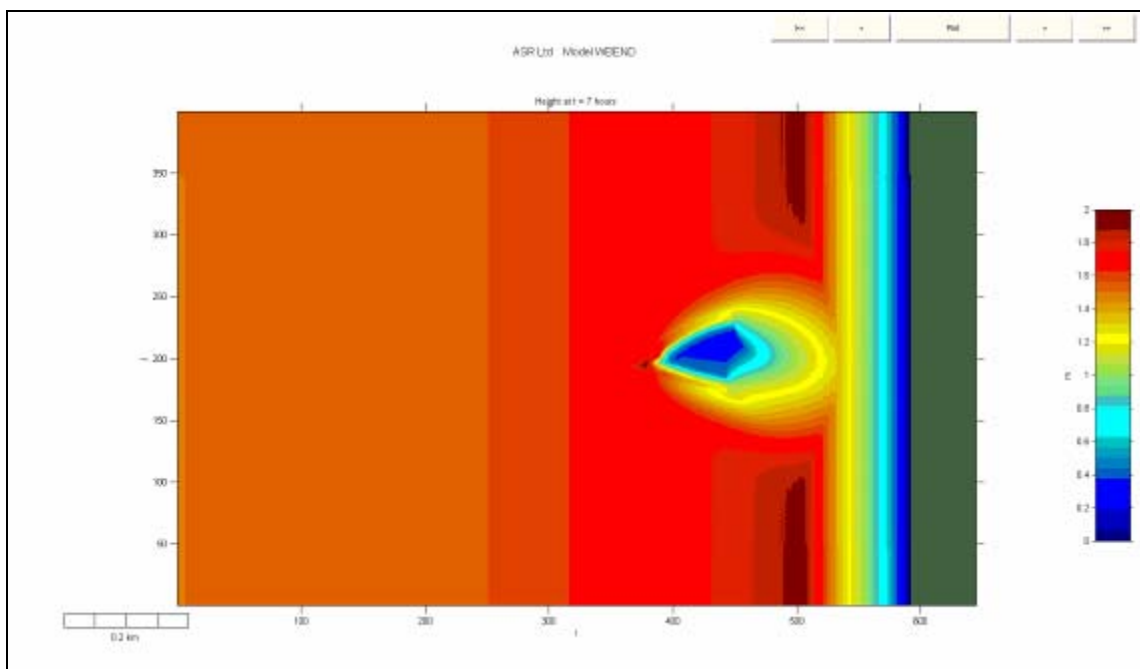


# Numerical Modeling Analysis of the Brevard County Multi-Purpose Artificial Surfing Reef Conceptual Design

A report prepared for the Feasibility Study of  
Multi-Purpose Artificial Surf Reefs along Brevard  
County, Florida



Prepared by



*Marine Consulting and Research*

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The Brevard County Natural Resources  
Management Office

Brevard County, Florida



***Marine Consulting and Research***

P.O. Box 320599, Cocoa Beach, Florida 32932, USA

Ph. +1 321 613-2528, [jhearin@asr-america.com](mailto:jhearin@asr-america.com)

[www.asr-america.com](http://www.asr-america.com)

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## Executive Summary

Four models from the 3DD Modeling Suite were used to assess the functional performance of the proposed Brevard Multi-Purpose Artificial Surfing Reef conceptual design: WBEND, 3DD Boussinesq, NGENIUS and 2DBEACH. Several factors were assessed including wave breaking, wave dissipation, wave rotation, wave peel angle, and shoreline response. Two inshore bathymetry grids, 2m x 2m and 10m x 10m, were constructed from bathymetry data provided by Coastal Technology Corporation. Planar bathymetry grids were utilized in order to isolate the impact of the reef and remove any effects caused by small-scale bathymetry irregularities.

The wave data utilized for this analysis was provided by Surfbreak Engineering Sciences (SES). SES transformed wave data to a point offshore of the proposed reef site at a depth of 10.6m relative to mean sea level (MSL).

The WBEND results indicate that waves 0.3 m high (1 ft) or greater will break on the reef at low and mid tides while waves 1.0 m high (3.2 ft) or greater will break at all tides. The results also indicate that the reef will significantly dissipate wave heights behind the reef for all wave conditions except small waves ( $H_s \leq 1.0$  m) at high tide. The results also show that the offshore reef location (300 m MSL) is outside of the SZW for all waves less than 3.0 m high (9.8 ft). The WBEND results suggest that the reef will act as a wave focus during high tide for waves less than 1.0 m high. Under these conditions the waves will pass over the reef unbroken and focus into an A-frame peak at the shore break which will be higher than the surrounding beach break. This wave focusing phenomena is desirable for surfing enhancement.

The 3DD Boussinesq Model was utilized for the investigation of wave rotation and peel angles. The results indicate that the reef will rotate the wave crests thereby reducing the southerly alongshore current. The 3DD Boussinesq results also predict that the peel angles for waves breaking over the reef will vary between 40–90 degrees. The predicted peel angles are considered desirable for surfing enhancement, although refinements are necessary for detailed design.

Empirical methods developed by Ranasinghe (2006), Black and Andrews (2001a, b) and Black (2003) were used to determine the offshore position of the conceptual reef design. Both methods predict that accretion will occur in the lee of the reef at its proposed location 300 m offshore of MSL. The estimated volume of the salient predicted using the Black method is 120,000 m<sup>3</sup> to 150,000m<sup>3</sup>.

The 2DBEACH and NGENIUS Models were used to analyze the circulation patterns and sediment transport in the vicinity of the reef. 2DBEACH predicts that four-cell circulation patterns will form behind the reef for all wave conditions tested. These counter-rotating cells are conducive to salient formation and beach accretion. The NGENIUS model predicts a salient will form in the shadow of the offshore reef. The estimated volume of the predicted salient is 100,000m<sup>3</sup> to 120,000m<sup>3</sup>. Model 2DBEACH predicts that the salient feature is stable and will serve to protect the beach from, storm wave events.

There was very good agreement between the magnitude of the salient predicted using the empirical method (Black) and the numerical model NGENIUS. The similarity between these predictions provides a higher degree of confidence in the coastal protection benefits of the proposed Multi-Purpose Artificial Surfing Reef.

All the modeling results presented in this report are preliminary and based on a minimal modeling effort. A full scale modeling program (numerical and physical) will be required during the detailed design phase to confirm these results.

## 1 Introduction

This report will describe the numerical modeling analysis performed for the conceptual design of a Multi-Purpose Artificial Surfing Reef (MPASR) for Brevard County, Florida. The functional performance of the proposed MPASR was evaluated for its effectiveness in several categories including wave breaking, wave dissipation, wave rotation, and sediment transport. This analysis was performed using the 3DD Modeling Suite developed by ASR Limited. A detailed description of the 3DD Modeling Suite is presented in Appendix A.

## 2 Wave Climate Data

The wave data utilized for this analysis was provided by Surfbreak Engineering Sciences (SES) based in Indialantic, Florida. SES transformed wave data to a point offshore of the proposed reef site at Osceola Lane in Cocoa Beach (FDEP Monument R-18). The data was transformed using STWAVE to a depth of 10.6m relative to mean sea level (MSL). A summary of the SES wave data is presented in Figure 2.1. The shore normal azimuth for this section of shoreline is approximately 100° true (Figure 2.2).

The mean wave conditions for this data were as follows:

Significant Wave Height ( $H_s$ ) = 0.8 meters = 2.6 feet

Peak Period ( $T_p$ ) = 9 seconds

Direction = 105° true

The wave data indicates that typical wave heights vary from 0.3 – 2.4 meters with predominant wave directions between 90 – 120 degrees true.

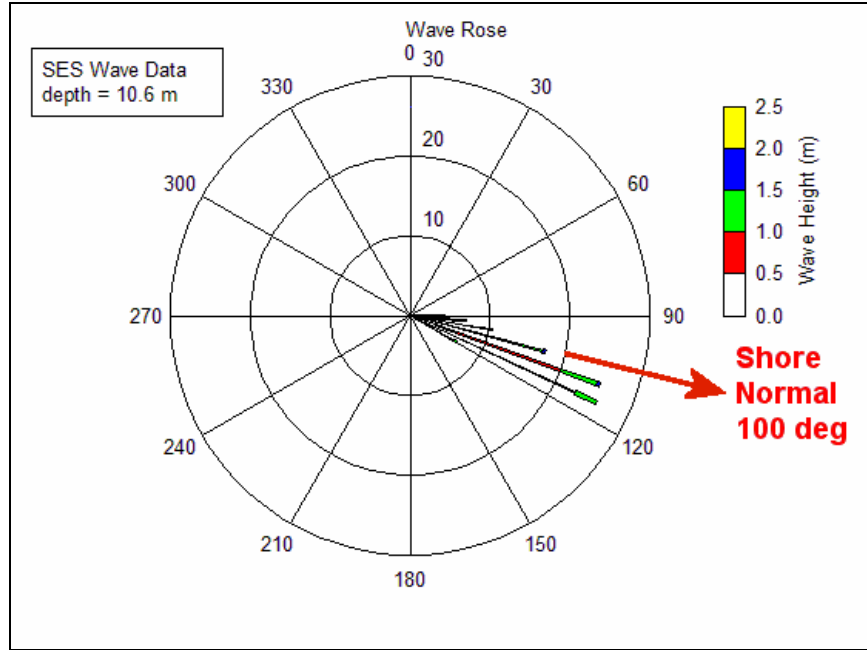


Figure 2.1 Wave Data at Reef Site (SES, 2008)

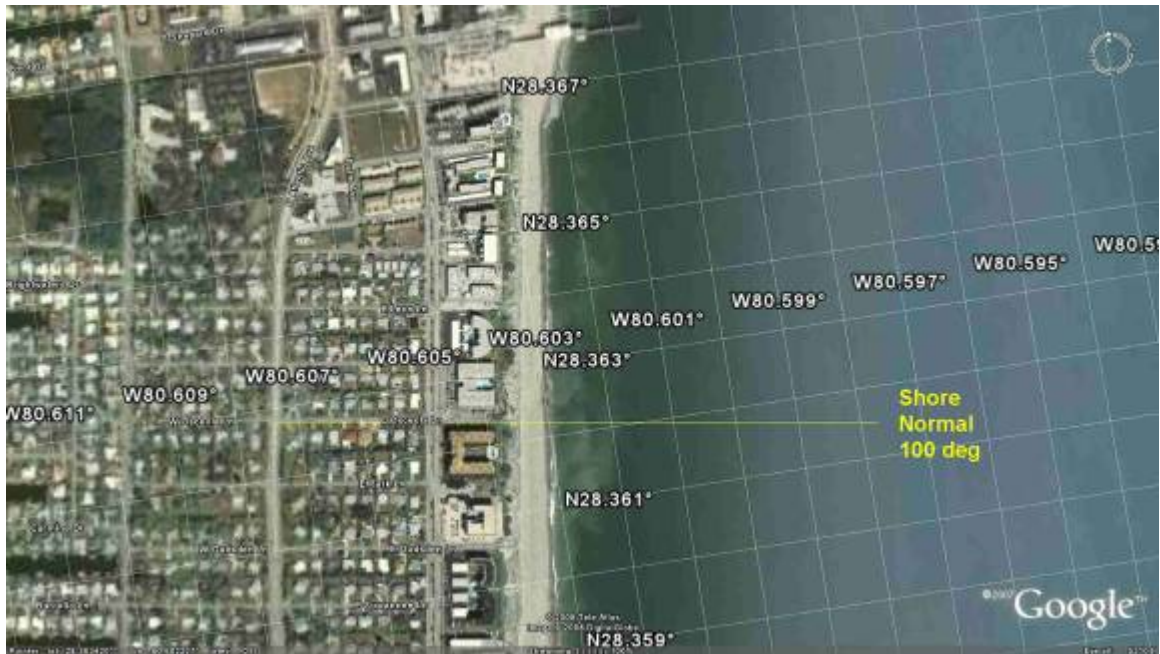


Figure 2.2 Proposed Brevard Reef Site (Google,2008)

### 3 Conceptual Design of Brevard County MPASR

The conceptual design calls for an asymmetric reef with a well defined focus and right and left breaking arms. The focus will concentrate the wave energy at the center of the reef and create a peak or “take-off zone”. The reef crest height was set at 1.0 m below mean sea level (MSL) to take full advantage of the energy dissipation caused by breaking the waves and to maximize the surfing opportunities during small wave conditions. The crest width (measured shore normal) of the MPASR is approximately 100 meters. The reef gradient is variable to maximize the wave breaking characteristics over the full range of expected wave heights (Mead, 2003). The total reef volume, based on the coastal protection requirements, the proposed offshore location and the local bathymetry, is approximately 23,000 m<sup>3</sup>.

The conceptual reef design has an effective alongshore length of 96m and an offshore location of 300m. The offshore location, originally specified in the conceptual design report prepared by ASR America, was selected to enhance the coastal protection properties of the reef. The offshore location is discussed in greater detail in Section 4.4.1 and Appendix B.

The Brevard County MPASR has been oriented 10 degrees to the north to improve the coastal protection properties of the reef via wave rotation and wave dissipation (Black and Mead, 2001). The basic reef configuration is shown in Figures 3.1 and 3.2.

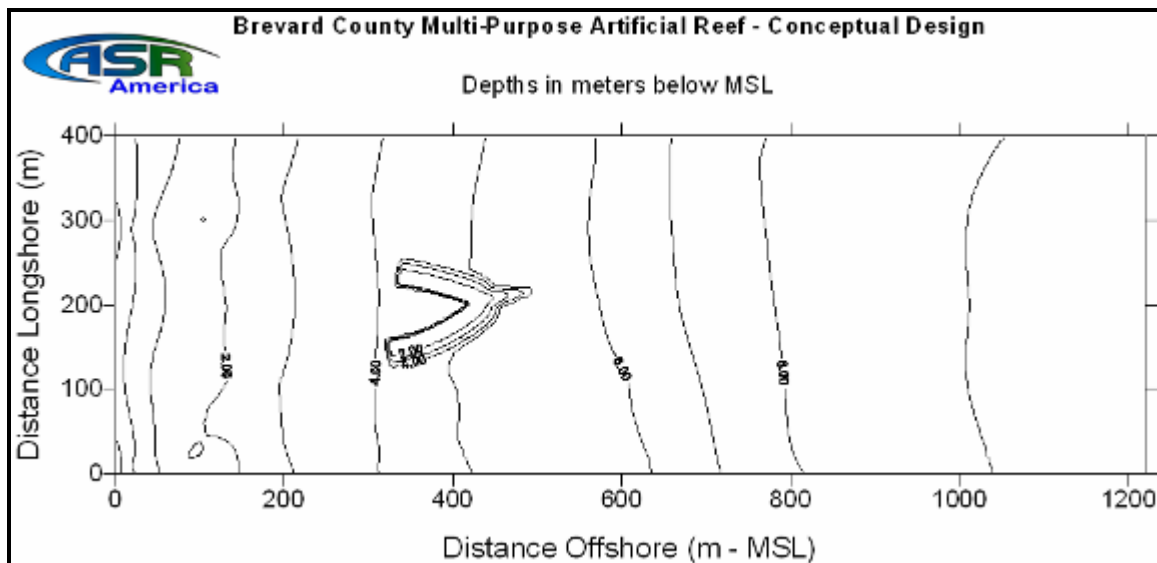


Figure 3.1 Brevard County Conceptual Reef Design

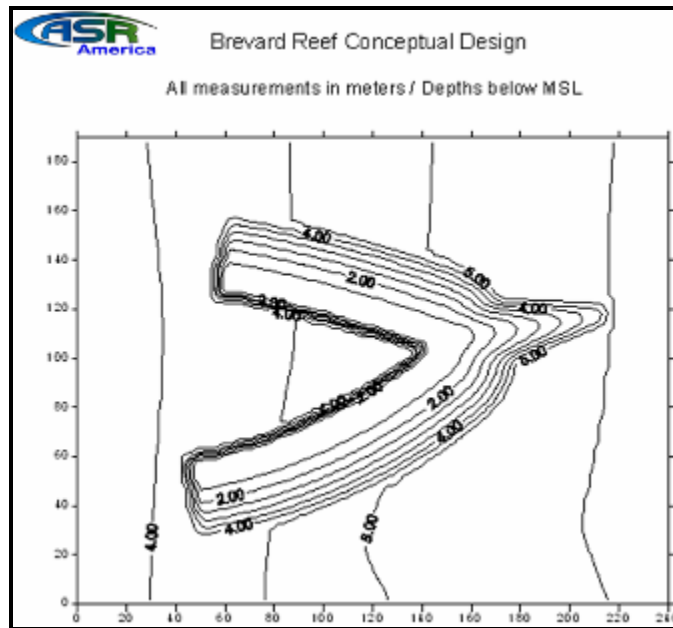


Figure 3.2 Brevard County Conceptual Reef Design

## 4 Numerical Modeling Analysis

Four models from the 3DD Modeling Suite were used for the assessment of functional performance: WBEND, 3DD Boussinesq, NGENIUS, and 2DBEACH (Appendix A). Several factors were assessed including wave breaking, wave dissipation, wave rotation, wave peel angle, and shoreline response.

### 4.1 Bathymetry Grids

Two inshore bathymetry grids, 2m x 2m and 10m x 10m, were constructed from bathymetry data provided by Coastal Technology Corporation (CT). Planar bathymetry grids were utilized in order to isolate the impact of the reef and remove any effects caused by small-scale bathymetry irregularities. The bathymetry grids were rotated 180° to conform to the operational requirements of the 3DD Modeling Suite. The grids used for this analysis are shown in Figure 4.1.

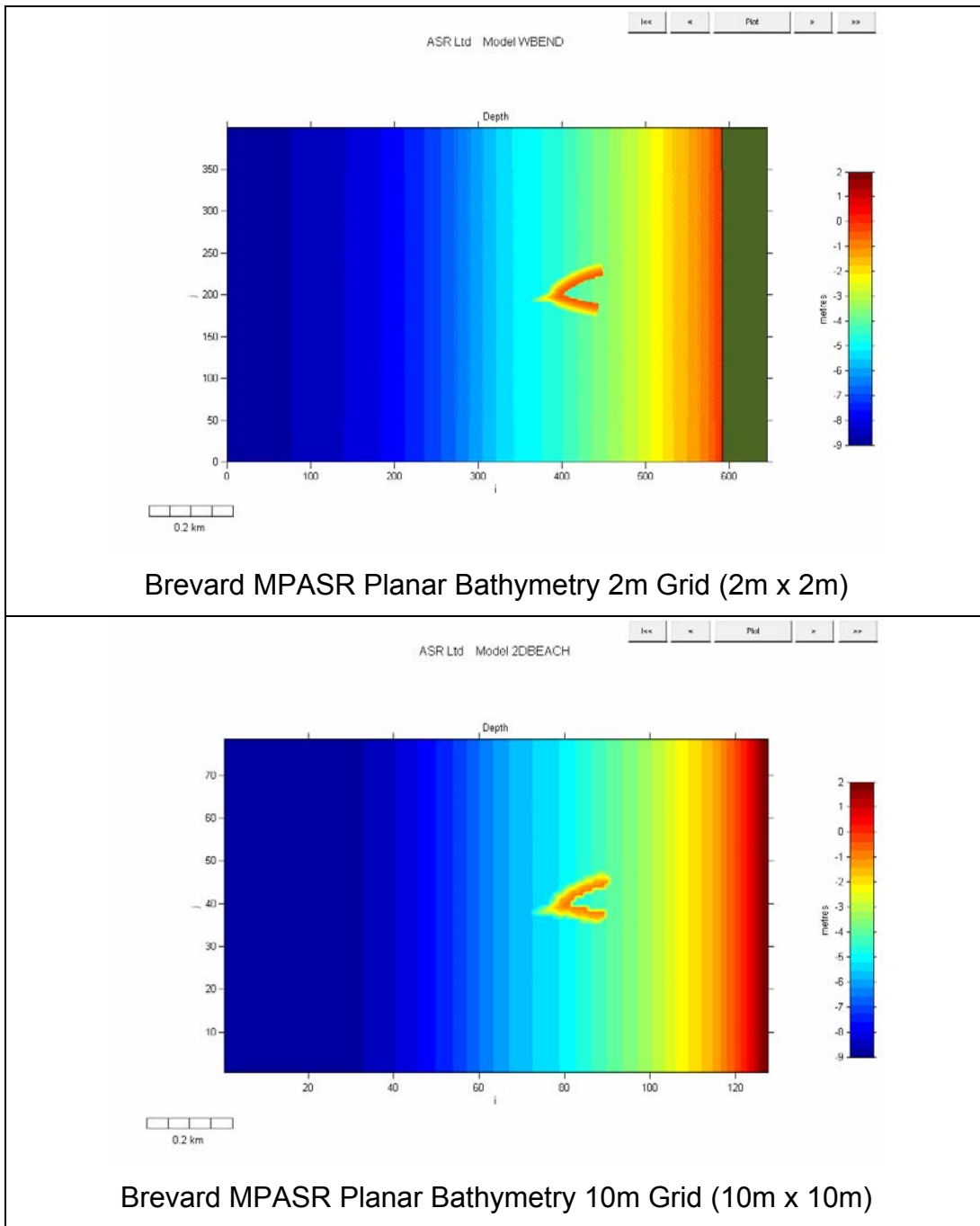


Figure 4.1 Brevard MPASR Planar Bathymetry Grids

## 4.2 Wave Breaking and Dissipation

Investigation of the wave breaking and dissipation aspects of the MPASR were performed using WBEND with the 2m grid. Fifty seven runs were performed using the wave input parameters listed in Table 4.1. Examples of the results are shown in Figures 4.2 – 4.6.

**Table 4.1 WBEND Wave Input Parameters**

Run	H (m)	T (sec)	Angle (deg)	Tide (m)	Run	H (m)	T (sec)	Angle (deg)	Tide (m)
1	0.30	9	0	-0.5	31	0.30	9	-10	-0.5
2	0.30	9	0	0.0	32	0.30	9	-10	0.0
3	0.30	9	0	0.5	33	0.30	9	-10	0.5
4	0.50	9	0	-0.5	34	0.50	9	-10	-0.5
5	0.50	9	0	0.0	35	0.50	9	-10	0.0
6	0.50	9	0	0.5	36	0.50	9	-10	0.5
7	1.00	9	0	-0.5	37	1.00	9	-10	-0.5
8	1.00	9	0	0.0	38	1.00	9	-10	0.0
9	1.00	9	0	0.5	39	1.00	9	-10	0.5
10	2.00	11	0	-0.5	40	2.00	11	-10	-0.5
11	2.00	11	0	0.0	41	2.00	11	-10	0.0
12	2.00	11	0	0.5	42	2.00	11	-10	0.5
13	2.40	14	0	-0.5	43	2.40	14	-10	-0.5
14	2.40	14	0	0.0	44	2.40	14	-10	0.0
15	2.40	14	0	0.5	45	2.40	14	-10	0.5
16	0.30	9	10	-0.5	46	0.3	6	0	-0.5
17	0.30	9	10	0.0	47	0.3	6	0	0.0
18	0.30	9	10	0.5	48	0.3	6	0	0.5
19	0.50	9	10	-0.5	49	0.5	6	0	-0.5
20	0.50	9	10	0.0	50	0.5	6	0	0.0
21	0.50	9	10	0.5	51	0.5	6	0	0.5
22	1.00	9	10	-0.5	52	1.5	10	0	-0.5
23	1.00	9	10	0.0	53	1.5	10	0	0.0
24	1.00	9	10	0.5	54	1.5	10	0	0.5
25	2.00	11	10	-0.5	55	3.0	15	0	-0.5
26	2.00	11	10	0.0	56	3.0	15	0	0.0
27	2.00	11	10	0.5	57	3.0	15	0	0.5
28	2.40	14	10	-0.5					
29	2.40	14	10	0.0					
30	2.40	14	10	0.5					

The WBEND results indicate that waves 0.3 m high (1 ft) or greater will break on the reef at low and mid tides while waves 1.0 m high (3.2 ft) or greater will break at all tides (Figures 4.2 – 4.3). The results also indicate that the reef will significantly dissipate wave heights behind the reef for all wave conditions except small waves ( $H_s \leq 1.0$  m) at high tide. The results also show that the reef is located outside the SZW for all wave conditions tested except 3.0 m high (9.8 ft) at low and mid tides (Figure 4.6).

It is interesting to note that the WBEND results suggest that the reef will act as a wave focus during high tide for waves less than 1.0 m high (Figures 4.2-4.3). Under these conditions the waves will pass over the reef unbroken and focus into an A-frame peak at the shore break which will be higher than the surrounding beach break. This wave focusing phenomena is desirable for surfing enhancement.

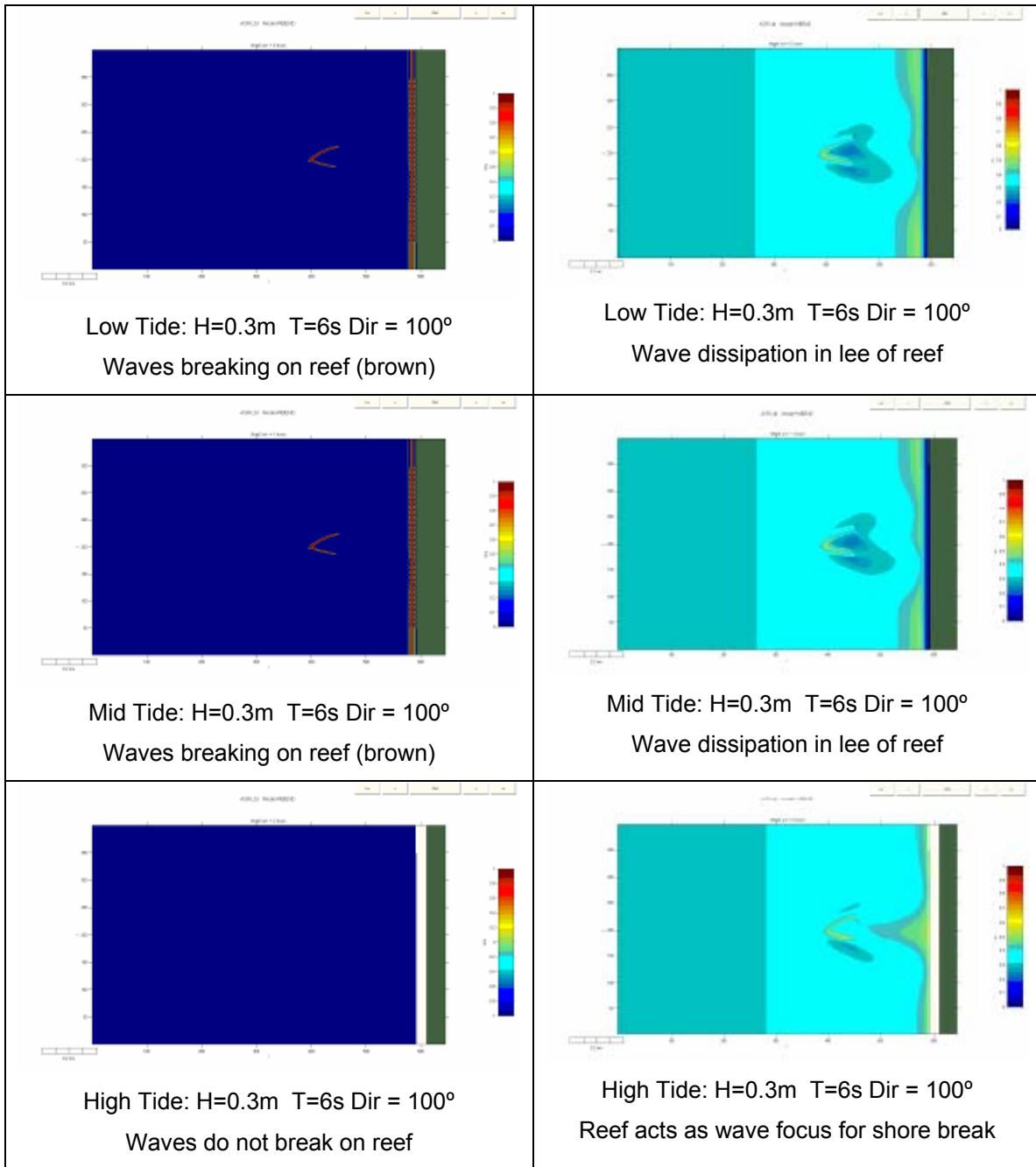


Figure 4.2 Wave Breaking and Dissipation: Wave Height = 0.3m

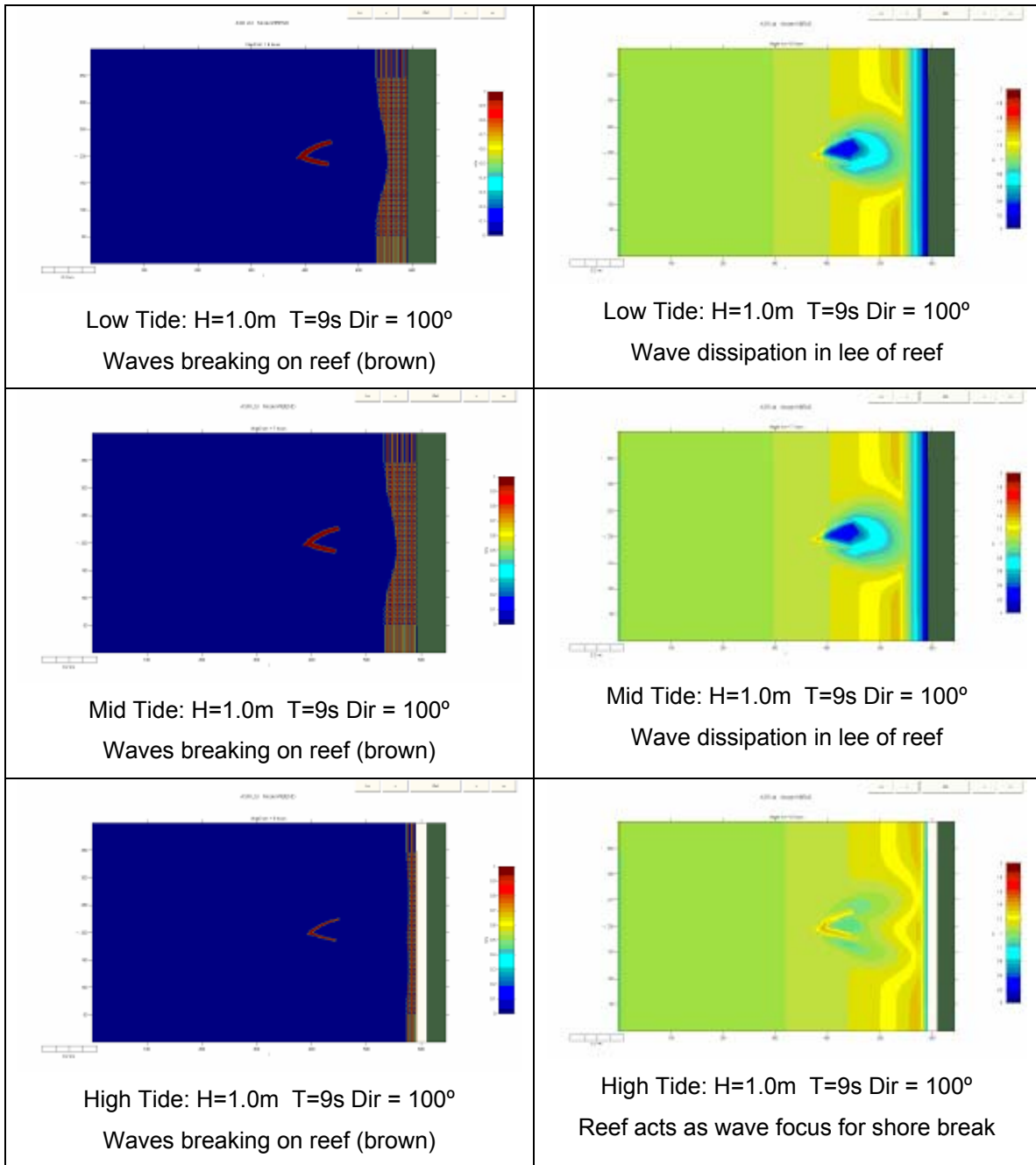


Figure 4.3 Wave Breaking and Dissipation: Wave Height = 1.0m

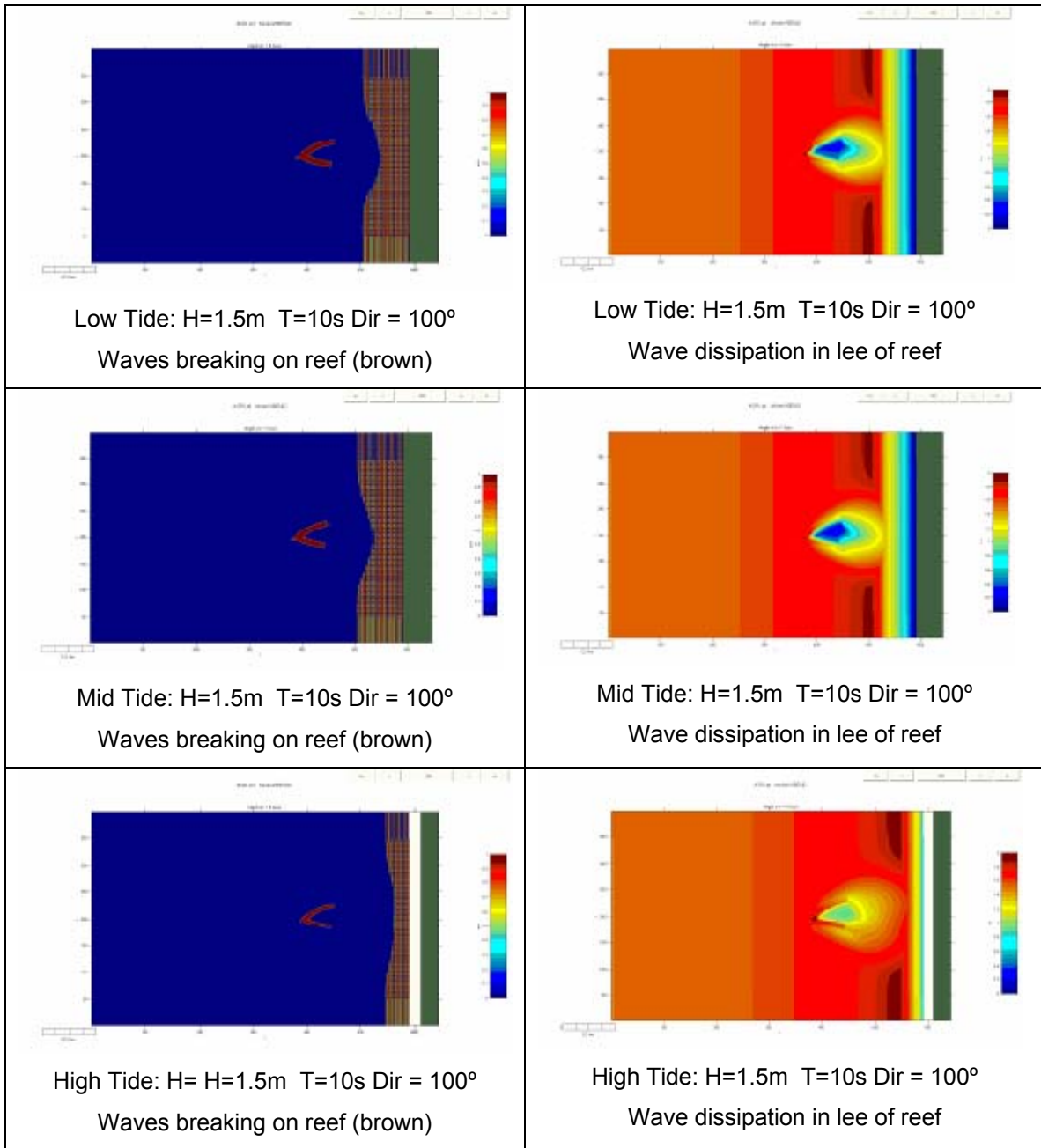


Figure 4.4 Wave Breaking and Dissipation: Wave Height = 1.5m

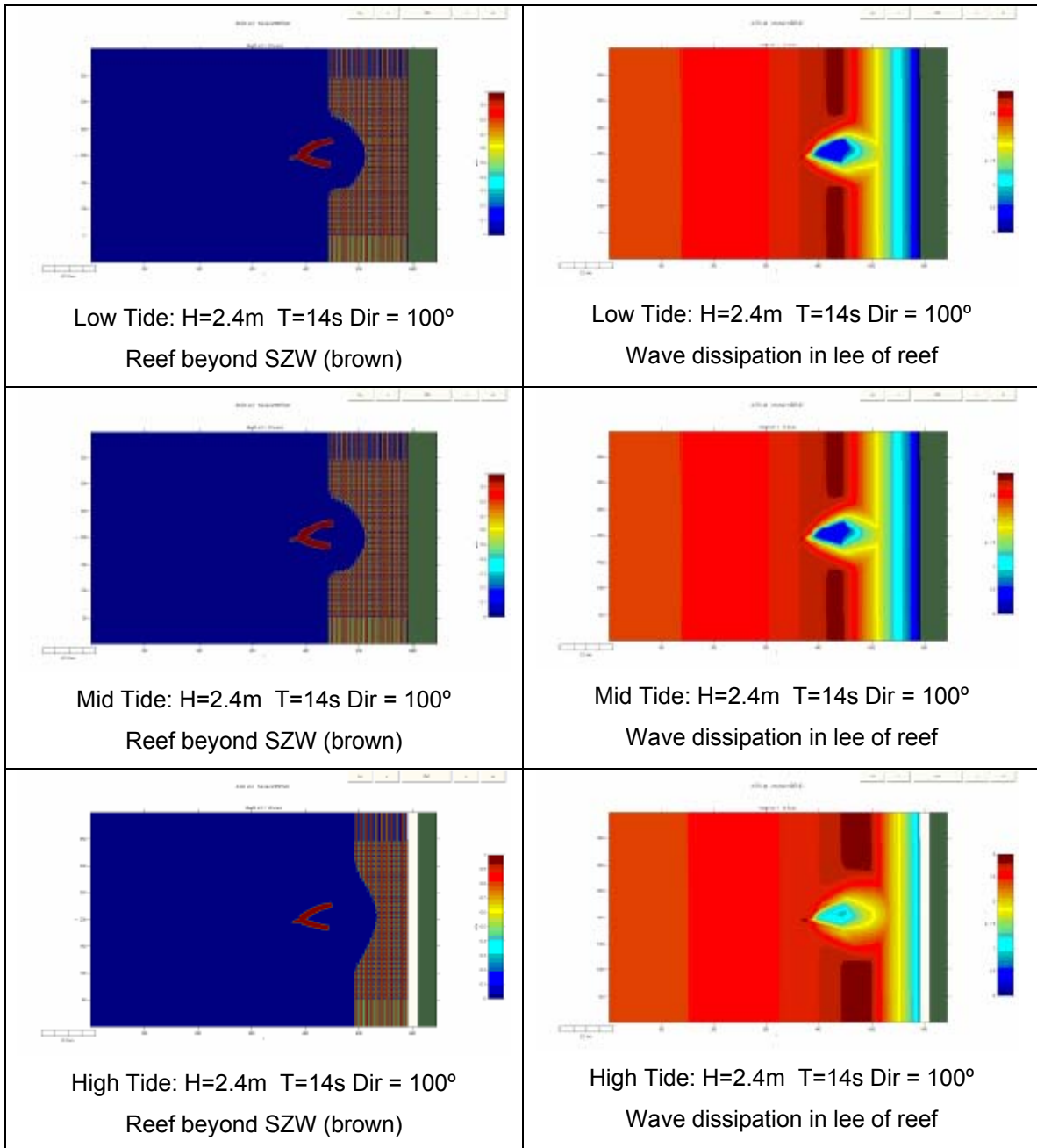


Figure 4.5 Wave Breaking and Dissipation: Wave Height = 2.4m

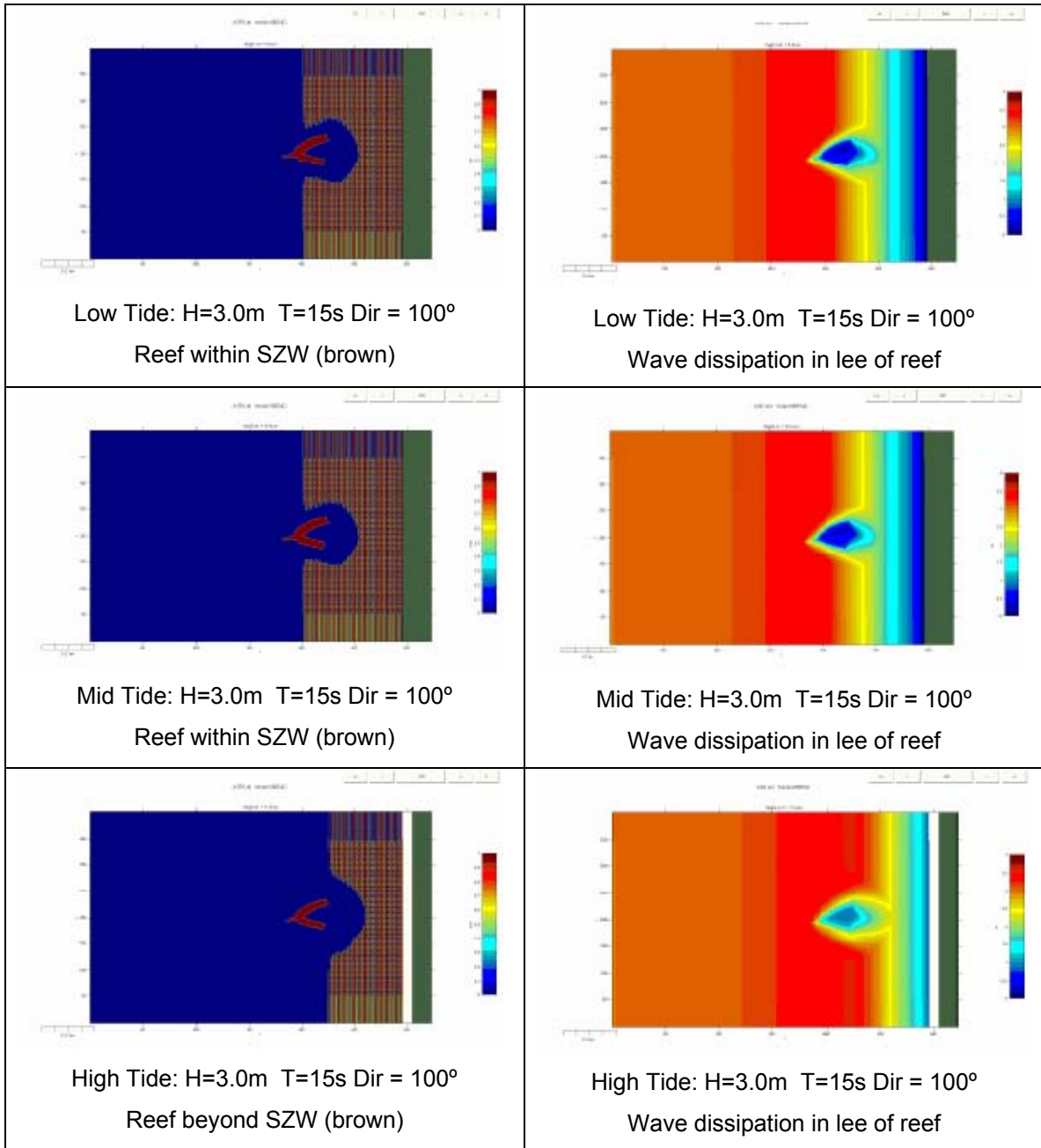


Figure 4.6 Wave Breaking and Dissipation: Wave Height = 3.0m

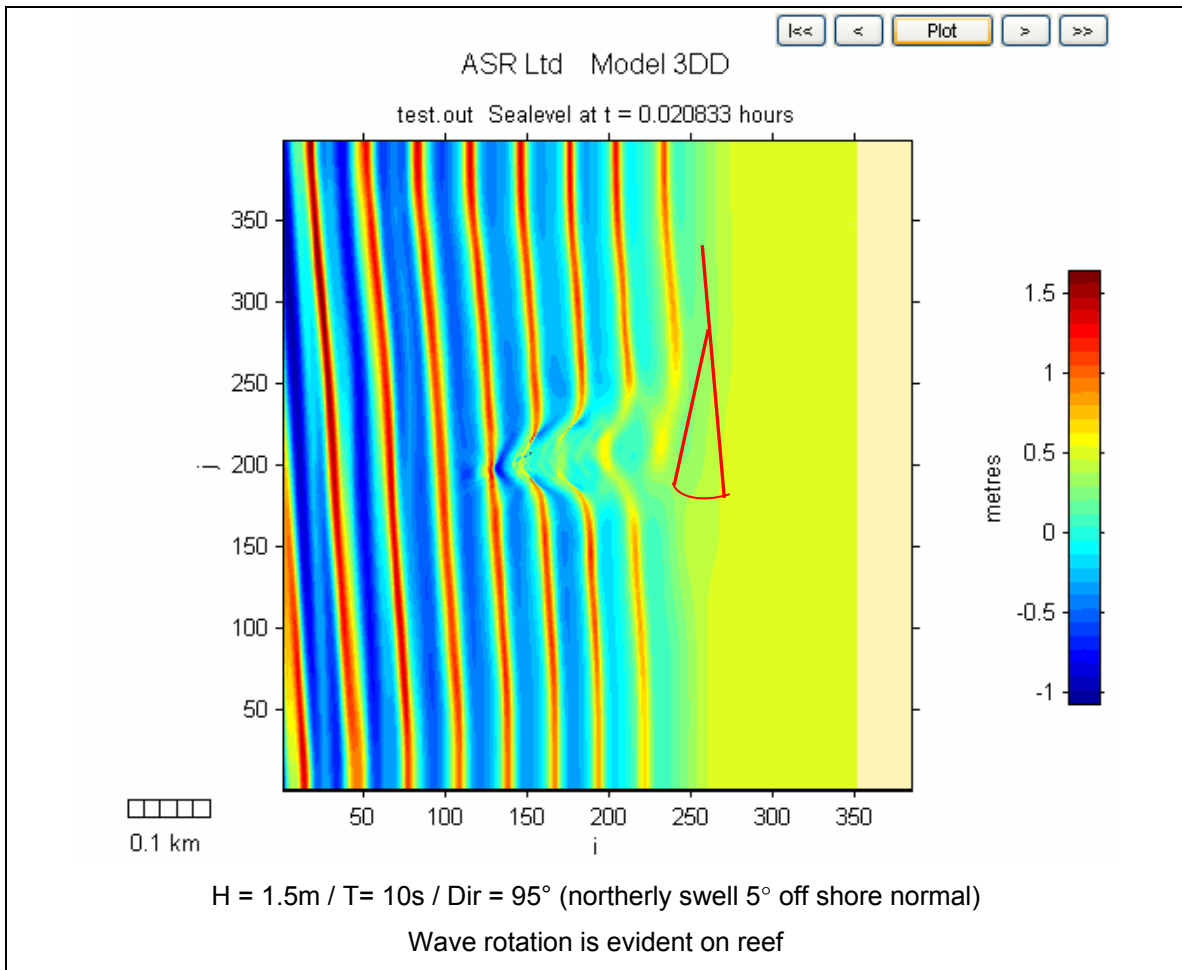
### 4.3 Wave Rotation and Peel Angle

Wave rotation can be used as an effective means of sand retention. Wave rotation refers to redirecting waves so that when they reach the beach and break they modify (reduce) the alongshore component of wave energy flux that generates alongshore currents and removes sand from the beach. In Brevard County, the net alongshore sediment transport is directed to the south (Chiu, 1986) (USACE, 1996). Thus, waves need to be rotated in a more northerly direction to decrease this southerly directed flow. The 3DD Boussinesq Model was utilized for the investigation of wave rotation, since this model best predicts refraction and diffraction of waves. Figure 4.7 shows two of the cases which were tested on the Brevard MPASR. The results indicate that the reef will rotate the wave crests thereby reducing the southerly alongshore current.

The 3DD Boussinesq Model was also utilized to predict the peel angles of the waves breaking on the reef. Examples of wave angles predicted by the model for waves approaching shore normal ( $H_s = 1.5$  m,  $T = 10$  s,  $Dir = 100$  deg true) are shown in Figure 4.8 and Table 4.2. Based on these results the peel angles for waves breaking over the reef will vary between 40–90 degrees. The peel angles for waves approaching from oblique angles will vary slightly with wave direction, height, and period. The predicted peel angles are considered desirable for surfing enhancement. Refinements may be necessary to optimize the surfing amenity based on the results of the detailed reef design.

**Table 4.2 Predicted Peel Angles for Shore Normal Waves**

Reef Section	Initial Wave Angle (deg)	Initial Peel Angle (deg)	Final Wave Angle (deg)	Final Peel Angle (deg)
Focus	0	90	10	80
Right Break	20	70	40	50
Left Break	20	70	50	40



**Figure 4.7 3DD Boussinesq Model Simulation** demonstrating Wave Rotation on the Brevard Multi-purpose Reef. Wave crests are rotated some  $20^\circ$  to counter the southerly directed alongshore transport,

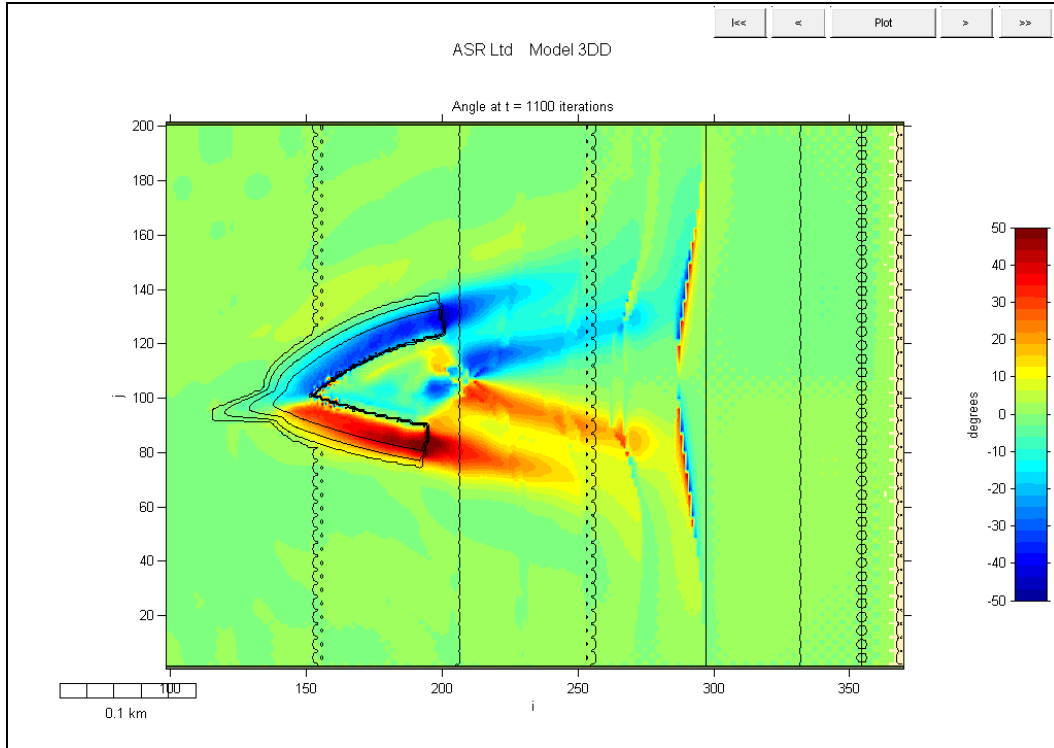


Figure 4.8 3DD Boussinesq Model Results for Wave Peel Angles

#### 4.4 Shoreline Response

On sandy shorelines, natural reefs and islands create wider beaches, termed salients<sup>1</sup> and tombolos<sup>2</sup> (Figure 4.9), due to sediment deposition in their lee. The primary function of a MPASR is to emulate 'nature's way' of using offshore reefs to protect the coast. For coastal protection, salient formation is desired because the gap between the offshore reef and the shore still allows alongshore transport of sediment, unlike a tombolo, which effectively acts as a groyne and leads to negative down-coast impacts (Black *et al.*, 1997; Black *et al.*, 1998; Black *et al.*, 2000a & b; Mead *et al.*, 2001) (Nielsen, 2001).

Alternately, submerged structures too close to the coast can cause erosion due to the circulation patterns that they set-up (Black, 2003; Ranasinghe *et al.*, 2006). Thus, the position of a reef offshore in relation to its dimensions and the existing oceanographic conditions must be determined by a number of methodologies.

<sup>1</sup> A salient is a build up of sand in the lee of an offshore structure that *does not* attach to the structure that formed it and so enables sediment to bypass between the obstacle and the shore and is therefore less likely to cause erosion on the adjacent coastline.

<sup>2</sup> A tombolo is a build up of sand in the lee of an offshore structure that *does* attach to the structure that formed it, blocking sediment movement alongshore and thus usually resulting in erosion of the downcoast shoreline.



A salient sand feature in the lee of a submerged reef



A tombolo sand feature in the lee of an emerged reef.

**Figure 4.9 Natural Salient and Tombolo Formations**

#### 4.4.1 Empirical Predictions of Shoreline Response

The offshore position of the reef is the key factor in determining whether the reef will cause erosion or accretion in its lee. The methods developed by Ranasinghe (2006) and Black (2001 and 2003) were used to determine the offshore position of the conceptual reef design performed by ASR America. A brief description of these methods is presented in Appendix B.

The surf zone width (SZW) is a function of the shoreline gradient and the wave breaking height. The gradient in Brevard County is approximately 1:100. The typical values for the SZW in Brevard County vary from approximately 75 m to 250 m (Table 4.3).

**Table 4.3 Typical Surf Zone Widths for Brevard County**

Wave Height (m)	SZW (m)
0.5	75
1.0	125
1.5	200
2.0	250

The conceptual reef design was positioned 300 m offshore from MSL which is more than twice the SZW for normal wave conditions (0.5m - 1.0m high) and still greater than the SZW for 2m high waves. The Ranasinghe method predicts that accretion will occur behind the reef for most wave conditions that occur in Brevard County.

The conceptual reef design has an effective alongshore length of 96m and an offshore distance of 300m which equates to a B/S ratio of 0.32. A salient with dimensions of approximately 100 m cross-shore and 800m alongshore is predicted to form behind the reef based on the relationships derived by Black. The estimated volume of this salient is between 120,000 m<sup>3</sup> and 150,000m<sup>3</sup>.

Both methods predict that accretion will occur in the lee of the conceptual reef design at the proposed location of 300m offshore of MSL.

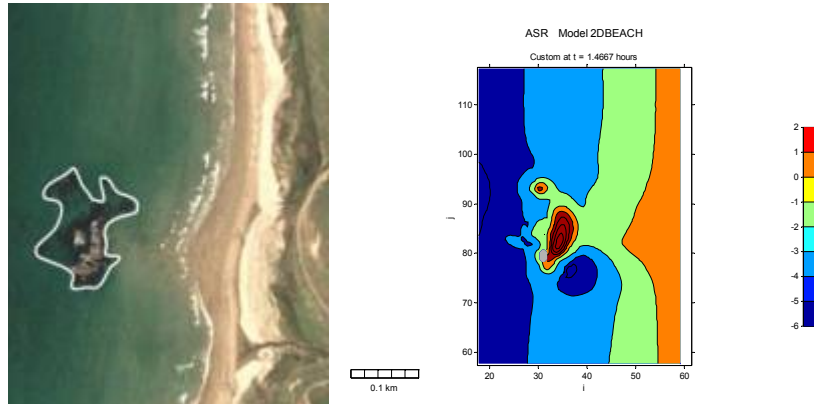
#### **4.4.2 Model 2DBEACH**

Beach evolution modeling was undertaken with Model 2DBEACH (Black and Rosenberg, 1992b) to assess the shoreline response of the conceptual reef design. In this phase, the model runs over long periods with varying wave and tide conditions to predict the long-term sedimentary response. The modeling is particularly focused on the development of the salient at the shoreline. These predictions effectively bring together all the hydrodynamics occurring in response to a reef (wave heights, wave angles, current speed and direction, wave set-up, etc.) and provide predictions of beach response. 2DBEACH has capacity to predict features such as rip currents, sand bar movement, beach transformations, storm erosion and the build-up of beaches after storms. Thus, this modeling exercise provides further evidence to support the offshore location with respect to the erosional/accretional phases of offshore structures discussed in Section 4.4.1.

2DBEACH uses a unique Lagrangian scheme to transform the wave heights. This involves releasing particles at the offshore boundary and heights are carried shoreward as propagating waves by the particles. The heights respond to the processes of refraction, shoaling, friction and breaking dissipation. The wave angles are also obtained using the Lagrangian technique, rather than solving the wave action equation. In essence, the model updates the angle carried by each particle using the initial angle of each particle as the initial condition. The final angle is obtained by calculating the angle change over the time step from the rotation caused by the depth changes along the particle path. The model has been confirmed using a series of model tests that were conducted by comparing the model to known analytical solutions on a plane beach, and for more complex cases, by comparing 2DBEACH results against those predicted by the sophisticated Boussinesq model.

The relevance of this is that on a double armed reef, waves rotate and cross-over in the lee of the reef. By using a Lagrangian method, this complex sea state is properly simulated. For example, at any model cell in the lee of the reef, there can be waves that have crossed either of the arms and the method adopted accounts for this multiple wave pattern. Specifically, the height in each cell is the average of wave heights carried by the particles. The direction in each cell is taken as the average direction of the particles, with each direction being weighted by the wave height. Thus, the larger waves have more influence on the final angle calculation. 2DBEACH can be used to simulate a spectral sea state with both multiple heights and directions. This scheme was used on example cases in northeastern New Zealand (Spendelow, 2004; Black and Mead, 2007). The results were very good, with the general plan shape and salient volume being predicted (e.g. Fig. 4.10). RTK GPS surveys of the bathymetry and beach,

along with multiple wave/current meter measurements, were used to calibrate and verify the modeling.



**Figure 4.10 Salient evolution modeling of a natural reef in New Zealand**

#### 4.4.3 Model 2DBEACH Input Parameters

The boundary conditions for general salient evolution during normal oceanographic conditions are listed below. This data set represents 91% of the inshore wave data provided by SES (Figure 4. 11).

- Wave heights: 365 cases from the inshore wave climate (0.3 - 2.4 m)
- Tidal levels: MSL +/- 0.5 m
- Angles: 365 matching cases for the wave heights
- Periods: 365 matching cases for the height and angles
- Horizontal eddy viscosity:  $1 \text{ m}^2\text{s}^{-1}$
- Horizontal eddy diffusivity:  $2 \text{ m}^2\text{s}^{-1}$
- Breaking criterion (Wave height / water depth): 0.78
- Roughness length: 0.5 m
- Wave friction factor: 0.01
- Model Elapsed Time: 365 days

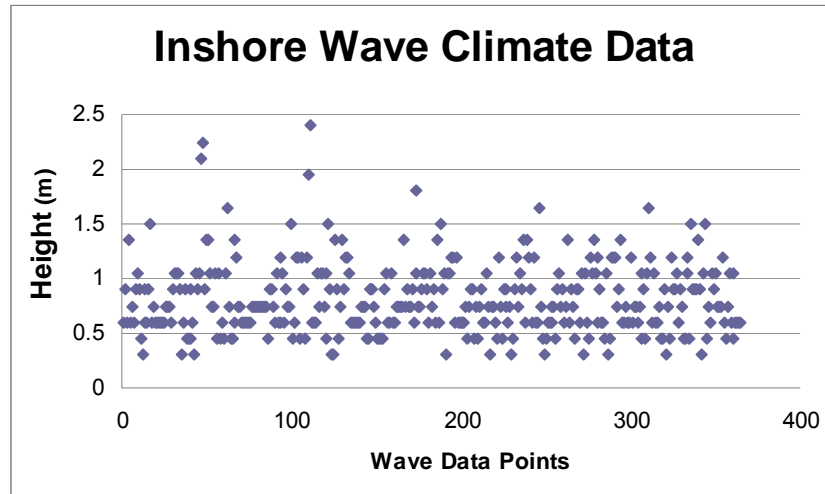


Figure 4.11 Inshore Wave Data (SES,2008)

To investigate shoreline responses to specific higher wave conditions the following boundary conditions were adopted for each case:

Wave heights: 1.5, 2.0, 2.5, 3.0 m  
Tidal levels: MSL + 0.5 m  
Angles: 100° (shore normal)  
Periods: 11 seconds  
Horizontal eddy viscosity:  $1 \text{ m}^2\text{s}^{-1}$   
Horizontal eddy diffusivity:  $2 \text{ m}^2\text{s}^{-1}$   
Breaking criterion (Wave height / water depth): 0.78  
Roughness length: 0.5 m  
Wave friction factor: 0.01  
Model Elapsed Time: 48 hours

#### 4.4.4 Model 2DBEACH Results – Circulation Patterns

The circulation patterns predicted by 2DBEACH are shown in Figure 4.12. These four-cell counter rotating patterns are conducive to salient formation and beach accretion as noted in Appendix B (Ranasinghe, 2006; Black, 2003). These results indicate that the offshore position of the reef will promote accretion at the shoreline.

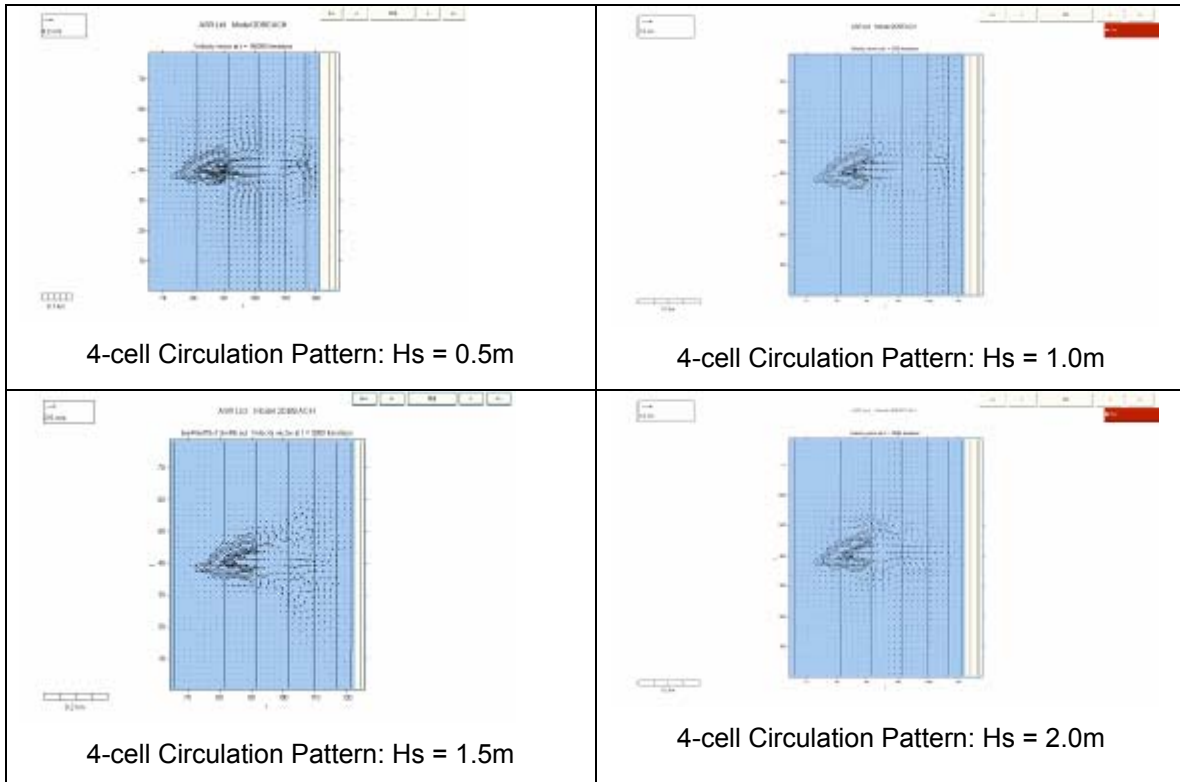


Figure 4.12 Model 2DBEACH Results – Circulation Patterns

#### 4.4.5 Model NGENIUS and 2DBEACH Results – Shoreline Response

The NGENIUS numerical model is an N-Line morphological model which breaks the shoreline into cross-shore segments or compartments. The wave conditions in each compartment are determined using a simplified set of equations for the wave refraction, shoaling and breaking. In each compartment the wave angle and height at the breakpoint are obtained and adopted to predict the along shore sediment transport across the compartment. A mass conservation equation is adopted to calculate the net gain/losses from each compartment by comparing the inputs and outputs from adjacent compartments, and the sea bed level is adjusted accordingly as the model proceeds. This model can be used with wave climate time series to rapidly assess long term morphological changes associated with a coastal structure.

Using the normal wave climate described above (365 days), the NGENIUS model was applied to the initial planar bathymetry with the reef in place. Figure 4.13 shows the initial and final bathymetry conditions. The NGENIUS model predicts a salient formation in the shadow of the offshore reef. The estimated volume of this salient is between 100,000m<sup>3</sup> and 120,000m<sup>3</sup>.

Model 2DBEACH was then used to assess the stability of the predicted shoreline change and salient formation. For these model runs the final bathymetry predicted by NGENIUS was used as the initial bathymetry for the 2DBEACH modeling. A typical wave climate (365 days) was then introduced to the model to assess the morphological response of the shoreline to the variable wave climate.

The results, shown in Figure 4.14, show that larger wave events can induce erosion of the salient, however this feature is expected to return with smaller wave conditions. Thus the salient feature is stable and will serve to protect the beach from, storm wave events.

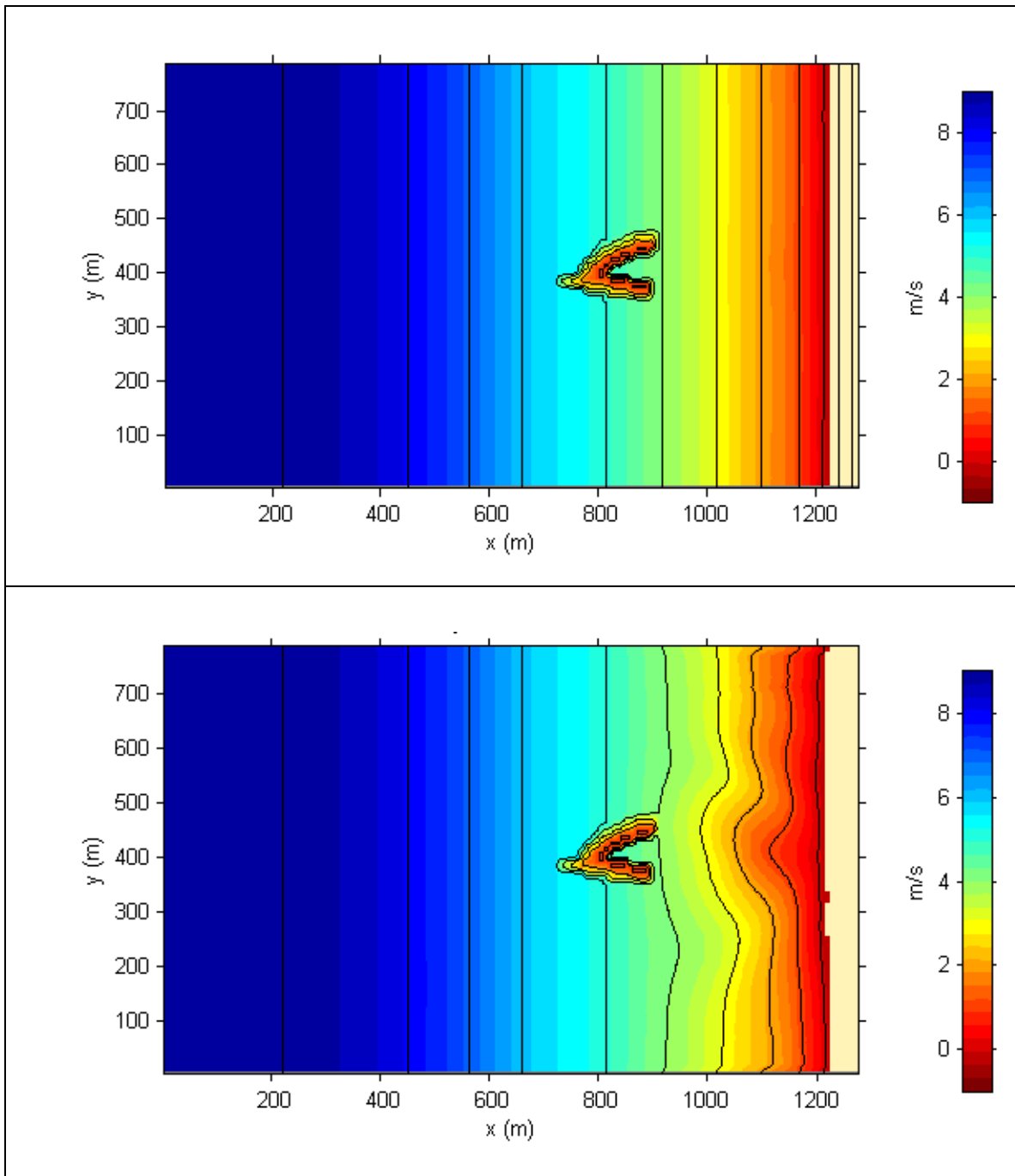


Figure 4.13 The initial and final shoreline configuration as predicted by NGENIUS

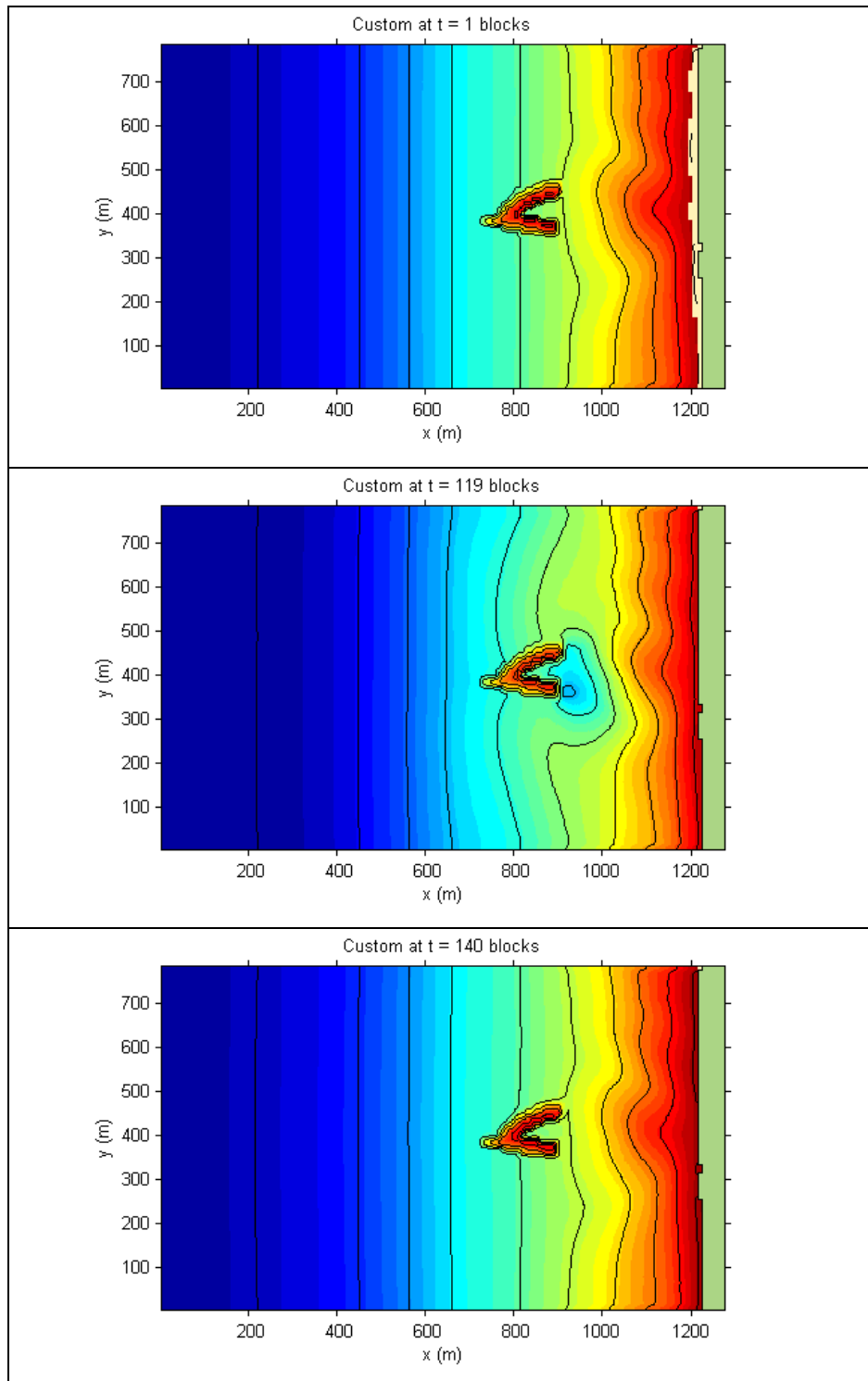


Figure 4.14 2DBEACH results showing the initial bathymetry (upper) then the response to a large wave event (mid) and the subsequent rebuilding of the salient (lower).

## 5 Summary and Conclusions

Four models from the 3DD Modeling Suite were used to assess the functional performance of the Brevard MPASR conceptual design: WBEND, 3DD Boussinesq, NGENIUS and 2DBEACH. Several factors were assessed including wave breaking, wave dissipation, wave rotation, wave peel angle, and shoreline response. Two inshore bathymetry grids, 2m x 2m and 10m x 10m, were constructed from bathymetry data provided by Coastal Technology Corporation. Planar bathymetry grids were utilized in order to isolate the impact of the reef and remove any effects caused by small-scale bathymetry irregularities.

The wave data utilized for this analysis was provided by Surfbreak Engineering Sciences (SES). SES transformed wave data to a point offshore of the proposed reef site at a depth of 10.6 m relative to mean sea level (MSL).

The WBEND results indicate that waves 0.3 m high (1 ft) or greater will break on the reef at low and mid tides while waves 1.0 m high (3.2 ft) or greater will break at all tides. The results also indicate that the reef will significantly dissipate wave heights behind the reef for all wave conditions except small waves ( $H_s \leq 1.0\text{m}$ ) at high tide. The results also show that the offshore reef location (300m MSL) is outside of the SZW for all waves less than 3.0 m high (9.8 ft). The WBEND results suggest that the reef will act as a wave focus during high tide for waves less than 1.0m high. Under these conditions the waves will pass over the reef unbroken and focus into an A-frame peak at the shore break which will be higher than the surrounding beach break. This wave focusing phenomena is desirable for surfing enhancement.

The 3DD Boussinesq Model was utilized for the investigation of wave rotation and peel angles. The results indicate that the reef will rotate the wave crests thereby reducing the southerly alongshore current. The results predict that the peel angles for waves breaking over the reef will vary between 40 – 90 degrees. The predicted peel angles are considered desirable for surfing enhancement.

Empirical methods developed by Ranasinghe (2006), Black and Andrews (2001a, b) and Black (2003) were used to determine the offshore position of the conceptual reef design. Both methods predict that accretion will occur in the lee of the reef at its proposed location 300 m offshore of MSL. The estimated volume of the salient predicted using the Black method is 120,000 m<sup>3</sup> to 150,000m<sup>3</sup>.

The 2DBEACH and NGENIUS Models were used to analyze the circulation patterns and sediment transport in the vicinity of the reef. 2DBEACH predicts that four-cell circulation patterns will form behind the reef for all wave conditions tested. These counter-rotating cells are conducive to salient formation and beach accretion. The NGENIUS model predicts a salient will form in the shadow of the offshore reef. The estimated volume of the predicted salient is 100,000m<sup>3</sup> to 120,000m<sup>3</sup>. Model 2DBEACH predicts that the salient feature is stable and will serve to protect the beach from, storm wave events.

There was very good agreement between the magnitude of the salient predicted using the empirical method (Black) and the numerical model NGENIUS. The similarity between these predictions provides a higher degree of confidence in the coastal protection benefits of the proposed MPASR.

All the modeling results presented in this report are preliminary and based on a minimal modeling effort. A full scale modeling program (numerical and physical) will be required during the detailed design phase to confirm these results.

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## Appendix A


### The 3DD Modeling Suite: Information Package

The numerical model suite **3DD** consists of a full set of marine and freshwater simulations of all physical processes relevant to planning, management, and research of our environment ([www.asrltd.co.nz](http://www.asrltd.co.nz)). The suite is fully matured, developed over a broad series of science programs and is now available for commercial and research use worldwide.

The current technology in  **Numerical Models** arose from focused studies, such as the “Wave and Sediment Dynamics” research funded by the Australian Research Council. The main success of the models, however, stems from years of practical application in every possible marine and freshwater environment, from rivers and lakes to beaches and seas. The applications range from biological to oil spill planning, port dredging and beach erosion and protection.

Experience in coastal research, driven by the conviction of coastal scientists to see better solutions to coastal problems, has meant that the **3DD** suite has become the primary tool for understanding, predicting and managing the environment, during many projects.

Modern, sophisticated computer models of oceans and bays can provide close predictions of waves, currents and sediment movement. When adequately confirmed by field data, these models provide an understanding of physical processes unparalleled by other methods of investigation.


 has highly experienced staff capable of undertaking the full range of tasks using models, and takes pride in its world position as an “international modeling house”. The numerical models of the 3DD suite are leased or used in research projects around the world.

The models from the **3DD** suite are:

<b>3DD</b> <sup>®</sup>	3-dimensional flows, dispersal, short-wave and ocean/atmos. heat transfer
<b>POL3DD</b> <sup>®</sup>	3-dimensional dispersal
<b>WGEN</b> <sup>®</sup>	Estuary wave climate
<b>WBEND</b> <sup>®</sup>	Refraction of monochromatic and spectral waves
<b>2DBEACH</b> <sup>®</sup>	Beach circulation and sediment transport.
<b>GENIUS</b> <sup>®</sup>	Sedimentation around coastal structures.

## Model 3DD<sup>©</sup>

The 3dimensional hydrodynamic model **3DD** (developed by Prof. Kerry Black) has been used successfully in numerous studies around the world and in New Zealand.

The model is a primary component of the  hydrodynamic modeling system, which provides accurate and comprehensive simulations of a complete range of processes, over time scales of seconds to weeks. Based around highly accurate mixed Eulerian/Lagrangian mathematical techniques, the model **3DD** provides state-of-the-art- hydrodynamic and dispersal simulations. Developed and sustained by comprehensive field measurements and supplementary modeling packages, the **3DD** suite has been validated to achieve an unprecedented level of numerical refinement. High-quality animated graphics allow the model outputs to be easily interpreted by non scientific people.

**3DD** is essentially five different models coupled into one fully-linked computer code dealing with:

- Side-view, 2-dimensional, 3-dimensional homogeneous and 3-dimensional stratified hydrodynamics
- Lagrangian and Eulerian dispersal models, including buoyant plumes
- Ocean/Atmosphere heat transfers
- "Boussinesq" short waves
- Radiation-stress wave-driven circulation

With continuity of style maintained throughout the model suite and the support software, **3DD** can be operated in 2 or 3 dimensions using the same input files, thereby ensuring an effortless transition.

**3DD** is fully coupled with dispersal, sediment transport, oil spill and wave refraction and wave generation models so that model-generated information can be transferred within the suite to enable the world's most complex environments to be accurately simulated.

The model's enhanced features include:

- Windows-based operation graphics to the screen at run-time as a diagnostic aid
- optional "batch mode" operation for multiple unattended simulations
- easy data entry
- third-order accurate derivative approximations to the advective momentum terms to eliminate grid-scale zig-zagging
- a boundary slip parameter which eliminates the problem of excessive damping of currents in narrow channels due to horizontal diffusion

- inter-tidal flooding and drying schemes which prevent development of velocity spikes on the sand banks, and no smoothing of bathymetry is required
- an "effective depth" formulation which prevents excessive frictional resistance in very shallow water
- a body force procedure to simulate large-scale pressure gradients associated with coastal trapped waves, other continental shelf waves or geostrophic gradients when sea level boundary data are unavailable
- a variety of vertical eddy viscosity formulations
- multiple station weather and environmental time series inputs full heat transfer formulations and time series inputs
- hot starts nested simulations
- "double" bathymetry resolution without increasing CPU requirements
- baroclinic side-view simulations for rapid speed

## Model POL3DD<sup>®</sup>

The dispersal model **POL3DD** (Pollution dispersal coupled to 3DD) tracks suspended “particles” to simulate water-borne dispersal including larval behaviors, oil spills, outfall and estuarine or beach sediment transport. The sediment model uses Lagrangian techniques which are particularly useful near sharp concentration gradients, as they exhibit minimal numerical diffusion/dispersion because the particle positions are exactly known and particle advection is calculated directly from the currents.

### Transport of effluent, pollutants, salinity and temperature

- concentrations of tracers from multiple sources in 3-dimensions
- vertical and horizontal salinity gradients

### Buoyant plumes and oil spills

- buoyant plumes using a novel layered technique simulating surface, multiple sub-surface and bottom layers
- surface transport and beachings of oil spills or other floating contaminants

### Sediment dynamics

- bedload and suspended load sediment transport
- sediment erosion/deposition
- full grain size distribution

### Decay

- time-varying bacterial inactivation
- selected mass transformation processes

### Larval transport

- larval dispersal
- active behavior

**POL3DD** is linked to a 3-dimensional hydrodynamic model (Model **3DD**) so that detailed flow patterns can be directly utilized. In addition, **POL3DD** can be simultaneously coupled to a wave generation model (**WGEN3DD**) or the wave refraction model (**WBEND**) so that bed entrainment by wave orbital motion, wave current/interaction and vertical mixing due to waves can be treated over the model grid.

## Model WGEN<sup>©</sup>

The wave generation model **WGEN** (Wave Generation coupled to 3DD) was developed for fetch-limited water bodies and treats plan shapes which change during the tidal cycle with the submergence and emergence of intertidal sand banks. **WGEN** applies the JONSWAP (Joint North Sea Wave Project) equations assuming pseudo-steadiness and is therefore most useful in small estuaries of up to about 40 km maximum fetch. Since the original version presented in 1992, the model has been extended to include depth-limited breaking, shoaling and bed friction in the JONSWAP formulae. WGEN has been linked to the hydrodynamic model 3DD so that nonlinear wave-current interactions in the bed friction term can be treated, while coupling with a sediment dynamics model provides for calculation of sediment transport in wave and current environments.

## Model WBEND<sup>©</sup>

Model **WBEND** is a 2-dimensional numerical wave refraction model for monochromatic waves or a wave spectrum over variable topography for refraction and shoreline alongshore sediment transport studies. The model applies a fast, iterative, finite-difference solution of the wave action equations to solve for wave height, wave period, breakpoint location, alongshore sediment transport, bottom orbital currents and near-bed reference concentration of suspended sediments.

**WBEND** has unique characteristics such as:

- an enhanced shoaling facility to overcome under-prediction of breakpoint wave height which is common to all other linear wave models
- proven capacity to simulate the difficult cases of surfing reef wave transformation, breakpoint peel angle and breakpoint height
- a pseudo-diffraction algorithm simulating diffusion of height and angle along the wave crests
- multiple bed friction choices
- prediction of bedform geometry in response to prevailing wave conditions, and feed-back into the bed friction term
- coupling to the hydrodynamic model 3DD and sediment model POL3DD for simulation of wave-driven circulation and sediment transport in wave and current environments

## Model 2DBeach<sup>©</sup>

Model **2DBeach** is a unique beach circulation and sediment transport model that uses a mixed Lagrangian and Eulerian solution scheme to obtain highly-accurate simulations over complex natural bathymetries. The height transformation method, plus **2DBeach**'s many features and simple operation, sets this model apart, and makes it one of the most appealing general-purpose beach models presently available.

In one fully coupled computer code, **2DBeach** contains:

- A Lagrangian wave height transformation model treating conditions beyond, through and inside the breakpoint
- A non-linear, wave-driven hydrodynamic model,
- A wave angle transformation simulation using a rapid iterative solution and
- A wave and current sediment transport model able to treat multiple grain sizes, "real-time" seabed adjustments and enhanced suspension around the breakpoint under plunging waves

**2Dbeach** has unprecedented capacity to predict features such as rip currents, sand bar movement, beach transformations, storm erosion and the build-up of beaches after storms.

In **2DBeach**, the unsteady wave height transformation equations are solved using a combination of Lagrangian and Eulerian methods, which eliminates the numerical diffusion errors that are common to purely Eulerian solutions. The Lagrangian scheme also effectively handles the sharp discontinuity in wave heights across the breakpoint.

A non-steady, non-linear hydrodynamic model is linked to the wave transformation models through radiation stress terms in the momentum balance equations. The sediment transport model uses a vertically-averaged form of the suspended sediment concentration equations to treat spatial variation in suspended sediment concentration and differential settlement and the consequential seabed "real-time" adjustments

The development of 2DBEACH is fully described in Black and Rosenberg (1992a & b). The model adopts a Lagrangian particle scheme for the propagation of wave height shorewards from the offshore boundary (Black and Rosenberg, 1992a). This enables direct computation of wave height transformation, breaking and frictional attenuation, and propagation over long distances. The scheme is effective on barred topography and across the breakpoint where gridded Eulerian schemes can be adversely affected by sharp height transitions after breaking,

particularly on complex topography. As the history of the wave is carried by the particle, wave reformation in a channel after breaking on an offshore bar or over a reef can be more accurately treated (Black and Rosenberg, 1992a).

The morphological module in 2DBEACH enables the computation of sediment transport and morphological evolution. The basic characteristics of the morphological module are as follows.

Bagnold's (1963) energetics approach was adopted for sediment transport calculations in the present study. Various forms of the energetics approach, which is considered to be one of the most physically sound approaches for estimating sediment transport (Bowen, 1980, Bailard, 1981), have been successfully adopted in a number of 2DV and 2DH morphodynamic models (Stive, 1986; Nairn and Southgate, 1993; Ranasinghe *et al.*, 1999). Following Baillard's (1981) re-interpretation of the energetics approach for sediment transport under the combined action of waves and currents, the following formulation was incorporated into 2DBEACH.

The total sediment transport load (immersed weight),  $i$ , is expressed as,

$$i = i_b + i_s \quad (1)$$

where  $i_b$  and  $i_s$  represents bedload and suspended load (immersed weight) respectively.

$$i_b = \frac{\varepsilon_b C_f \rho \bar{u}^3}{\tan \phi - \frac{\bar{u} \tan \beta}{|\bar{u}|}} \quad (2)$$

$$i_s = \frac{\varepsilon_s C_f \rho \bar{u}^3}{\frac{W}{\bar{u}} - \varepsilon_s \tan \beta} \quad (3)$$

where  $C_f = 0.5f_w$  (when  $f_w$  is calculated as in Swart (1974)),  $\vec{u} = \bar{u} + \tilde{u} \cos \theta$  where  $\bar{u}$  = mean current velocity,  $\tilde{u}$  = wave orbital velocity, and  $\theta$  = the angle between the mean current and wave direction,  $W$  = sediment fall velocity,  $\beta$  = beach slope,  $\varepsilon_b$  and  $\varepsilon_s$  = bedload and suspended load efficiency factors respectively,  $\rho$  = density of seawater,  $\phi$  = angle of repose

The total immersed weight thus calculated is then converted into a volumetric sediment transport rate by using,

$$q = \frac{i}{(\rho_s - \rho)ga} \quad (4)$$

where  $a$  = bed porosity,  $g$  = gravitational acceleration,  $q$  = volumetric sediment transport rate per meter length ( $m^2/s$ ), and  $\rho_s$  = sediment density.

The total volumetric sediment transport rate,  $q$ , which is in the direction of the mean current, is then resolved into the  $x$  and  $y$  directions of the finite difference grid, and the bed levels are updated by solving the 2D sediment continuity equation,

$$\frac{\partial z}{\partial t} = \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \quad (5)$$

where  $q_x$  and  $q_y$  = sediment transport rates ( $m^2/s$ ) in  $x$  and  $y$  directions respectively, and  $z$  = bed level.

The model additionally incorporates a horizontal eddy diffusivity term, which acts to linearize the concentration gradients. The importance of this term has been fully discussed by Black et al. (2002).

The bed levels are updated every few hydrodynamic time steps to ensure a smooth evolution of the model bathymetry so that hydrodynamic instabilities do not occur.

## Model NGenius<sup>®</sup>

Model **NGENIUS** predicts refraction, breakpoint wave conditions and alongshore sediment transport on beaches. **NGENIUS** is similar to its well-known counterpart GENESIS (Hanson and Kraus, 1989) but with some extra features including frictional attenuation of wave height and a more physically-based treatment of wave transmission factors across submerged reefs.

In **NGENIUS**, the results are obtained by assuming that the alongshore variability in bathymetry is small so that Snell's Law is applicable. When this assumption is not acceptable, wave transformation predictions should be made using the more complex model **WBEND**.

**NGENIUS** accepts a time series of wave conditions to find net alongshore sediment fluxes. Offshore wave heights are transformed into shallow water using linear wave relationships to find the refraction and shoaling coefficients. Frictional attenuation is applied by approximating the methods adopted by **WBEND**. Breakpoint height and angle are obtained by iterating the linear wave refraction and shoaling relationships. Alongshore sediment transport is calculated using the CERC formula applied in GENESIS.

## Appendix B

### Shoreline Response to a Multi-Purpose Artificial Reef

#### Shoreline Response Predictions from Black and Andrews

Using aerial photographs, Black and Andrews (2001a) analyzed naturally occurring salient formations in New Zealand and Australia. Their research focused on developing empirical relationships to describe salient shapes and dimensions. Additionally they used these relationships to form predictive expressions for salient size based on reef width and offshore distance. Refer to Figure 1 for the salient parameter descriptions.

#### Physical Dimensions:

- B - Reef width
- S - Distance offshore to landward side of reef
- $Y_{off}$  - Salient amplitude
- $X_{off}$  - Distance between reef and salient
- $D_{tot}$  - Length of salient

#### Predictive Expressions:

- (1)  $B/S \leq 0.1$  Salient may not form
- (2)  $B/S > 0.1$  Salient may form
- (3)  $B/S > 0.6$  Tombolo may form
- (4)  $X_{off} / B = 0.498 (B/S)^{-1.268}$
- (5)  $X_{off} = S - Y_{off}$
- (6)  $Y_{off} / D_{tot} = 0.125 \pm 0.020$

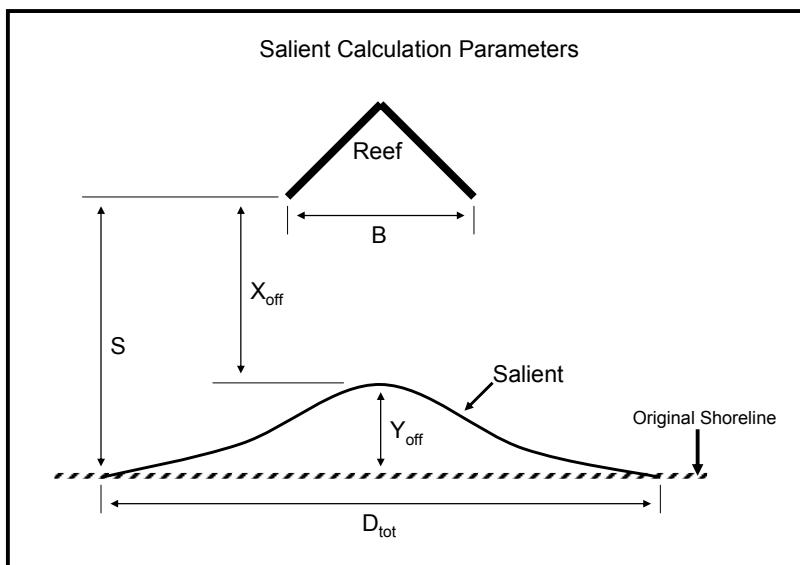


Figure 1. Salient Calculation Parameters (Black and Andrews, 2001a)

A plot of the Black and Andrews relationship between B/S and Y/B shows that the maximum salient size occurs for a B/S ratio of approximately 0.18 but drops off rapidly when the B/S ratio drops below 0.15. Black also demonstrated that if a reef was placed too close to the shoreline (B/S > 1.0) that erosion could result due to compression of the alongshore currents between the reef and the natural shoreline (Black, 2003). Black (2003) recommends a design B/S ratio between 0.25 – 0.50 to minimize the total reef volume (and associated costs) while insuring good salient formation. The method developed by Black and Andrews has been confirmed by computer modeling and actual shoreline response behind the Narrowneck and Mount Maunganui Artificial Reefs (Black and Mead, 2007).

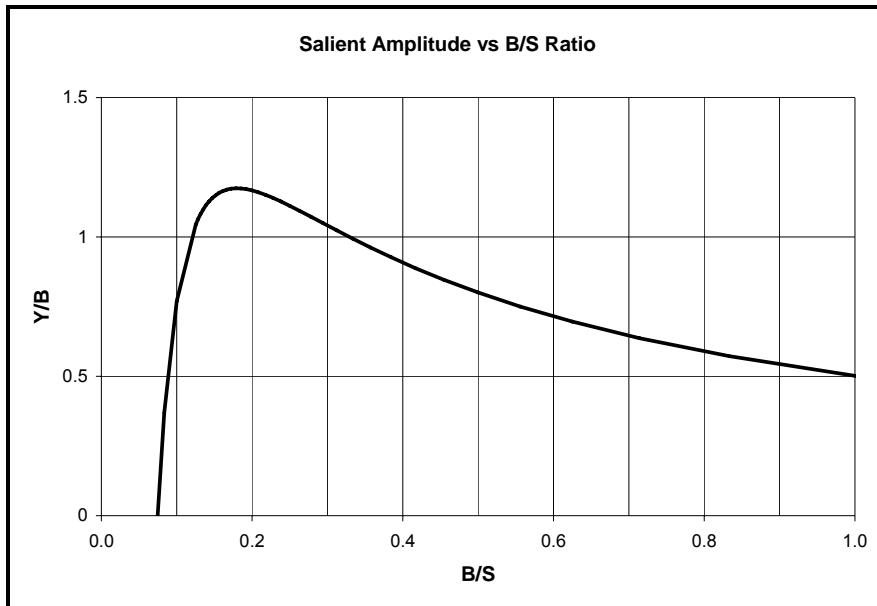


Figure 2. Salient Formation versus B/S Ratio

### Shoreline Response Predictions from Ranasinghe, Turner and Symonds

Ranasinghe *et al.*, (2006), performed a numerical and physical modeling study on an idealized wedge shape to develop the following relationships for predicting shoreline response behind a MPASR.

- $S_a / SZW > 1.5$  Accretion is expected
- $S_a / SZW < 1.0$  Erosion is expected

Where:

- Y – salient amplitude
- B – width of reef
- SZW – natural surf zone width
- $S_a$  – distance offshore to apex of reef crest

Unfortunately Ranasinghe *et al.* did not define the SZW in their relationship. Black and Mead (2007) suggested that the SZW be calculated as:

- $SZW = H_b / (\tilde{a} \tan B)$

Where:

- $H_b$  - the breakpoint height,
- $\tilde{a} = H_b / d_b$  is the breaking criterion (typically = 0.78)
- $d_b$  - the water depth at the breakpoint
- $\tan B$  - the average beach slope

Black and Mead (2007) also suggested that the distance to the base of the reef (landward end) is a more appropriate measure of the offshore parameter ( $S_a$ ) since the zone between the base of the reef and the shoreline is where most of the currents induced by the reef occur. The Ranasinghe *et al.* relationship predicts that the maximum salient will occur when the reef is positioned approximately twice the natural surf zone width offshore. They also predict that erosion will occur if the reef is positioned within the natural surf zone (Figures 3 and 4).

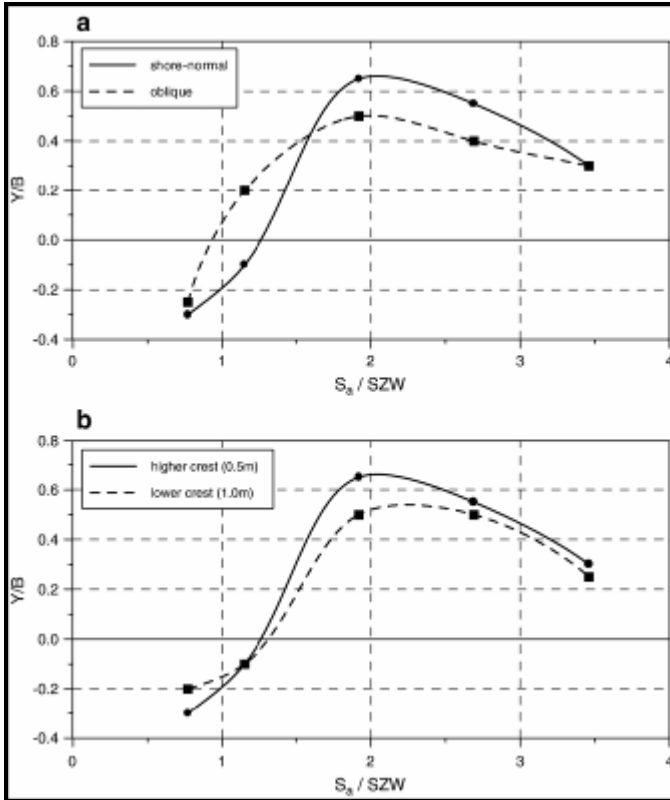


Figure 3. Shoreline Response to MPASR (Ranasinghe et al., 2006)

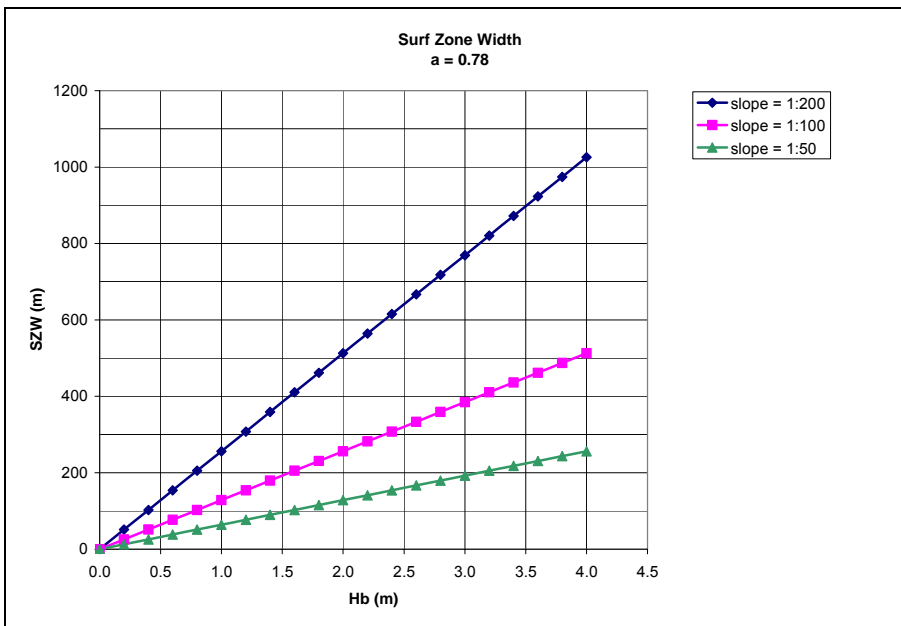


Figure 4. Plot of Typical Surf Zone Widths

**Mechanisms of Shoreline Response to a MPASR**

Ranasinghe et al. (2006) concluded that shoreline response to a MPASR is governed by nearshore circulation patterns consisting of onshore flow over the reef and longshore gradients in water surface level in the lee of the structure. The mode of shoreline response to a MPASR will vary between erosion and accretion based on the distance of the reef from the undisturbed shoreline. If the reef is positioned far enough offshore counter-rotating circulation cells will develop behind the reef. These counter-rotating cells will cause accretion. If the reef is too close to shore the opposing longshore currents are compressed and will cause erosion (Figure 5 A and B).

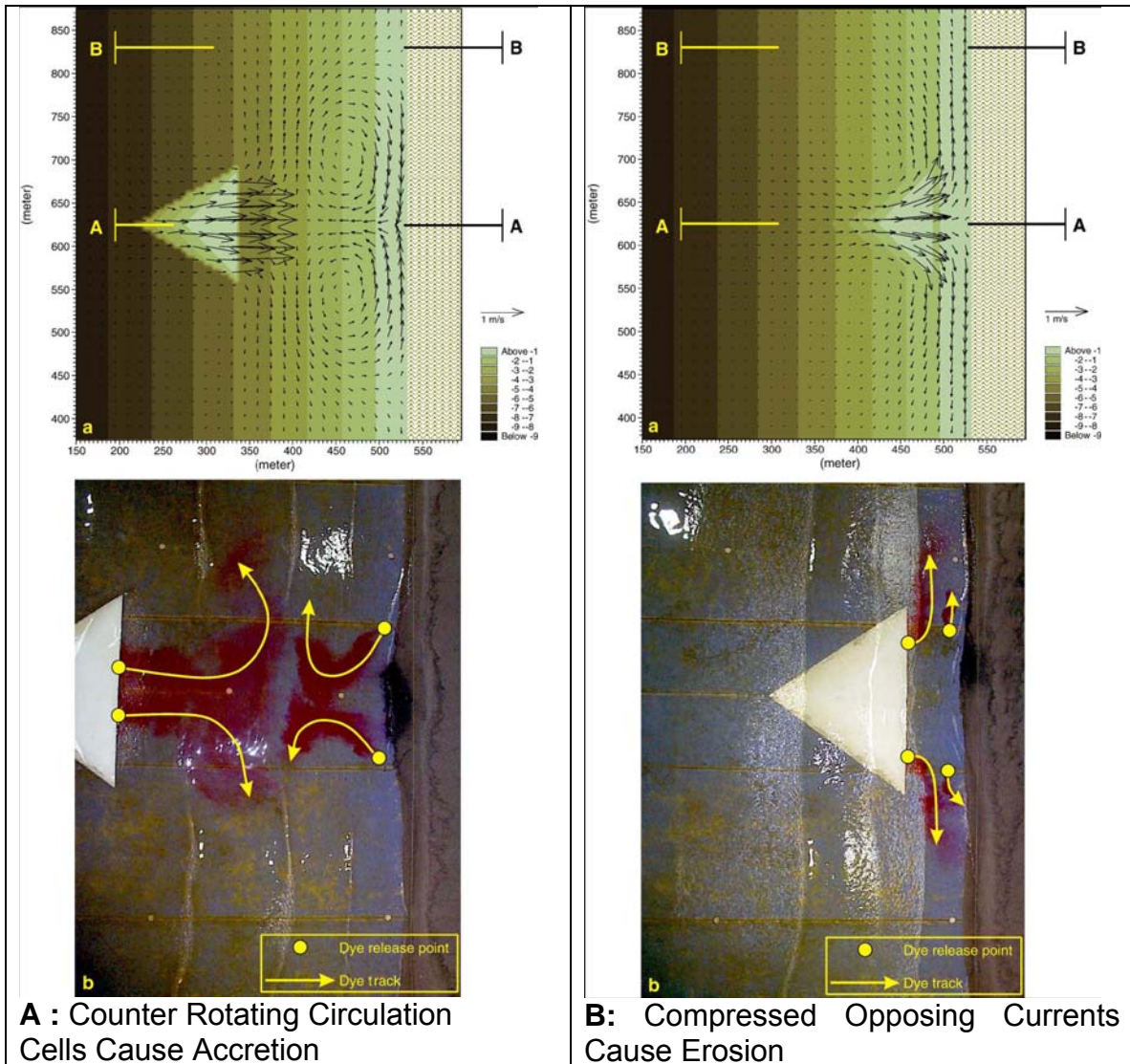


Figure 5. Currents Induced by MPASR (Ranasinghe et al., 2006)

Black and Mead (2007) found that the mechanisms controlling shoreline response behind an actual MPASR are more complex than the idealized case modeled by Ranasinghe et al. (2006). Black and Mead concluded that the processes involved are (1) wave sheltering caused by the reef; (2) wave crest rotation which reduces the longshore currents; (3) wave breaking on the reef reducing the set-up of water level at the beach in its lee; (4) counter-rotating vortices in the lee of the reef helping to direct sediment into the salient; and (5) Diffusion of sediment into the lee of the reef.