1174	0,1190	0,1260	0,1250	0,0029
	RMSE	0,2388	0,1998	0,1856	0,1908	0,2149	0,2184	0,2388	0,2302	0,3417	0,1798	0,2603	0,2633	0,2774	0,2678	0,0042
	SI	0,1315	0,0514	0,0628	0,0623	0,0675	0,0762	0,0864	0,0692	0,1631	0,0372	0,0803	0,0845	0,0943	0,0829	0,0000
	Bias	0,072	0,131	0,106	0,112	0,138	0,124	0,132	0,125	0,121	0,056	0,093	0,080	0,070	0,052	0,003

Table 4.15: Statistical result of 207 sample models with BKD 1.0 and 0.6 parameters.

BKD 1.0 0.6 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6626	0,8974	0,8753	0,8920	0,9006	0,9166	0,9185	0,9561	0,9646	0,9831	0,9886	0,9906	0,9904	0,9936	1,0000
	MAE	0,2045	0,0779	0,0860	0,0792	0,0727	0,0772	0,0733	0,0574	0,1106	0,0550	0,0413	0,0454	0,0548	0,0599	0,0028
	RMSE	0,2648	0,1375	0,1277	0,1208	0,1159	0,1161	0,1245	0,1043	0,1856	0,0916	0,0825	0,0798	0,1223	0,1218	0,0037
	SI	0,1169	0,0236	0,0219	0,0200	0,0201	0,0189	0,0214	0,0135	0,0387	0,0070	0,0068	0,0063	0,0149	0,0144	0,0000
	Bias	-0,035	-0,039	-0,052	-0,043	-0,014	-0,024	-0,010	-0,003	0,008	-0,032	0,007	-0,002	-0,009	-0,016	0,003

Table 4.16: Statistical result of 207 sample models with BKD 1.0 and 0.35 parameters. (#23)

BKD 1.0 0.35 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,5542	0,7737	0,7105	0,7355	0,7308	0,7500	0,7687	0,8585	0,8432	0,9217	0,8861	0,8830	0,8890	0,9170	1,0000
	MAE	0,1920	0,1962	0,1707	0,1736	0,1918	0,1818	0,1848	0,1774	0,2191	0,1158	0,1444	0,1438	0,1509	0,1475	0,0031
	RMSE	0,2510	0,2531	0,2320	0,2387	0,2649	0,2677	0,2879	0,2813	0,3906	0,2288	0,3140	0,3173	0,3288	0,3201	0,0049
	SI	0,1505	0,0780	0,0948	0,0951	0,1027	0,1159	0,1292	0,1076	0,2297	0,0629	0,1255	0,1317	0,1416	0,1259	0,0000
	Bias	0,110	0,189	0,157	0,163	0,189	0,174	0,182	0,171	0,162	0,088	0,123	0,109	0,097	0,075	0,003

Table 4.17: Statistical result of 207 sample models with BKD 1.0 and 1.5 parameters.

BKD 1.0 1.5 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6966	0,8117	0,7779	0,7961	0,8447	0,8855	0,9142	0,9359	0,9819	0,9577	0,9815	0,9877	0,9881	0,9936	1,0000
	MAE	0,3076	0,2586	0,3102	0,2946	0,2593	0,2505	0,2249	0,1912	0,1457	0,1475	0,0841	0,0779	0,0812	0,0675	0,0028
	RMSE	0,3988	0,4422	0,5290	0,5168	0,4792	0,4570	0,4210	0,3823	0,2490	0,3213	0,1982	0,1698	0,1797	0,1371	0,0037
	SI	0,1638	0,1045	0,1406	0,1368	0,1259	0,1101	0,0948	0,0802	0,0295	0,0569	0,0255	0,0182	0,0214	0,0133	0,0000
	Bias	-0,132	-0,241	-0,300	-0,285	-0,241	-0,240	-0,213	-0,177	-0,138	-0,134	-0,070	-0,070	-0,069	-0,054	0,003

Table 4.18: Statistical result of 207 sample models with BKD 1.1 and 0.45 parameters. (#18)

BKD 1.1 0.45 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6082	0,8591	0,8146	0,8340	0,8315	0,8452	0,8500	0,9118	0,9032	0,9603	0,9476	0,9485	0,9519	0,9672	1,0000
	MAE	0,1783	0,1093	0,1013	0,1024	0,1117	0,1120	0,1133	0,1083	0,1658	0,0752	0,0975	0,1000	0,1075	0,1072	0,0029
	RMSE	0,2379	0,1635	0,1534	0,1570	0,1789	0,1834	0,2042	0,1949	0,3068	0,1442	0,2159	0,2183	0,2352	0,2243	0,0040
	SI	0,1251	0,0376	0,0451	0,0442	0,0481	0,0543	0,0630	0,0491	0,1251	0,0233	0,0523	0,0550	0,0645	0,0555	0,0000
	Bias	0,048	0,088	0,066	0,073	0,099	0,087	0,097	0,093	0,093	0,032	0,070	0,059	0,050	0,034	0,003

Table 4.19: Statistical result of 207 sample models with BKD 1.1 and 0.46 parameters. (#17)

BKD 1.1 0.46 + RTC	LOCATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	CC	0,6134	0,8643	0,8215	0,8406	0,8387	0,8524	0,8566	0,9162	0,9087	0,9631	0,9523	0,9534	0,9565	0,9707	1,0000
	MAE	0,1782	0,1023	0,0966	0,0972	0,1057	0,1068	0,1081	0,1025	0,1612	0,0721	0,0931	0,0959	0,1034	0,1033	0,0028
	RMSE	0,2381	0,1563	0,1470	0,1502	0,1712	0,1758	0,1964	0,1866	0,2983	0,1365	0,2058	0,2080	0,2257	0,2147	0,0039
	SI	0,1237	0,0351	0,0419	0,0409	0,0445	0,0501	0,0582	0,0449	0,1169	0,0208	0,0470	0,0494	0,0587	0,0504	0,0000
	Bias	0,042	0,079	0,058	0,064	0,091	0,078	0,089	0,086	0,087	0,027	0,066	0,055	0,045	0,030	0,003

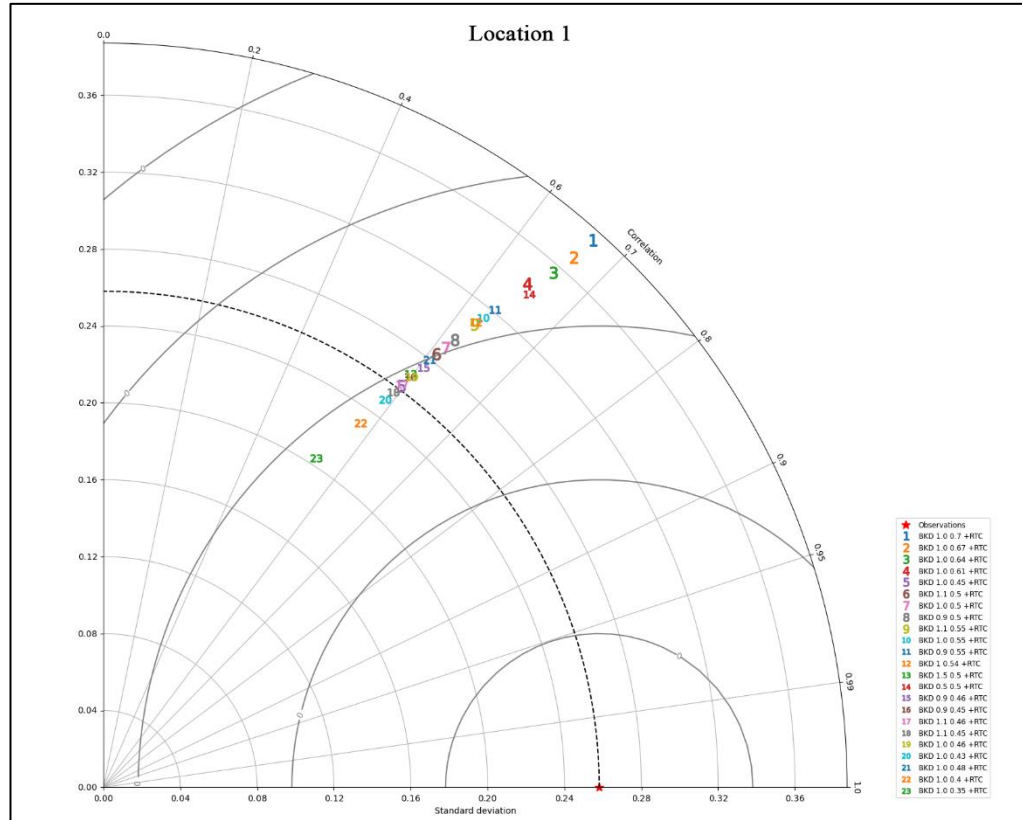


Figure 4.7: Comparison of BKD Default and Calibrated models in Taylor Diagram.

In the Taylor Diagram shown in Figure 4.7, the default model is shown as model number 12. Accordingly, increasing the alpha value to 1.1 and the gamma value to 0.55, as in model number 9, did not change the position of the model much. On the other hand, while the alpha value was set as 1, the gamma value taking 0.4 and smaller values increased the error rate in the model. These models are shown in models 23 and 22 in the diagram. The models in the other corner (1, 2, 3, 4 and 14) showed that when the alpha value was set to 1, gamma values of 0.6 and higher did not increase the model accuracy.

A closer look at the other models as shown in Figure 4.8, the model number 5, i.e., BKD 1.0 0.45 + RTC model, provided the closest result to the observations at location 1, which is the shallowest location. Most of the wave breaking occurs here, but the effectiveness of the model was checked by drawing a Taylor diagram at location 2.

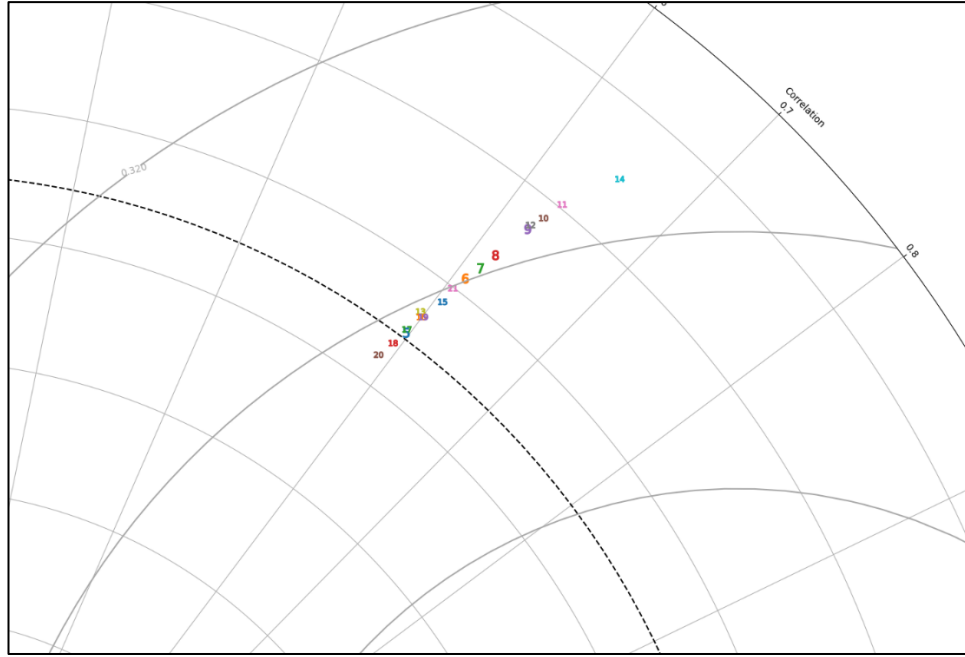


Figure 4.8: Calibrated models in Taylor diagram.

Figure 4.9 shows that the BKD 1.0 0.45 + RTC model at location 2 does not give results as close to the observation values as in location 1. The closest model to the observations at location 2 was model number 4, i.e., BKD 1.0 0.61 + RTC model. The evaluation of tunable parameters will be based on this model in the next subsection.

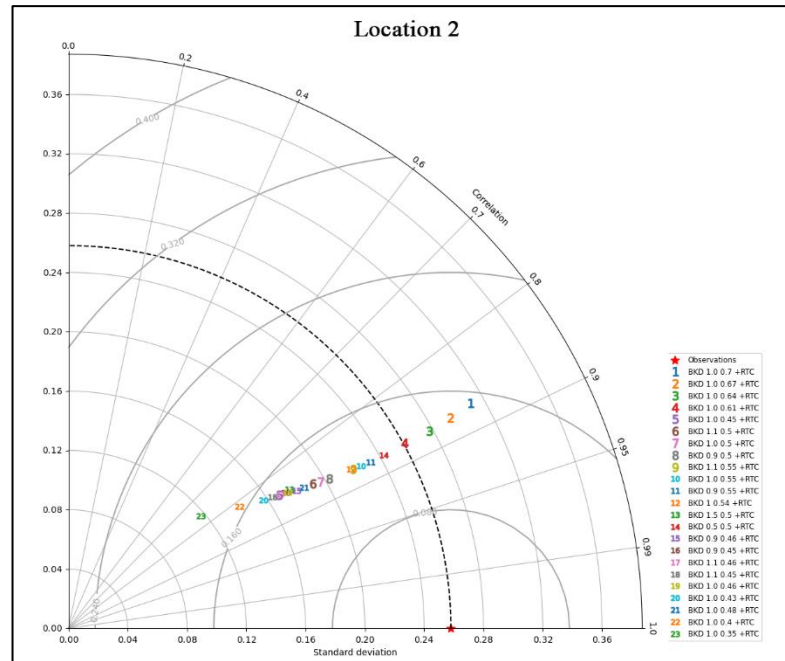


Figure 4.9: Comparison of BKD Default and Calibrated models in Taylor Diagram.

4.1.2.1. Tuneable Parameters in BKD Models

Due to the large number of combinations, the calibration of the adjustable parameters was carried out after the alpha and gamma values were determined by calibration and it was concluded that the most appropriate a1, a2 and a3 values were RTC (i.e. 7.59, -8.06 and 8.09 respectively). Each of a1, a2 and a3 values was calibrated by trial-and-error method using values of 1, 10, 15 and 20. Since the parameter a2 is negative at the default values suggested by SWAN, the models were run by trying values of -20, -15, -10 and -1.

Table 4.20: Statistical result of 207 sample models with BKD 1.0 0.6 + 10 -20 20 parameters.

BKD 1.0 0.6 + 10 -20 20	LOCATION	CC	MAE	RMSE	SI	Bias
	1	0,674	0,221	0,279	0,123	-0,045
	2	0,895	0,082	0,141	0,023	-0,047
	3	0,876	0,088	0,131	0,022	-0,056
	4	0,892	0,081	0,124	0,020	-0,048
	5	0,905	0,070	0,115	0,019	-0,017
	6	0,921	0,075	0,115	0,018	-0,027
	7	0,925	0,071	0,121	0,020	-0,014
	8	0,960	0,056	0,101	0,012	-0,011
	9	0,972	0,101	0,166	0,030	-0,003
	10	0,984	0,062	0,104	0,008	-0,045
	11	0,990	0,038	0,074	0,005	0,001
	12	0,992	0,042	0,072	0,005	-0,007
	13	0,992	0,051	0,117	0,013	-0,014
	14	0,994	0,056	0,117	0,013	-0,021
	15	1,000	0,003	0,004	0,000	0,003

Table 4.20 shows the results of the model run with 10, -20 and 20 values instead of RTC parameters. At location 1, while the RMSE value was 0.26 in the model run with RTC parameters, the error increased to approximately 0.28 in this model. The correlation coefficient value increased at location 1.

Table 4.21 shows the statistical results of the model where 10, -10 and 10 are used as tuneable parameters. In this model, the error rate increased as the correlation coefficient increased. While the MSE was maximum 0.2 m in the RTC model, it increased to about 0.22 m in this model at location 1.

Table 4.21: Statistical result of 207 sample models with BKD 1.0 0.6 + 10 -10 10 15 parameters.

BKD 1.0 0.6 + 10 -10 10	LOCATION	CC	MAE	RMSE	SI	Bias
	1	0,674	0,221	0,279	0,123	-0,045
	2	0,895	0,082	0,141	0,023	-0,047
	3	0,876	0,088	0,131	0,022	-0,056
	4	0,892	0,081	0,124	0,020	-0,048
	5	0,905	0,070	0,115	0,019	-0,017
	6	0,921	0,075	0,115	0,018	-0,027
	7	0,924	0,071	0,121	0,020	-0,014
	8	0,960	0,057	0,101	0,012	-0,011
	9	0,972	0,101	0,166	0,030	-0,003
	10	0,984	0,062	0,104	0,008	-0,045
	11	0,990	0,038	0,074	0,005	0,001
	12	0,992	0,042	0,072	0,005	-0,007
	13	0,992	0,051	0,117	0,013	-0,014
	14	0,994	0,056	0,117	0,013	-0,020
	15	1,000	0,003	0,004	0,000	0,003

Although there are 3 Tuneable parameters in SWAN BKD models, changing these values did not cause major changes in the models. Instead of these parameters, alpha and gamma values have a stronger effect on wave breaking energy dissipation.

Conclusions and recommendations concerning the error values in the models are discussed in chapter 5. Nevertheless, subsection 4.3 provides some information about the outlier results in the observations and models.

4.3. Exceptional Errors (Outlier Waves) in Models

The CC value of the calibrated CON model is 66%, while the MAE value is 0.17 m and the RMSE value is 0.23. These error values can be better seen in the H_s (SWAN)/ H_s (Observations) chart (see Figure 4.10).

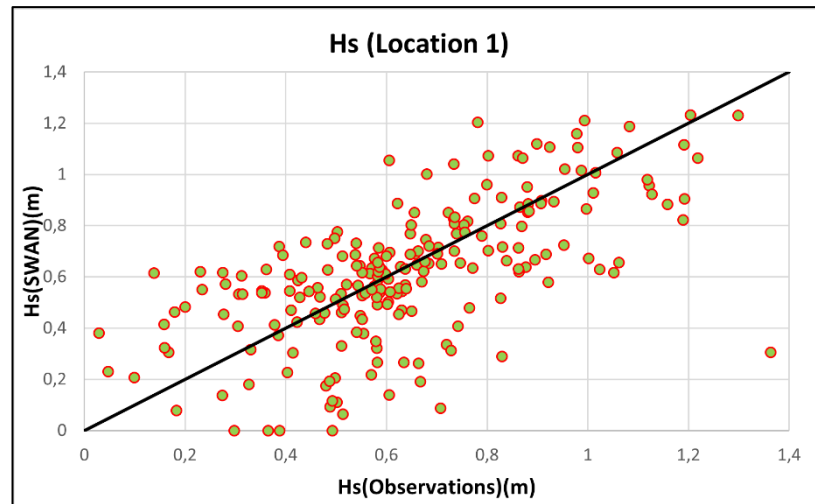


Figure 4.10: H_s (SWAN)/ H_s (Observations) chart of September 1994 observations and calibrated SWAN model (CON 0.82 0.65) at Location 1.

In a good forecast model, predictions and observations should be close to each other. The points in an ideal model should be close to the 45-degree black line starting from the origin in Figure 4.10. According to the model, in most cases the model calculated a wave height close to the measurements. However, in a few cases SWAN calculated a higher wave height than the measurements. Also, in some of the models SWAN calculated a smaller wave height than it should be. Some of these cases are shown in the charts below.

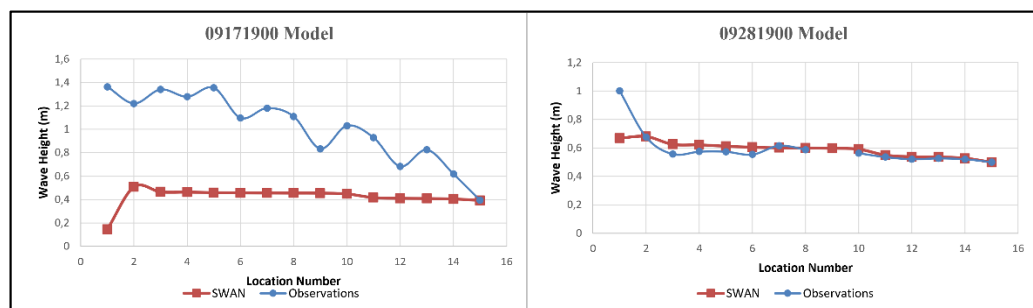


Figure 4.11: Underestimation of wave height (m) of 17th and 28th September 1994 according to calibrated SWAN model (CON 0.82 0.65).

Cases of 09171900 and 09281900 shows that SWAN underestimated the wave height. However, the wave height observed here unexpectedly increased as it approached shallow water. Nevertheless, when the wave approaches the shore, it should break and lose its height. This may be due to the sensors measuring incorrect data or an anomaly in the waves. Unreasonably, no wave breaking is observed in these models.

On the other hand, in some cases SWAN calculated a higher wave height than the observations. For example, according to the observations in case number 092216000, while the wave height decreased from location 9, but the decrease in SWAN was less (see Figure 4.12 (right)).

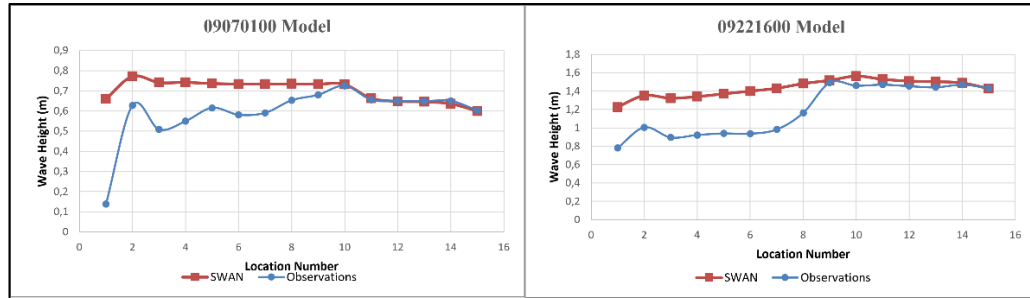


Figure 4.12: Overestimation of wave height (m) of 7th and 22nd September 1994 according to calibrated SWAN model (CON 0.82 0.65).

Another case of overestimation is seen in case 09070100. According to the observations in this case, the wave height, which was approximately 0.6 metres at location 2, decreased to 0.14 metres at location 1, which is the closest point to the shore. In this case, SWAN did not sufficiently account for the dissipation of the wave energy (see Figure 4.12 (left)).

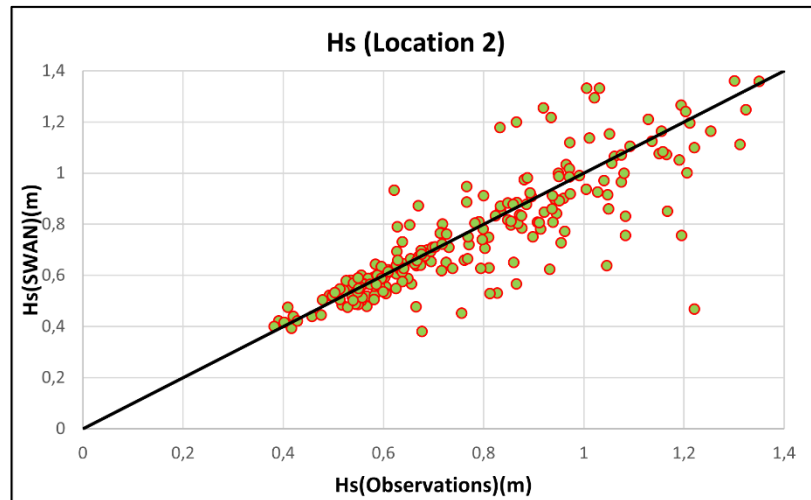


Figure 4.13: H_s (SWAN)/ H_s (Observations) chart of September 1994 observations and calibrated SWAN model (CON 0.82 0.65) at Location 2.

At location 2, which is the second closest point to the shore, the predictions are closer to the observations. The correlation coefficient at this point increased to about 0.83. However, there are still some outliers. For example, in the case of 09171900 the

wave height was approximately 1.22 metres, whereas according to SWAN it was calculated as 0.45 metres. This can be seen in Figure 4.13 as the point relatively closer to the upper left corner. Outlier measurements and calculation values are also present in the BKD models as well as in the CON models.

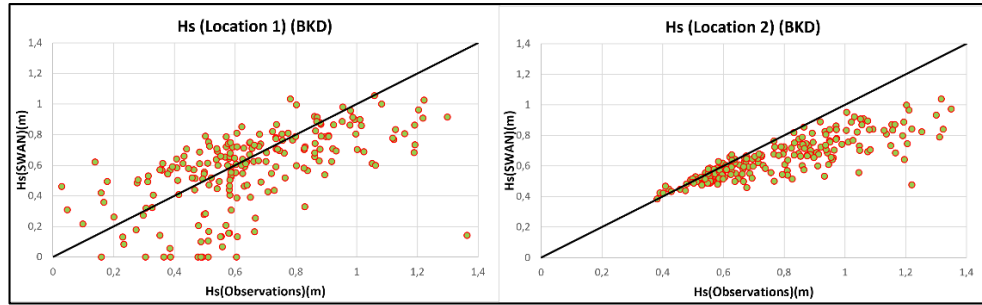


Figure 4.14: H_s (SWAN)/ H_s (Observations) chart of September 1994 observations and calibrated SWAN BKD model (BKD 1.0 0.45 + RTC) at Location 1 and Location 2.

As can be seen in Figure 4.14, there are overestimates and underestimates also in the BKD models. However, unlike the CON models, there are more underestimates than overestimates in the BKD models. This is seen more clearly at Location 2.

4.4. Effect of Parameters on Wave Heights

In this section, the effect of the parameters used in the model, which is found as a result of calibration and gives optimum results, on the wave height is analysed. As a result of the calibration, alpha value was 0.82 and gamma value was 0.65. The comparison of the calibrated model with the wave observations at 13:00 on 21 September 1994 is shown in Figure 4.15. The calibrated model predicted the wave height close to the measurements but slightly overestimated it. The difference between the measurement and SWAN model predictions decreases at locations 13, 11, 10, 9, 8 and 2, while the difference between the wave heights is relatively high at other locations. The reason for the decrease in the difference at these points is that the wave height in the measurements increased slightly at some points. According to Figure 4.15, this wave breaks at location 2 and dissipates most of its energy, reducing the wave height from 0.74m to less than 0.4m. Similar situation was observed in the calibrated SWAN model. According to the model, the wave breaks at location 2 and the wave height decreases from 0.78 metres to 0.5 metres.

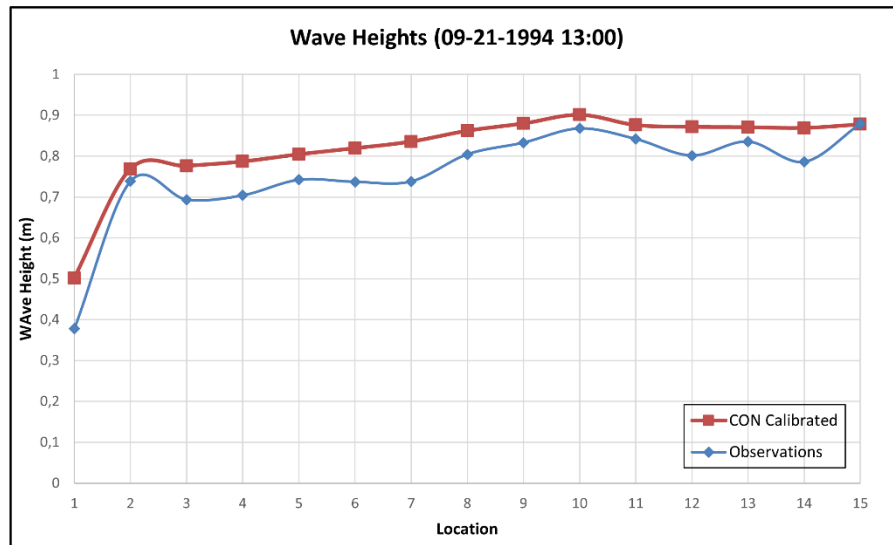


Figure 4.15: Wave heights of the calibrated model and field observations at 13:00 on 21 September 1994.

In order to examine the effect of alpha and gamma parameters in SWAN Models, alpha and gamma parameters of the calibrated model were changed and compared with the measurements. While the gamma value was kept constant at 0.65, the alpha value was increased from 0.82 to 0.9 and the CON 0.9 0.65 model was created. In SWAN, the gamma value was increased from 0.65 to 0.7 while the alpha value was kept constant in order to examine the effect of gamma value on the wave height. These two models are shown in Figure 4.16 in green and purple respectively. Accordingly, an increase of approximately 10 % in alpha value caused a slight decrease in wave height. While this decrease is clearly visible in shallow water, the difference between the wave heights in deep water (between locations 10-15) is close to zero. The increase in the alpha value caused a change of approximately 1.3% at location 2 where the wave breaks. At location 1, which is the shallowest point, the rate of change is approximately 4%. At location 1, the wave height decreased from 0.5 metres in the calibrated model to 0.48 metres in the CON 0.9 0.65 model. On the other hand, in the CON 0.82 0.7 model shown in purple in Figure 4.16, the change is more clearly seen. An 8% increase in gamma value increased the wave height in shallow water. This increase was approximately 6.8% at location 1 and 5.7% at location 2. While this ratio is high in shallow water, it decreases as it approaches to intermediate and deep water. In this model where the Gamma value was increased to 0.7, the wave height increased to 0.54 metres at location 1. Figure 4.16 clearly shows that the changes in alpha and gamma values are more effective in shallow water. This is because SWAN models calculate

wave heights at shallow points starting from the deepest point. It is also seen that small changes in gamma value have a greater effect on the wave height. Accordingly, gamma parameter is more sensitive than alpha parameter. Since the gamma parameter determines the breaking criterion, a sufficient increase in this value could have caused the wave to break deeper instead of location 2. However, this was not observed in the models analysed in this subsection.

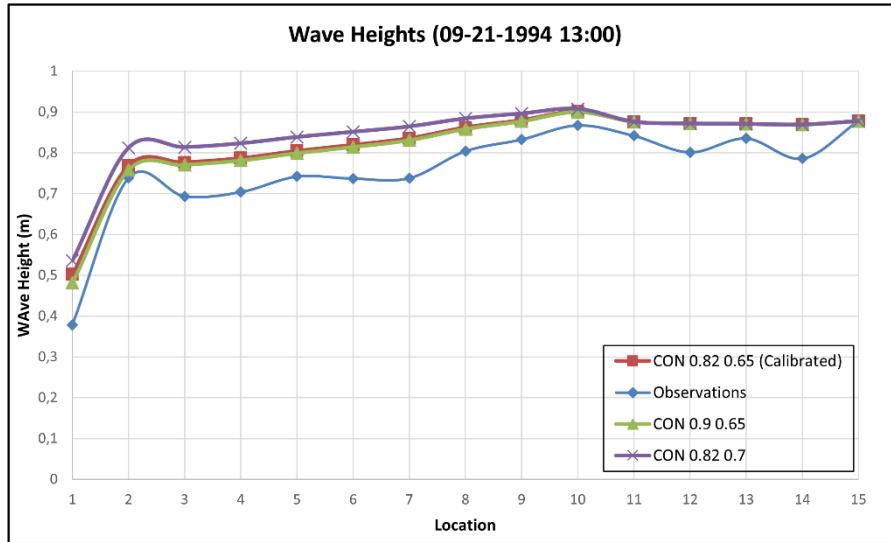


Figure 4.16: Wave heights of the CON 0.82 0.65 (calibrated model), CON 0.9 0.65, CON 0.82 0.7 models and field observations at 13:00 on 21 September 1994.

The other parameter affecting the wave height in SWAN is the bottom friction. Figure 4.15 and Figure 4.16 show that the models calculate higher wave heights than the measurements. Bottom friction can reduce the height difference between the wave heights calculated by the models and the observations. As mentioned in subsection 1.2.2.4, there are different types of base friction in SWAN. In this section, the effect of JONSWAP and RIPPLES parameters on the wave heights in the existing model is analysed. Accordingly, the models with the JONSWAP bottom friction effect were compared with the CON Calibrated model without friction and the observations. Figure 4.17 and Figure 4.18 compares the calibrated model where the bottom friction is not taken into account with the models where the JONSWAP parameter $C_b = 0.038 \text{ m}^2\text{s}^{-3}$ and $C_b = 0.057 \text{ m}^2\text{s}^{-3}$ (see equation (1.37)). The model using the JONSWAP C_b value proposed by SWAN provided a lower wave height prediction than the frictionless calibrated model. The JONSWAP 0.057 model, which is 50% more than the default C_b value, caused the wave height to decrease more at all points.

Consequently, JONSWAP bottom friction affected the wave height at all points and caused it to be lower predicted.

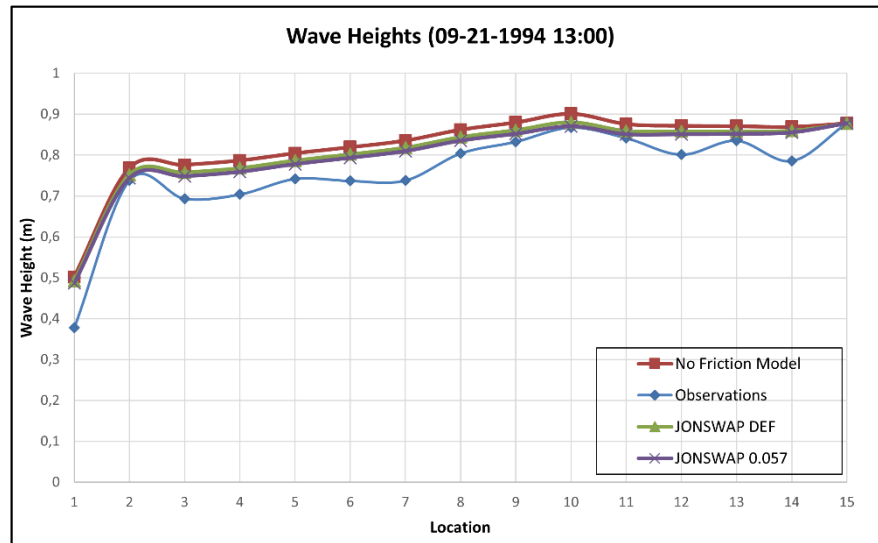


Figure 4.17: Comparison of wave heights of the CON Calibrated (red), JONSWAP 0.038 (green), JONSWAP 0.057(purple) models and field observations (blue) at 13:00 on 21 September 1994 from location 1 to location 15.

Figure 4.18 shows a more detailed view at the 8 shallowest points. Accordingly, when JONSWAP friction is included in the model, the wave height is calculated to be about 2% lower on average at all points. Increasing the C_b parameter by 50% resulted in a 3% lower wave height compared to the default parameter. The point most affected by the bottom friction is location 3, which is the location before the point where the breaking occurs. This shows that JONSWAP bottom friction is effective near the shore and at points where the water height is high.

The other base friction parameter in SWAN is Ripples. There are two different values for the base friction of ripples. The first one is the specific gravity of the sediment and the second one is the diameter of the sediment. 3 Models were run for different specific gravity values and wave heights were compared. The specific gravity of the sediment given as default in SWAN is 2.65 g/cm^3 and the diameter of the sediment is 1 mm. Sediment diameter was kept constant as 1 mm and specific gravity was changed as 2.0 and 2.71 g/cm^3 .

Figure 4.19 compares the results of these models and field measurement values. Accordingly, the models with Ripples bottom friction showed lower wave height than the calibrated model without friction.

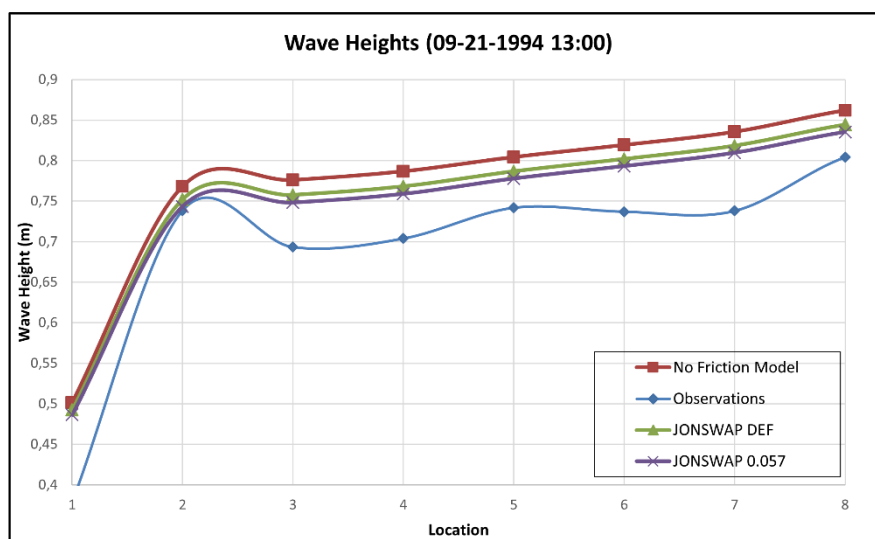


Figure 4.18: Comparison of wave heights of the CON Calibrated (red), JONSWAP 0.038 (green), JONSWAP 0.057(purple) models and field observations (blue) at 13:00 on 21 September 1994 from location 1 to location 8.

According to Figure 4.19, increasing the sediment specific gravity from 2.65 g/cm^3 to 2.71 g/cm^3 reduced the Ripples bottom friction effect. In other words, lower sediment specific gravity decreased the wave height. Accordingly, the sediment specific gravity of 2.0 g/cm^3 decreased the wave height at all points and at some points the wave height reached a value smaller than the observation values. Also, changing the Ripples parameter is more sensitive than changing the JONSWAP bottom friction.

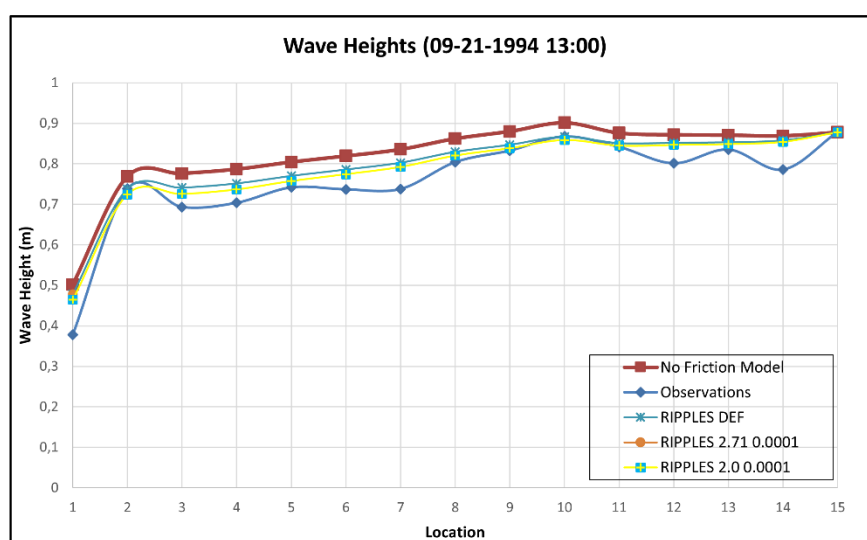


Figure 4.19: Comparison of wave heights of the CON Calibrated, Ripples 2.65 0.0001, Ripples 2.71 0.0001, Ripples 2.0 0.0001 models and field observations (blue) at 13:00 on 21 September 1994 from location 1 to location 8.

5. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study is to investigate wave breaking and bottom friction energy dissipation and nonlinear processes in deep and shallow water conditions using the SWAN model. The results presented in chapter 4 refer to models run with SWAN recommended parameters and their calibrated values for the wave conditions at the DUCK94 experimental field. According to the given results, 2 models were selected and run with all 799 wave conditions in the DUCK94 spectral wave data. One of these 2 models is CON type and the other is BKD type model. The purposes of these models are to construct a model that can make wave predictions with maximum accuracy in the experimental field.

Table 5.1: Statistical result of 799 models with CON 0.82 0.65 parameters.

CON 0.82 0.65	LOCATION	CC	MAE	RMSE	SI	Bias
	1	0,6901	0,2792	0,3702	0,3529	-0,1868
	2	0,8292	0,2495	0,3661	0,2820	-0,1638
	3	0,8323	0,2349	0,3537	0,2215	-0,1744
	4	0,8807	0,1498	0,2491	0,1009	-0,0913
	5	0,8969	0,2287	0,3578	0,2293	-0,1619
	6	0,9231	0,1504	0,2479	0,0974	-0,1023
	7	0,9348	0,1468	0,2469	0,0924	-0,1030
	8	0,9575	0,1375	0,2421	0,0862	-0,0990
	9	0,9529	0,2029	0,3223	0,1667	-0,1441
	10	0,9755	0,1302	0,2339	0,0793	-0,0836
	11	0,9818	0,0902	0,2033	0,0483	-0,0398
	12	0,9875	0,0843	0,1748	0,0325	-0,0502
	13	0,9891	0,0897	0,2057	0,0485	-0,0381
	14	0,9903	0,0812	0,1844	0,0358	-0,0457
	15	1,0000	0,0016	0,0028	0,0000	0,0016

Table 5.1 is the CON 0.82 0.65 model, which is one of the calibrated models. This model was applied to all 799 wave conditions given in the data set of DUCK94 experiments and it was determined that the correlation ratio took different values between 69% and 100% from the shallowest location to the deepest location. Since the number of models is much higher than the number of models before calibration, the increase in correlation may indicate a misleading accuracy. Therefore, the MAE and RMSE error rates in the Table 5.1 should be evaluated. The average RMSE error at all points of this model is 0.25 and the MAE error value is about 0.15 m. However, at

location 1, which is the shallowest measurement and calculation point, the RMSE is 0.37 while the MAE is 0.27 metres. This indicates that the model does not have a high accuracy at location 1 where the average wave height is 0.69m. To better see the locations where the errors are maximised, the significant wave height (H_s) for location 1 in Figure 5.1 can be compared between the observation and model results.

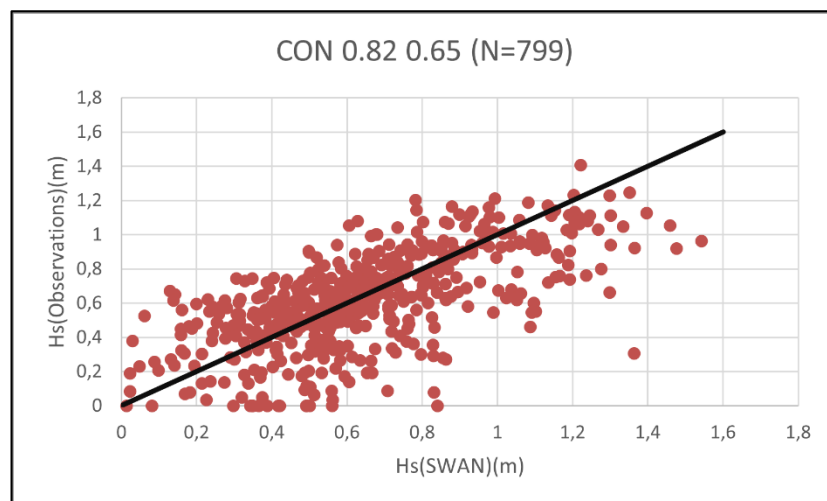


Figure 5.1: H_s (Observations)/ H_s (SWAN) chart of 799 wave observations and SWAN model (CON 0.82 0.65) at Location 1.

The Figure 5.1 shows the models under- and overestimated by SWAN. SWAN calculated some waves smaller than 0.8 metres to be close to zero. Table 5.2 shows the success rate of the calibrated SWAN model depending on the wave height.

Table 5.2: Performance comparison of the calibrated CON 0.82 0.65 model according to significant wave height at location 1.

CON 0.82 0.65 Location 1	Hs<0.8m		0.8m<Hs<1.2m		Hs>1.2m	
	N	226	N	106	N	23
	CC	0,4438	CC	0,2858	CC	-0,2521
	RMSE	0,1635	RMSE	0,0947	RMSE	0,0316
	MAE	0,2107	MAE	0,1837	MAE	0,1248
	SI	0,1149	SI	0,0988	SI	0,7605

As seen in the Table 5.2, the error of the model is higher at the location number 1 where the breaking occurs in conditions where the wave height is relatively large. In particular, the correlation coefficient is negative under wave conditions where the significant wave height is higher than 1.2 metres. On the other hand, the best results of the model are obtained in the conditions of waves smaller than 0.8 m, although it

calculates the small waves very close to zero. A similar situation exists at location 2, which is the point where wave breaking has not yet occurred in some wave conditions and where breaking has occurred in others. In Figure 5.2 shows that the success rate of the calibrated SWAN model is high when the significant wave height is less than 0.8 metres.

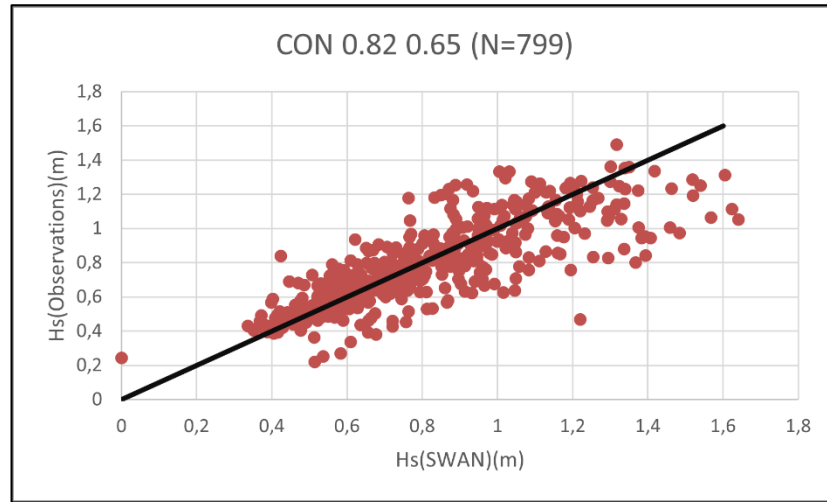


Figure 5.2: H_s (Observations)/ H_s (SWAN) chart of 799 wave observations and SWAN model (CON 1.45 0.5) at Location 2.

Table 5.3 shows that the success and error rates for waves with significant wave heights greater than 1.2 m and between 0.8 m and 1.2 m at location 2 are less successful than for small waves in the first condition. In addition, shows that when the significant wave height was less than 0.8 m, the RMSE was 0.065 and the MAE was 0.1 m. On the other hand, in conditions where the wave height was between 0.8 and 1.2 metres, the RMSE was 0.13 and the MAE was 0.12 m.

Table 5.3: Performance comparison of the calibrated CON 0.82 0.65 model according to significant wave height at location 2.

CON 0.82 0.65 Location 2	Hs<0.8m		0.8m<Hs<1.2m		Hs>1.2m	
	N	419	N	246	N	87
	CC	0,6605	CC	0,4380	CC	0,0836
	RMSE	0,0651	RMSE	0,1269	RMSE	0,0937
	MAE	0,1007	MAE	0,1257	MAE	0,1470
	SI	0,0245	SI	0,0294	SI	0,2301

The performance of the calibrated model can be seen more clearly in the time series plot. Figure 5.3 shows the significant wave heights at location 1 and Figure 5.4

shows the significant wave heights at location 2 between 19.07.1994 and 03.11.1994 according to DUCK94 experimental data and calibrated CON model.

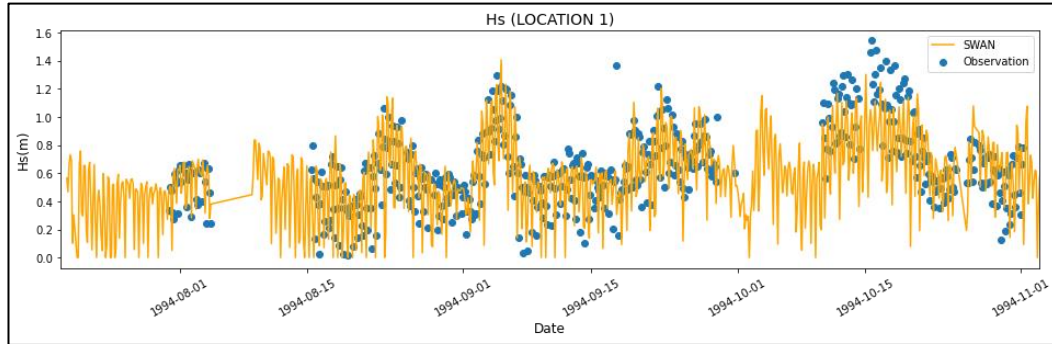


Figure 5.3: Significant wave height values observed and calculated by SWAN at location 1 at Duck Beach between 19 July 1994 and 3 November 1994.

Figure 5.3 shows that the calibrated SWAN model obtained closer results at low wave heights than at medium wave heights and high wave heights. On the other hand, the model could not accurately predict the cases where the wave height exceeded 1.4 metres. Since many waves have not yet broken at location 2, the values calculated by SWAN seem to be closer to the observed wave height values (Figure 5.4).

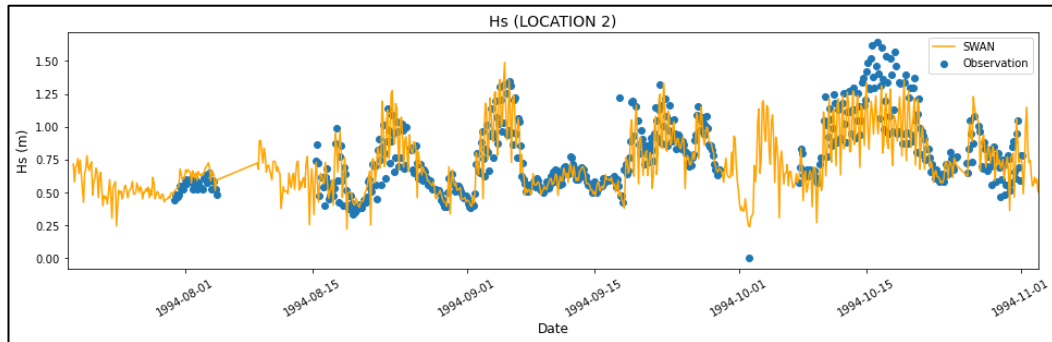


Figure 5.4: Significant wave height values observed and calculated by SWAN at location 2 at Duck Beach between 19 July 1994 and 3 November 1994.

The statistical results of the models run with the calibrated BKD parameter under 799 wave conditions are given in Table 5.4. It is $1.0 \pm 0.45 + \text{RTC}$ model which provides the best results at the shallowest point. As seen in the Table 5.4, the correlation increased in the BKD model compared to the CON model, but the RMSE and MAE error values were observed to be very high, especially in shallow water conditions. Especially in the first 4 shallowest points, the error of the BKD model was higher than

the CON model. At the locations where deep-water conditions dominate, the BKD model was slightly more successful than the CON model.

Table 5.4: Statistical result of 799 models with BKD [1.0 0.45] + [7.59 -8.06 8.09] parameters.

BKD [1.0 0.45] + [7.59 -8.06 8.09]	LOCATION	CC	MAE	RMSE	SI	Bias
	1	0,6040	0,1782	0,2364	0,1290	0,0708
	2	0,8503	0,1417	0,1978	0,0504	0,1288
	3	0,7952	0,1268	0,1838	0,0616	0,1036
	4	0,8176	0,1296	0,1889	0,0611	0,1097
	5	0,8138	0,1427	0,2128	0,0662	0,1348
	6	0,8299	0,1372	0,2163	0,0747	0,1214
	7	0,8402	0,1391	0,2364	0,0847	0,1298
	8	0,9144	0,1337	0,2279	0,0679	0,1225
	9	0,9016	0,1845	0,3383	0,1600	0,1188
	10	0,9682	0,0890	0,1780	0,0365	0,0544
	11	0,9453	0,1163	0,2577	0,0787	0,0908
	12	0,9449	0,1178	0,2607	0,0828	0,0788
	13	0,9497	0,1248	0,2747	0,0925	0,0686
	14	0,9706	0,1238	0,2652	0,0813	0,0512
	15	1,0000	0,0029	0,0042	0,0000	0,0029

The most important reason for the high error value of the BKD model at shallow points is that it overestimates the significant wave height. As can be seen in Figure 5.5, most of the 799 wave conditions are in the upper left area of the black line. This means that the significant wave height calculated by SWAN is higher than the observed wave height value. In contrast to the CON model, underestimation of the significant wave height is very rare in the BKD model. This may be due to the fact that the BKD model chooses a value referenced to the vertical slope instead of taking a constant breaker index.

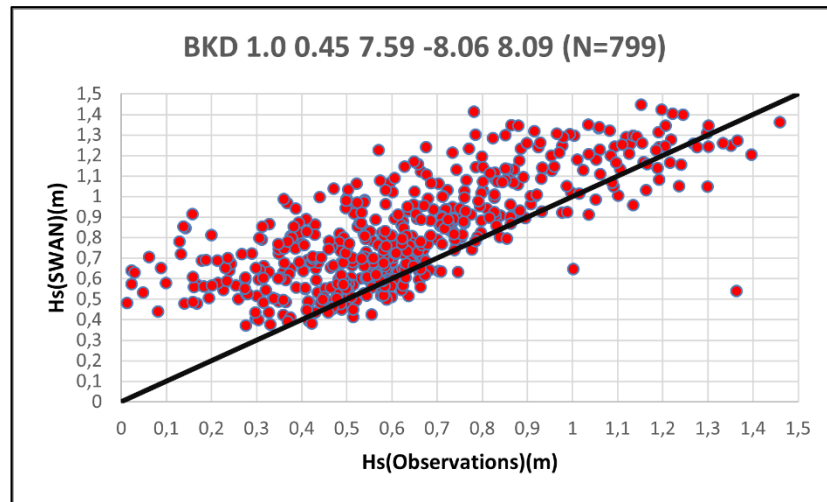


Figure 5.5: H_s (Observations)/ H_s (SWAN) chart of 799 wave observations and SWAN model (BKD [1.0 0.45] + [7.59 -8.06 8.09]) at Location 1.

Table 5.5 compares the success of the model according to significant wave height ranges. Accordingly, the calibrated BKD model is very poor at predicting medium height waves. The MAE value of the model is 0.66 metres while the RMSE value is 0.68.

Table 5.5: Performance comparison of the calibrated BKD model according to significant wave height at location 1.

BKD Calibrated Model Location 1	Hs<0.4m		0.4m<Hs<1.1m		Hs>1.1m	
	N	98	N	393	N	44
	CC	0,1243	CC	0,6118	CC	0,0378
	RMSE	0,3960	RMSE	0,6853	RMSE	0,1905
	MAE	0,3607	MAE	0,6641	MAE	0,1345
	SI	0,0640	SI	0,0400	SI	0,0236

Figure 5.6 depicts a more balanced observation/prediction chart with fewer outliers at location 2 in the calibrated BKD model. At location 2, the prediction success of medium height waves is quite high.

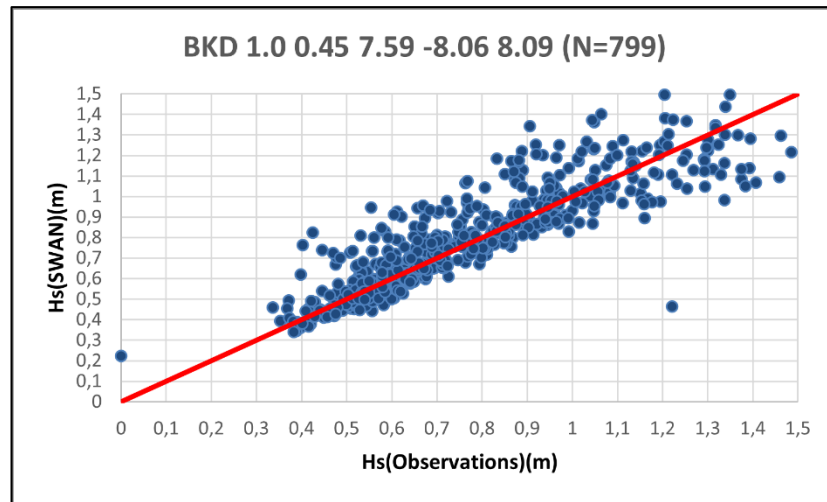


Figure 5.6: H_s (Observations)/ H_s (SWAN) chart of 799 wave observations and SWAN model (BKD [1.0 0.45] + [7.59 -8.06 8.09]) at Location 2.

As summarised in Table 5.6, while the error rate of the BKD model was 0.2 metres in 73 wave conditions higher than 1.1 metres, this value decreased to 0.14 metres in all wave conditions between 0.4 metres and 1.1 metres and the correlation coefficient reached approximately 80%. Since there were 16 waves with a significant wave height less than 0.4 metres, they were not included in the Table 5.6.

Table 5.6: Performance comparison of the calibrated BKD [1.0 0.45] + [7.59 -8.06 8.09] model according to significant wave height at location 2.

BKD Calibrated Model Location 2	0.4m<Hs<1.1m		Hs>1.1m	
	N	477	N	73
	CC	0,8347	CC	0,2785
	RMSE	0,0818	RMSE	0,1689
	MAE	0,1456	MAE	0,2133
	SI	0,0297	SI	0,0219

The overestimation of the BKD model at the shallowest location is clearly visible in the time series charts. According to Figure 5.7, unlike the CON model, the BKD model failed to estimate the waves with low wave heights and overestimated the waves with high wave heights.

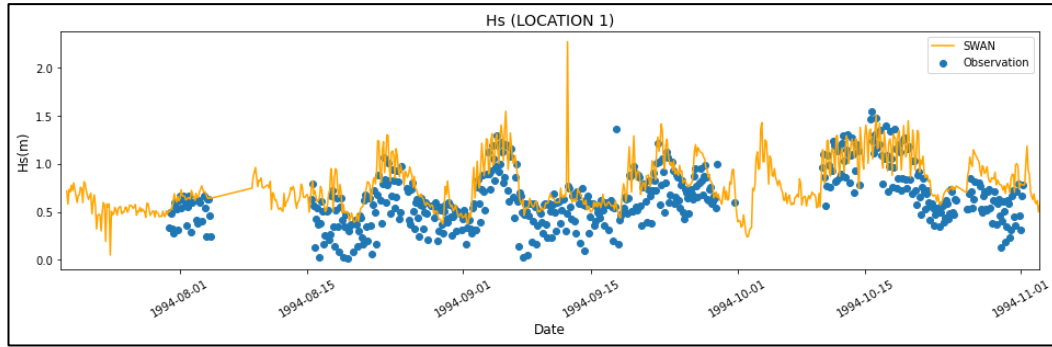


Figure 5.7: Significant wave height values observed and calculated by SWAN BKD model at location 1 at Duck Beach between 19 July 1994 and 3 November 1994.

When Figure 5.8 is analysed, it can be seen that, this situation is specific to the shallowest location. At location 2, the predictions of the models are more accurate than at location 1. This indicates that the overestimation is due to the BKD wave breaking parameter.

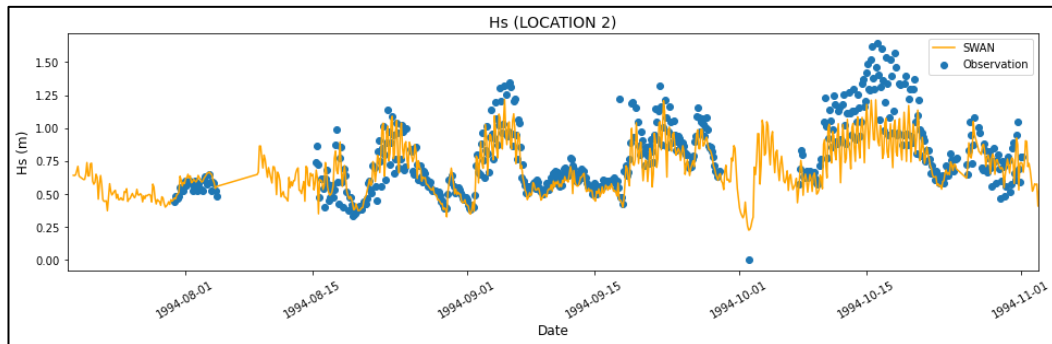


Figure 5.8: Significant wave height values observed and calculated by SWAN BKD model at location 2 at Duck Beach between 19 July 1994 and 3 November 1994.

Table 5.7 and Table 5.8 are presented for comparison between the 799 models run with the parameters recommended by SWAN, the calibrated models, and the versions of these models with TRIAD wave-wave interaction added in shallow and deep-water conditions. In addition, in order to simplify the comparison of shallow water and deep-water models separately, locations 1 to 8 are given in the Table 5.7 and locations 9 to 15 are given in the Table 5.8.

Table 5.7: Comparison of the performance of the model with the calibrated models run with all wave data with the parameters proposed by SWAN for the shallowest 8 locations.

N=799	Location	1	2	3	4	5	6	7	8
CON DEF	CC	0,682	0,855	0,836	0,886	0,902	0,928	0,939	0,958
	MAE	0,287	0,250	0,244	0,157	0,233	0,156	0,153	0,144
	RMSE	0,379	0,370	0,364	0,256	0,365	0,254	0,254	0,250
	SI	0,363	0,246	0,198	0,089	0,206	0,087	0,083	0,079
	Bias	-0,168	-0,192	-0,202	-0,118	-0,186	-0,125	-0,126	-0,121
CON Calibrated DEF	CC	0,650	0,829	0,832	0,881	0,897	0,923	0,935	0,957
	MAE	0,279	0,250	0,235	0,150	0,229	0,150	0,147	0,138
	RMSE	0,370	0,366	0,354	0,249	0,358	0,248	0,247	0,242
	SI	0,400	0,282	0,221	0,101	0,229	0,097	0,092	0,086
	Bias	-0,144	-0,164	-0,174	-0,091	-0,162	-0,102	-0,103	-0,099
BKD DEF	CC	0,620	0,840	0,763	0,826	0,838	0,875	0,888	0,913
	MAE	0,200	0,250	0,232	0,146	0,226	0,144	0,144	0,138
	RMSE	0,315	0,379	0,363	0,260	0,362	0,259	0,261	0,258
	SI	0,120	0,246	0,234	0,115	0,249	0,113	0,108	0,102
	Bias	0,005	-0,200	-0,169	-0,080	-0,145	-0,086	-0,089	-0,084
CON Calibrated DEF + TRIAD	CC	0,652	0,850	0,830	0,879	0,889	0,919	0,931	0,952
	MAE	0,284	0,248	0,225	0,146	0,229	0,148	0,145	0,144
	RMSE	0,370	0,354	0,340	0,245	0,348	0,245	0,244	0,244
	SI	0,345	0,328	0,266	0,126	0,282	0,127	0,122	0,117
	Bias	-0,195	-0,125	-0,129	-0,043	-0,112	-0,051	-0,048	-0,043
BKD Calibrated DEF+TRIAD	CC	0,617	0,830	0,793	0,817	0,847	0,916	0,929	0,951
	MAE	0,276	0,260	0,232	0,156	0,216	0,149	0,146	0,144
	RMSE	0,389	0,379	0,353	0,260	0,362	0,247	0,246	0,245
	SI	0,160	0,246	0,234	0,232	0,225	0,129	0,124	0,119
	Bias	0,034	-0,200	-0,157	-0,078	-0,165	-0,050	-0,048	-0,042

According to this Table 5.7, although the calibration coefficient of the model run with the breaking type and values recommended by SWAN is high, the error rates are too high. In fact, the model's MAE value and RMSE value at the shallowest position are 0.28 meters and 0.38 respectively. These values are quite high compared, and in this study, it is aimed to reduce these values by calibration process. When the other models were compared, it was observed that the BKD model performed with lower accuracy than the CON model in shallow water. It has already been noted that the calibrated BKD models are slightly more successful in mid-water conditions. This situation can also be seen in the MAE values in the Table 5.7.

Table 5.8: Comparison of the performance of the model with calibrated models run with all wave data with SWAN recommended parameters for location 8 to location 15.

N=799	Location	9	10	11	12	13	14	15
CON DEF	CC	0,960	0,970	0,984	0,994	0,992	0,995	1,000
	MAE	0,205	0,152	0,090	0,086	0,086	0,073	0,001
	RMSE	0,328	0,258	0,204	0,173	0,205	0,180	0,002
	SI	0,125	0,070	0,039	0,025	0,041	0,030	0,000
	Bias	-0,188	-0,121	-0,068	-0,074	-0,060	-0,061	0,001
CON Calibrated DEF	CC	0,913	0,936	0,940	0,969	0,979	0,981	1,000
	MAE	0,198	0,134	0,106	0,097	0,110	0,093	0,001
	RMSE	0,331	0,254	0,246	0,199	0,257	0,235	0,003
	SI	0,180	0,092	0,076	0,048	0,080	0,061	0,000
	Bias	-0,131	-0,074	-0,016	-0,026	-0,015	-0,031	0,001
BKD DEF	CC	0,914	0,937	0,940	0,969	0,978	0,981	1,000
	MAE	0,197	0,134	0,106	0,097	0,110	0,093	0,001
	RMSE	0,330	0,253	0,246	0,200	0,257	0,235	0,003
	SI	0,180	0,093	0,076	0,048	0,081	0,061	0,000
	Bias	-0,131	-0,073	-0,015	-0,025	-0,015	-0,030	0,001
CON Calibrated DEF + TRIAD	CC	0,940	0,963	0,959	0,965	0,970	0,971	1,000
	MAE	0,213	0,149	0,121	0,110	0,123	0,106	0,002
	RMSE	0,334	0,252	0,251	0,222	0,252	0,233	0,005
	SI	0,233	0,119	0,089	0,066	0,086	0,069	0,000
	Bias	-0,087	-0,025	0,012	-0,001	0,008	-0,005	0,002
BKD Calibrated DEF+TRIAD	CC	0,938	0,962	0,958	0,965	0,969	0,971	1,000
	MAE	0,214	0,150	0,121	0,110	0,122	0,106	0,002
	RMSE	0,335	0,253	0,251	0,222	0,252	0,233	0,005
	SI	0,235	0,119	0,089	0,066	0,086	0,069	0,000
	Bias	-0,086	-0,025	0,012	-0,002	0,008	-0,005	0,002

Since the calculations in SWAN are made by accepting the deepest point as the boundary condition, it is normal for the accuracy rate to increase and the error rates to decrease as the evaluated point approaches location 15. This increase in accuracy should not be incorrectly assessed. In addition, the error and correlation values at deep water locations in Table 5.8 are very close to each other. This should also be taken into account in the evaluation.

Table 5.8 shows that the model with the highest accuracy in deep water conditions is the model recommended by SWAN (CON DEF). However, the high error rate of this model in shallow water leads to the conclusion that the model is not suitable in the overall evaluation. Apart from this, another conclusion that can be drawn from the Table 5.8 is that the calibrated BKD model works slightly better than the CON

models in intermediate deep water. In addition, TRIAD wave-wave interaction did not have a direct effect on accuracy in deep water conditions. It is already known that the TRIAD interaction is effective in shallow water. On the other hand, the TRIAD effect in SWAN CON models had a positive effect especially at location 1, as it slightly minimised the waves with higher significant wave height.

In this study, the data obtained from the DUCK94 experiment and the calibrated models of the BKD and CON parameters in SWAN and the versions of these models that include the TRIAD and bottom friction effects are evaluated. However, the accuracy of the models is directly linked to the accuracy, intactness, and bias of the data. The sources of errors in these models can be caused not only by the model itself, but also by errors in the data, lack of sufficient bottom profile data and interruption of the continuous data flow of the sensors. These issues should be considered when using these data in possible future studies.

In this study, the effect of alpha and gamma values, which are the breaking parameters in the calibration process in the models examined in this study, and the effect of bottom friction on the wave height were examined. The effect of TRIAD wave-wave interaction on the energy density spectra is also shown.

All models used in this study are organised in 1 dimension. In addition, wave data are also given as spectra in 1 dimension. It is also possible to use 2D models in SWAN. By modelling in 2 dimensions, the accuracy of the results can be increased. In addition, the results can be analysed in more detail by making the computational grids smoother.

The use of parameters that reduce wave heights such as bottom friction in CON models can increase the accuracy of the models. In addition, considering that most of the wave data are overestimated in the BKD models, the addition of the bottom friction parameter to these models may allow more accurate predictions to be obtained.

Data science technologies and artificial intelligence algorithms developed in recent years can be used in wave prediction and/or to improve the quality of data to be used in wave prediction models. In recent studies, the usability of Artificial Neural Networks (ANN) alone or in combination with the numerical models in wave prediction is discussed [Malekmohamadi et al., 2008][Makarynsky et al., 2005].

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BIOGRAPHY

Fatih Bahri AYDIN graduated from Konya Necmettin Erbakan University in 2020 with a bachelor's degree in civil engineering. In 2020, he started his master's programme in Civil Engineering at Gebze Technical University.

APPENDICES

Appendix A: Publications Made Within the Scope of Thesis Study

AYDIN, F.B. and AYDOGAN, B., “Performance Evaluation of Wave Breaking Parameters in SWAN Spectral Wave Model”, GTU FBE 7. Lisansüstü Araştırmalar Sempozyumu, June. 1-2 2023, 64.

Appendix B: Example SWAN Command File

```
PROJECT 'project_003"A577" '1'
MODE STATIONARY ONED
SET DEPMIN=0.01 MAXMES=999 MAXERR=3 PWTAIL=4
SET LEVEL 0.165
SET CARTESIAN
SETUP 0
CGRID REGULAR -885 0 0 755 0. 754 0 &
CIRCLE 180 0.04 1.4961 38
!BOUND SHAPE JONSWAP 3.3 PEAK DSPR POWER
INPGRID BOTTOM REGULAR -885 0 0 754 0 1 1
READ BOTTOM 1. 'profile11.bot' 1 0 FREE
!NPGRID CURRENT REGULAR 0 0 0 100 0 10 1
!EAD CURRENT
BOUN SIDE W CONSTANT FILE 'sinir.SP1' 1

WIND 0 00
GEN3 KOMEN
BREAK 1. 0.73
!OFF WCAP
!OFF BREAKING
!FRIC JONSWAP CONSTANT 0.038
!FRIC RIPPLES 2.65 0.0005
```

```
!WCAP KOMEN 2.36e-5 3.02e-3 2. 1. 1.  
!TURB 0.03 CURRENT 0.004  
!TRIAD  
NUM ACCUR 0.02 0.02 0.02 98 15  
OUTPUT OPTIONS '%' TABLE 16 BLOCK 9 1000 SPEC 8  
CURVE 'curve' -885 0 755 755 0  
Table 'curve' HEADER 'project_003.tab' XP YP HSIGN RTP TM01  
TMM10 DIR &  
DSPR DEPTH SETUP  
POIN 'PALL' FILE 'points.txt'  
  
SPEC 'PALL' SPEC1D ABS 'Default.sp1'  
SPEC 'PALL' SPEC2D ABS 'Default.sp2'  
  
TEST 0 0  
COMPUTE  
STOP
```