ASR
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11 January 2011

ATTN: Leslea Meyerhoff
City of Solana Beach
635 S. HWY 101
Solana Beach, California, USA 92075

Re: Peer Review
Fletcher Cove Reef Conceptual Design
Solana Beach, California

This peer-review has primarily considered the March 2010 Fletcher Conceptual Design, Solana Beach, California (EIC, 2010). The October 2001 “Regional Beach Sand Retention Strategy” (M&N, 2001) was also reviewed, as this document provides the basis for some of the analysis applied in the EIC (2010) report. In addition, empirical assessment and some basic numerical modeling were undertaken to support the review and provide a more useful indicator of a conceptual design for Fetcher Cove. I am familiar with the site, having lived at Fletcher Cove for 4 months in 1988, and have a good understanding of the coastal processes in this area, having undertaken projects on the Californian coast and the vast amount of information that Scripps have produced for the locality.

To summarize the findings of this peer-review, the EIC (2010) report does not provide a satisfactory design or shoreline response assessment of the recommended conceptual design based on our current and historic understanding of the impacts of submerged structures on coastal processes:

1. The conceptual design report does not take into account the majority of large body of existing science on submerged breakwater/reef design and impacts, and where relevant methods are applied they are applied incorrectly;
2. The recommended design is based on a method of design and shoreline response assessment that is deficient in a number of respects, and;
3. The recommended design ignores the impacts of submergence at water levels above mean sea level (MSL).

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The recommended design appears to represent, at least partially, a follow-on from the suggested beach response to shore-connected reefs as presented in the M&N (2001) study, with some attempt to separate it from the shore.

It is my opinion that very little appropriate investigation or application of the existing published knowledge on shoreline impacts was undertaken in connection with the EIC (2010) report and its recommended design. More specifically, the EIC (2010) study relies on science relating to shoreline response to offshore structures dating back prior to the year 2000, and does not take into account more recent foundation science since the year 2000 that has better addressed predictive methods for shoreline response to submerged structures.

Given this shortcoming, the information, analysis and recommendations of the EIC (2010) report are of limited value when considering an offshore structure to retain sand at Fletcher Cove. In my opinion, the findings and recommendations of the EIC (2010) report are problematic to the extent that they will not fulfill the design criteria and goals for a multi-purpose sand-retention device at Fletcher Cove. Our analysis is that the recommended MSL reef will not retain sand; to the contrary, it will likely cause and/or exacerbate beach erosion. In short, it is my opinion that accepting the recommendations and implementing the design contained in the EIC (2010) report would lead to a costly mistake if taken further.

This being said, ASR believes that a well-designed and positioned submerged reef at Fetcher Cove could indeed greatly increase the width of the existing beach. Development of such a solution requires a renewed systematic approach which applies the full gamut of existing knowledge and state-of-the art methods for submerged reef design and impact assessment.

I recommend that your technical staff review the following document that outlines my findings with respect to the EIC (2010) report, and that we schedule a teleconference to clarify any areas as needed. Any modifications/clarifications can then be incorporated prior to release to the local stakeholders.

Yours truly,

Shaw Mead

Dr. Shaw Mead

(Technical Director)

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PEER REVIEW

FLETCHER COVE REEF CONCEPTUAL DESIGN
SOLANA BEACH, CALIFORNIA, USA

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Peer Review
Fletcher Cove Reef Conceptual Design Solana Beach, California – Peer Review

Version	Date	Status	Approved By:
1	6 January 2011		JCB

Client: City of Solana Beach

Report Status:

Shaw Mead (*BSc, MSc(Hons), PhD*)

Cover: Fetcher Cover on a sunny day (Source: Kinkzero).

Executive Summary

This peer-review has considered the March 2010 Fletcher Conceptual Design, Solana Beach, California (EIC, 2010). Following peer-review, basic empirical and numerical assessments were undertaken to consider the feasibility of an MPR at Fletcher Cove.

To summarize the findings of this peer-review, the EIC (2010) report does not provide a satisfactory design or shoreline response assessment of the recommended conceptual design based on our current and historic understanding of the impacts of submerged structures on coastal processes:

1. The conceptual design report does not take into account the majority of large body of existing science on submerged breakwater/reef design and impacts, and where relevant methods are applied they are applied incorrectly;
2. The recommended design is based on a method of design and shoreline response assessment that is deficient in a number of respects, and;
3. The recommended design ignores the impacts of submergence at water levels above mean sea level (MSL).

As a result, the findings and recommendations of the EIC (2010) report are of limited value, and will not fulfill the design criteria and goals for a multi-purpose sand-retention device at Fletcher Cove. Our conclusion is that the recommended MSL reef will not retain sand; to the contrary, it will likely cause and/or exacerbate beach erosion. In short, accepting the recommendations and implementing the design contained in the EIC (2010) report would lead to a costly mistake if taken further.

This being said, ASR believes that a well-designed and positioned submerged reef at Fetcher Cove could indeed greatly increase the width of the existing beach and provide additional benefits (*e.g.*, local habitat enhancement and surfing amenity). Development of such a solution requires a renewed systematic approach which applies the full gamut of existing knowledge and state-of-the art methods for submerged reef design and impact assessment.

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1 INTRODUCTION

ASR was commissioned to peer-review the report entitled *Fletcher Cove Reef Conceptual Design* by Everest International Consultants (EIC, 2010). The scope and deliverables of this review includes the following:

- ASR will carry out a professional peer review of the report entitled *Fletcher Cove Reef Conceptual Design* by Everest International Consultants.
- This review will encompass a comprehensive analysis of the findings of this report, including application of relevant literature and a hydrodynamic assessment of the report's proposed reef design as related to the requirements of the City of Solana Beach.
- This project will provide the City of Solana Beach and local stakeholders with an independent scientific analysis of the current proposed reef design at Fletcher Cove.

Fletcher Cove is located along the coast of the City of Solana Beach, approximately 35 miles north of San Diego, California (Figure 1.1). The Cove is approximately 120 m wide and flanked by cliffs to the north and south. This Cove is the highest use beach in the City of Solana Beach.

The purpose of the EIC (2010) study was to develop a conceptual sand retention reef design for Fletcher Cove and estimate the up-coast and down-coast shoreline impacts resulting from that reef. The primary objectives of that study included:

- Establishing a list of design criteria, including a target salient size. A salient is the outwardly projecting beach retained by a reef;
- Estimate salient size for an initial reef design provided by the USACE and compare that to the design criteria;
- Optimize a reef design to achieve the target design criteria, and;
- Estimate potential shoreline changes caused by the optimized reef.

Secondary objectives that may or may not be addressed in the study included the need to develop a design that is efficient, enhances surfing, and enhances offshore habitat.

To achieve these goals, a set of design criteria were developed by the USACE, City of Solana Beach and Everest International Consultants, Inc., including:

1. The reef should provide an approximate 30 meter wide beach at mean sea level (MSL).
2. Any reef induced beach width (salient) should be pre-filled to avoid potential downcoast effects.
3. The reef should not be shore connected.
4. The reef should not have adverse effects on surfing, hard bottom habitat, or aesthetics.

Figure 1.1: Location map of Fletcher Cove (Source: EIC, 2010).

Primarily, this peer-review has considered the EIC (2010) report. The "Regional Beach Sand Retention Strategy" (M&N, 2001) was also reviewed, as this document provides the basis for some of the analysis applied in the EIC (2010) report and the context of the desire to retain beach material following renourishment. In addition, empirical assessment/literature review and some basic numerical modeling were undertaken to support the findings of the peer-review, assess the findings of the EIC (2010) report with respect to design and impacts, and provide a more useful indicator of a conceptual design for Fetcher Cove. The reader is referred to the EIC (2010) report for more details on reef and salient definitions, if required.

1.1 Reviewer's Qualifications and Experience:

This review has primarily been undertaken by Dr. Shaw Mead, Technical Director of ASR. Dr. Mead holds BSc and MSc (Hons) degrees from the University of Auckland (School of Biological Sciences), and a PhD degree from the University of Waikato (Earth Sciences). His background in coastal oceanography and marine ecology, specialising in hydrodynamic numerical modelling, coastal processes, offshore submerged reefs, coastal protection and amenity enhancement, and ecological assessment, allows him to effectively bridge the multi-disciplinary gap between physical processes and marine ecological impacts. Dr. Mead has 17 years of experience in marine research and consulting, is an author to 37 peer-reviewed scientific papers, and has solely or jointly produced over 200 technical reports pertaining to coastal oceanography, marine ecology and aquaculture. Dr. Mead has undertaken over a thousand research and consulting SCUBA dives and led many comprehensive field investigations that have addressed metocean, biological and chemical components of the coastal environment. He is affiliated to the New Zealand Marine Science Society and the New Zealand Coastal Society (Institute of Professional Engineers New Zealand).

Dr. Mead studied for his MSc degree at the University of Auckland's Leigh Marine Laboratory, undertaking subtidal research there directed at the fertilization success of sea urchins as a basis for the sustainable management and development of the commercial market. The marine ecological components of his Doctorate were directed towards subtidal habitat enhancement of marine structures, while the physical oceanography component was focussed on understanding the effects of coastal bathymetry on wave breaking characteristics using field measurements and hydrodynamic numerical modelling. His PhD thesis in physical oceanography is based on a series of peer-reviewed papers that together with more than 30 popular articles, have presented novel techniques to record the shape of surfing reefs, specify the breaking tube condition and to break-down surfing reefs into their morphological components using numerical modelling. Dr. Mead's research and consulting have led to major advances in our knowledge of offshore reefs for the development of multiple-use structures (coastal protection, amenities such as surfing, wind-surfing, diving, fishing, and ecological enhancement), and have incorporated numerical modelling of waves, currents and sediment transport to develop the designs and assess the impacts of coastal structures over a large range of spatial and temporal scales. Dr. Mead is a world-leader in multi-purpose reef design and research, enabling the incorporation of high-quality surfing reefs into multi-purpose coastal structures.

Over the past 15 years he has been involved in a wide range of coastal consulting and research projects that have included the design of coastal structures and developments, and assessments and monitoring of physical and ecological effects of marine construction, coastal erosion control, marine reserves, dredging, outfalls, oil industry, aquaculture ventures and various other coastal and estuarine projects that have included hydrodynamic (waves and currents), sediment transport and dispersion modelling (including contaminants, suspended sediments, freshwater, hypersaline water, nutrients and petro-chemicals).

Further to this, and with direct relevance to the present review, is the focus of his PhD and subsequent consulting and research work on wave/structure interactions and the impacts of coastal structures on waves, currents and sediment transport. The scale of the various investigations he has been involved with has ranged from 10's of meters (e.g. stormwater outlets on the beach), to 10's of kilometres (e.g. coastal protection strategies, breakwater port developments, coastal subdivisions). Methods and tools including time-series aerial photograph and chart analysis, numerical modelling (both un-calibrated and calibrated), and local data analysis (e.g. wind/wave, currents, beach profiles, bathymetric survey, sediment grain size, water level), have been applied within the framework of existing knowledge and science (e.g. beach response to offshore obstacles, spit formation and breaching dynamics, coastal trapped waves, seasonal change, climatic variability, the physics governing coastal processes) and anecdotal evidence (e.g. observations both historic and personal) in order to understand and quantify the existing environments and the impacts of any proposed structures within these environments.

Dr. Mead has acted as a peer-reviewer for a number of Journals, Conferences and Technical reports and regularly undertakes Expert Witness roles for Environmental Hearings and in the Environmental Court. Further details are supplied in his CV.

2 GENERAL REVIEW COMMENTS

2.1 Introduction

The following provides general comments with respect to what level the EIC (2010) report has achieved the goals of the study. The purpose of the EIC (2010) study was to develop a conceptual sand retention reef design for Fletcher Cove and estimate the up-coast and down-coast shoreline impacts resulting from that reef. The primary objectives of that study included:

- Establishing a list of design criteria, including a target salient size. A salient is the outwardly projecting beach retained by a reef;
- Estimate salient size for an initial reef design provided by the USACE and compare that to the design criteria;
- Optimize a reef design to achieve the target design criteria, and;
- Estimate potential shoreline changes caused by the optimized reef.

Secondary objectives that may or may not be addressed in the study included the need to develop a design that is efficient, enhances surfing, and enhances offshore habitat.

To achieve these goals, a set of design criteria were developed by the USACE, City of Solana Beach and Everest International Consultants, Inc., including:

- The reef should provide an approximate 30 m wide beach at mean sea level (MSL).
- Any reef induced beach width (salient) should be pre-filled to avoid potential downcoast effects.
- The reef should not be shore connected.
- The reef should not have adverse effects on surfing, hard bottom habitat, or aesthetics.

Figure 2.1 presents the recommended concept design to meet the above criteria (EIC, 2010). Unfortunately, this MSL reef does not meet the majority of these goals and criteria, and would not result in the accretion of a salient, rather it would induce erosion.

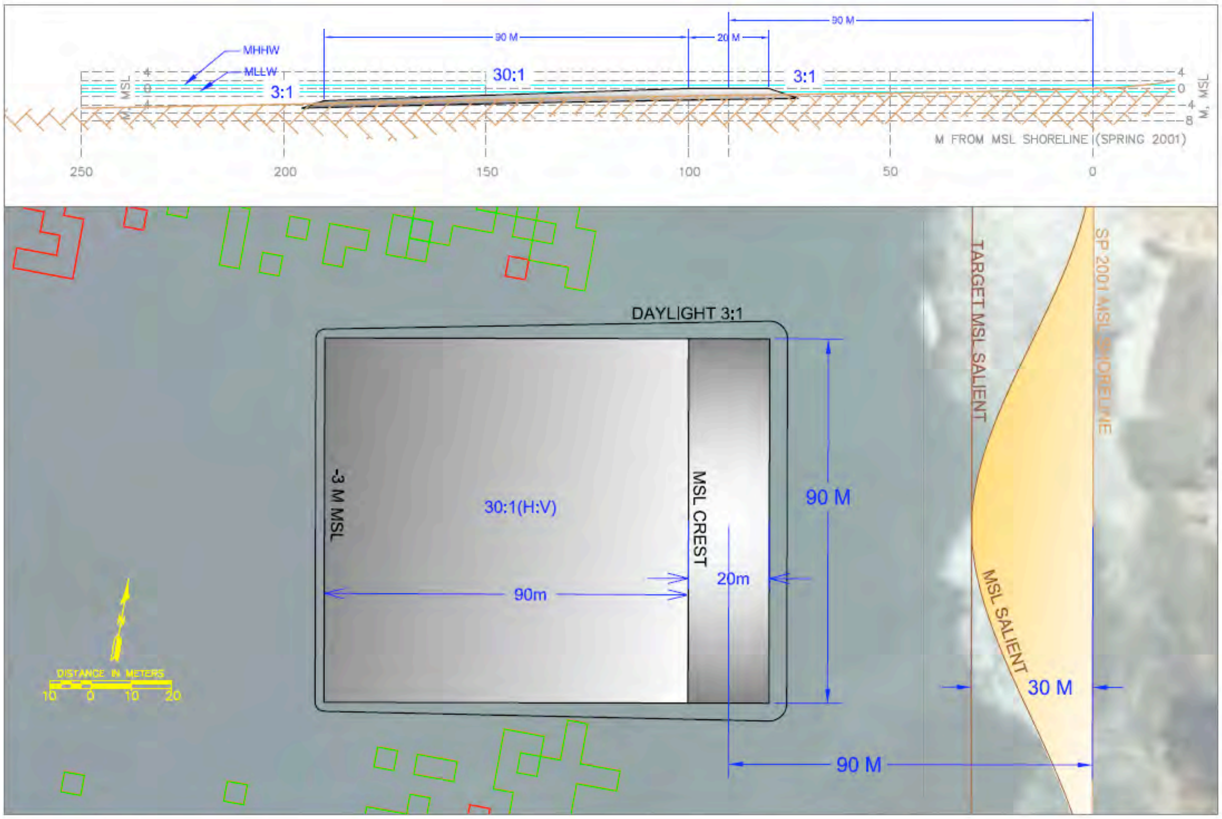

Figure 2.1 The recommended MSL reef concept design (EIC, 2010).

2.2 Primary Objectives

The EIC (2010) study used a process to estimate salient size and optimize a reef design that resulted in an incorrect assessment of the salient size (the recommended MSL reef will cause beach erosion if constructed, not a salient), and did not optimize the design in terms of the volume of reef constructed for the size of the salient it would create.

Full details and explanation as to why the MSL reef would not achieve the goals of the conceptual design are provided along with supporting scientific and engineering literature in Section 3 below. To summarize:

- The K_t Method used for design and setting the beach response criteria is fundamentally flawed because:
  a) It is based on a relationship that includes breakwaters, structures that have fundamentally different impacts on the shoreline in comparison to submerged structures – these 2 different types of offshore structures should be separated in beach response analysis;

b) The 7 'reef' data points are shore-connected features (i.e. submerged headlands or geological features that extend from well above the high tide mark and out to sea), and not reefs detached from the shoreline, which is what the method has been used to assess – they area misrepresentative of what is being considered;

c) The trend lines plotted for the various Kt levels do not well fit the data, and no correlation coefficients are presented for these fits – indeed without the trend lines plotted (Figure A.3, EIC, 2010) the data resemble a scatter of data which would be unlikely to provide any useful predictions due to the variables used for this method, as described in Black and Andrews (2001a) and;

d) Distance of the structure offshore is a critical parameter with respect to predicted shoreline response to offshore obstacles, but the K_t Method is based on only the transmission coefficient and the alongshore length of the structure, and *there is no variability in beach response with differing distances offshore*. For example, according to the K_t Method, a 100 m length structure with a Kt of 0.4 will result in a 20 m wide salient whether it is 10 m or 1000 m offshore or any distance in between.

- The Reef/Island Method is discounted as over-predicting shoreline response and counter intuitive, despite the Southern California shoreline response characteristics falling close to the line of fit and within the bounds of the dataset that was used to develop this shoreline response formula (Figure 2.2):

a) Since the Southern Californian data points are within the limits of this robust method of empirical shoreline response to offshore obstacles (as compared to, and supported by, laboratory and field data – e.g. Nir, 1982; Gourlay, 1981; Shore Protection Manual, 1984; Hsu and Silvester, 1990), the Black and Andrews (2001a) method should be given more weight in the assessment than a method that does not take into account one of the most important parameters in shoreline response, the distance offshore, and;

b) Initially increasing and then reducing shoreline response with increasing distance of the obstacle offshore is just what would be expected (i.e. is not counter intuitive), with varying responses due to the alongshore length, due to the relative amount of wave penetration around the structure with respect to the directional spread of incident waves and distance offshore in relation to the alongshore length of the structure (Figure 2.3).

- The 'Scour Check', including using the method proposed by Ranasinghe et al. (2006), is incorrectly applied and ignores the fact that the MSL reef will be within the range of water level above the reef crest that will cause erosion during higher tidal periods and especially during storm surge events when the majority of beach erosion occurs:

a) Ranasinghe et al., (2006) and Black and Mead (2003) demonstrated that submerged or semi-emergent structures will cause erosion if they are inside the surfzone. Ranasinghe recommend that the landward edge of the reef structure be 1.5x the distance from the shoreline in order to gain net accretion, while Black and Mead (2003) suggest that optimal beach response for a reef is some 2-4x the alongshore length of the reef – the rules of thumb.

b) However, EIC (2010) discount these findings citing that the MSL reef behaves like an emergent structure:

   1. The MSL reef is only emergent to mid-tide, and;

   2. Ranasinghe et al., (2006) tested water levels above the crest of 0.5 m and 1.0 m, with the MSL reef being submerged by 0.6 m at mean high water and 0.8 m at mean highest high water, and greater depths during storm activity due to wind and wave set-up and inverse barometric pressure. That is, *the MSL reef is not an emergent structure* and it will cause erosion due to compression of the surfzone in its lee causing a 2-cell circulation pattern.

   3. If the MSL reef was an emergent structure, it would impact on the aesthetics of the Cove

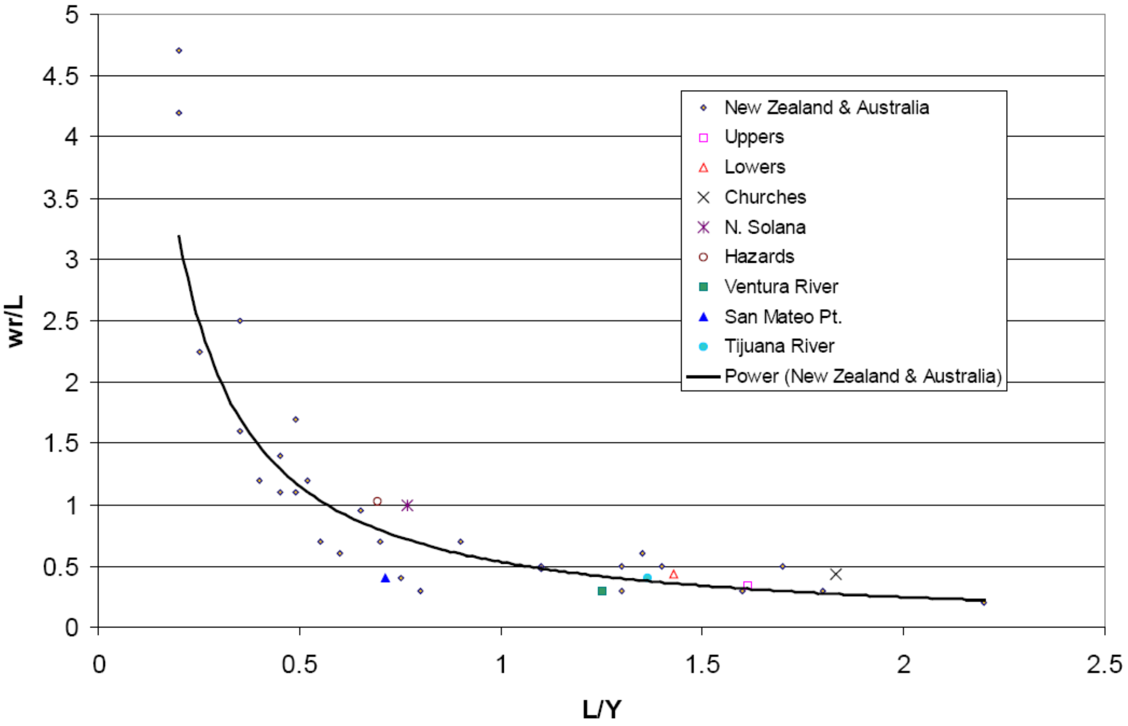

Figure 2.2 *Ratios of length of reef to distance offshore (L/Y) versus shoreline response to length of reef (wr/L) for reef from Black and Andrews (2001a) including Southern Californian reefs (EIC, 2010).*

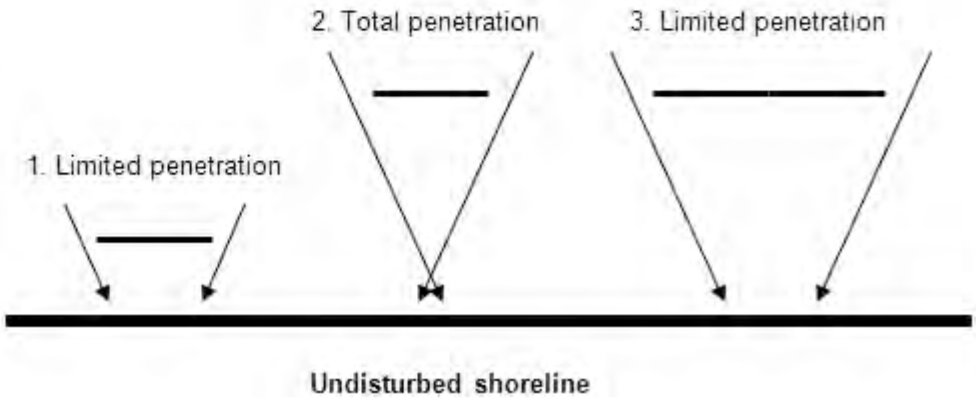

Figure 2.3 *The effect of obstacle position and length on wave sheltering: (1) short reef nearshore; (2) short reef offshore; (3) double length reef offshore. (Black and Andrews, 2001b)*

- Since inside edge of the MSL reef is located above mean lowest low water mark MLLW), this reef could be considered shore-connected, and therefore **does not** meet the design criteria.

- Following the design and impact assessment with the flawed Kt Method, an empirical method of calculating the upcoast and downcoast shoreline changes was used. This again is a serious flaw of the report since it is based on the incorrect assumption that beach morphology will respond the same to a groyne as it does to an offshore structure. Groynes block alongshore sediment transport, while offshore structures are more effective in reducing cross-shore sediment transport.

- A good example of the different mechanics behind groyne function and beach response and offshore reef function and beach response is Boscombe Reef on the south coast of England. In this location some 60 groynes are located along a 19 km stretch of Poole Bay, however, due to the predominant cross-shore transport mechanism during storm (erosive) conditions, they are ineffective and the beach requires renourishment every 10-12 years. With construction of the Boscombe reef, which provides an alongshore length of 60 m and is located some 200 m offshore, a salient of ~60 m wide and >500 m long has developed (which is in close agreement with the Black and Andrews (2001a) empirical method of shoreline response prediction). A recent peer-reviewed paper on the Boscombe Reef is attached as Appendix 1 (Mead et al., 2010), which clearly shows the difference in beach response between groynes and offshore reefs in the same location. Beach response to groynes cannot be used as a method of estimating shoreline response to offshore reefs.

The methodology and analysis undertaken by EIC (2010), the recommended MSL reef does not meet 3 out of 4 of the Goals (noting that the first goal was simply setting the salient size of 30 m width), and does not meet 3 out of the 4 design criteria (noting the second is a recommendation for pre-filling the salient). While it is stated in the EIC (2010) report that the secondary objectives of the need to develop a design that is efficient, enhances surfing, and enhances offshore habitat *may or may not be addressed in the study,* since these features are intrinsically linked to the volume of the reef (e.g. see Table 3.3 in the EIC (2010) report), some attempt should have been made to incorporate these objectives at the conceptual level.

2.3 Implications of Efficiency and Surfing Objectives

The secondary goals of efficient design, enhancing surfing and enhancing offshore habitat are not all met; only the enhancement of habitat is met, which is really an artifact of replacing mobile abrasive sandy substrate with a hard and relatively complex structure (i.e. it is not addressed or designed in the study, although existing habitat is not compromised by placement of the concept designs). Of the large body of work in the area of incorporating surfing into offshore structures, only one dated reference was cited and incorrectly applied.

The surfing amenity and efficiency in the design are linked, since both are associated with the volume/shape of the structure. The wide square crests of the MLLW and the recommended MSL reef design do not incorporate any surfing amenity, since the waves will ‘close-out’ on these shore parallel structures. Waves must peel along the reef for surfing, and the gradient of the reef slope dictates the breaking intensity of the waves as they peel. The main influence on the breaking intensity (shape) and peel angle of a breaking wave is the underlying bathymetry (Peregrine, 1983; Battjes, 1988; Mead, 2001). Since the wave shape (Button, 1991; Sayce, 1997; Couriel *et al.*, 1998; Sayce *et al.*, 1999; Mead and Black, 2001c) and peel angle (Walker, 1974a, b; Dally, 1990; Black *et* al., 1997; Hutt, 1997; Hutt *et al.*, 1998; Mead and Black, 1999b) are very important parameters of surfing waves, some consideration of these is required even at a concept stage to ensure that relative volumes and reasonable reef shapes are utilized for volume assessment (which is associated with the efficiency of the design).

2.3.1 Peel Angles

The peel angle (α) describes the line of the whitewater as the wave breaks and determines the speed of the surfing ride (Figure 2.4). Surfers prefer to travel across the unbroken part of the wave, racing the breaking section as the wave moves shorewards. Zero peel angle refers to a “close-out” which is too fast for riding (all the wave breaks simultaneously as commonly observed on beaches with uniform longshore bathymetry), while 90^o is a “fat” or slow wave with no longshore translation of the breaking section (most commonly seen on reefs where the end of the whitewater travels directly inshore, parallel with the crest normal). Since wave breaking is depth-dependent (e.g. the rule of thumb is that a wave will break when the wave height to water depth ratio is 0.78), the bathymetry has the major influence on the peel angle, with swell peakiness and wave period as secondary factors (Hutt, 1997).

Thus, the reef crest should be angled to the swell crests if the waves are to peel down the reef. Since the early 1970’s when MPR designs were first considered, square reefs such as those in the present cases of MLLW and MSL reefs (EIC, 2010) have never been used in concept or feasibility designs since a critical component of these stages of the projects is estimating the rough order volume of the structures in order to estimate the rough order costs. If surfing is to be incorporated into the reefs, *even if the details are to be considered in future studies*, a square crest does not provide a useful representation of the final structure. Delta shaped reefs are the norm (For example, Walker, 1994, Mocke, 2003, M&N 2001; Ranasinghe et al, 2006), and in the present case, an asymmetrical reef with a longer southern arm to compensate for southerly directed wave driven sediment transport (i.e. wave rotation, Black and Mead, 2001) would be most appropriate.

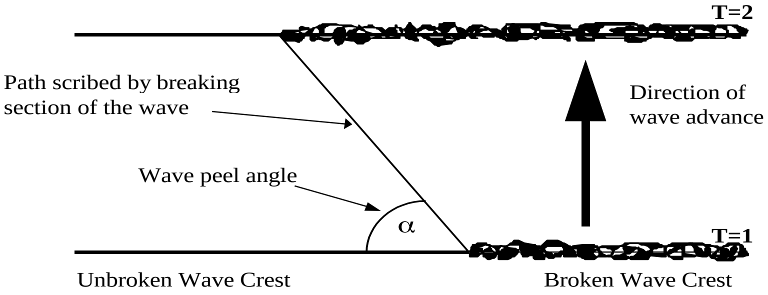

Figure 2.4 Schematic diagram of the wave peel angle showing movement of the breakpoint during an increment of time. (Source – Hutt, 1997)

Similarly, the gradient of the reef should be such that waves will break with a steep face to allow surfers to generate high board speeds (Walker, 1974; Sayce, 1997; Sayce et al., 1999; Mead and Black, 2001). The EIC (2010) study selects a uniform reef face gradient of 1:30 through a reference to Walker (1974), which can be considered a medium intensity wave with a steep face, but rarely tubing (Mead and Black, 2001). This approach however does not consider the effect of wave-orthogonal gradient on peeling to create a surfable wave.

The orthogonal gradient is the gradient that is oriented 90º to the wave crest, When a wave approaches an angled reef that peels the wave as it breaks, the orthogonal gradient is far less than the reef's contour-normal gradient. This is shown in Figure 2.3. As a result of the square MSL recommended concept reef, the reef gradient has to be 2-3x gentler than it would in reality, i.e. if it was to peel waves in a way that was conducive to surfing. Thus, the 25,000 m^3 volume of the square MSL recommended concept reef is greatly over-estimated (by at least 2x) for a MPR placed in this recommended location (Figure 2.1). Even though, if the MSL recommended concept reef were constructed as shown in Figure 2.1 it would cause erosion (as discussed in detail below), it is also of very limited use with respect to estimating the volume (efficiency) or incorporation of surfing amenity; indeed, the structure is several times the volume of the salient it supposedly creates (Figure 2.1).

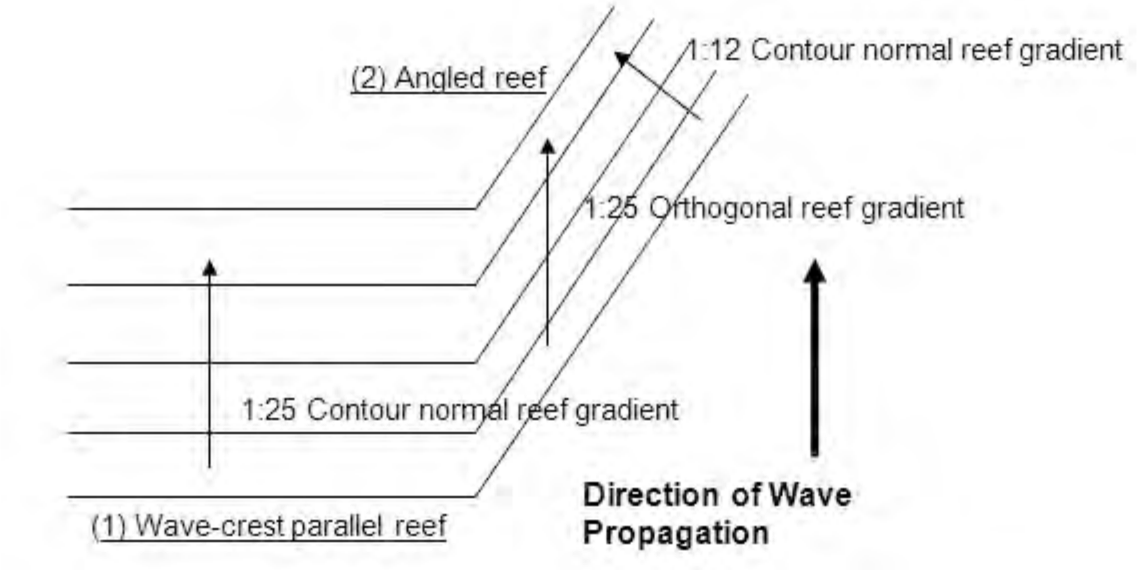

Figure 2.5 *The orientation of the reef face to the direction of wave propagation (wave orthogonal direction) has a large impact on the reef face gradient (contour normal reef gradient) and therefore the volume of the structure. The wave-crest parallel reef orientation (1) that has no surfing amenity is over 4x the volume of the angled reef orientation (2).*

3 APPLICATION OF EMPIRICAL REEF DESIGN AND SHORELINE RESPONSE TOOLS

3.1 Introduction

This section considers application of the relevant science and predictive tools to develop the concept design and assess the shoreline response. Of the large body of work in the area of predicting shoreline response and morphology in the lee of offshore structures, much was not considered and that considered by EIC (2010) was incorrectly applied and/or interpreted. Of the large body of work in the area of incorporating surfing into offshore structures, only one dated reference was cited and incorrectly applied.

3.2 Shoreline Response

The EIC (2010) findings and recommendations are fundamentally flawed due to the application of the K_t Method and incorrect application/understanding of the Black and Andrews (2001a, b) and Ranasinghe et al. (2006) methods. While the attempts to use local structures to develop a useful predictive tool are definitely valid, using emergent structures (e.g. breakwaters) as part of this analysis is a fundamental flaw in the methodology because submerged and semi-emergent structures have fundamentally different impacts on the local hydrodynamics that drive the beach response (as described in Black et al., 2003; Ranasinghe et al., 2006 in comparison to Chasten et al., 1993). Using the fillet response of a groyne/jetty to determine the potential shoreline change due to the placement of a reef, as EIC (2010) have, is similarly fundamentally flawed – these 2 very different types of coastal structures impact very differently on hydrodynamic and sediment transport processes (e.g. Black, 2000).

As described in Section 2 above, the Kt Method is fundamentally flawed for a number of reasons. Of these, the lack of variability in beach response when an offshore structure is moved different distances offshore is the most apparent, and means the analysis and recommendations are not valid. There are a range of readily available publications that present methods to assess the beach response to offshore structures (e.g. Nir, 1982; Gourlay, 1981; Shore Protection Manual, 1984; Hsu and Silvester, 1990; Black and Andrews, 2001a; Ranasinghe et al., 2006) and in all cases, the 2 most important parameters are the alongshore length of the structure and *the distance of the structure offshore*. Table 3.1 and Figure 3.1 below present the results of the changes to the salient width that are caused when the Initial, MLLW and MSL reefs are placed at different distances offshore. As can be seen, there is *no variability in the size of the salient when the reef's position is changed*.

The results of the Kt method, i.e. no change in the salient width with different offshore distances of the reef, are not supported by any field or laboratory results that have previously addressed this area of coastal oceanography. Therefore, they cannot be relied upon to provide any useful results with respect to the shoreline response of the 3 reefs assessed by EIC (2010). The results of the reef/island (Black and Andrews, 2001a) assessment and the scour (Ranasinghe et al., 2006) assessment of these 3 reefs presented by EIC (2010) are also fundamentally flawed due to their applications of these methods (discussed below) and further support my findings that the EIC (2010) recommended MSL conceptual reef design are incorrect.

Table 3.1. Reef parameters and salient width (red columns) using the Kt Method to predict the shoreline response for increasing distances offshore.

Distance Offshore		**Initial Reef**			**MLLW Reef**			**MSL Reef**	
	L/Y	**ys/Y**	**ys**	**L/Y**	**ys/Y**	**ys**	**L/Y**	**ys/Y**	**ys**
50	1.6	0.2	**10**	1.92	0.4	20	1.8	0.6	30
100	0.8	0.1	**10**	0.96	0.2	20	0.9	0.3	30
150	0.5333333	0.0666667	**10**	0.64	0.1334	20	0.6	0.2	30
200	0.4	0.05	**10**	0.48	0.098	20	0.45	0.15	30
250	0.32	0.04	**10**	0.384	0.08	20	0.36	0.12	30
300	0.2666667	0.03333	**10**	0.32	0.0667	20	0.3	0.1	30
400	0.2	0.025	**10**	0.24	0.05	20	0.225	0.075	30
600	0.1333333	0.0167	**10**	0.16	0.0334	20	0.15	0.05	30

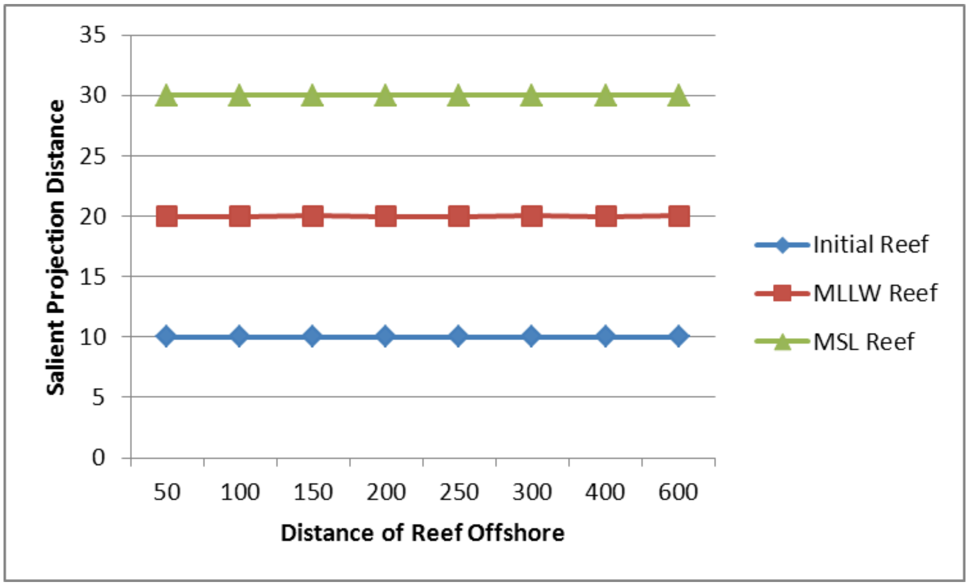

Figure 3.1. Graph show that there is no change to the salient project distance for reefs located at increasing distances offshore when the Kt Method is applied.

The beach response to groynes is fundamentally different than that to offshore structures, therefore the application of the empirical method for groyne fillet prediction used by EIC (2010) to assess the shoreline change due to the presence of an offshore structure is incorrect and provides an invalid estimate of shoreline change. In simple terms, the assumption that a salient will perform similar to a shore-normal groyne of the same dimensions is flawed because:

- Groynes do not interact with waves offshore of the beach as do offshore structures, thus the beach that is the groyne fillet is subject to a different wave climate than that of the salient behind an offshore structure.
- Groynes are non-erodible and so remain a constant length, whereas salients are dynamic features that response to metocean conditions and allow sediment to move in both directions along the beach (e.g. Black and Mead, 2007; Blacka et al., 2008; Weppe, 2009; Mead et al., 2010)
- Groynes are known to cause erosion of the downcoast side because they trap sand on the upcoast and prevent it moving around the end of the groyne, whereas salients allow sand to move up and down the coast

If the aim was to consider the shoreline response due to tombolo formation in the lee of an offshore structure (e.g. Venice Breakwater), then this groyne fillet method would have had some merit, since a tombolo welded to the structure acts similarly to a groyne. The dynamics of hydrodynamic and sediment transport around offshore structures are detailed in several papers (e.g. Black and Mead, 2007; Blacka et al., 2008; Weppe, 2009; Mead et al., 2010), while "Functioning and Design of Coastal Groins: The Interaction of Groins and the Beach – Process and Planning" (JCR, 2004) provides a good basis with respect to the dynamics of hydrodynamic and sediment transport around groynes (see Basco and Pope, 2004 for review). As described above, the shoreline response of Southern Californian features fit well with the empirical data of Black and Andrews (2001a) (Figure 2.2), which is supported by independent field and laboratory data (e.g. Nir, 1982; Gourlay, 1981; Shore Protection Manual, 1984; Hsu and Silvester, 1990), and so would be a more appropriate method of assessing potential shoreline change at this conceptual stage than the groyne method.

3.3 The Reef/Island and Scour Checks

Following the analysis of the salient response to the 3 reefs using the flawed Kt Method, EIC (2010) checked their results with the Reef/Island methods developed by Black and Andrews (2001a, b) and the erosion/accretion method (Scour) developed by Ranasinghe et al., (2006). The former check, Reef/Island, was discounted when the results did not match those of the Kt Method because:

- It was considered to be counter intuitive that there would be a relationship between distance offshore and the size of the salient produced, and;

- It was considered to over-predict the salient response for 3 breakwaters in Southern California (Appendix C, EIC, 2010)

As detailed above, there is an overwhelming volume of evidence available in peer-reviewed publications that demonstrate the fundamental relationship between the shoreline response and distance of the structure offshore. It is of great concern that these publications were over-looked or discounted in favor of a flawed method developed in non peer-reviewed technical reports.

When the correct application of the reef method was applied to Southern Californian reefs (Figure 2.2 or Figure C.1 of EIC, 2010), they all fall within the data set and close to the line of best fit, i.e. these data are a good fit for the Reefs/Island method. EIC (2010) then apply these same reefs in their Figure C.3 which is described as the Reef/Island Method and conclude that they are a bad fit. However, the reason that these data are a bad fit to this graph and the curves is that they are *not applying the same parameters as the Reef/Island Method uses*. Rather they are applying the parameters of ys/Y versus L/S, which relate to B/S versus Y/S in the terminology of Black and Andrews (2001a), which as presented in Figure 7 of Black and Andrews (2001a) results in a wide scatter of data from which they conclude:

> "*Indeed, such simple relationships degenerate to an expectation that the island width should be related to the distance offshore of the island, and such relationships are not expected to provide useful predictions.*"

This again highlights the fundamental flaws in both the Kt Method and the assessment undertaken by EIC (2010).

Further to this, in Appendix C of the EIC (2010) report, Table C.2 presents the results of applying the Reef/Island method to 3 breakwaters (one of which was a wreck) in Southern California. Again, the Black and Andrews (2001a) method is discounted by EIC (2010) as being over-predictive, meanwhile, the Kt Method, which was developed using these data points, both over-predicts and greatly under-predicts (Santa Monica) the salient response for these breakwaters.

Table 3.2 Comparison of salient width (ys) predictions with the Kt Method, the Reef/Island Methods and the actual measured dimensions for Southern Californian breakwaters

Breakwater	**L**	**L/Y**	**y_s/Y**	**y_s Kt Method**	**y_s Island or Reef**	**y_s actual**
Coronado 1938	213	0.230047	0.15	31.95	30-54	37-46
Venice 1935	326	0.56135	0.38	123.88	136-150	113
Santa Monica 1960-88	610	1	0.32	195.2	305-366	210-302

During EIC's (2010) check using the Reef/Island Methods, they present Table 3.2, which shows a reverse trend in salient response in comparison to the Kt Method. There is no comment as to why such an inverse response should be caused, which should have raised concerns given the scientific basis of the Black and Andrews (2001a) Method and the supporting field and laboratory data. However, it is assumed that the fundamental flaws in the Kt Method were unknown to EIC (2010).

Black and Andrews (2001a) repeatedly cite that the results from their investigation of natural reefs (which are more in line with the types of broad crested structures that have been assessed by EIC (2010) and built in Australia, the UK and India) indicate that the salients behind these natural features were larger than the salients created in the lee of manmade structures. This is believed to be most likely due to the greater offshore width of these natural structures in comparison to man-made shore-parallel structures. Thus, given:

- The close fit of Californian structures to the Black and Andrews (2001a) method of shoreline response
- The fundamental flaws in the Kt Method (i.e. no change to salient dimensions with increasing distance of the structure offshore)

- The misrepresentation of the Black and Andrews (2001a) method (Figure C.2, EIC, 2010), and;

- The unwarranted dismissal of the Black and Andrews (2001a) method due to perceived over-prediction (despite the good fit for Southern Californian reefs), and it being counter intuitive,

it is obvious that application of the Black and Andrews (2001a) method to select a design and assess shoreline response *would have been far better method of assessment than the Kt Method*.

EIC's (2010) application of Ranasinghe et al.'s (2006) Scour Check is similarly flawed and unreasonably discounted. Although EIC (2010) point out the erosive impacts of locating submerged structures close to the beach and cite previous disasters where such positioning has led to erosion (e.g. the PEP reefs in Florida – Martin and Smith, 1997), the recommended MSL conceptual design *is well inside the surf-zone is submerged 50% of the time and will result in net erosion of the beach*.

Reefs close to the beach cause erosion because water levels in the lee of the reef are set-up by wave-driven currents over the crest of the reef. This increased water level and the virtual compression of the surf-zone behind the structure leads to strong alongshore currents and beach erosion. Since the structures cannot erode, the beach does so to compensate for the increased alongshore currents. This scour zone behind the reef is seen whether the reef is inside or outside of the surfzone, however, the proximity of the reef to the beach dictates whether the beach itself will scour or whether the scour will occur on the seabed behind the reef and set-up a 4-cell circulation pattern that will help form a salient (Black and Mead, 2003; Ranasinghe et al., 2006).

This local scour can be seen in the bathymetry surveys of the Boscombe Reef in the UK, which is set some 3x the alongshore distance of the reef offshore (i.e. outside the average wave height surfzone) and causes an asymmetric salient of very similar dimensions to that predicted by the Black and Andrews (2001a) method and the morphological modeling undertaken during the detailed design phase (Appendix 1). Similar to the salient response of the Narrowneck Reef on the Gold Coast in Australia (Appendix 2), the asymmetry of the salient is due to the predominant alongshore sediment transport from the west to the east (north to south at Narrowneck).

Simple consideration of the level of water above the crest of the recommended MSL reef design due to tidal cycles and storm surge and relation to the comprehensive physical and numerical modeling studies presented by Ranasinghe et al., (2006) (repeatedly cited by EIC (2010)), should have alerted EIC (2010) to the fact that the MSL reef would cause erosion. The MSL reef is submerged by 0.6 m at mean high water and 0.8 m at mean highest high water, and at greater depths during storm activity due to wind and wave set-up and low barometric pressure (i.e. storm surge). Ranasinghe et al., (2006) tested reefs with water levels of 0.5 m and 1.0 m above the crest and found that if the inshore edge of reefs were within 1.5x the surfzone width, they would cause erosion. The MSL reef is within the surfzone during all phases of the tide, and waves can penetrate over the reef crest for some 50% of the time. The recommended MSL reef is not an emergent structure and will not behave as an emergent structure as suggested by EIC (2010). The MSL reef is semi-emergent and it will cause erosion due to compression of the surfzone in its lee causing a 2-cell circulation pattern during higher phases of the tide.

In short, many of the deficiencies identified above emanate from the fact that the model that was applied does not simulate complex hydrodynamic processes around submerged nearshore structures.

The following Section presents the correct application of empirical and basic numerical methods for developing a conceptual reef design at Fletcher Cove, Solana Beach, including the application of the Black and Andrews (2001a) and Ranasinghe et al., (2006) methods. The GENESIS modeling undertaken by EIC (2010) does not require comment, since the short-comings of using this model in this situation are pointed out in Appendix 4 of the EIC (2010) report.

4 CONCEPTUAL DESIGN PROCESS

4.1 Introduction

SANDAG adopted the Regional Shoreline Preservation Strategy (RSPS) in 1993, and considered sand retention strategies as one of a number of tactics recognized in the RSPS that could be used to compliment the placement of sand on the region's beaches (M&N, 2001). The M&N (2001) report titled "Regional Beach Sand Retention Strategy", provides a very good background and comprehensive first order, or screen-level, assessment of sand retention application along the San Diego coast. The report assesses Needs, Constraints and Opportunities for sand retention measures in the area, and considers first order shoreline response to structures in order to develop an economic analysis.

In the M&N (2001) report, Multi-Purpose Reefs (MPR's) were considered to be cost effective, to have low environmental impacts and to provide opportunities for habitat and recreational (surfing) enhancement. Along the coast from Camp Pendelton to the Mexican Border, each City region was considered. With the exception of Oceanside (which preferred groynes), MPR's were a preferred option for all the City Councils; sites where MPR's could likely be applied were identified in each of the regions. In all cases, it was considered that these sites could benefit from the placement of reef habitat. With respect to cost effectiveness, the economic analysis indicate that at 'erosion hotspots' such as Solana Beach, over a 50 year life cycle, structure retained beaches are far more cost effective than nourishment alone – i.e. $9.3M vs $20.3M for structure-retained vs nourishment alone.

In the M&N (2001) report, a method for assessing the size of salients behind offshore structures was developed to consider the shoreline response to a variety of breakwater structures on the California coast. While this is a potential method of predicting shoreline response on the area, there were several limitations that make it non-valid submerged or semi-emergent reefs, including:

- The cases used are all shore-parallel structures and most are fully emergent at all tides;
- There are only 4 data points used to develop the empirical relationship, and;
- The impacts of wave-driven circulation in the lee of submerged or semi-emergent structures was not fully understood (e.g. Black and Mead, 2003, Ranasinghe et al., 2006).

The first level reef design by M&N (2001) was a shore-connected structure, which had some merit due to the predominance of natural shore-connected structures along the Southern California coast. However, such a reef has some major down falls with respect to efficiency and surfability, since a) relatively little sand is retained in the salient in comparison to the volume of the structures, and b) the reef would be located within the surf zone for the majority of the time surfing conditions occur and so would likely provide little in the way of surfing amenity (e.g. the artificial reef at El Segundo). It seems that the EIC (2010) conceptual design has continued with the shore-connected reef approach, without consideration of the existing knowledge in this area.

M&N (2001) regularly point out through their report that more study is needed in the area and that example projects such as the Narrowneck Reef on the Gold Coast, Australia, should be monitored to gain better understanding of beach response to MPR's in the future. However, 10 years later the EIC (2010) report does not consider the data from existing projects such as the Narrowneck Reef, and does not either consider or correctly apply the published literature on the shoreline response to these type of structures that has become available since 2001 (e.g. Black and Andrews, 2001a, b; Black and Mead, 2003; Ranasinghe et al., 2006; Turner, 2006; Blacka et al., 2008; Weppe, 2009; Mead et al., 2010).

Although MPR's are often considered a new kind of coastal protection structure, submerged breakwaters/reefs have been applied as coastal protection and harbour protecton devices for more than a century. On the coast, a well-designed submerged breakwater/reef results in a shoreline response known as a salient, i.e. a widening of the beach. Along with the structure, this wider beach works to protect the coast (a wide healthy beach is the best form of coastal protection). Changing attitudes to our the environment, environmental management, socio-ecoomics of beaches, etc, has led to a great deal of focus on submerged/detached breakwaters/reefs over the past few decades, since the result in a wider beach that has functional, social and economic benefits. Managed Attack is now becoming more widely advocated than Managed Retreat, since it costs less to protect valuable infrastructure and there are the added economic benefits of a wide beach (e.g. North Germany's coastal management plan, ICCE, 2010).

Multi-purpose reefs are not a completely new concept, they are the natural progress of incorporating amenity and ecological enhancement into traditional coastal protection structures (i.e. submerged breakwaters/reefs).While the multi-purpose aspects are relatively new, offshore reefs (also known as submerged breakwaters and artificial reefs) have been successfully and commonly applied world-wide in the past few decades (Adams and Sonu, 1986; Pilarczyk, 1990; Pilarczyk and Zeidler, 1996; Smith *et al*., 2001; Van der Meer and Pilarczyk, 1998; Harris, 2002; Pilarczyk, 2003; ChiranJeev and Mani, 2003) and are particularly popular in Japan (Figure 4.1). Today, the design approach includes using state-of-the-art tools to optimally design and position these structures (numerical hydrodynamic and sediment transport models that have been continually adapted to the design and impact assessment of multi-purpose reef over the past decade and a half (e.g. the 3DD Suite)), the incorporation surfing amenity (e.g. ASR holds a database of over 40 world-class surfing breaks (including breaks in California) that includes bathymetry, peel angle and breaker intensity parameters of each break), and the incorporation of ecological enhancement (while this will occur as an 'artefact' of placing stable complex substrate where previously there was mobile abrasive sand substrate, species and site specific enhancement can also be applied).

The following Sections provide a basic assessment for a conceptual design at Fletcher Cove, Solana Beach.

Figure 4.1. Submerged reefs for coastal protection in Japan

4.2 Reef Plan Shape

As described in Section 2.3 above, the square reef with a shore-normal gradient (MSL recommended reef (EIC, 2010)) is not very useful with respect to considering the design volume (efficiency) and surfing aspects. Even at a conceptual stage, a reef plan shape that is closer to the kind of structure that would be applied to meet the objectives should be used; the delta-shaped reef has commonly been applied for conceptual design investigations, as well as scientific investigations and final designs (e.g. Mocke 2003; Ranasinghe et al., 2006; Mead et al., 2006; Borrero and Mead, 2009). Figure 4.2 provides an example conceptual design for Fletcher Cove, while it would be likely in the next phase of detailed design that a wave-rotator reef would be useful due to the ~50,000 cubic yards of net southwards transport at the site (M&N, 2001).

Submerged reefs function through wave dissipation and wave rotation, which leads to salient growth in the lee of a reef. Wave energy is dissipated on the reef resulting in less energy at the beach in the lee of the reef and the consequent deposition of sediment. Wave rotation is a novel approach to coastal protection and is well described by Pilazyck (2003):

> *"It is also worth noting that Black and Mead (2001) have introduced a new concept of coastal protection by applying wave rotation due to the presence of submerged structures. Wave rotation targets the cause of the erosion, i.e. longshore wave-driven currents. Offshore structures are oriented to rotate waves so that the longshore current (and sediment transport) is reduced inshore. The realigned wave angle at the breaking point (in harmony with the alignment of the beach) results in reduced longshore flows and sediment accretion in the lee of the rotating reef."*

Thus, where oblique incident waves are the main cause of erosion, wave rotation can play a significant role in the functional aspects of submerged reefs. This is achieved with or without waves breaking on the reef, and so is not reliant on wave transmission (e.g. Arhens, 1984). At Fletcher Cove, this would result in a reef with a longer southern arm in order to rotate waves to a more northerly direction.

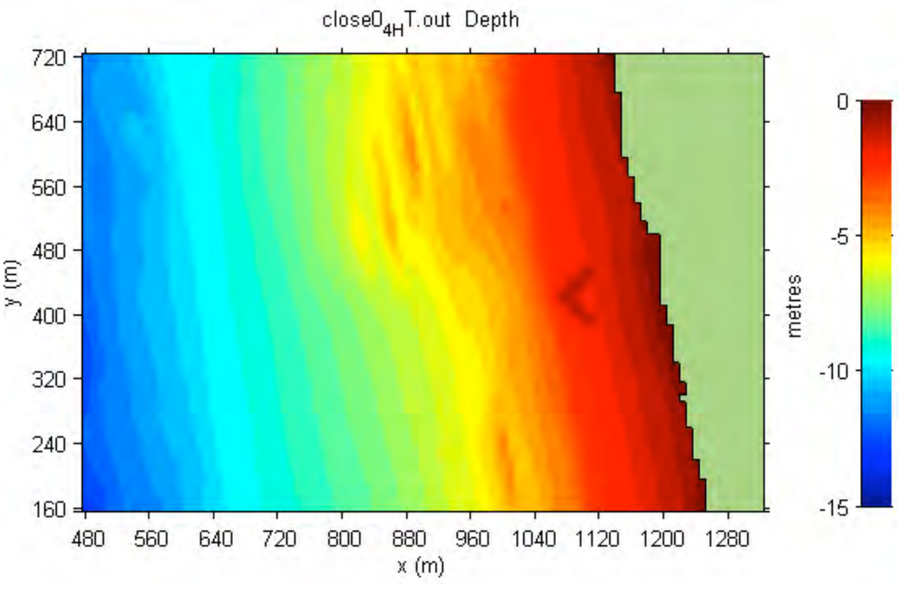

Figure 4.2. A conceptual delta-shaped reef on the Fletcher Cove bathymetry.

4.3 Positioning the Reef Offshore

As described in Section 3 above, the EIC (2010) assessment does not take into account the large body of existing literature that indicates length of structure and distance offshore are the largest contributors to salient size formation, since the Kt Method does not change the salient size when the distance offshore is changed. This is a critical aspect, since the shoreline response is determined by the size of the structure and its distance offshore, and so the size of the structure is determined by the length of the coast that requires protection. In addition, the EIC (2010) assessment does not take into account the literature that indicates submerged structures or semi-emergent structures must be located outside the active surf zone to prevent erosion (Black and Mead, 2003; Ranasinghe et al., 2006). To assess the position of the reef offshore, either empirical methods or basic numerical modeling can be undertaken.

4.3.1 Empirical Assessment

Ranasinghe et al., (2006) and Black and Andrews (2001a) are the most applicable empirical methods, both are relatively easy to apply and are well supported by literature, field, laboratory and numerical modeling data.

In order to optimise the offshore location of the reef, the most common wave condition is considered. Based on analysis of the Torrey Pines buoy dataset the average wave conditions are 1.09 m Hs, at 13 seconds.

The Initial, MLLW and MSL reef positions and three additional offshore reefs were assessed, with the latter having distances offshore of 100 m (Reef Close), 200 m (Reef Mid), and 250 m (Reef Far) offshore. The Ranasinghe *et al.* (2006) method indicates that a submerged structure must be outside the width of the surf zone (or SZW) to ensure an accretionary beach response (similar to the findings of Black and Mead, 2003). This analysis is based on a series of laboratory and numerical experiments which established a relationship between the incident wave conditions and the reef geometry (Figure 4.3). The ultimate result was a set of design curves (Figure 4.4) that relate these quantities. It is important to note the Ranasinghe *et al.* (2006) relationships are based on a reef with a crest height set at 0.5 m and 1.0 m below mean water level. Using the relationships in Figure 4.4 we can determine the predicted salient width for the typical inshore wave conditions. These values are compared in Table 4.1.

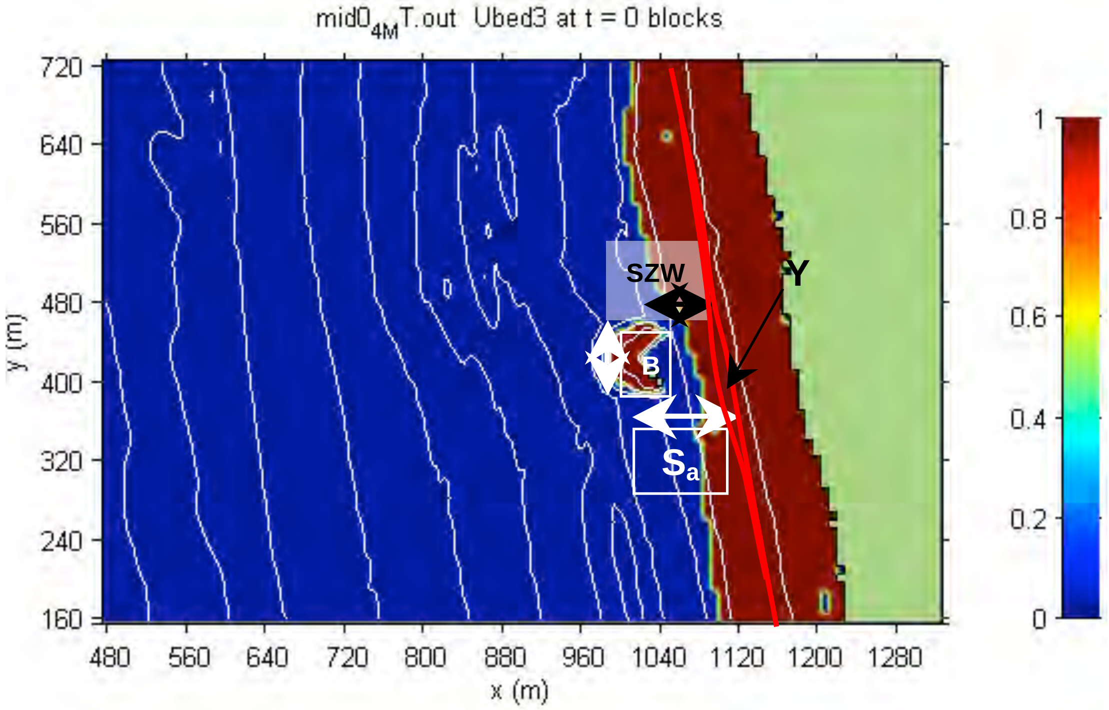

Figure 4.3. *Schematic diagram for quantities used in the Ranashinghe et al. (2006) salient formation relationships*

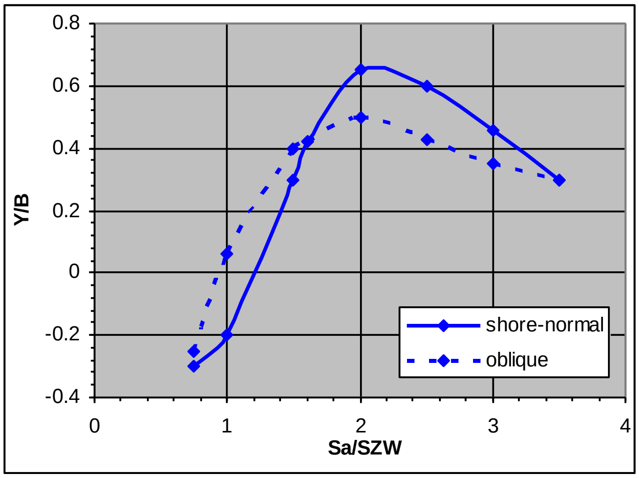

Figure 4.4. *Relationship between reef geometry (Sa – offshore distance, B – cross-shore width), wave conditions (SZW – surf zone width) and salient width (Y) based on laboratory physical model experiments. Figure reproduced from Ranasinghe et al. (2006). Solid line is for normally incident waves, dashed line is for obliquely incident waves.*

Table 4.1. Results of the Ranasinghe et al., (2006) erosion/accretion prediction method.

Reef	ReefClose	ReefMid	ReefFar	Initial Design	No. 2 Design	No.3 Design
Wave	Typical	Typical	Typical	Typical	Typical	Typical
Sa	100	200	300	200	100	90
B	80	80	80	80	96	90
SZW	120	120	120	120	120	120
Sa/SZW	0.83	1.67	2.50	1.67	0.83	0.75
Y/B norm	<1	0.48	0.6	0.48	<1	<1
Y/B obl	<1	0.44	0.43	0.44	<1	<1
Y norm	EROSIVE	**38**	**48**	**38**	EROSIVE	EROSIVE
Y obl	EROSIVE	**35**	**34**	**35**	EROSIVE	EROSIVE

Based on the Ranasinghe et al. (2006) analysis, the MLLW, MSL and 100 m offshore reef would all cause erosion under average wave conditions, because they are inside the surfzone (Table 4.1). With respect to beach erosion, a wide beach is considered the best form of defence, in the next stage, detailed design, morphological numerical modelling using the actual wave climate (e.g. spectral modelling using a compressed time series to represent the long-term conditions – e.g. Benedet et al., 2010), and long-term impacts of storm events can be better assessed for reef positioning, even so, these results indicate that a reef located at least 100 m offshore will ensure that erosion does not occur under the average wave conditions.

The Black and Andrews (2001a) method can next be applied to assess the extent of salient response due to the reefs alongshore dimension and distance offshore. The EIC (2010) established criteria that included development of a salient at least 30 m wide at the apex. By applying the Black and Andrews (2001a) reef equation, it can be seen that all the reef except for the MLLW reef will result in salients of over 30 m wide (Figure 4.5). However, when this is considered together with the Ranasinghe et al., (2006) surf zone width condition, the 100 m offshore reef and the MSL reef are discounted due to their erosion causing impacts (Figure 4.5).

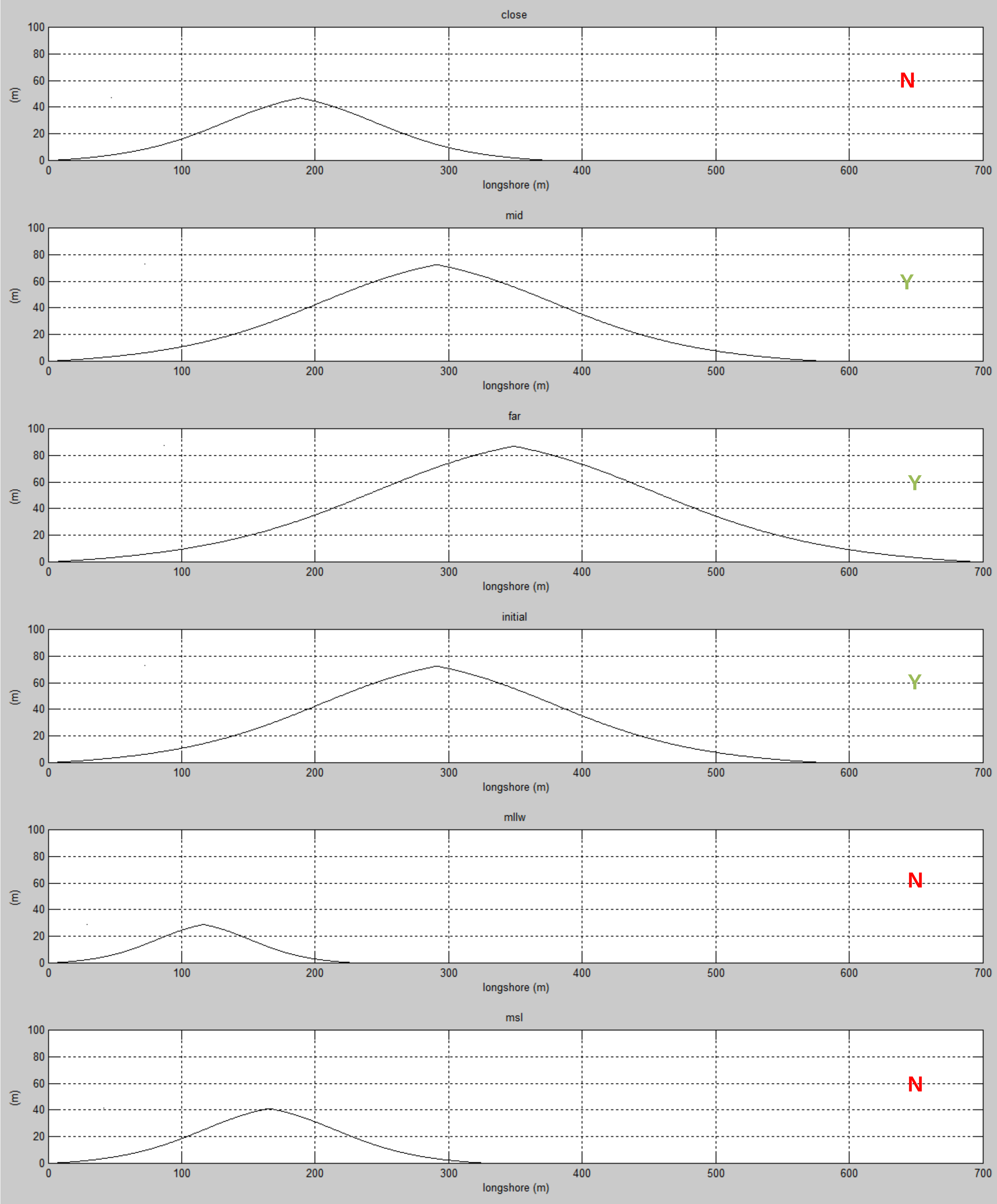

Figure 4.5. Salient response to reefs located 100, 200 and 300 m offshore, the Initial, MLLW and MSL reefs based on Black and Andrews (2001a). The 'Y' indicates that the case fits the Ranasinghe et al., (2006) method, while the 'N' indicates that it does not.

4.3.2 Basic Numerical Modelling

A basic refraction/diffraction model can be used to determine the width of the surfzone in combination with the empirical methods, which can also incorporate differing crest heights to gain a basic understanding of the wave sheltering afforded. Here we have applied WBEND from the 3DD Suite. Appendix 3 provides some basic descriptions of the 3DD Suite Models. For this type of assessment, enhanced shoaling is used to overcome under-prediction of breakpoint wave height which is common to other linear wave models. The breakpoint and wave height changes can then be used to assess the position of the reef in relation to the surfzone width on the natural bathymetry.

Bathymetry for the modeling was derived from the recent USGS dataset (Barnard and Hoover, 2010). The dataset is collated survey data from multiple sources which provides a seamless, high-resolution (3 m), coastal digital elevation model (DEM) for Southern California. The full DEM is composed of multiple DEM tiles and the area of interest relates to DEM ID ‘sd6’ for the Solana area. The DEM horizontal coordinate system is UTM NAD 83 Zone 11 North, and vertical datum is NAVD88. 12 different reefs were incorporated into the existing bathymetry at Fletcher Cove.

Prior to inclusion of the reefs, the locations of the surfing amenity and existing ecology, both of which are not to be effected by any new construction, were investigated through interview with long-time local residence and surfers:

Surf – The break at Fletcher Cove is known as “Pillbox” (there used to be some old gunnery locations there to fend off the invading Japanese in WWII). It is located at the north end of the cove. It breaks both ways, left and right. More activity occurs on the right during W and NW swells, which happens 8-9 months out of the year or so. A relatively easy wave, decent for beginners, currently breaks on low tide only unless there's a big swell. It used to be a much better and much more popular wave 10 years ago when there was a wide sandy beach. However, it's still considered a decent local spot and usually has a handful of guys on it when there's swell and the tide is low.

There is very little surfing happening straight out from the cove, or south of it, until you head down the beach about a quarter mile.

Reef Ecology - Not surprisingly, the reef ecology situation mimics the surf breaks. The only real hard reef is the Pillbox surf reef at the north end of the cove. The rest of the bottom is mostly sand stretching about a quarter mile down the coast. The reef that does exist is considered typical for North County San Diego – it's made up of larger smooth rock with patches of seagrass and sand. This is represented in the Figures in the EIC (2010) report.

The results of this basic modelling exercise are presented in Appendix 4, where the breakpoint and wave height plots are given for the 3 offshore reefs (100 m, 200 m and 300 m) with 3 different crest heights (MLLW, +0.4 m and MSL), the Initial, MLLW and

MSL reefs, at 3 different tidal levels (low, mid and high tides). From the Figures presented in Appendix 4, it can be seen that:

During average wave conditions, the 200 m, 300 m and Initial Reefs are mostly outside the surfzone during all tidal phases and that wave height reduction behind the structures is increased with increasing crest height. During 1-year return wave events (2.5 m), the same reefs are mostly outside the surfzone, except for the 200 m offshore reef at lowtide. During 5-year return period wave events (5 m), all reef structures are within the surf zone.

4.4 Considering Circulation Patterns

Another useful simple method to assess the potential for salient development is to investigate circulation patterns in the lee of the reef, as described by Black and Mead (2003) and Ranasinghe et al., (2006). Figure 4.6 is an example of this kind of assessment, which has not been carried out for the reefs at Fletcher Cove due to the limitations of the scope. The presence of the 4-cell circulation pattern as seen in Figure 4.6 is another indicator that a salient will form.

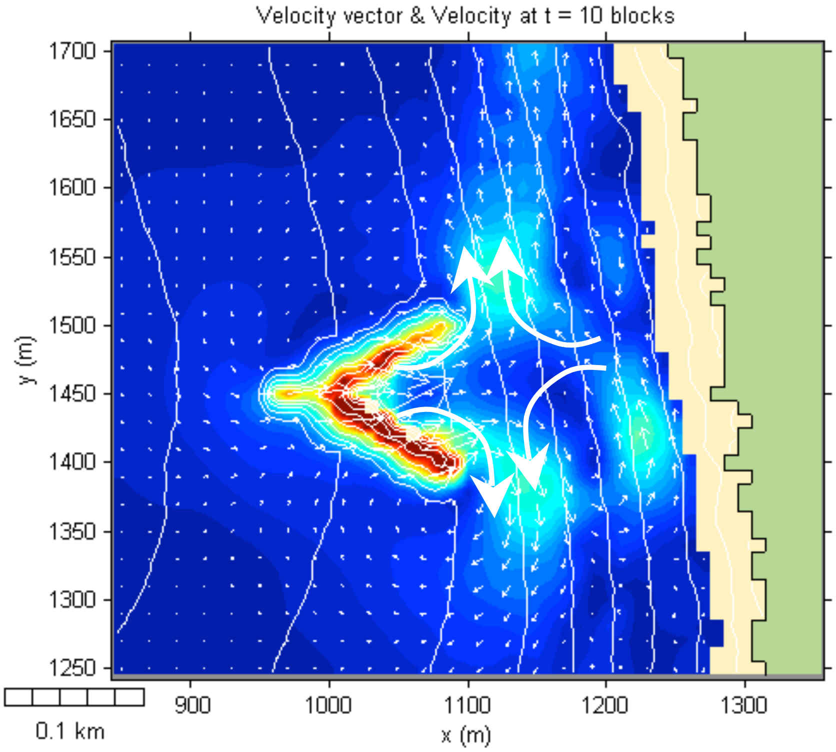

Figure 4.6. The 4-cell circulation pattern in the lee of an offshore submerged reef is a useful indicator of salient development.

4.5 Summary

The above basic assessment for the application of a submerged reef at Fletcher Cove, Solana Beach, has indicated that a reef of some 200 m offshore will ensure that it will result in the development of a salient. The next step would be to develop a detailed design for the site, which would include optimization of the alongshore length of the structure and morphological numerical modeling, which should be supported by onsite wave/current measurements for model calibration.

As can be seen from Figure 4.5, salients well exceeding 30 m are predicted, and although there is likely some over prediction due to the difference between manmade and natural structures, an MPR structure mimics a natural reef structure, and the results from existing projects indicate that these predictions are reasonably representative (Mead et al., 2010). Since Fletcher Cove is only some 120 m wide, a reduction of the 80 m long reef crest (for the 3 new reefs tested and the Initial Reef) could be warranted.

By using a full spectral wave climate, which can be simplified without loss of representation (e.g. Benedet et al., 2010), different crest levels (sensitivity testing) and storm return period scenarios can be tested to assess the effects of wave transmission. Figure 4.7 presents the results of calibrated morphological modeling to assess the different salient sizes/volumes that occur for a reef with the same alongshore dimensions and distance offshore, but differing crest levels. As noted by M&N (2001), determining the impacts of salient response due to reef crest height is difficult when structures are semi-emergent and sometimes allowing waves to pass fully or partially over the structures and sometimes not; crest height, varying tidal levels and varying wave events all combine to make this process complex to assess. A calibrated morphological model is the best tool to address this issue, which can have significant impact on the structures efficiency and therefore cost (e.g. Mead et al., 2004).

This type of detailed design and functional assessment should also incorporate an assessment of the effectiveness of wave-rotation at this site and surfing amenity into the structure, before proceeding with the additional criteria listed in Section 5.2 of EIC (2010).

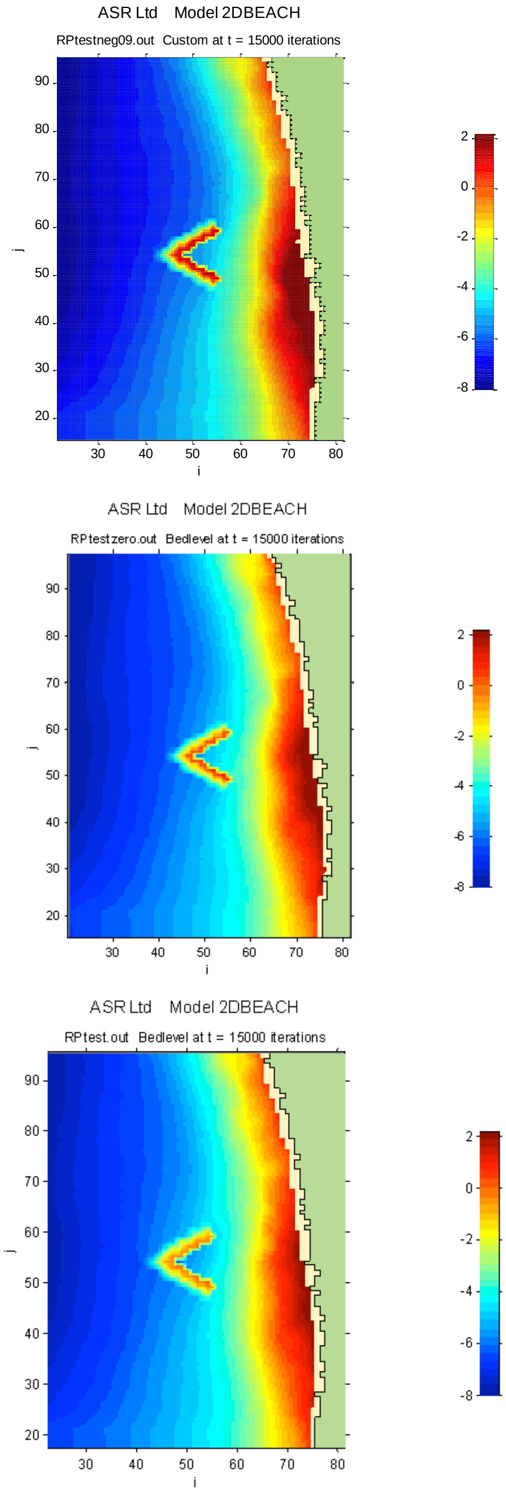

Figure 4.7. Morphological modelling using spectral wave boundary conditions on similar sized and positioned reefs with increasing crest level (bottom to top). (Borrero and Mead, 2009)

REFERENCES

Adams, C. B., and C. J. Sonu, 1986. Wave Transmission across Submerged Near-Surface Breakwaters. Proceedings 20th Coastal Engineering Conference, ASCE, 1729-1738

Ahrens, J. P., 1984. Reef Type Breakwaters. Coastal Engineering - 1984, B. L. Edge, ed., 1985. pp. 2648-2662

Ahren and Cox, 1990. Design and Performance of Reef Breakwaters. J. Coast. Res. 61-75

Barnard, P.L., and Hoover, D., 2010, A seamless, high-resolution coastal digital elevation model (DEM) for southern California. U.S. Geological Survey Data Series 487, 8 p. and database (http://pubs.usgs.gov/ds/487/).

Basco, D. R., and J. Pope, 2004. Groin Functional Design Guidance from the Coastal Engineering Manual. Special Issue 33, Journal of Coastal Research, 121-130.

Battjes, J. A., 1974. Surf Similarity. *Proc. 14th Coastal Engineering Conference*, ASCE, 466-480

Benedet., L., J. Dobrochinski, A. Klein, D. Walstra and R. Bonanata, 2010. Evalustion of wave climate schematization methodologies for morphological models over engineering timescales. Proceedings of 32nd International Conference on Coastal Engineering. Shanghai, China, June 30 – July 5, 2010.

Black, K.P., C.J. Andrews, M.O. Green, R.G. Gorman, T.R. Healy, T.M. Hume, J.A. Hutt, S.T. Mead and A.J. Sayce, 1997. Wave Dynamics and Shoreline Response on and around Surfing Reefs. 1st International Surfing Reef Symposium, Sydney, March, 1997.

Black, K.; Mead, S.; McComb, P. and Healy, T., 1999. Numerical modelling to amalgamate recreational amenity and coastal protection on sandy and rocky coasts. Coastal Structures ‘99 Conference, 2, 823-832, Spain, 6 June 1999.

Black, K. P., 2000. Artificial Surfing Reefs for Coastal Erosion Control and Amenity: Theory and Application. Proceedings of the International Coastal Symposium, 2000.

Black, K. P., & S. T. Mead, 2001. *Wave Rotation for Coastal Protection*. Proceedings of the Australasian Coasts & Ports Conference, Gold Coast, Queensland, Australia, 25-28 September 2001

Black, K. P., and C. Andrews, 2001a. Sandy Shoreline Response to Offshore obstacles Part 1: Salient and Tombolo Geometry and Shape. Journal of Coastal Research, Special Issue 29: 82-93.

Black, K. P., and C. Andrews, 2001b. Sandy Shoreline Response to Offshore obstacles Part 2: Discussion of Formative Mechanisms. Journal of Coastal Research, Special Issue 29: 94-101.

Black and Mead, 2003. Numerical Predictions of Salient Formation in the Lee of Offshore Reefs. Proceedings of the 3rd International Surfing Reef Conference, June 23-25 2003. ISBN 0-473-09801-6

Black K. P., and S. T. Mead, 2007. Sand bank responses to a multi-purpose reef on an exposed sandy coast. Shore and Beach 75(4):55-66.

Blacka, M.J., Anderson, D.J. and Mallen Lopez, L., 2008. Analysis of Shoreline Variability, Seasonality and Erosion / Accretion Trends: February 2008 - July 2008. Report 18: Northern Gold Coast Coastal Imaging System. WRL Technical Report 2008/27, Water Research Laboratory, University of New South Wales.

Borrero, J. C., and S. T. Mead, 2009. La Roche Percée: Optimized Design of a Multi-Purpose Erosion Control Structure. Prepared for Capse Nord, September 2009.

Button, M., 1991. *Laboratory Study of Artificial Surfing Reefs*. Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991. Pp 85 + appendices

Chasten, M. A., J.D. Rosati, J.W. Mc Cormick, and R.E. Randall. 1993. Engineering Design Guidance for Detached Breakwaters as Shoreline Stabilization Structures. USACE, Waterways Experiment Station Technical Report CERC-93-19.

Couriel, E. D., P. R. Horton and D. R. Cox, 1998. Supplementary 2-D Physical Modelling of Breaking Wave Characteristics. WRL Technical Report 98/14, March, 1998.

Dally, W. R., 1990. Stochastic Modelling of Surfing Climate. Proceedings, Coastal Engineering Conference, ASCE, Vol. 1, 516-529.

Gourlay, M. R., 1981. Beach Processes in the Vicinity of Offshore Breakwaters. Proceedings of the Fifth Australasian Conference on Coastal and Ocean Engineering, Perth.

Harris, L., 2002. Submerged reef structures for habitat enhancement and shoreline erosion abatement. U.S. Army Corps of Engineers Coastal & Hydraulic Engineering Technical Note (CHETN), Vicksburg, MS.

Hsu, J. R. C., and R. Silvester, 1990. Accretion Behind Single Offshore Breakwaters. Journal of Waterway, Port, Coastal and Ocean Engineering 116(3); 362-381

Hutt, J. A., 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished Thesis, University of Waikato, New Zealand.

Hutt, J. A, K. P. Black, A. Jackson and J. McGrath, 1999. Designing the Shape of the Gold Coast Reef: Field Investigations. Proc. Coasts & Ports ‘99, Vol. 2: 299-304.

Mead, S. T., 2000. Incorporating High-Quality Surfing Breaks into Multi-Purpose Reefs. Doctor of Philosophy in Coastal Oceanography and Surfing Reefs thesis. University of Waikato. Pp 209 + appendices.

Mead, S. T. & K. P. Black, 2001a. Field Studies Leading to the Bathymetric Classification of World-Class Surfing Breaks. Special Issue of the Journal of Coastal Research on Surfing p5-20.

Mead, S. T. & K. P. Black, 2001b. Functional Component Combinations Controlling Surfing Wave Quality at World-Class Surfing Breaks. Special Issue of the Journal of Coastal Research on Surfing p21-32.

Mead, S. T. & K. P. Black, 2001c. Predicting the Breaking Intensity of Surfing Waves. Special Issue of the Journal of Coastal Research on Surfing p51-65.

Mead, S. T., K. P. Black, B. Scarfe, L. Harris, J. Sample and C. Blenkinsopp, 2004. Oil Piers Reef: Phase II – Detailed Design and Environmental Impact Assessment. Report prepared for the US Army Corp of Engineers, January, 2004.

Mead, S. T., J. C. Borrero, K. P. Black and J. Frazerhurst, 2006. *Multi-Purpose Reefs at Wells Estate Beach: Feasibility Study.* Report Prepared for AfriCoast Engineers, November 2006.

Mead S.T, C. Blenkinsopp, J. C. Borrero and A. Moores, 2010. Design and Construction of the Boscombe Multi-Purpose Reef. Proceedings of 32nd International Conference on Coastal Engineering. Shanghai, China, June 30 – July 5, 2010.

Mocke, G., F. Smit, S. Fernando and K. Al Zahed, 2003. Coastal Protection and Amenity Value of an Artificial Surf Reef for Dubai. Proceedings of the 3rd International Surfing Reef Symposium, Raglan, New Zealand, June 22-25, 2003

Nir, Y., 1982. Offshore oartifical structures and their influence on the Israel and Sinai Mediterranean beaches. Proceedings of the 18th International Conference on Coastal Engineering. 2069-2085.

Peregrine, D. H., 1983. Breaking Waves on Beaches. Ann. Rev. Fluid Mech., 15:149-178.

Pilarczyk, K. W. 1990. Coastal Protection. Published by A. A. Balkema, Rotterdam.

Pilarczyk, K. W. & R. B. Zeidler, 1996. Offshore Breakwaters and Shore Evolution Control. Ppublished by A. A. Balkema, Rotterdam. 560p

Pilarczyk, K. W., 2003. Design of low-crested (submerged) structures – an overview. 6th International Conference on Coastal and Port Engineering in Developing Countries, Colombo, Sri Lanka, 2003

Ranasinghe, R., Turner, I.L. and Symonds, G (2006). Shoreline response to multi-functional artificial surfing reefs: A numerical and physical modelling study. Coastal Engineering 53: 589-611.

Sayce, A., 1997. *Transformation of Surfing Waves Over Steep and Complex Reefs*. Unpublished Thesis, University of Waikato, New Zealand.

Sayce, A., K. P. Black and R. Gorman, 1999. Breaking Wave Shape on Surfing Reefs. *Proc. Coasts & Ports '99*, Vol. 2:596-603.

Shore Protection Manual, 1984. 4th Edition, 2 volumes, US Army Engineering Waterways Experiment Station, Coastal Engineering Research Centre, Washington. 337p.

Smith, J.T., Harris, L.E., and Tabar, J., 1998. Preliminary evaluation of the Vero Beach, FL prefabricated submerged breakwater. Beach Preservation Technology '98, FSBPA, Tallahassee, FL

Turner, I. L., 2006. Discriminating Modes of Shoreline Response to Offshore-Detached Structures. Journal of Waterway, Port, Coastal and Ocean Engineering, V132, Issue 3, pp 180-191.

Van der Meer W. and K. W. Pilarczyk, 1998. Stability of Low-Crest and Reef Breakwaters.

Walker, J. R., 1974a. Wave Transformations Over a Sloping Bottom and Over a Three-Dimensional Shoal. PhD. Dissertation, University of Hawaii, 1974.

Walker, J. R., 1974b. *Recreational Surf Parameters*. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1974.

Weppe, S., T. Healy, B. Scarfe and D. Immenga, 2009. Shoreline response to an offshore submerged multifunction reef at Mount Maunganui, New Zealand. Proceedings of the 19th Australasian Coasts and Ports Conference, Wellington, NZ, 16-18 September 2009.

APPENDIX 1 – BOSCOMBE REEF (MEAD ET AL., 2010)

DESIGN AND CONSTRUCTION OF THE BOSCOMBE MULTI-PURPOSE REEF

Shaw T. Mead[1], Chris Blenkinsopp[2], Andrew Moores[1], and Jose Borrero[1]

The Boscombe Reef is a multipurpose reef structure designed primarily for the enhancement of surfing amenity at Boscombe, Poole Bay, England. The reef was designed to maximise the small and generally poor-quality surfing wave climate of the eastern English Channel coast. The reef was constructed from 54 large, sand filled geotextile containers ranging in size from 1 to 5 m diameters and 15 to 70 m long with a total volume of approximately 13,000 m^3. Construction of the reef began in the summer of 2008, was suspended during the following winter and was completed in the late summer of 2009. The reef is now in service and provides a high intensity right hand surfing ride of up to 70 m and a shorter left hand ride of up to 30 m. Although the reef was not designed as a coastal protection structure, monitoring of the morphological response supports that the reef promotes shore protection through the formation of an inshore salient.

Keywords: artificial reef; submerged breakwater; surfing; recreation; shore protection; salient formation

INTRODUCTION

The Bournemouth Borough Council commissioned ASR Ltd to develop a multi-purpose reef for recreational purposes in Boscombe. The reef is part of a municipal redevelopment scheme, the Boscombe Spa, which included the refurbishment of the local pier as well as the development of restaurants, shops and residential property. The aim of the reef project was to enhance surfing at a site which presently provides only mediocre surfing conditions. While designed primarily for surfing, the coastal protection aspects of these structures is also of interest.

NEARSHORE ENVIRONMENT AND DESIGN CRITERIA

Boscombe is located in the western English Channel on the south coast of England, approximately 150 km, southwest of London. Due to its location, Boscombe is sheltered from the large swells of the north Atlantic Ocean. Frequently however, local winds produce short choppy seas affecting the area. Despite the adverse conditions for recreational wave riding, surfing is nevertheless a popular activity here, with the third largest surfing population in the UK.

Since multi-purpose reef design projects are limited by physical and economic constraints, the design must take into account a wide range of factors to obtain the optimum solution for a particular location. At Boscombe, the key factors investigated as part of the iterative reef design process were the wave climate, the wind climate and the crest height.

For the design process, detailed field studies were conducted at the proposed reef site. This included surveys to accurately represent the nearshore bathymetry. Wave data was collected from both a waverider directional buoy located 1 km offshore of the Boscombe Pier (Figure 1a) and supplemented with a 6 week deployment of an in-situ wave and current meter in 5 m water depth at the proposed reef site. Wave transformation studies were conducted between the two data sets to establish an inshore wave climate for the design process. The design wave conditions for the reef were for $H_{10} = 1$ m ± 0.5 m; $T = 7$ s ± 2 s , and wave direction coming from 191ºN ± 6º.

Water level information was derived from a tide gauge located on the Bournemouth Pier. The tidal range between MHWS and MLWS at Bournmouth is 1.76 m. The tidal signal at Boscombe is asymmetrical in nature with a prolonged double-peak high water period and a short sharp change in water levels at low tide (Figure 1b). This asymmetric tidal curve means that water levels are above mid-tide level for 75% of the time and had significant impact on the reef design. To ensure that waves break on the reef for a reasonable proportion of the tidal cycle it was necessary to raise the crest to a level above mean low water springs.

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[2] Water Research Laboratory, University of New South Wales.

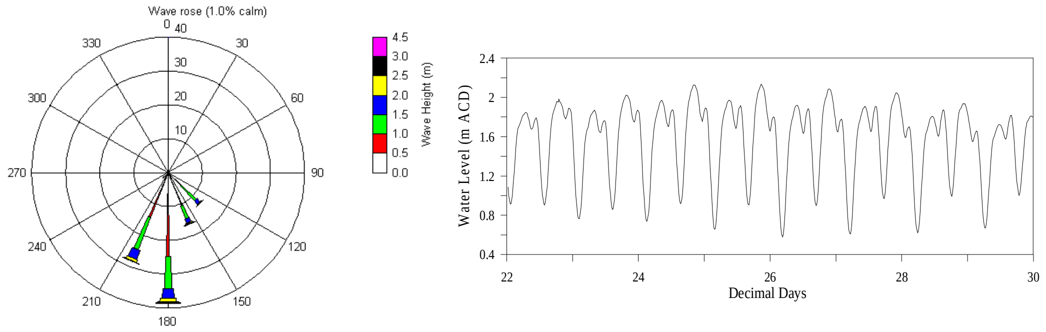


Figure 1. (a) A rose plot for the Boscombe wave climate showing waves coming from predominantly a southerly and south-southeasterly wave direction. (b) A time series of the highly asymmetrical tide signal at the reef site.

Table 1. Water levels at Boscombe.

Tide Level	Water Level (m, ACD)
HAT	2.59
MHWS	2.21
MHWN	1.67
MLWN	1.17
MLWS	0.45
LAT	-0.06

A wind rose for the site is shown in Figure 2. The data suggests that southwesterly winds are most common, however the wind can come from virtually any direction. The wind climate can be severe with winds frequently exceeding 10 m/s (19.4 knots). Indeed, local surfers report that surfing conditions are frequently driven by or in conjunction with strong local winds – a less than ideal situation

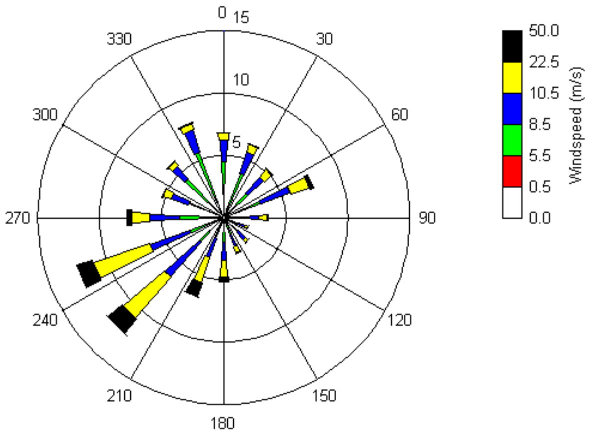


Figure 2. Wind rose plot for Boscombe.

MULTIPURPOSE REEF DESIGN

The final reef design incorporated the following main features; a dual level reef with a focus section (Mead and Black, 2001a, b) designed to draw maximum wave energy onto the reef and a wedge section (Mead and Black, 2001a, b) along the crest to break waves in a manner suitable for high-quality surfing. The design has a crest height of 0.5 m above chart datum. The reef produces a predominant right hand surfing ride approximately 70 m long with a shorter 30 m long left hand break. The white water generated after breaking on the left-handed wave dampens short-period chop originating from the south west quadrant so that it does not propagate through to the main right-handed wave. This design was set in water depths of 3-5 m (CD) (Figure 3 a).

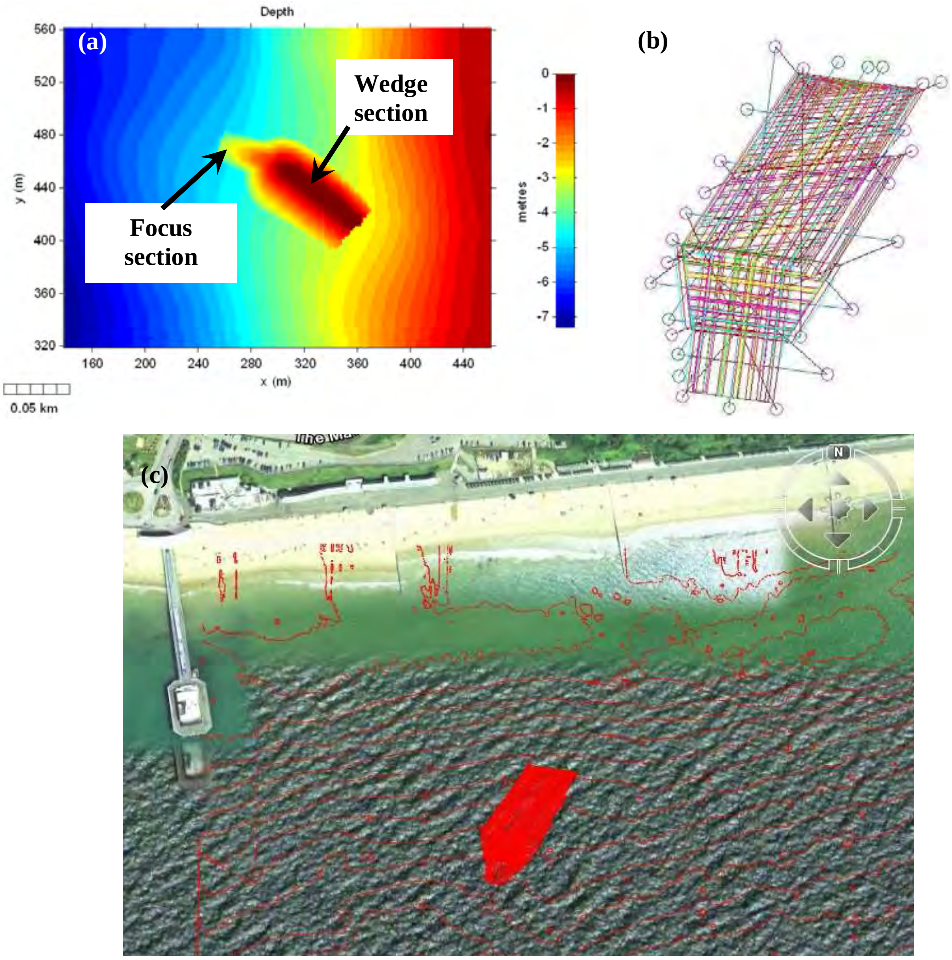


Figure 3 (a) Computer generated, numerical model design shape of the Boscombe Multipurpose Reef, (b) a schematic of the geotextile container layout and section anchoring strategy for the full scale prototype and (c) location of reef 280 m offshore and east of Boscombe Pier, Poole Bay, England.

The design peel angle for wave breaking over the reef was optimized to cater to surfers with skill levels of 3-6 (intermediate to competent surfers, Hutt et al., 2001). In the present case, considering that surfable wave heights generally occurring at Bournemouth are on the order of 0.5 to 1.2 m, peel angles of 50 to 70 degrees would be appropriate (Figure 4).

The reef design was further optimised through physical laboratory scale modelling. For these studies a model of the reef at 1:30 scale was built using scaled construction elements representing the sand filled geotextile containers to be used to construct the reef in reality. With this method the reef shape could be fine-tuned and the container layout specified prior to construction. Validation based on qualitative assessments of the wave breaking on the completed reef indicates that the laboratory modelling was reasonably accurate (Figure 5).

Further design/impact modelling was undertaken for environmental impact assessment and permitting purposes, which is not presented here.

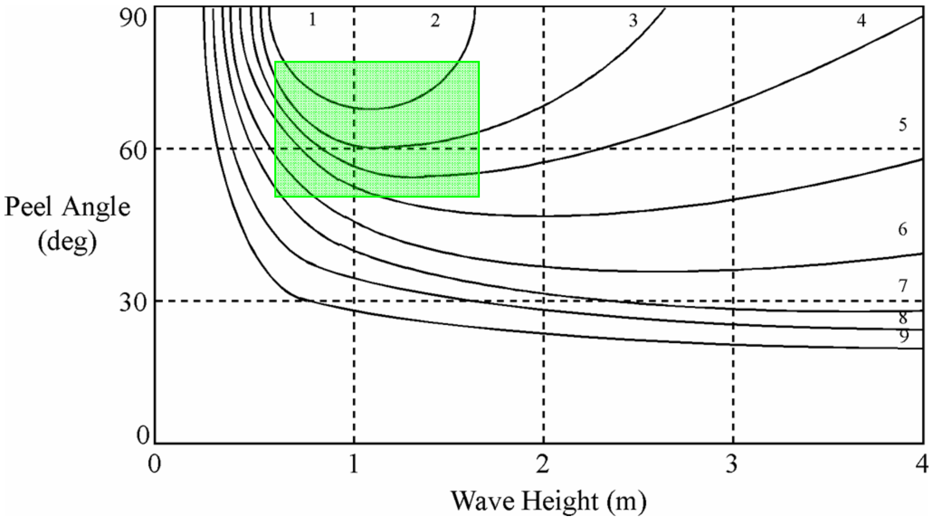


Figure 4. Design range of peel angle and wave height using the method og Hutt et al., 2001 for the Boscombe Reef

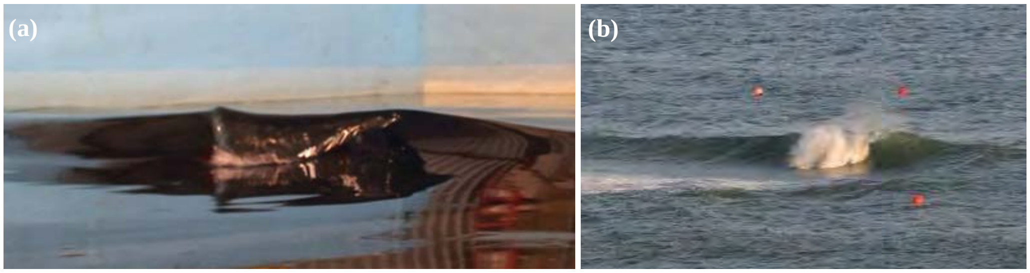


Figure 5. (a) Wave breaking over a 1:30 scale laboratory model of the Boscombe Reef and (b) a wave breaking over the nearly completed reef.

REEF CONSTRUCTION

Reef construction began in the summer of 2008. Construction was based on using large sand filled geotextile containers arranged in sections. The sections were compromised of up to 14 individual containers ranging in size from 15 to 40 m long with diameters on the order of 1 to 4 m. Each section was deployed from a barge and anchored to the sea bed with 5 ton concrete blocks. The containers were filled through the use of a land-based pumping system connected to the reef via a 200 m long pipeline. Clean sand stocked-piled on the beach was pumped out to the reef in a sand/water slurry and the filling was controlled by divers (Figure 6 a,b).

This methodology of deploying sections of containers was employed for the lower layer of containers, however due to the large number of longer (70 m) containers in the main upper section, single container deployment was undertaken to reduce risk. If inclement whether set in and containers were left unfilled, there was a risk of containers shifting from their design location. Indeed, weather was a factor during the first construction season and in conjunction to a late start on the project, only the first layer of the reef was able to be finished. Once winter set in, construction was suspended until the following summer. During the second construction season in the summer 2009, each container was folded on to a floating raft, hitched into position and anchored to the lower layer by divers before filling. This method was effective and efficient and allowed the reef to be completed before the end of the construction window in September 2009 (Figure 7).

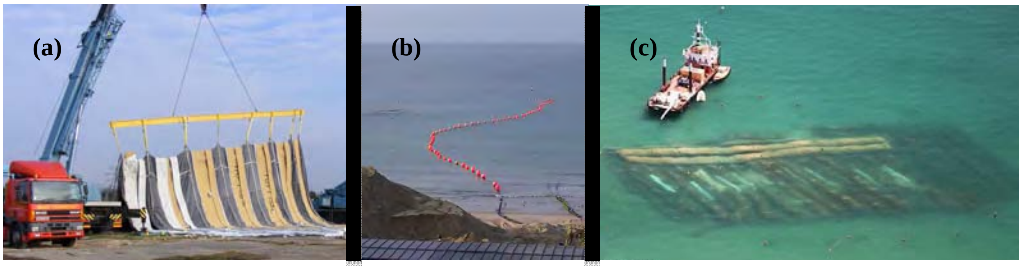


Figure 6. (a) Hoisting a section of unfilled geotextile containers on to the barge for deployment (b) the sand slurry pipeline (c) the completed lower layer with two of the top layer containers in place.

Figure 7. Aerial view of the Boscombe Reef September 2009.

POST CONSTRUCTION MONITORING

Since construction, the reef has been independently monitored for surfing performance, with a preliminary monitoring report delivered in March, 2010. This report judged the reef on 5 performance criteria including ride length, wave quality, wave height amplification, wave intensity and consistency. It should be noted that a baseline study of surfing conditions at Boscombe suggested that acceptable surfing conditions (prompting at least 5 surfers to enter the water and attempt to surf) occurred at Boscombe only 20% of the time (Davidson, 2009). It should also be noted, that at the exact reef location (200 m offshore) surfing conditions occurred 0% of the time, thus, even 1 day of surfing is an improvement over pre-reef conditions. The interim monitoring report found that the reef had achieved 4 out of 5 of the performance criteria, with ride length on the right hander being sometimes effected during longer period and lower tide conditions, when waves can be very fast and sometimes break with a collapsing form after take-off (although it is noted that the longer period wave conditions are outside the design wave specifications). 3 small containers will be added to the lower part of the reef in the location where the focus meets the wedge on the offshore side of the reef to influence the shoaling/breaking of longer period waves and increase ride length.

Surfing

In terms of surfing, under design conditions (H_{10} = 1 m ± 0.5 m; T = 7 s ± 2 s , and wave direction coming from 191°N ± 6°), the reef has produced high-quality breaking waves suitable for stand up surfing, as per the design. When conditions are outside of the specified design range, the reef still produces rideable waves, however these are frequently more suitable to body-boarding due to the intense plunging nature of the wave breaking induced by the reef (see Figure 8 and supplemental material for a range of surfing and body boarding photos from the Boscombe Reef). Since the reef was completed in the late summer of 2009, it was able to be utilized in the Autumn and early Winter months of September through December. Indeed, this season is known to be the best time of year for surfing along the South Coast of England and this was also reported in the baseline study of surfing conditions (Davidson, 2009).

Based on an analysis of the wave climate at Boscombe, it was determined that the appropriate conditions for surfing existed on 20 different occasions between September 2009 and March 2010 (the period covering the preliminary assessment of surfability). The breakdown of good surfing conditions, marginal surfing conditions and poor surfing conditions are detailed in supplemental material 2. It should also be noted that the winter of 2009 – 2010 was one of the coldest and snowiest on record for England, and this undoubtedly had an effect on the number of surfing participants willing to enter the water at Boscombe. As this report goes to press, the Boscombe reef will enter its second year of service.

Figure 8. A body boarder surfing on the completed Boscombe Reef. Additional photos are provided in the suppemental material.

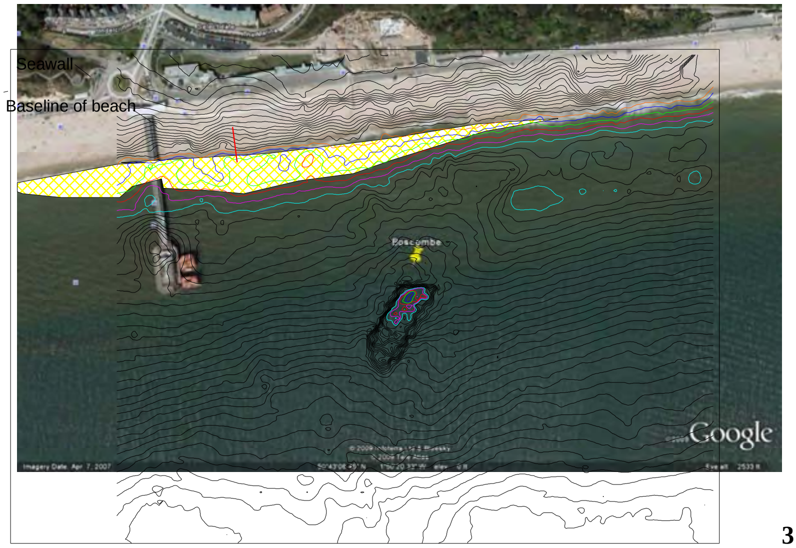
Shoreline Response

Since June 2008 (pre-construction) ASR has commissioned 17 bathymetry surveys and 3 beach profile surveys (the latter have coincided with the time/date of a bathymetry survey). Seven of the surveys are post-completion of the reef, and although intensive calibrated numerical modelling of morphological processes has been undertaken, here we are present a brief time-series view of the beach response with the combined bathymetry and beach profile surveys.

While net sediment transport is west to east due to the prevailing SW wind conditions, the short period of the waves means that initially cross-shore (offshore) sediment transport occurs. This cross-shore transport renders the groynes along the length of Poole Bay (some 60 groynes along 19 km of beach) ineffective, especially when the compartments are full following renourishment, which occurs every 10-12 years or so. Internationally, detached or submerged breakwaters have been used typically along coastlines with small tidal fluctuations to control the cross-shore sand transport processes (e.g. Nielsen, 2001). Thus, as was demonstrated in the design/impact modelling for the project, a significant salient has developed in the lee of the reef, and extends asymmetrically to the west due to the west-east transport of sediment. Figure 9 presents overlays of the bathymetry and beach surveys from October 2009, January 2010 and March 2010 that show the development of the salient, and Figure 10 shows the salient response to the presence of the Boscombe Reef from the air.

This beach response to the Boscombe Reef provides support that detached and submerged reefs or breakwaters would be a useful option for retention of renourishment material in Poole Bay in the future.

9 October 2009



31 January 2010

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Figure 9. Time-series bathymetry and beach profile surveys indicating the development of the salient in response to Boscombe Reef.

Figure 10. Aerial view of the beach response in the lee of Boscombe Reef (10 March 2010)

Geotextile Container Stability

The sand filled geotextile containers (SFC's) used in the construction of the reef are very large, with lengths of 15 to 40 m and diameters of 1 to 4 m. As a result the individual construction units are quite massive and sufficiently stable under the typical and extreme wave loads experienced at Boscombe. No indication of container failures has been observed thus far art Boscombe and we remain confident that the reef structure is stable. In terms of settlement and scour, the reef has settled somewhat, reducing the overall crest height. However the magnitude of the settlement, determined from the post construction bathymetric surveys, is 0.5 m or less, as specified in the design.

SUMMARY AND CONCLUSIONS

Boscombe Reef was designed for the local conditions in Poole Bay to create a surfing break as a focus for the Boscombe Spa development on England's southern coast. The reef is comprised of 2 main sections, a Focus to increase wave height and define the take-off zone, and a Wedge to peel the waves down as they break in a way and at a rate conducive with surfing. The reef provides primarily a righthand break (~70 m long) due to the prevailing wind from the southwest, with a shorter lefthand break (~30 m long) that also helps to reduce the surface chop that is common of the local sea conditions.

Construction of the reef was undertaken with 54 sand-filled geotextile containers varying in length from 15 m to 70 m, and with diameters of up to 4 m. The containers were filled with sand from a beach-based slurry pump set-up, with divers placing the containers in predetermined locations in a two-layer configuration and monitoring the filling process. The large size of these sand-filled geotextile containers results in a very stable structure, following the expected initial settlement of up to 0.5 m.

The reef has consistently produced surfing waves to the design specifications, especially under design wave conditions (H_{10} = 1 m ± 0.5 m; T = 7 s ± 2 s, and wave direction coming from 191ºN ± 6º), and has worked well in the capacity of a focus to compliment the Boscombe Spa development.

Monitoring of the beach response has recorded the development of a large salient in the lee of the reef. This salient is asymmetrical, with the location being more west of the reef position offshore, which is a consequence of the predominant west to east sediment transport direction. This beach response to the Boscombe Reef provides support that detached and submerged reefs or breakwaters would be a useful option for retention of renourishment material in Poole Bay in the future.

ACKNOWLEDGMENTS

The authors would like to acknowledge Edward Aitken for his diligent bathymetry and beach surveying, the Bournemouth Borough Council for their forward thinking and development of award-winning Boscombe Spa development, and the surfers and bodyboarders of Boscombe who have maintained support with regards to the Boscombe Multipurpose Reef.

REFERENCES

Davidson, M. 2009. A baseline Study of Surfing Conditions in the Boscombe Region and an investigation of Potential Improvements Due to the Installation of an Artificial Surfing Reef. University of Plymouth, Technical Report BDC052009-002.

Hutt, J.; Black, K. and Mead, S., 2001. Classification of Surf Breaks in Relation to Surfing Skill. Special Issue 29, *Journal of Coastal Research* p66-81.

Mead, S. T. & K. P. Black, 2001a. Field Studies Leading to the Bathymetric Classification of World-Class Surfing Breaks. Special Issue 29 of the *Journal of Coastal Research* on Surfing p5-20.

Mead, S. T. & K. P. Black, 2001b. Functional Component Combinations Controlling Surfing Wave Quality at World-Class Surfing Breaks. Special Issue 29 of the *Journal of Coastal Research* on Surfing p21-32.

Nielsen, L, 2001. *Newcastle Coastal Zone Management Plan: Coastal Engineering Advice*. Technical report for Umwelt (Australia) Pty Ltd, March 2001.

APPENDIX 2 – THE GOLD COAST REEF

The Development of Multi-Purpose Reefs for Coastal Protection

In 1995, the Artificial Reefs Program (ARP) was initiated at the Centre of Excellence in Coastal Oceanography and Marine Geology, a joint graduate school in the University of Waikato and the National Institute of Water and Atmospheric Research (NIWA), in Hamilton, New Zealand. By unifying senior scientists and experienced industrial partners, the ARP aimed to:

- enhance the coastal amenity value of developed shorelines by evaluating multiple use options (surfing, diving, recreational and commercial fishing, navigation and swimming safety) for incorporation into coastal constructions.

A team of scientists and industry experts was involved including biologists, physicists, engineers, planners and environmental managers, so that both the environmental aspects and the coastal processes could be fully investigated to enable the complete development of multi-purpose artificial reefs. A series of related studies provided the input into the broader program so that engineers who build offshore protection works became aware of and were able to incorporate the proposed concepts into their structural designs to fulfil the demands and requirements of the marine environment, recreationalists and developers.

ASR Ltd represents the commercial offshoot of the ARP, and although selected graduate students are still involved in the ARP (with joint supervision from ASR Ltd and the University of Waikato), the primary aim of the Program has been achieved. Indeed, in addition to numerous research theses, individual journal and conference papers and consulting reports, Special Issue No. 29 of the Journal of Coastal Research (Winter 2001), “Natural and Artificial Reefs for Surfing and Coastal Protection” includes over a dozen scientific papers on the design, impacts and construction of Multi-Purpose Reefs.

The first reef designed by ASR Ltd at Narrowneck on the Gold Coast in Queensland, Australia, won the State Environmental Award. This project has demonstrated the effectiveness of Multi-Purpose Reef technology, with significant widening of the beach without down stream impacts (the Narrowneck area of the Gold has a net northerly sediment transport of ~500,000 m^3/yr), enhanced marine life and quality surfing waves. A similar project has recently been completed for Lyall Bay (New Zealand), and ASR Ltd has recently been and is currently involved in a range of Multi-Purpose Reef projects that are primarily for either coastal protection (erosion control, submerged port walls), the creation of surfing breaks or ecological enhancement, in New Zealand (8), Australia (5), Fiji (1), Costa Rica (1), the USA (3) India (1), Indonesia (1), Bahrain (1) and the UK (5), with construction of three of these reefs scheduled to proceed in the next 12 months. The majority of these reef projects are in locations where the existing coastline is already developed, and where much of their income is derived from the tourism industry – these projects are often driven by the socio-economic benefits that Multi-Purpose Reefs provide. Indeed, the public demand for beaches for recreation, combined with the increasing value society places on the natural environment, has led to a dramatic increase in the development of submerged reef projects world-wide (e.g. Ahren and Cox, 1990; Hsu and Silvester, 1990; Pilarczyk and Zeidler, 1996; Hall and Seabrook, 1998; Black *et al.,* 1998; Harris, 2001; Mead *et al*., 2003; Babtie, 2003).

Example Project – The Narrowneck Submerged Reef, Queensland, Australia

The erosion problem at Narrowneck, 1 km north of Surfer's Paradise on the Gold Coast, in Queensland. The Gold Coast is Australia's primary tourist destination, with the wide sandy beaches being a major attraction. The erosion problem on the Gold Coast was confined to a hotspot at Narrowneck, where only the coastal road separates the Broadwater from the sea. This causeway was breached several times in the previous century and coastal protection was proposed as part of the Gold Coast Beach Protection Strategy to address this problem. The wave climate and sediment transport regime at the Gold Coast is dominated by SE swell, which results in large net sediment transport in one direction (~500,000 m^3/yr).

Traditional coastal protection methods were considered (e.g. groynes, rock rip-rap, etc.). However, a socio-economic assessment found that for every dollar spent on enhancing the beach, $60-80 was returned via tourism (Raybould and Mules, 1997). Consequently, an offshore submerged reef was proposed and design works were undertaken by ASR consultants (Black *et al.*, 1998). The aims of the project were to:

- widen the beach and dunes along Surfers Paradise Esplanade.
- improve the surfing climate at Narrowneck.

A comprehensive field program was undertaken, with the results being utilised for reef design and sediment transport modelling (i.e. to assess the functional performance of the reef). The resulting final design was a 128,000 m^3 submerged reef (Figs. 1 and 3). The main purpose of the Narrowneck reef is to retain sand nourishment material that was pumped onto the beach from the Broad water. Figure 3 demonstrates how successful the Narrowneck submerged reef has been at retaining nourishment material on Surfer's Paradise Beach. Argus coastal imaging has shown that wave energy is dissipated by the reef for up to 90% of the time and that Narrowneck reef is an erosion control point on the coast (Turner *et al*., 1999).

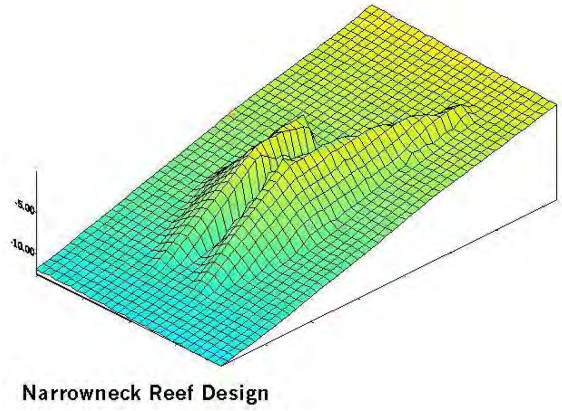


Figure 1. 3-dimensional representation of the Narrowneck Multi-Purpose Reef.

The Narrowneck reef was built using over 400 Terrafix 1200/1209RP geotextile containers, with standard 20 m long by 5 m diameter units. Terrafix 1200RP sand filled containers (SFC's) can be custom designed to suit the required purpose by sewing or ultra-sonically welding large sheets of material together to form enclosed units. A wide range of sand-filled geotextile construction units in a variety of shapes and sizes have been used for coastal projects around the world. At Narrowneck, the ~300 tonne SFC's were filled inside a split-hull dredge, sealed and then positioned with GPS before dropping to the seabed. The resulting reef can be seen in the aerial photograph (Fig. 3), with recently added SFC's still sand-coloured, while SFC's that were placed at an earlier date are colonized by marine life and are much darker (like a natural reef) as a result.

SPLIT HULL HOPPER DREDGE FILLING SANDBAG

SPLIT HULL HOPPER DREDGE PLACING SANDBAGS

Figure 2. Terrafix 1200R SFC's being filled and placed during construction of the Gold Coast reef.

Figure 3. The view of Surfer's Paradise with the Multi-Purpose Reef in the foreground. The lighter coloured containers had only just been deployed, while the darker containers are colonised by marine life.

The Gold Coast reef has been a huge success, not only in terms of coastal protection (Fig. 4), but also providing a surfing facility (recent reports describe the reef as the 'best surfing spot on the coast') and a 'natural' reef ecosystem that supports a dive trail (Fig. 5). An important outcome of the project was the confirmation (via beach profile monitoring and Argus coastal imaging) of no downdrift impacts on the coast. In 2000, the Narrowneck reef project won the prestigious Queensland State Environmental Award. Recent re-assessment of the economic impacts of the reef have confirmed a benefit:cost ratio of 70:1 (McGrath, 2002).

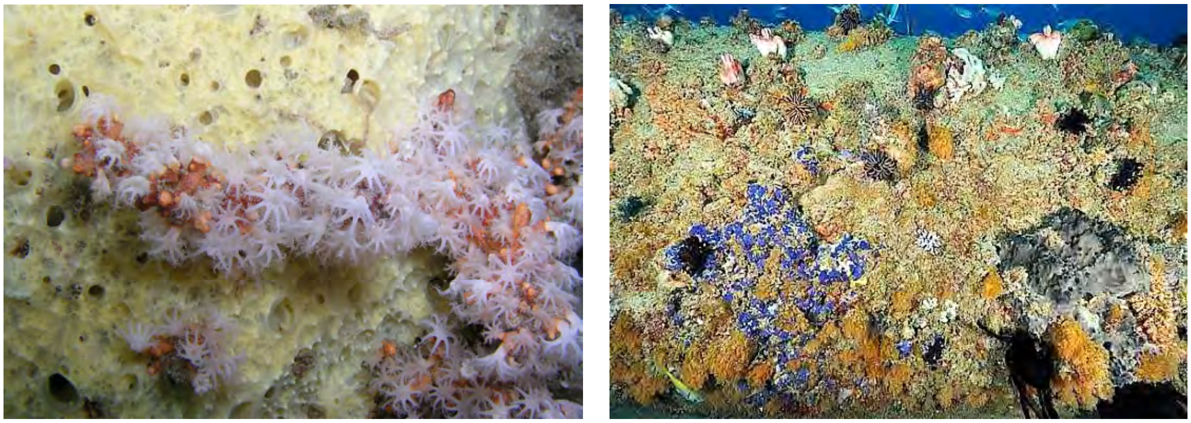


Figure 4. Soft coral and other marine life flourishing on the Multi-Purpose Reef approximately 10 years after construction.

Figure 5. Coastal protection with the Narrowneck submerged reef. Top to Bottom: Beach condition before reef construction (construction commenced in August 1999); After reef construction; The view looking south showing the wide salient in the lee of the reef.

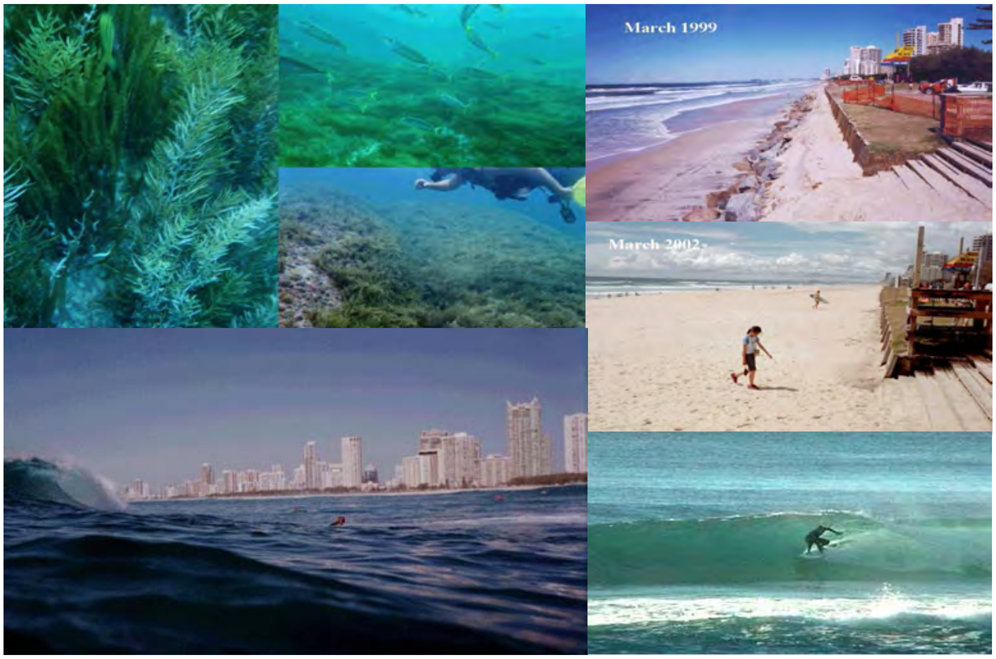
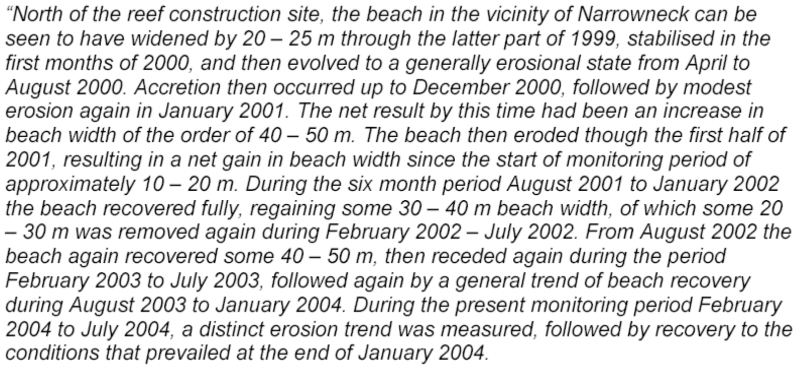


Figure 6. The Narrowneck Multi-Purpose Reef. Clockwise from top left, colonization of the reef has resulted in a dive-trail; before and after reef construction (construction commenced in August 1999); surfing on the reef; the view from the surf.

Narrowneck Reef Monitoring Report Summary



> *“North of the reef construction site, the beach in the vicinity of Narrowneck can be seen to have widened by 20 – 25 m through the latter part of 1999, stabilised in the first months of 2000, and then evolved to a generally erosional state from April to August 2000. Accretion then occurred up to December 2000, followed by modest erosion again in January 2001. The net result by this time had been an increase in beach width of the order of 40 – 50 m. The beach then eroded though the first half of 2001, resulting in a net gain in beach width since the start of monitoring period of approximately 10 – 20 m. During the six month period August 2001 to January 2002 the beach recovered fully, regaining some 30 – 40 m beach width, of which some 20 – 30 m was removed again during February 2002 – July 2002. From August 2002 the beach again recovered some 40 – 50 m, then receded again during the period February 2003 to July 2003, followed again by a general trend of beach recovery during August 2003 to January 2004. During the present monitoring period February 2004 to July 2004, a distinct erosion trend was measured, followed by recovery to the conditions that prevailed at the end of January 2004.*

> *By the end of the present six month monitoring period the beach immediately north of the reef Narrowneck was typically of the order 20 m wider than at the commencement of monitoring in 1999. It should be noted that extensive sand nourishment had commenced in this area prior to the commencement of monitoring (refer Section 2.3), so the actual increase in beach width since implementation of the NGBPS is likely to be somewhat greater than this figure. At the centre of the reef construction site and the two transects to the south (all located in deposition area A3), beach widening of 50 – 60 m was observed through to early 2000 in response to ongoing nourishment during this time. At the centre of the reef construction site and 150 m south, this was followed by a period of erosion through to March then accretion to May, after which time a general accretionary trend persisted. At the transect 300 m south the beach continued to increase in width at a generally steady rate through 2000. Again, the net result had been an increase in beach width of the order of 50 – 60 m. Storms in March, April and July 2001 resulted in recession of the shoreline, with the beach in mid 2001 approximately 30 m wider than at the commencement of the monitoring program.*
>
> *Through August 2001 to January 2002 the beach in the lee of the reef and to the south recovered to the conditions of January 2001. During the period February 2002 to July 2002 the beach width decreased by 20 – 30 m, then recovered through to the end of 2002 and continue to accrete some 30 – 40 m, mirroring the shoreline erosion–accretion changes observed north of the reef. Through to July 2003 recession again occurred, followed by accretion to January 2004. As was observed to the north of the reef, a period of erosion followed by recovery was measured from February 2004 to July 2004.*
>
> *By the end of the present monitoring period the beach to the south (up-drift) of the reef was of the order of 40+ m wider than at the commencement of monitoring. In the lee of the reef, an additional 30 m had been maintained.*
>
> *Wave breaking on the reef at Narrowneck is commonly visible in images obtained by the coastal imaging system (photo 8). In previous monitoring reports completed during the initial construction phase of the reef, the progressive increase in the occurrence of wave breaking was documented and quantified as additional geocontainers were added. Further geocontainers were placed on the reef crest in late 2001 and again in November 2002.2). Since that time it has been observed that waves break across the reef structure once the incident significant wave height exceeds around 1 m. It is concluded that the reef continues to achieve the objective of enhancing potential surfing opportunities at Narrowneck."*

Turner, I.L., 2004. **Analysis of Shoreline Change: February 2004 to July 2004. Report 10: Northern Gold Coast Coastal Imaging System**. WRL Technical Report 2004/07, Water Research Laboratory, University of New South Wales.

Further monitoring reports on the beach response at Narrowneck reef can be found at: http://www.wrl.unsw.edu.au/coastalimaging/public/goldcst/index.php?page=goldcstMonitoringReports.html

Summary of the beach changes at Narrowneck based on monitoring data (J. McGrath pers. comm.):

1. Prior to reef construction, the Gold Coast beaches had been nourished on average every ten years since the 1970's. The last nourishment was done in 1987 (prior to 1999 project).

2. The average rate of beach recession was ~5 meters per year prior to the reef project. (Current rates are -1.5 to -3.6 according to WRL 2008/06). The

current reduced beach recession is caused by a combination of over nourishment and reef stabilization.

3. The beach in the lee of the reef was purposely over-nourished in 1999-2000 (more so than the other sections of the project) with the understanding that the erosion rates would be higher at that location as the beach system moved towards dynamic equilibrium. In other words were higher erosion rates behind expected the reef and they expect that to continue until a dynamic equilibrium had been achieved.

4. The south reach experienced accretion for the first 6 years as the salient moved towards equilibrium (WRL 2008/06 table 7.1.).

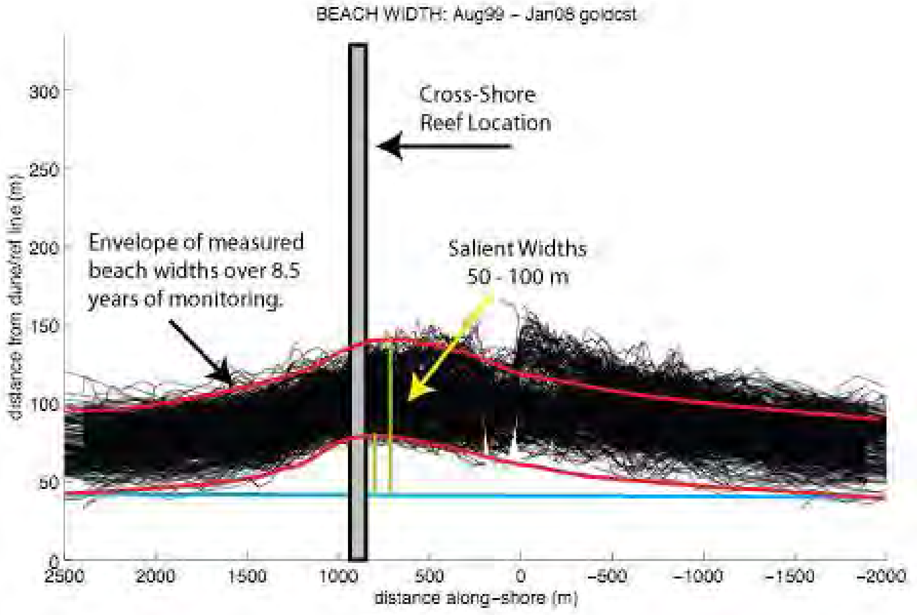
5. Now that the south reach has achieved relative equilibrium the excess sediment is moving northward resulting in the slightly erosional trend of the last two years (-1.5m/yr).

6. The erosion trend is expected to equalize along the project shoreline once the entire system has reached equilibrium.

7. The reef has significantly stabilized the nourishment project and reduced the total rate of beach recession rate along the entire project.

8. It is not anticipated that any nourishment projects will be required in the area until 2030. In other words, the reef has extended the renourishment cycle well beyond the 10 year cycle that was experienced before the reef.

The figure below indicates the impressive beach response achieved by the GC reef, some 3.5 km.



Current and Recent ASR Projects Relevant to Coastal Processes and Protection

Project	Commencement Date	Client	Works Undertaken
IRE Sand Mining Project, Southern India	May 1999	CESS, India	Instrument deployments followed by wave transformation and sediment transport modelling to ascertain impacts of sand mining on the coast.
Takapuna Boat Ramp/Surf Reef Feasibility Study	Completed 1999	North Shore City Council	Wave transformation modeling to ascertain the impacts of constructing a breakwater on the existing coast and surfing break
Narrowneck Reef: Erosion Control and Surfing Enhancement	Oct 1999 (construction)	Gold Coast City Council	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to protect the coast and provide a high-quality surfing break
Noosa, Australia Beach Erosion Solutions	Stage I August, 1999 - Stage II April 2002	Noosa Shire Council	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to protect the coast and provide high-quality surfing breaks
New Plymouth Foreshore Redevelopment	May, 1999	New Plymouth District Council	Field investigations, wave transformation modelling and preliminary reef design for a submerged reef to provide a beach and a high-quality surfing break
Mount Maunganui Surfing Reef	February 1999	Tauranga District Council	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to protect the coast, provide habitat for marine organisms and provide high-quality surfing breaks
Wave and Sediment Dynamics on Beaches	August, 1999	NIWA	A large multi-facetted project that included field investigations, wave transformation modeling and sediment transport modelling
Bournemouth Surfing Reefs Feasibility Study	February, 2000	MAFF, England	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to protect the coast,

Project	Commencement Date	Client	Works Undertaken
			provide habitat for marine organisms and enhance surfing
Opunake Surfing Reef Feasibility Study	Stage I September 2000 – Stage II July 2003	South Taranaki District Council	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to provide a high-quality surfing break and habitat for marine organisms
Lyall Bay Surfing Reef Feasibility Study	Stage I October 2000 – Stage II October 2002	Lyall Bay Reef Charifable Trust	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to provide a high-quality surfing break and protect the coast
Newquay Surfing Reef Feasibility Study	July 2001	Newquay Artificial Reef Forum	Wave transformation modelling, sediment transport modelling and preliminary reef design for a submerged reef to provide a high-quality surfing break
Westshore Coastal Processes and Erosion Control Investigation	May 2001	Napier City Council	Field investigations, wave transformation modeling and sediment transport modelling to assess the coastal processes and preliminary reef design for a submerged reef to protect the coast
Port Gisborne Expansion	September 2001	Port Gisborne	Field investigations, wave transformation modelling, sediment transport modelling and Port wall design to incorporate Port protection, a high-quality surfing break and habitat for marine organisms
Port Dredge Spoil Disposal	August, 2003	Westgate Transport, Taranaki	Wave transformation modelling and preliminary dredge mound design to ensure no negative impacts to the coast
Oil Piers Sand Retention: Ventura, California	March 2003	The US Army Corp of Engineers	Field investigations, wave transformation modelling, sediment transport modelling and reef design for a submerged reef to protect the coast and provide a high-quality surfing break
Geraldton Surfing Reef Feasibility Study	July 2003	BBIG	Field investigations, wave transformation modelling, sediment transport modelling and preliminary reef design for a submerged reef provide a high-quality surfing break

Project	Commencement Date	Client	Works Undertaken
Borth Multi-Purpose Reef	February 2003	Ceregidion	Wave transformation modelling, sediment transport modelling and Preliminary reef design for a submerged reef to protect the coast and provide a high-quality surfing break
Orewa Beach Multi-Purpose Reef	October 2003	OBRCT and Rodney District Council	Field investigations, wave transformation modelling, sediment transport modelling and preliminary reef design for a submerged reef to protect the coast, provide a high-quality surfing break and habitat for marine organisms
Opunake Surfing Reef	December 2004	South Taranaki District Council	Studies for Resource Consent application for the Opunake Surfing Reef, Taranaki, New Zealand. Detailed design, physical and biological impact studies and hearing evidence needed to obtain Resource Consents.
Palm Beach Coastal Protection Options	May 2004	SOS Incorporated	A review of the design and impact assessment for 3 submerged reefs proposed for Palm Beach in Australia
Nanuku Surfing Reef Feasibility Study	June 2004	Hatherly Dunedin	Feasibility study for a surfing reef at Nanuku Island, Fiji, for tourism development
Boscombe Surfing Reef	August 2004	Bournemouth Borough Council	Boscombe surfing reef detailed design - field data collection, numerical modelling and initial design reporting.
Sandbanks Coastal Protection Options	January 2005	H R Wallingford	Desk study of alternative coastal defence options at Sandbanks, Poole, England
Cape Otway	February 2005	Woodside Energy	Assessment of the nearshore wave conditions at Cape Otway in Victoria, Australia for the emergence point of a subsea pipeline. Detailed study with numerical and physical modelling
Urenui Beach Protction	March 2005	New Plymouth City Council	A review of coastal management and an assessment of options for Urenui Beach and first order determination of the coastal processes

Project	Commencement Date	Client	Works Undertaken
Oakura Beach Erosion Control	May 2005	New Plymouth City Council	An investigation of the shoreline erosion along the western beach of Oakura and recommendations for mitigation
Ohau and Oteranga Bay Investigations	June 2005	Meridian Energy	Physical process investigation and breakwater design for Oteranga Bay and Ohau Bay, Wellington, for construction of Makara wind farm construction. Numerical modelling, wave Climate Hindcasting and physical impact assessment
Mount Maunganui Reef	July 2005	Mount Reef Trust	Physical modelling to amalgamate construction materials and methods with detailed design and construction management
Incorporation of Multi-Purpose Beach Control Structures into the Barcelona Beach Development (Spain)	August 2005	Associación Catalana de Surf	Preliminary design options for Multi-Purpose Reefs to provide coastal protection and surfing amenity as part of the Barcelona Beach Development Plan
Bay View Coastal Hazard Zoning and Beach Nourishment Plan (New Zealand)	September 2005	Fore World Development Ltd	Review of coastal hazard zones and development of a beach nourishment plan for Bay View Beach
Long Branch Surfing Reef (USA)	November 2005	SEA	Wave transformation modelling, sediment transport modelling and detailed design of a sand-filled geotextile container multi-purpose submerged reef and beach amenities to provide a high-quality surfing break and sand retention.
Cape St Francis Beach Rehabilitation (South Africa)	January 2006	SFBBT	Field investigations, wave transformation modelling, sediment transport modelling and preliminary design of multi-purpose submerged reefs and beach amenities to retain a wide sandy beach and allow for the removal of rock revetments, while providing high-quality surfing breaks and tourism enhancement
Pollok Beach and Wells Estate (South Africa),	May 2006	AfriCoast Engineers	Field investigations, wave transformation modelling, sediment transport modelling and preliminary design of sand-filled geotextile container

Project	Commencement Date	Client	Works Undertaken
Multi-Purpose Surfing Reefs			multi-purpose submerged reefs and beach amenities to retain a wide sandy beach and allow for the removal of rock revetments, while providing high-quality surfing breaks and tourism enhancement
Boscombe Surfing Reef (United Kingdom)	June2006	Bournemouth Borough Council	Boscombe surfing reef detailed design – physical modelling and construction management. Construction summer 2007
Hydrodynamics and Sediment Transport for the Southern Pipeline	March 2006	URS/Tauranga District Council	Field data collection and numerical modelling to assess the impacts of various submarine and bridge-pile pipeline routes on the inner Tauranga Harbour
Port Phillip Bay and Western Port Water Quality Receiving Model	February 2006	Environmental Protection Agency, Victoria, Australia	Development of a 3-D circulation model to simulate hydrodynamic behaviour of Port Phillip Bay and Western Port and associated estuarine, ocean and catchment (model) boundaries. In addition, the capability to model the water quality constituents of TN, TP, TSS, salt (EC), zinc, lead , pathogens (E.coli, enterococci), Chl-a, and gross pollutants (litter), as well as sediment transport and coastal erosion and deposition due to tidal currents and wave action. Output include in-house use for the EPA with associated training and documentation.
Los Rosadas Beach Access and Amenity Enhancement	January 2007	Costa Chamela Corp, Mexico	The project involves undertaking the feasibility and preliminary design studies for a sand-filled geotextile container multi-purpose structure to provide sheltered boat launching and surfing amenity at Las Rosada, Mexico. Field work (bathymetry survey, instrument deployment and diver surveys) and numerical modelling.
Preliminary Assessment of the Feasibility of Providing a New Entrance to Matakana Island	February 2007	Pritchard Group	Pritchard Group commissioned ASR Ltd to undertaken an assessment to confirm the feasibility of providing a new entrance to Matakana Island. This included reviewing existing information (modelling), site visit and bathymetry survey.

Project	Commencement Date	Client	Works Undertaken
Detailed Design for Beach Enhancement at 4 Port Elizabeth Beaches	March 2007	Nelson Mandela Bay Municipality, South Africa	Numerical and physical modelling for the detailed design of 4 projects in Port Elizabeth. Projects range from retaining sand on the beach to safe-swimming areas and surfing break development. Design layouts and construction plans and costings are also included.
Receiving water quality modeling scenarios of Port Phillip Bay and Western Port for the Water Quality Improvement Plan	April 2007	Melbourne Water	Conduct and complete modelling scenarios from the developed receiving water quality model for the Port Phillip Bay and Western Port Water Quality Improvement Plan (WQIP) that integrate with catchment model scenarios outputs, and inform the offsets project (including field data collection).
*North End Beach Development	May 2007	Africoast Engineers	North End currently has no sandy beach, just rock revetment due to the presence of the Port blocking littoral sand transport. This project considers the feasibility of developing a sandy beach at North End through field investigations and numerical modelling.
Dispersion Modelling of Hypersaline Water in Port Phillip Bay and Western Port	May 2007	GHD	Scenario modelling of hypersaline water dispersion from various locations in Port Phillip Bay and Western Port using ASR's existing calibrated hydrodynamic models
Likuri (Robinson Crusoe) Island Marina Development	June 2007	Harrison Grierson	Field studies (wave/current measurements, bathymetry surveys, grab samples) and numerical modelling to evaluate the environmental impacts and functional performance for a super-yacht marina and swimming lagoons. This project is aimed at ensuring sediment transport is not modified in a way that would have negative impacts on the island, as well as ecological impacts on mangroves and benthic invertebrates.
Opoturu Bridge/Causeway Assessment	July 2007	Maunsell Ltd	Review of hydrological modelling and expert advice on sedimentation for a proposed bridge/causeway upgrade, including field data collection and modelling for extreme water level analysis to design the height of

Project	Commencement Date	Client	Works Undertaken
			the bridge soffit
Establishing Numerical models and Collection of Preliminary Field Data for the Proposed Wonthaggi Desalination Plant	September 2007	GHD	Review of existing information, establishing numerical models and collection of preliminary oceanographic data for the Wonthaggi coast and Bass Strait, for environmental impact assessment of Melbourne's proposed desalination plant.
Orewa Beach Rehabilitation (New Zealand)	September 2007	OBRCT and Rodney District Council	Detailed reef design and Resource Consent Application for sand-filled geotextile container submerged Multi-Purpose Reefs to protect the coast while retaining a wide sandy beach, and providing a high-quality surfing break and habitat for marine organisms
Mossel Bay Fish Farm – Currents and Dispersal Modelling	December 2007	CCA Environmental (PTY) Ltd	An impact study (including deployment of instruments for data collection) of a proposed fish farm offshore of Mossel Bay, South Africa.
Raglan Harbour Model	January 2008	Research Grant	Development of a calibrated numerical model for the Raglan Harbour and Bar – field data collection and numerical model development.
Final Design and Impact Assessments of a New Entrance to Matakana Island	February 2008	Pritchard Group	Final design and impacts assessment (physical and ecological) of a new entrance to Matakana Island. The resort application is currently being processes (Nov 2008).
Opoturu Bridge/Causeway Numerical Modelling and Ecological Assessment	May 2008	Raglan Land Co.	Development of a numerical model to test impacts due to the removal of the existing causeway and construction of a bridge at Opotoru. Ecological assessment of the rocky substrates at Opotoru and other areas of the Raglan Harbour. Reports to support Resource Consent Application.
Corniche Bay Beach Development (Mauritius)	April 2008	Arup Consultants	Corniche Bay is a 5-star resort that is to be developed in south western Mauritius. ASR is a part of a large team of consultants, with our particular brief to developing a wide sandy beach for the frontage of the

Project	Commencement Date	Client	Works Undertaken
			resort, and consideration of additional water-based amenities.
Development of a Coastal Management Plan for South West India	July 2008-2010	Asian Development Bank	Development of beach management solutions for >40 beaches on the southwest coast of India, including field data collection and detailed design for 4 demonstration sites (MPR's).
Boscombe Surfing Reef Construction (United Kingdom)	August 2008 – August 2009	Bournemouth Borough Council	Construction of the Boscombe Multi-Purpose Reef. The bottom layer of the ~14,000 m^3 reef has been completed. Remobilization is scheduled for next April (2009) and completion is expected in autumn 2009.
Sustainable Kelp Harvesting, Waihau Bay, New Zealand	November 2008	CASL/Agrisea	A 5 year project of clearance and monitoring of varying sized patches of Ecklonia radiata, a kelp used for developing high potency fertilizer for agriculture and viticulture.
Western Treatment Plant Outfall Study	December 2008 – September 2009 (in progress)	Melbourne Water	Field data collection and establishment of numerical models for determining the dispersion of POC from the Western Treatment Plant outfalls. This project is being undertaken for the renewal of outfall permits.
La Roche Percee, New Caledonia – Beach Renourishment and Multi-Purpose Reef Development	January 2009	CAPSE Nord	Field data collection, numerical modelling and design assessment for beach restoration and coastal protection. Previous failed coastal protection methods have left this turtle nesting area unsuitable for turtles or amenity. Renourishment will be retained by an offshore submerged reef.
Maraetai Beach Coastal Processes and AEE	February 2009	Harrison Grierson Manukau City Council	Bathymetry survey, instrument deployment and numerical modelling of Maraetai Beach, Auckland to assess the coastal processes and likely impact of renourishment for coastal protection.
Uitoe Peninsula Resort Development, New Caledonia	February 2009	CAPSE Nord	Instrument deployment and numerical modelling of tidal currents for the construction of a channel/marina and wave modelling of a

Project	Commencement Date	Client	Works Undertaken
			breakwater for channel entrance protection.
Whitianga Viral Fate Modelling, New Zealand	March 2009	Thames District Council	Hydrodynamic modelling of viral particles from the Whitianga outfall to determine health issues at swimming beaches and in aquaculture areas.
Re-Imaging the Folkstone Shore, England	August 2009	Strandhouse	Preliminary investigation of a series of options to enhance the coastal amenity while working within the available environmental constraints such as the large tidal range and the small, windy wave climate.
Port Phillip Bay Submerged Reefs, Australia	September 2009	Department of Sustainability and Environment, Victoria	The Victorian Coastal Strategy identifies the development of a strategic plan for the management of coastal protection as a key action items for the DSE to address. This strategic plan is to take into account climate change risks, impacts and determine the relative costs and benefits of any future beach protection management options. As part of this effort, this study investigates the use of detached offshore reefs as a means of coastal protection in Port Phillip Bay.
Borth Reef Detailed Design and Construction Documentation, Wales	October 2009	Royal Haskoning	Undertake numerical and physical modelling and aid in the development of the final design of the Borth Multi-Purpose Reef
Extreme Water Level Predictions for Dixon Island, West Australia	November 2009	RPSMetOcean Engineers	Numerical modelling of extreme water levels due to tides, storm surge and extreme wave events for the design of a new ship loading structure.
Re-Imaging the Folkestone Shore, England	February 2010	Trevor Minter OBE DL	Desktop numerical modelling study to consider creating unique and interesting water-based activities to serve as a focal point for the Folkestone beaches.
Whangateau Harbour Flushing Study, New Zealand	March 2010	Omaha Park Limited	Development of a hydrodynamic modelling and expert witness evidence presentation of the flushing capacity of Whangateau Harbour.
Review of the impacts of the Port Motueka Sand-Deflection Groyne	April 2010	Ben Van Dyke	A first level review of the potential effects of a 700 m long by 1.5 m high geotextile groyne/breakwater that was constructed in 1995-96 with the

Project	Commencement Date	Client	Works Undertaken
			intention to deflect southerly directed sand from the Motueka Spit offshore and maintain a navigable channel to Port Motueka.
Wailagilala Island Beach Development, Fiji	May 2010	Sean Howard	Field data collection and preliminary numerical modelling to create a more user-friendly sandy beachfront along the 300-400 m stretch of beach on the southwestern side of the main island.
Firth of Thames Hydrodynamic Model, New Zealand	May 2010	Environment Waikato	Development of a hydrodynamic model of the Firth of Thames for the assistance with future management options.
GoodEarth Port Development, India	June 2010	Silambimangalam Shipyard Port Development	Development of hydrodynamic models to determine tidal, wind-driven and wave-driven currents at the proposed shipyard and to investigate potential environmental impacts on the Pitchvaram mangrove forest and mitigation methods if required.

APPENDIX 3 – THE 3DD SUITE OF NUMERICAL MODELS

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). The suite is fully matured, developed over a broad series of science programmes and is now available for commercial and research use worldwide.

The current technology in ASR **Numerical Models** arose from focussed 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.

ASR has highly experienced staff capable of undertaking the full range of tasks using models, and takes pride in its world position as an “international modelling 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:

3DD$^{\copyright}$	3-dimensional flows, dispersal, short-wave and ocean/atmos. heat transfer
POL3DD$^{\copyright}$	3-dimensional dispersal
WGEN$^{\copyright}$	Estuary wave climate
WBEND$^{\copyright}$	Refraction of monochromatic and spectral waves
2DBEACH$^{\copyright}$	Beach circulation and sediment transport.
GENIUS$^{\copyright}$	Sedimentation around coastal structures.

Model 3DD©

The 3dimensional hydrodynamic model **3DD** has been used successfully in numerous studies around the world and in New Zealand.

The model is a primary component of the ASR hydrodynamic modelling 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 modelling 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©

The dispersal model **POL3DD** (POLlution dispersal coupled to 3DD) tracks suspended "particles" to simulate water-borne dispersal including larval behaviours, 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 behaviour

POL3DD is linked to a 3-dimensional hydrodynamic model (Model **3DD**) so that detailed flow patterns can be directly utilised. 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©

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©

Model **WBEND** is a 2-dimensional numerical wave refraction model for monochromatic waves or a wave spectrum over variable topography for refraction and shoreline longshore 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, longshore 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©

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

Model GENIUS©

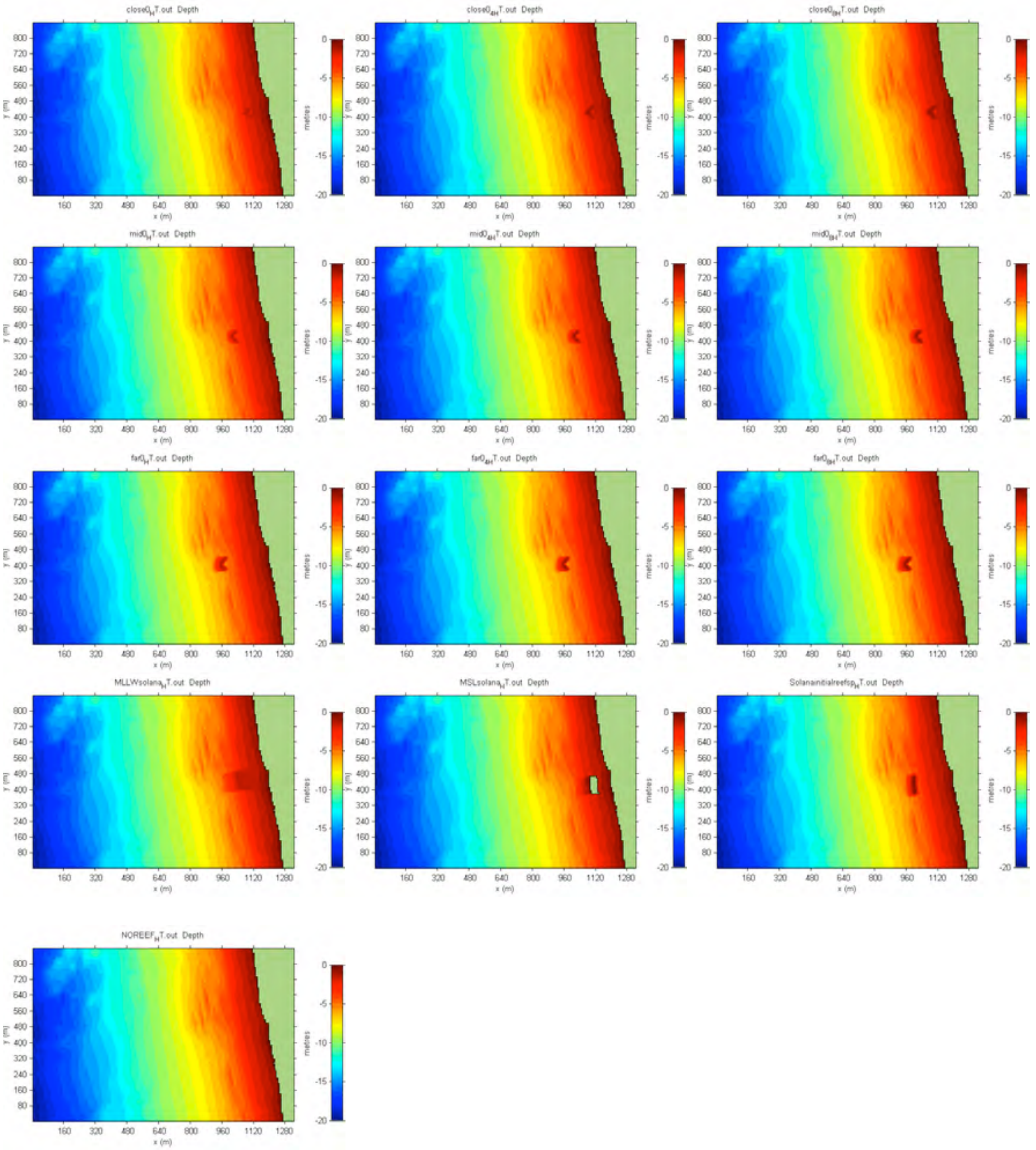
Model **GENIUS** predicts refraction, breakpoint wave conditions and longshore sediment transport on beaches. **GENIUS** is similar to its well-known counterpart GENESIS (Hanson and Kraus, 1989) but with some extra features including frictional attenuation of wave height and a more physically-based treatment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

In **GENIUS**, the results are obtained by assuming that the longshore 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**.

GENIUS accepts a time series of wave conditions to find net longshore 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. Longshore sediment transport is calculated using the CERC formula applied in GENESIS.

APPENDIX 4 – SURFZONE MODELING

Bathymetry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mid0$_{8H}$T.out Depth
far0$_H$T.out Depth
far0$_{4H}$T.out Depth
far0$_{8H}$T.out Depth
MLLWsolana$_H$T.out Depth
MSLsolana$_H$T.out Depth
Solanainitialreefsp$_H$T.out Depth
NOREEF$_H$T.out Depth
y (m)
800
720
640
560
480
400
320
240
160
80
x (m)
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800
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1280
metres
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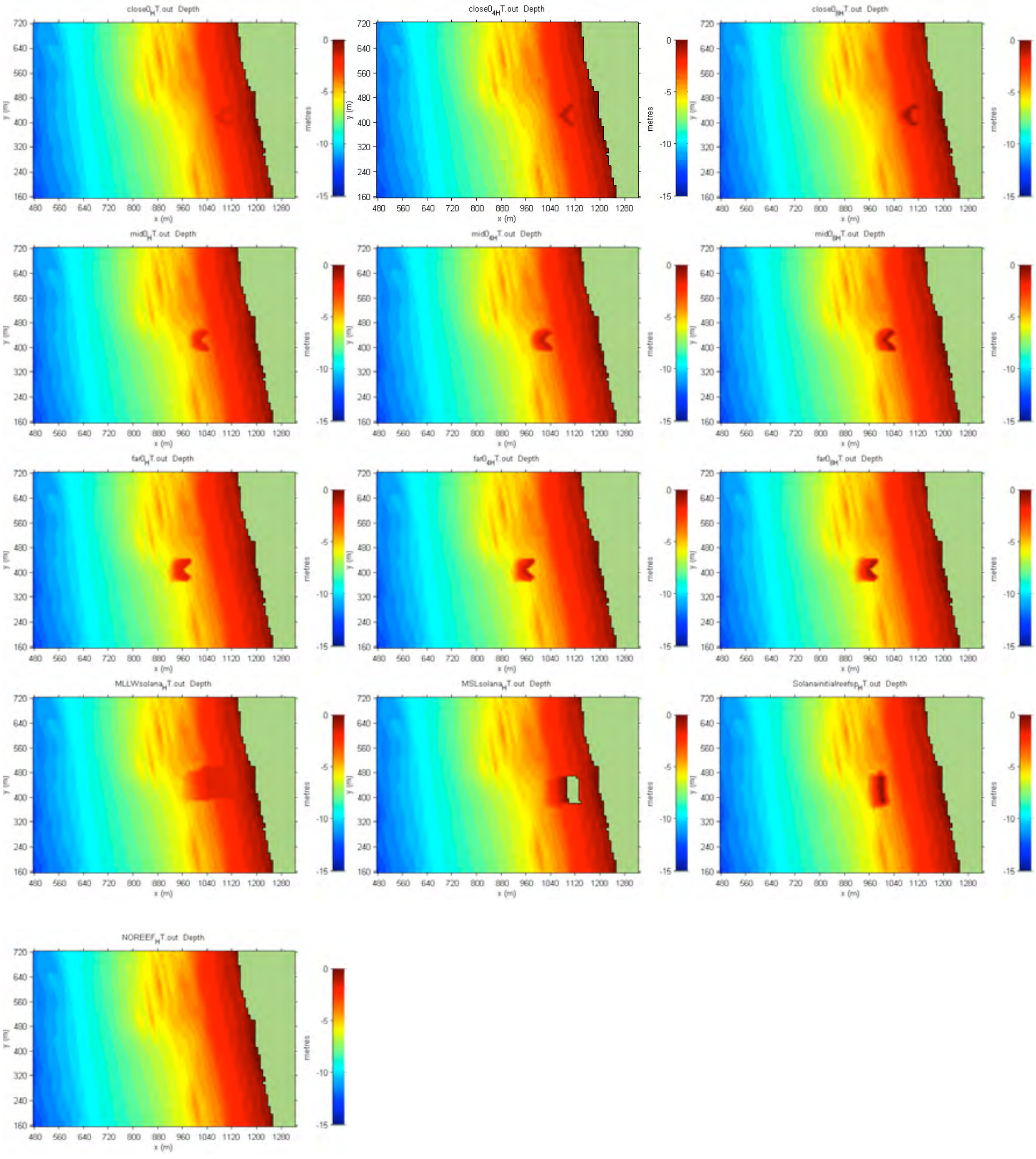
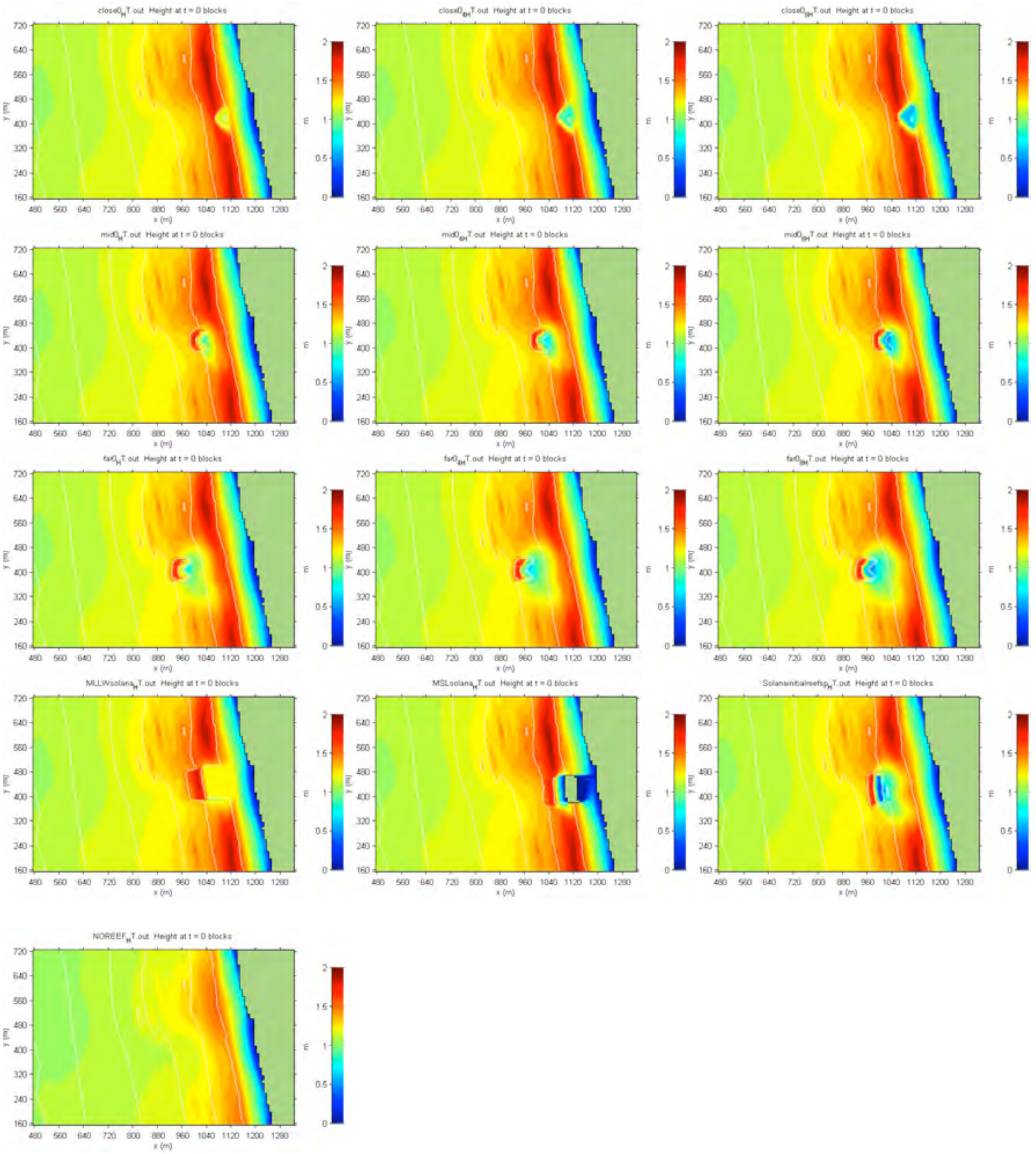
-10
-15
-20

Bathymetry Zoomed



WBEND High Tide Hs 1m



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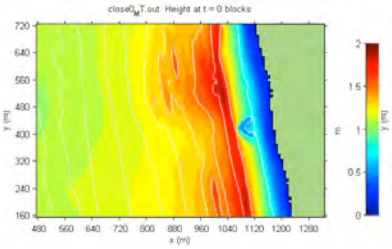

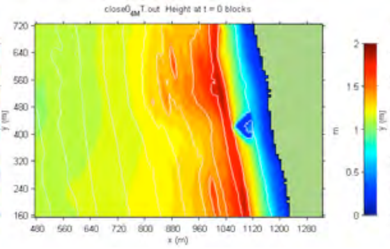

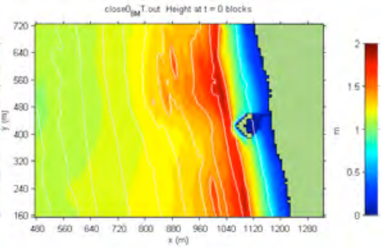

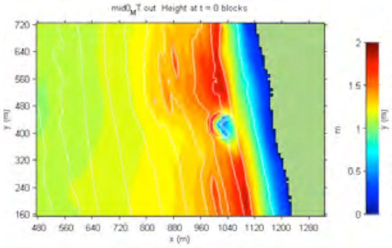

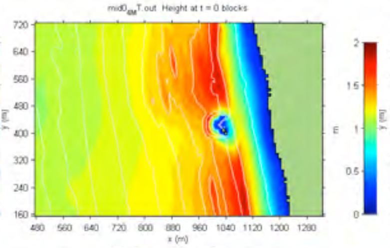

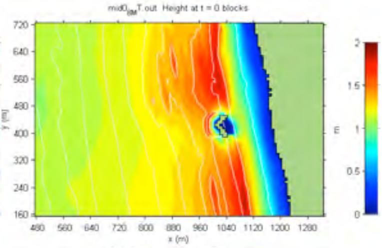

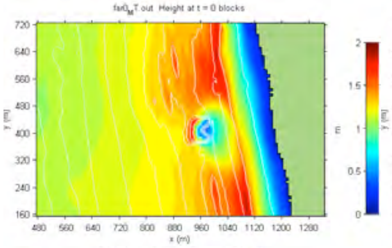

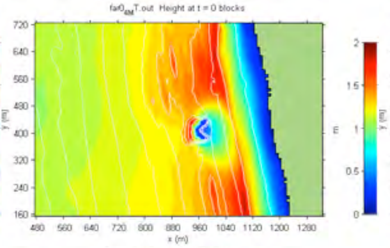

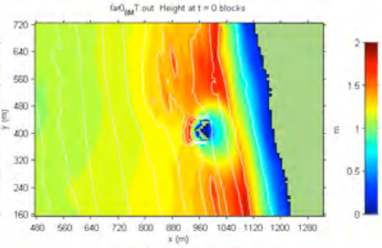

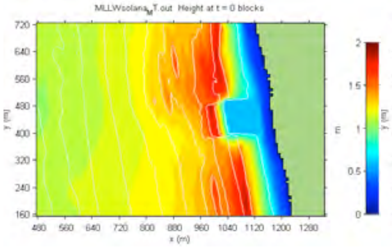

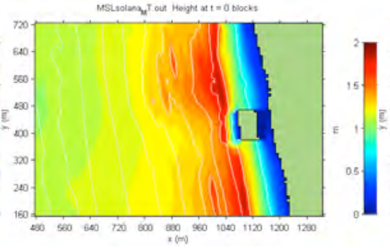

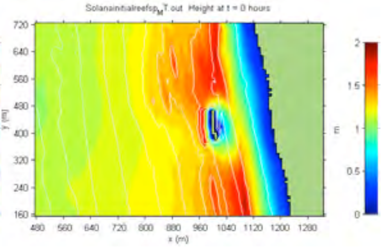

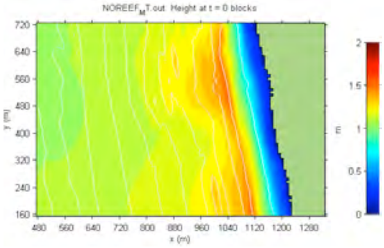

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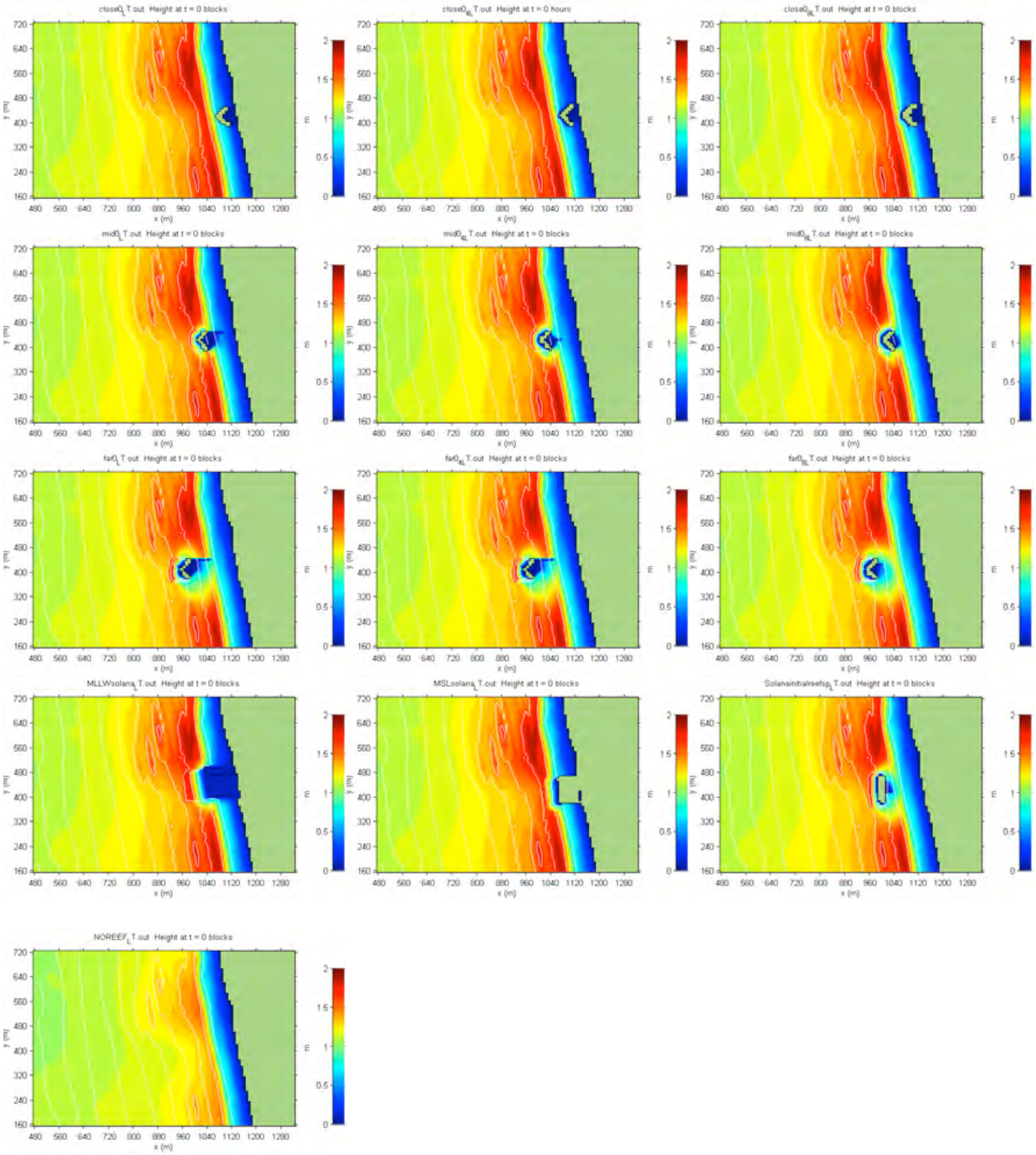

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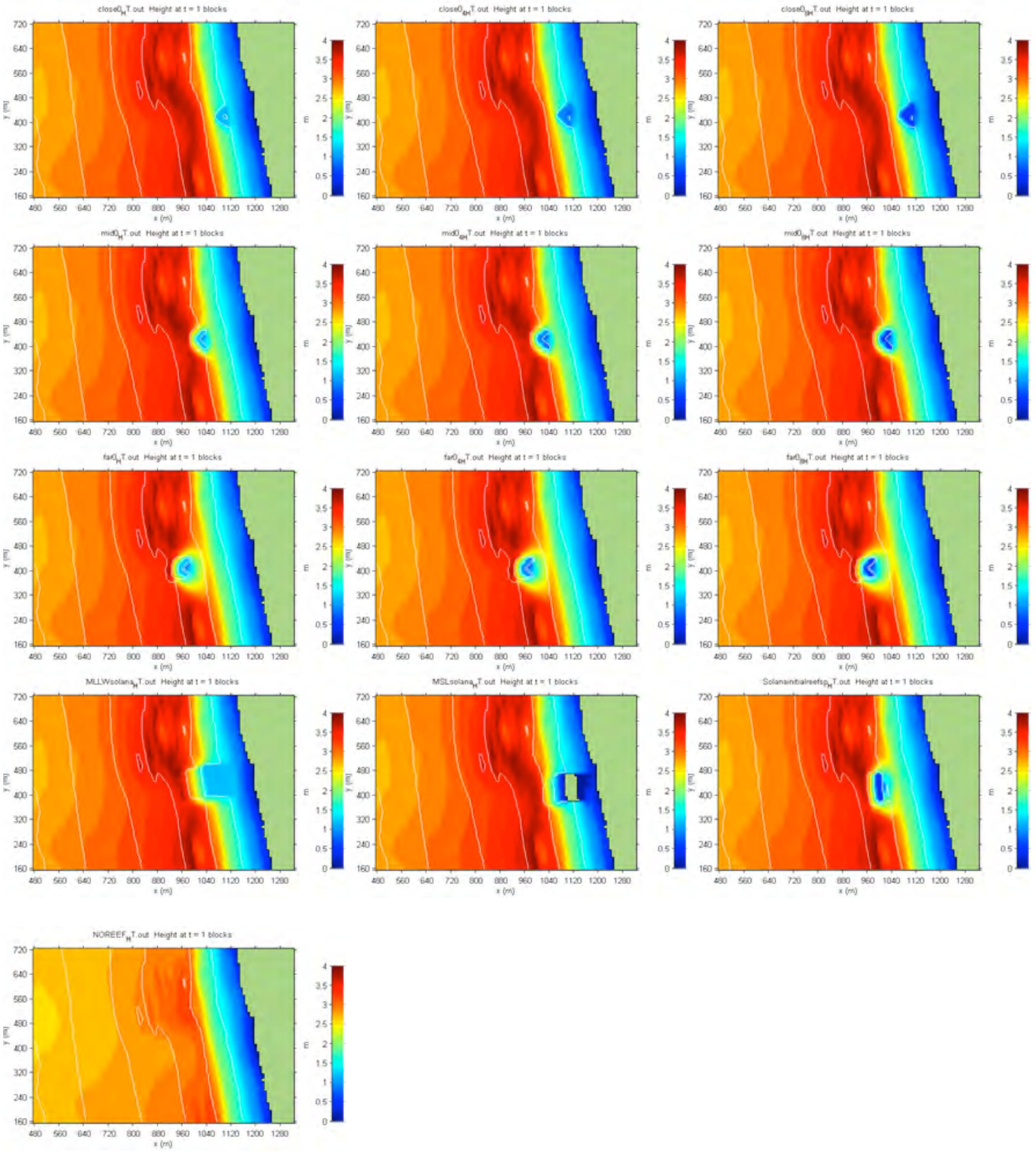

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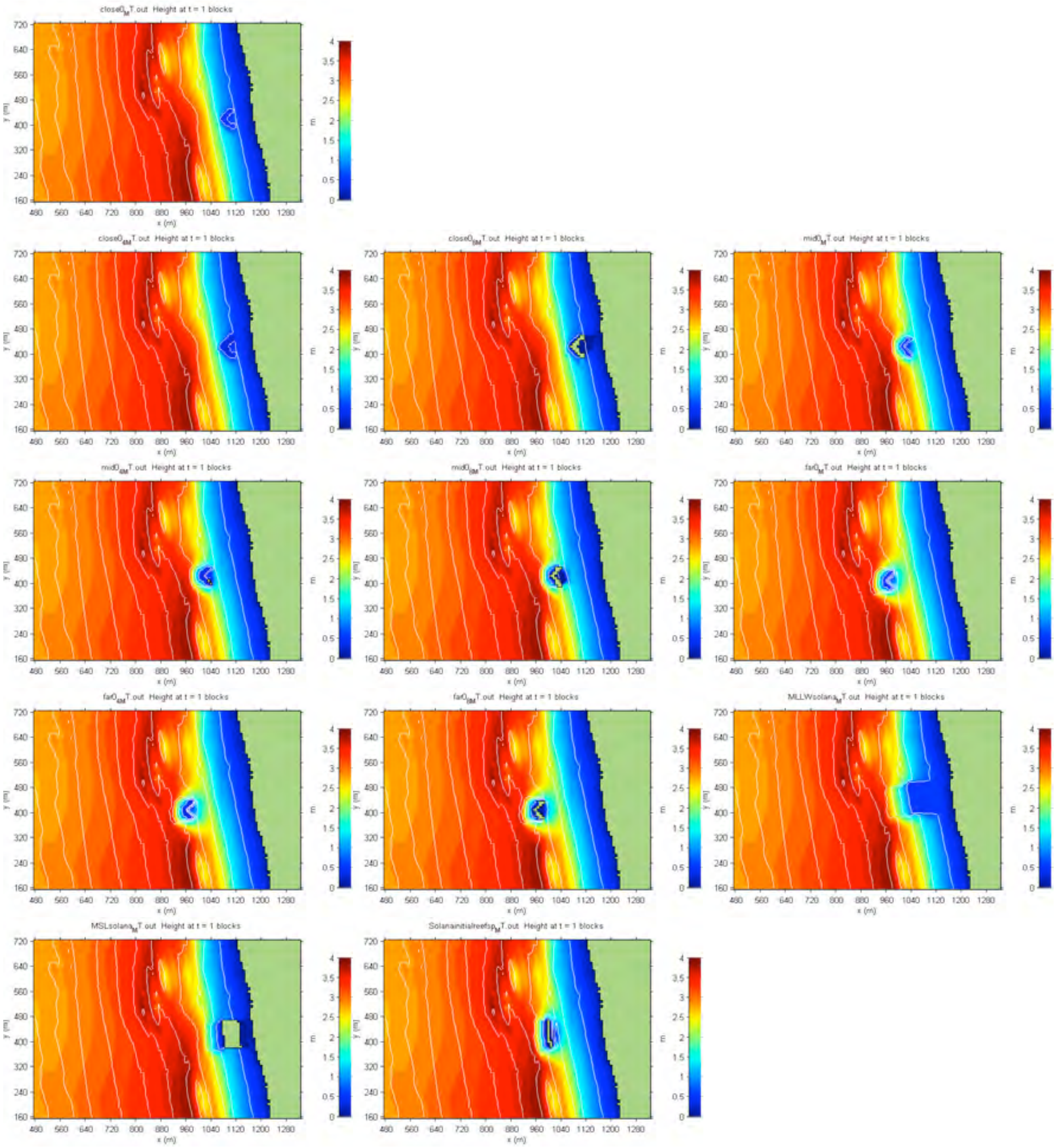

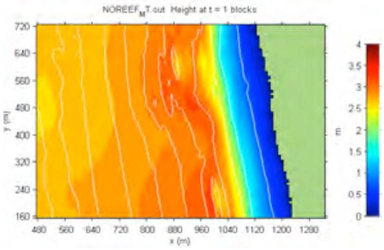
NOREEF$_M$T.out Height at t = 1 blocks
720
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560
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400
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240
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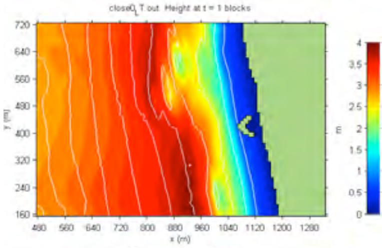
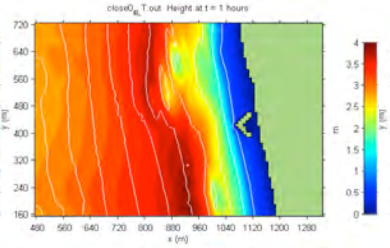
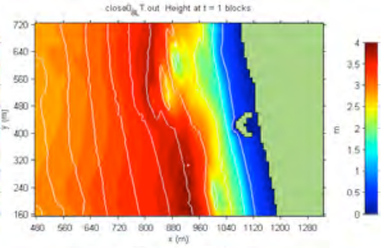
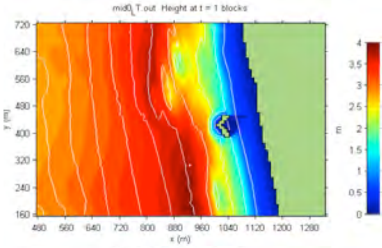
y (m)
480
560
640
720
800
880
960
1040
1120
1200
1280
x (m)
m
4
3.5
3
2.5
2
1.5
1
0.5
0

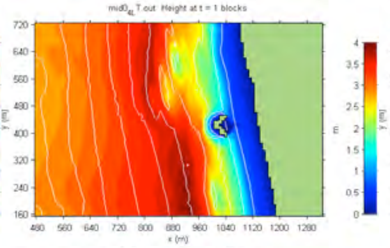
WBEND Low Tide Hs 2.5m

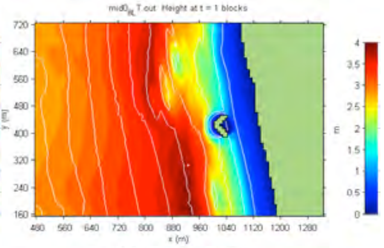


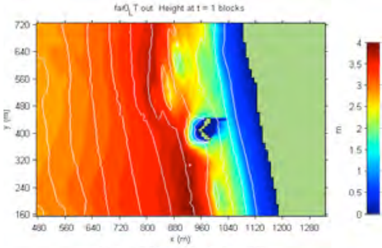


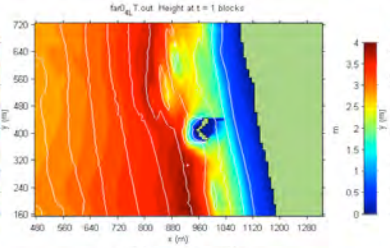


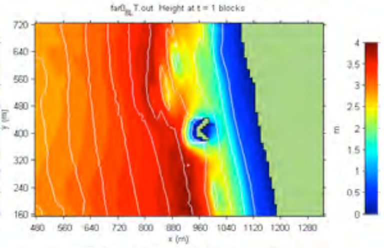


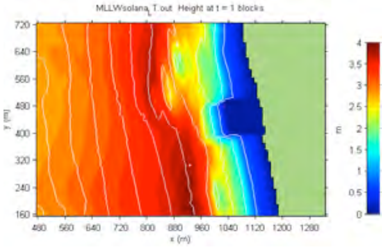


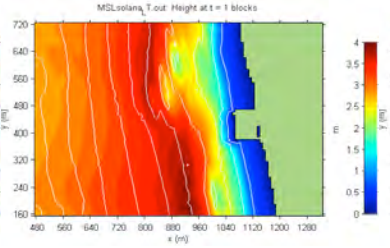


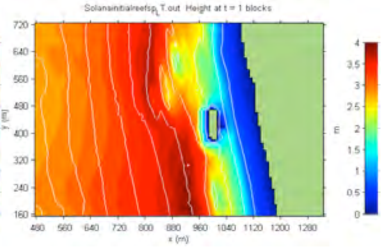


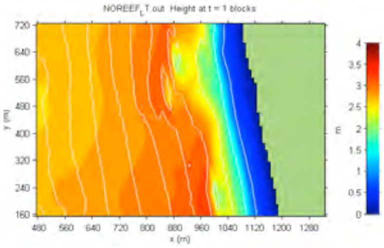












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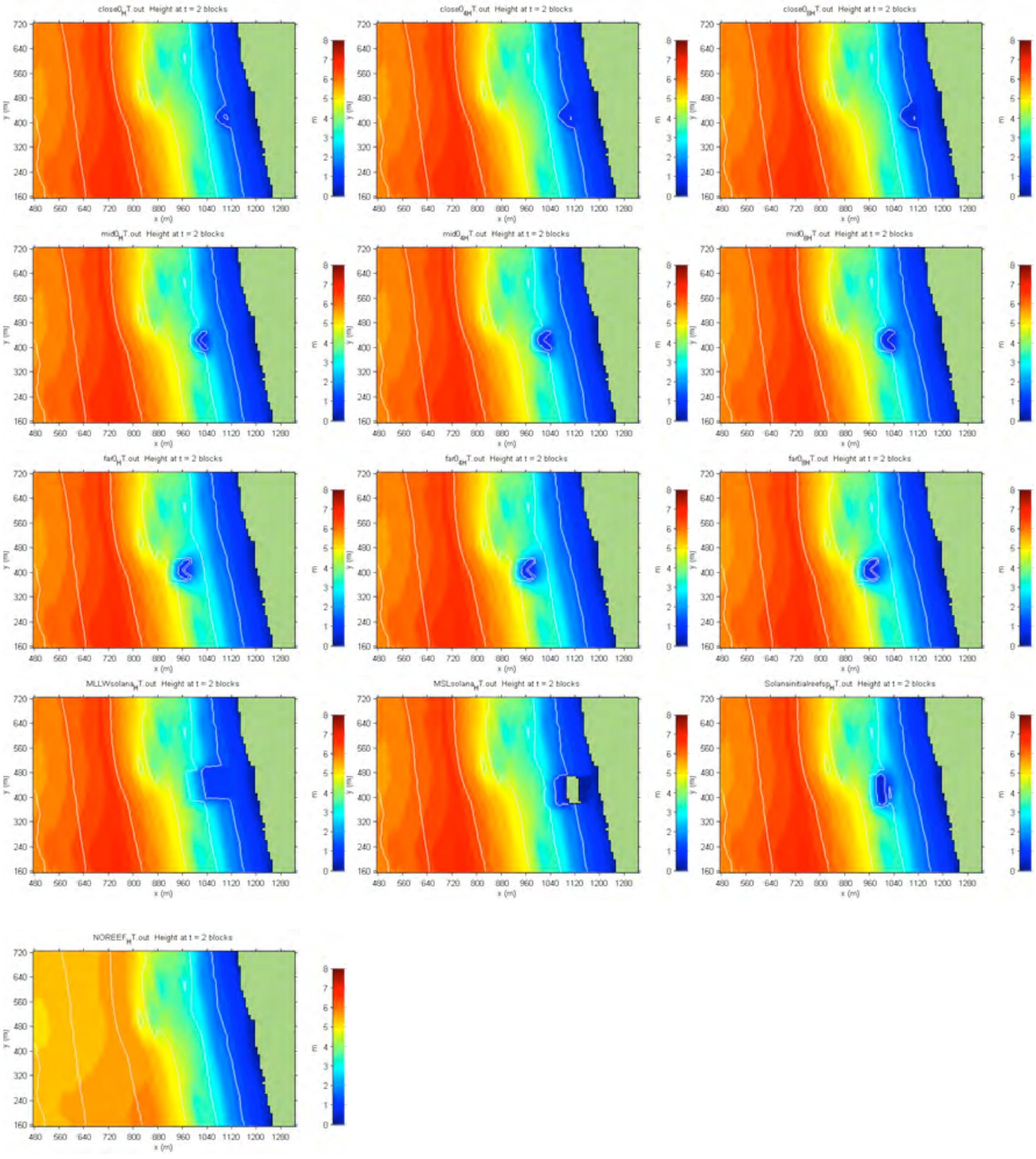

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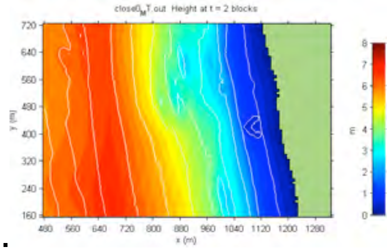

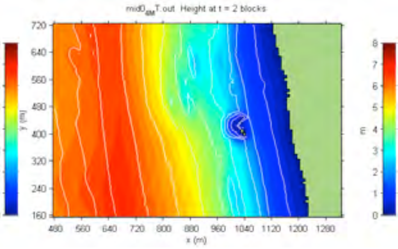

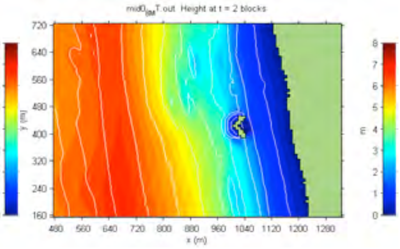

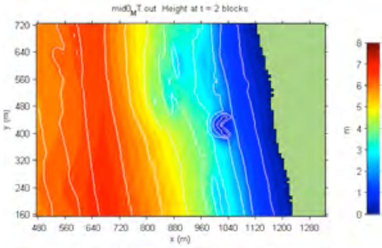

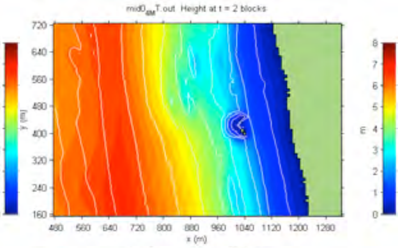

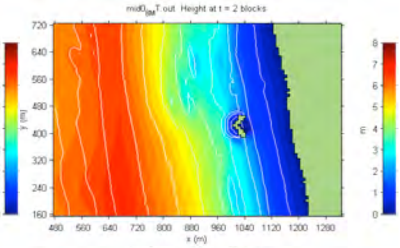

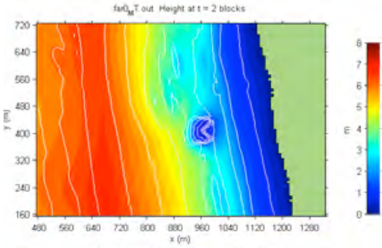

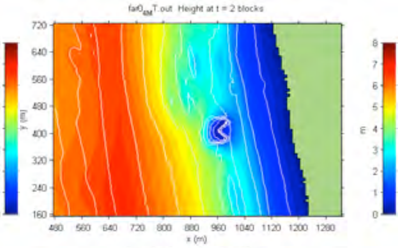

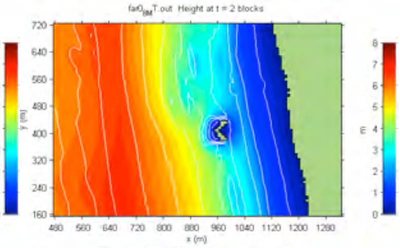

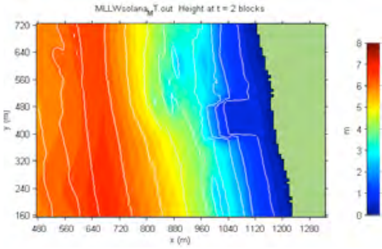

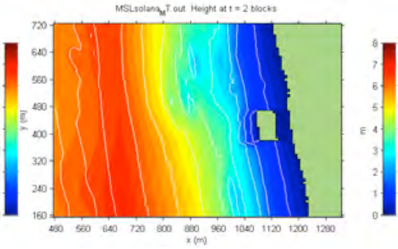

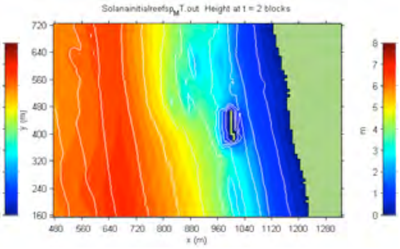

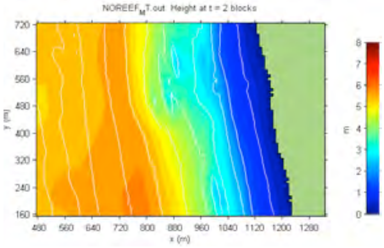

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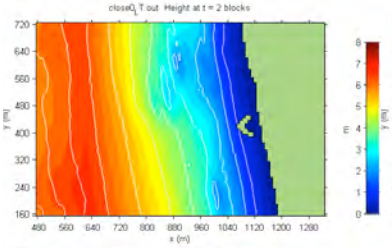

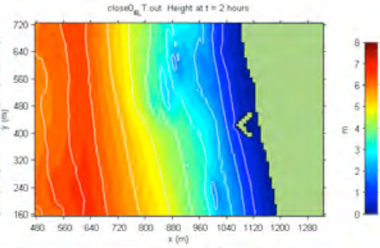

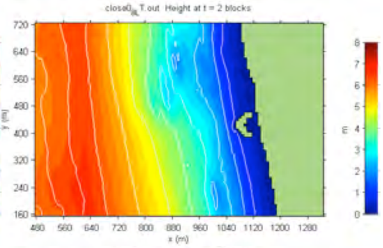

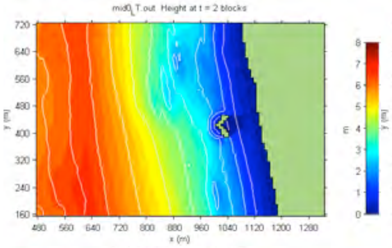

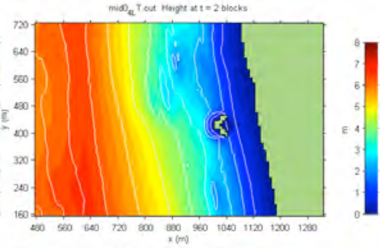

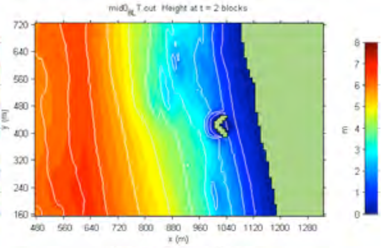

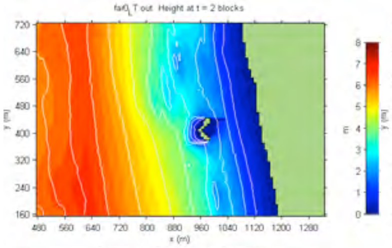

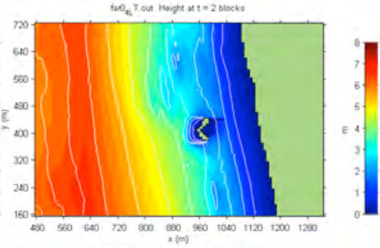

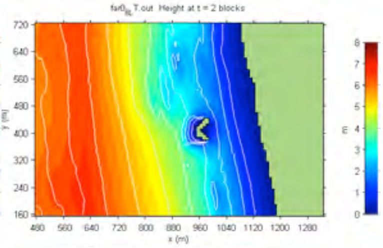

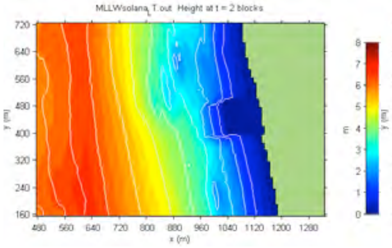

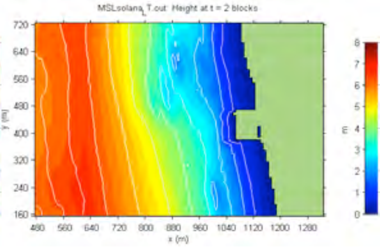

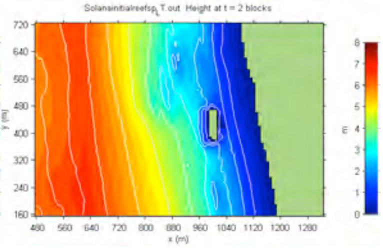

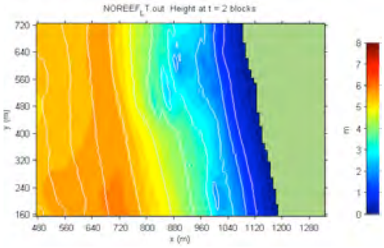

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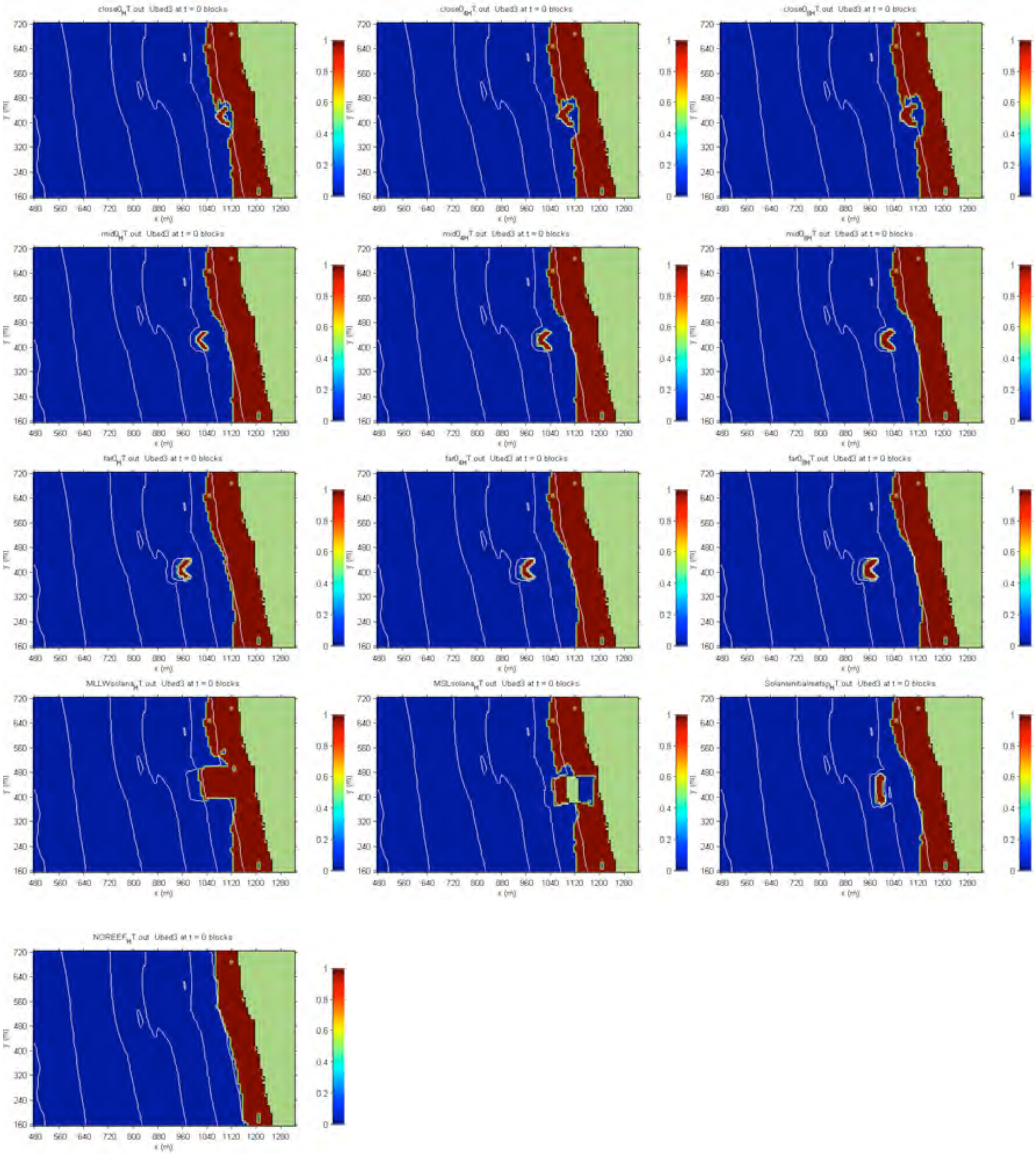

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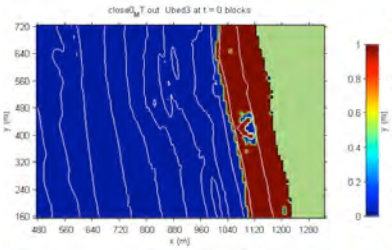

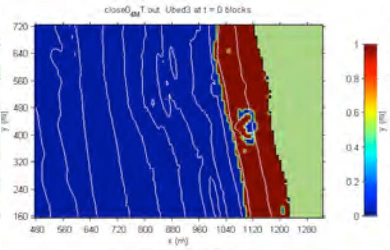

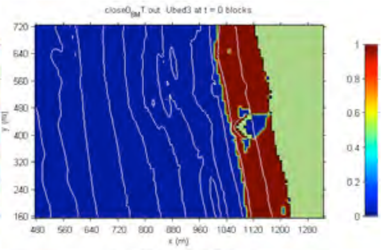

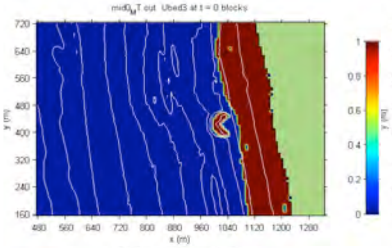

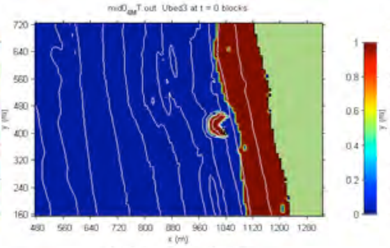

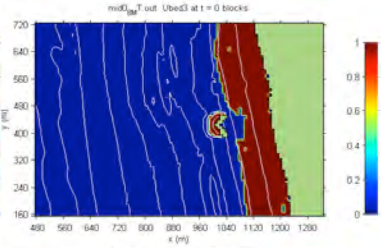

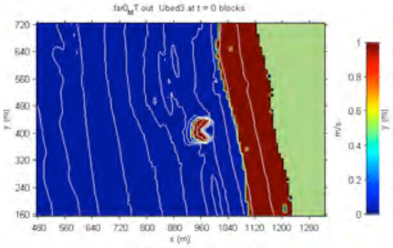

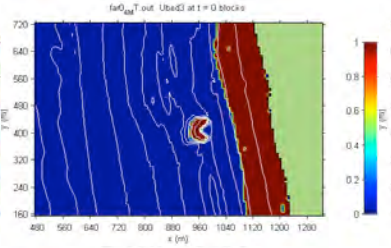

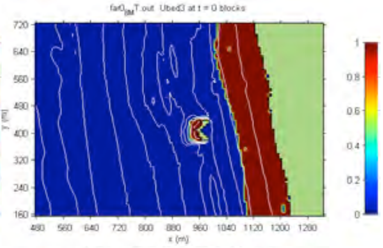

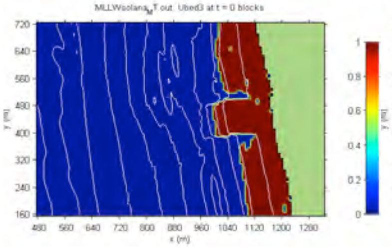

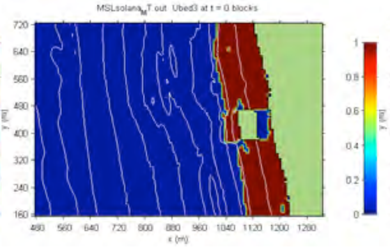

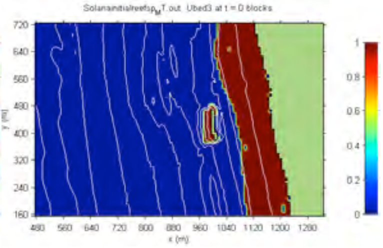

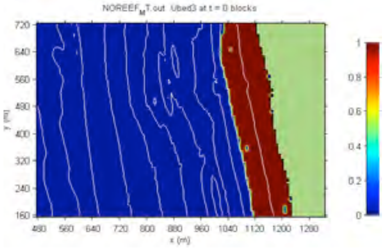

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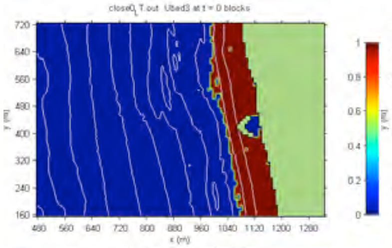

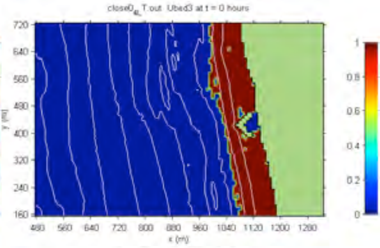

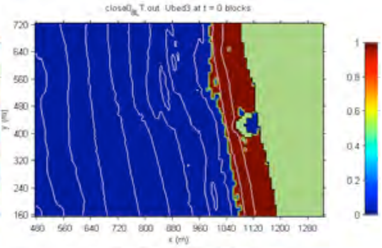

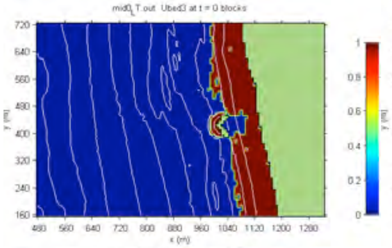

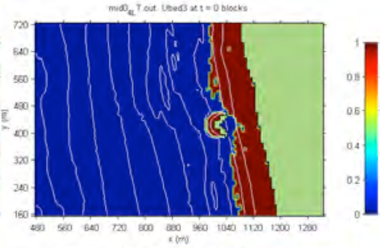

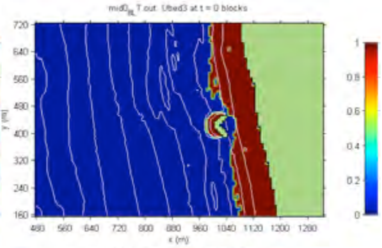

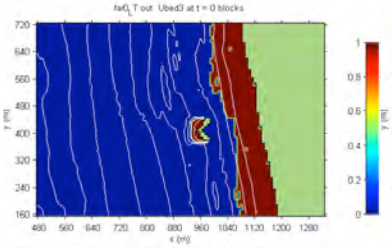

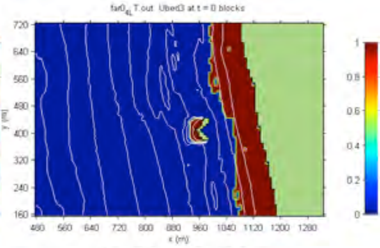

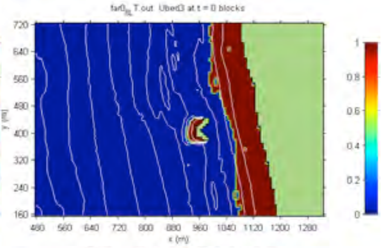

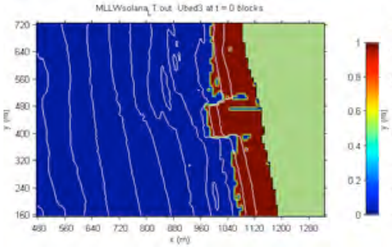

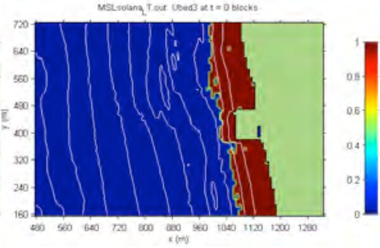

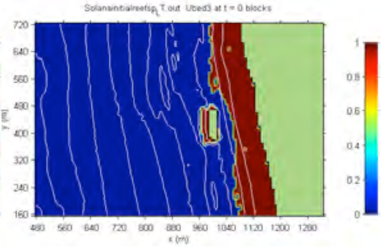

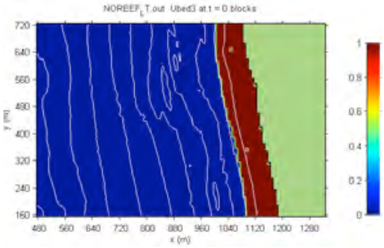

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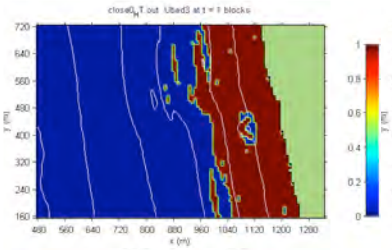

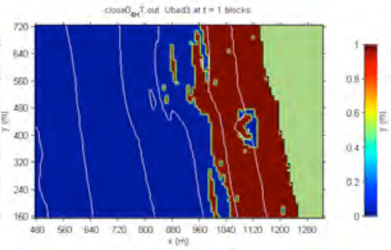

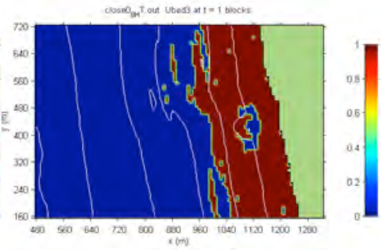

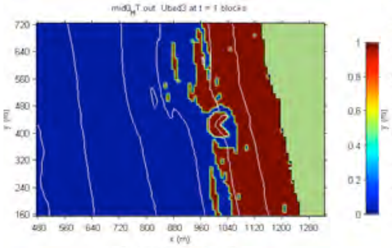

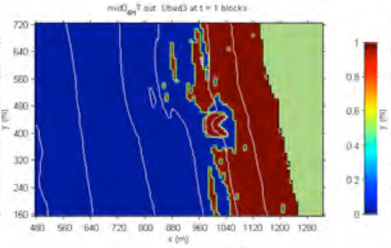

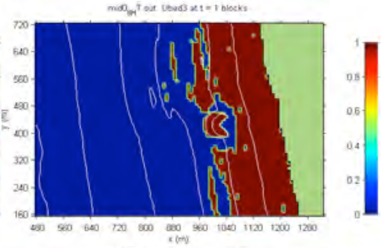

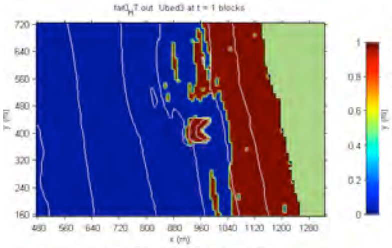

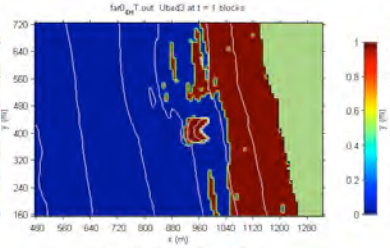

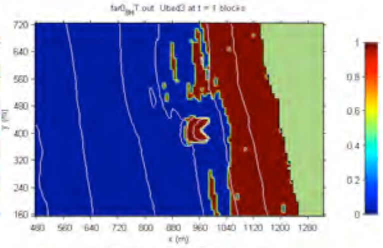

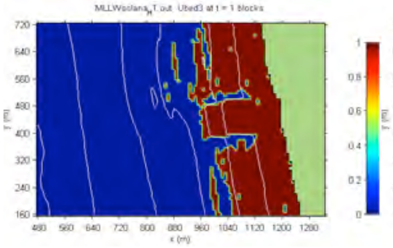

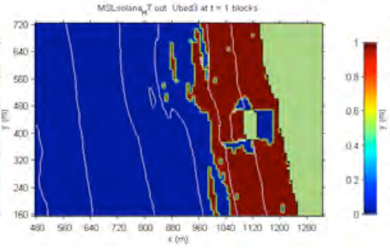

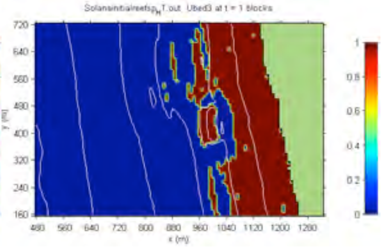

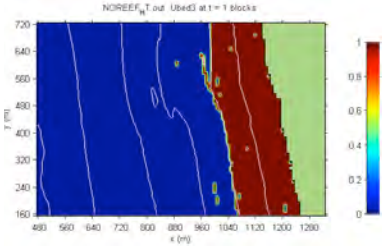

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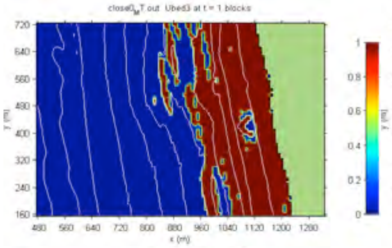

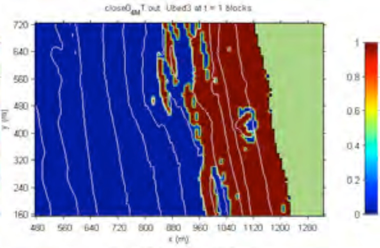

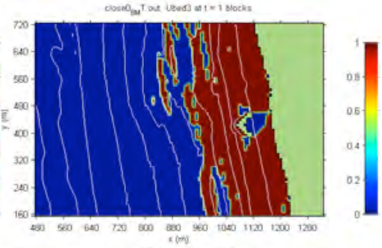

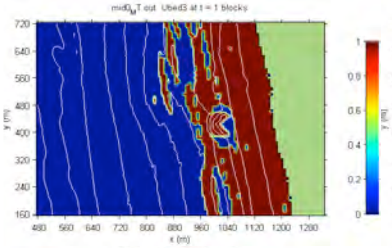

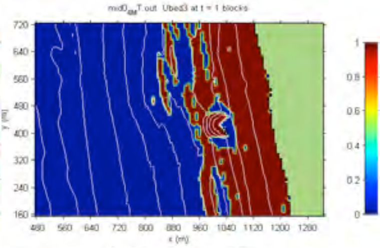

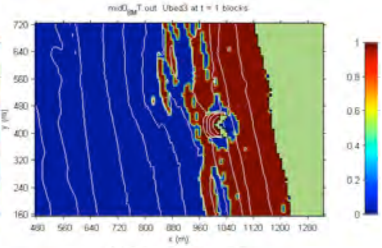

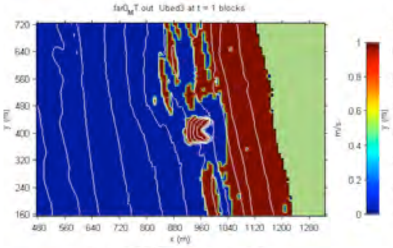

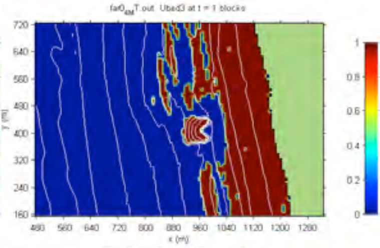

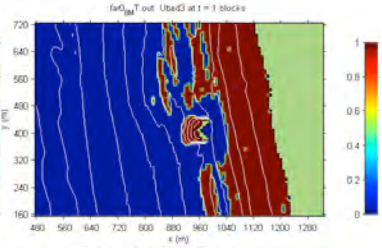

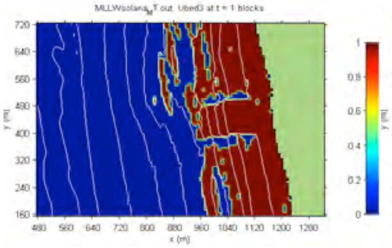

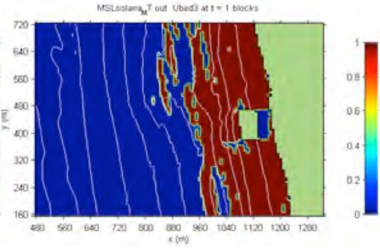

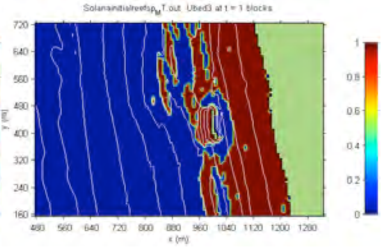

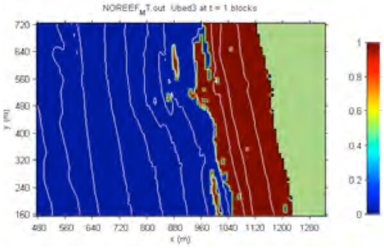

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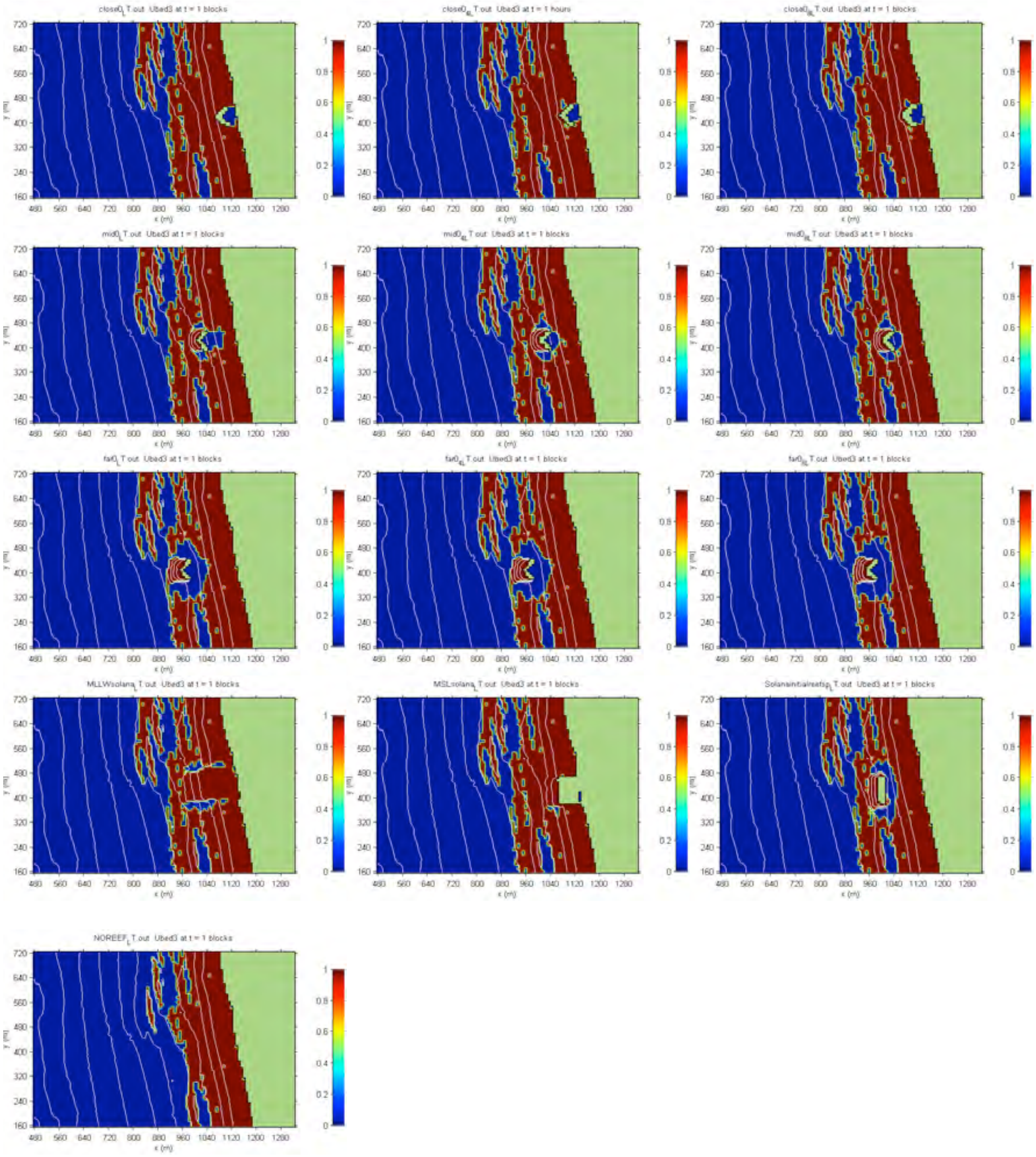

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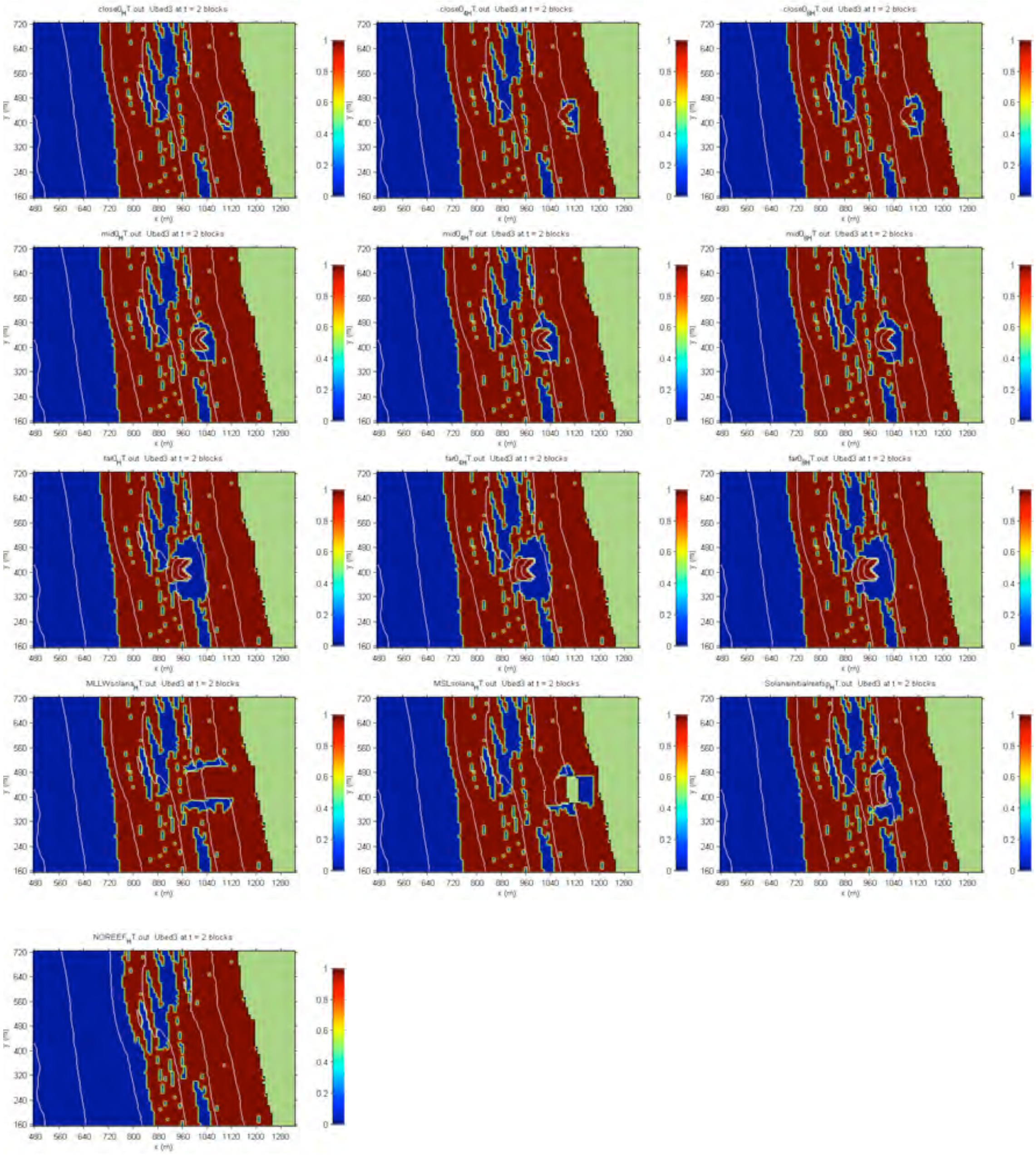

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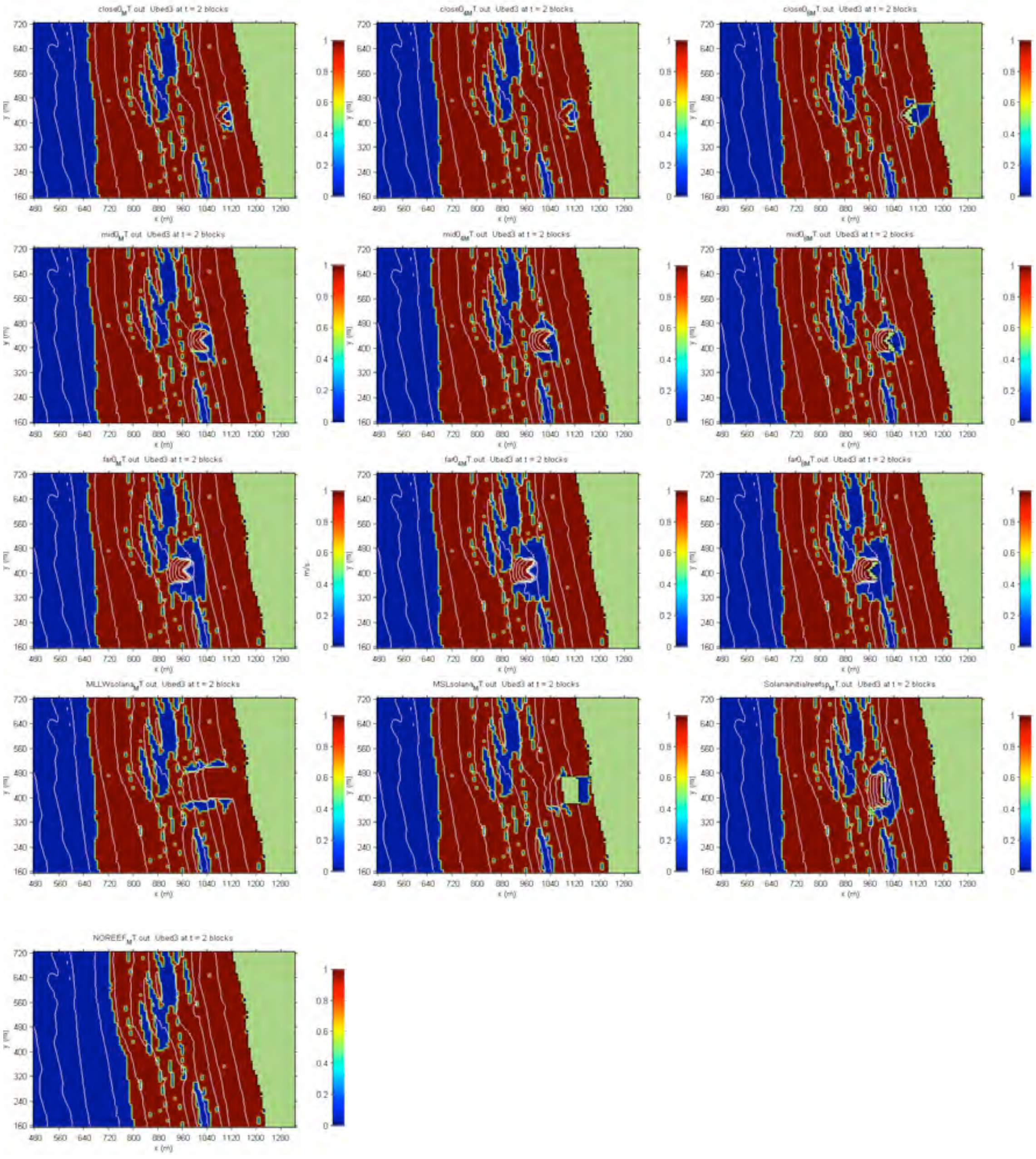

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