Performance Monitoring of the Cable Station Artificial Surfing Reef

By

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Cover Page Photo: Wave breaking at Cable Station Artificial Surfing Reef, 6th of May, 1999 (4:00pm)

5 Webb Place
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25th October, 1999

The Dean,
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Dear Sir,

I have great pleasure in submitting this thesis entitled “Performance Monitoring of the Cable Station Artificial Reef” as partial fulfilment of the requirements for the degree of Bachelor of Engineering (Environmental) with Honours.

Yours sincerely,

Stacey R. Bancroft

i Acknowledgments

I would like to thank my supervisor, Dr. Chari Pattiaratchi, for all his help and patience this year… and for his ability to untie knots, upside down, in 2 metres of water, on a breaking reef.

I would also like to thank Matt Eliot, Tony Edwards and Pieter Goldie for endeavouring to answer all my questions.

Thank you to Jeff Doucette, Sonia Le quilleuc and Febrina Sumanti for their help with field work out on the reef.

A very special thanks must go to my family, my heroes. Thank you so much for all your support over the years.

To all my engineering friends, thankyou and congratulations… we finally made it.

Last but not least, to the ocean and Ryan… for keeping me sane and happy.

ii Executive Summary

Unlike many other sports, for which new recreational facilities may be built to meet increased demand, surfing has previously been confined to a limited number of natural surf sites. The idea of creating surfable waves through the construction of artificial reefs has been a dream in the minds of surfers for many years. This dream is now a reality, with the construction of the world's first artificial surfing reef at Cable Station in Perth, Western Australia.

The principal aim of the present study was to assess the performance of the Cable Station Artificial Surfing Reef through the use of field measurements. These field measurements included the deployment of an S4 current meter and a pressure sensor at the reef location; fortnightly beach width measurements; and recording aerial footage of the surf break from a helicopter. Images recorded by a web camera located in the vicinity of the reef were also assessed to determine the breaking characteristics of the reef.

It has been concluded from the studies undertaken that the Cable Station reef is working to design specifications and is performing as well, or better than, was predicted. Observations of days breaking and days surfable during the study period of February to August were found to be greater than predicted for the reef. Aerial footage of the reef taken on the 17th of October indicated effective peeling to the left and right, with peel angles of approximately 45 degrees. According to the criteria set by Walker (1974), the day observed would be classed as being suitable for surfers of intermediate ability.

The assessment of conditions required to produce surfable waves on the reef has produced a predictive tool for determining whether the reef will be working under a given matrix of wave, wind and water level conditions. It was determined that wave data recorded at Deep Channel, Cottesloe is a good estimate of the incident swell conditions at Cable Station.

No detrimental environmental impacts due to the reef itself, in terms of the sediment regime and biological activity, were observed. The increased traffic to the site is causing some dune erosion due to access problems, however plans for the construction of an access route are already underway.

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1 INTRODUCTION

In Australia, surfing is not only a recreational pursuit, it is a prominent sub-culture within our society. With approximately 90% of Australia's population located in the coastal zone, significant demands are placed on our coastal resources. The economic and cultural benefits of this surfing lifestyle have usually been overlooked during the development of coastal engineering projects, and as such has resulted in the demise of several good surfing locations around Australia.

In Western Australia (WA), it has been estimated that approximately 300 000 people (16% of the population) participate in surfing (WA Surf Rider Association, *pers. comm*). The Perth metropolitan coastline, where most of this population reside, is sheltered from the direct effect of swell and storm wave activity by an extensive chain of offshore reefs. As a result, the wave energy at the shoreline tends to be low, except at a few locations, where surfing activity tends to be concentrated (Pattiaratchi, 1997a).

Due to this lack of suitable surf sites, competition between surfers, swimmers and fishermen for the use of the water has increased and resulted in a number of injuries to both surfers and swimmers. At the 'good' surf locations in Perth, such as Trigg Beach, overcrowding of surfers leads to conflict between individuals as well as increases in the number of injuries that occur.

Unlike many other sports, for which new recreational facilities may be built to meet increased demand, surfing has previously been confined to this limited number of natural surf sites. The idea of creating surfable waves through the construction of artificial reefs has been a dream in the minds of surfers around the world for many years. This dream is now a reality, with the construction of the world's first artificial reef designed specifically to produce surfable waves at Cable Station in Perth, Western Australia.

In 1988, after many years of appeals from Perth's surfing community, the WA Surf Rider Association, the Surf Life Saving Association and industries associated with surfing merchandise, the Government of WA formed a committee to investigate the feasibility of constructing an artificial reef along the Perth metropolitan coastline. Many studies followed, including investigation into the location, design, environmental impact, economic and social aspects, and predicted surfability of such a reef.

Construction of the reef at the selected location, Cable Station, began in February, 1999 and was deemed to be 95% complete in May, 1999. The purpose of this thesis was hence to monitor the performance of this 'world-first' artificial surfing reef through the use of field measurements. Many aspects of the reefs performance have been assessed, including comparison of wave conditions with design and surfability predictions, and the environmental impacts of the reef.

During the course of this study, it was recognised that there is no comprehensive document which brings together all the studies which have led to the construction of the artificial reef. This document should fulfil that role, to some extent, via a review of all the work which has led to the creation of the Cable Station Artificial Surfing Reef.

Interest in the creation of artificial surfing reefs is rapidly increasing around the world, and as such, the success of the Cable Station artificial reef will surely have an impact on the design and construction of such reefs in the future. This project provides an initial assessment of the performance of the Cable Station artificial reef that will influence the directions taken in future reef design.

2 LITERATURE REVIEW

2.1 Background Theory

This section will discuss the theory used throughout this thesis. Included will be an outline of the general characteristics of surfing, theories of wave generation, transformation and breaking, long-period sea level fluctuations and nearshore processes. The theory addressed will be used in assessment and discussion of the performance of the Cable Station Artificial Surfing Reef.

2.1.1 GENERAL CHARACTERISTICS OF SURFING

Surfing is the sport of riding a breaking wave and is practiced using various forms of equipment, such as a board, a canoe, a sail-boat, a body-board, or even using no equipment, for body surfing. The most popular surfing form is board surfing and is the form generally referred to in this report, though the basic techniques pertain to all surfing forms in general (Walker, 1974).

The active functions of surfing are practiced at specific locations called "surf sites". These are areas where waves break in a consistent and desirable form under given conditions. The active functions of surfing include entering and leaving the surf area, catching the wave, riding, ending the ride, returning to the takeoff area, and recovering loose surfboards. The location of, and even the existence of, a surf site depends upon the interaction of the wave and wind conditions, tide level, bottom configuration, and access to the site.

The mechanics of surfing are first for the surfer to attain a position just seaward of the breaker zone. When a desirable wave approaches, the surfer paddles with the direction of wave advance, utilising the force of gravity relative to the slope of the wave face to attain a velocity equal to the velocity of the wave (Walker, 1974). This is termed "catching a wave". Once the wave is caught, the surfer assumes a standing or crouching position, and then slides, or "drops", forward down the face of the wave from a position near the crest toward the trough, travelling at a velocity greater than that of the wave. During this drop, the wave begins to break, and the breaking then proceeds shoreward and laterally along the crest. After the acceleration experienced during the drop, the surfer then initiates a turn to the right or to the left, depending on whether on a left or right peeling wave, escaping from the turbulent breaking region.

The surfer manoeuvres on the wave face in the vicinity of the junction of the broken wave and the breaking region, called the "peel" or the "curl", by shifting her feet and weight to control the response of the surfboard. The surfer ends her ride either when she "kicks out" back over the wave crest, or when she loses control of the board. If the surfer loses her board, it is transported by wind, wave or current forces into the surfboard recovery area. The surfer must then retrieve her board and return to the take-off area through the return zone. An idealised schematic of these areas can be seen in Figure 2.1.

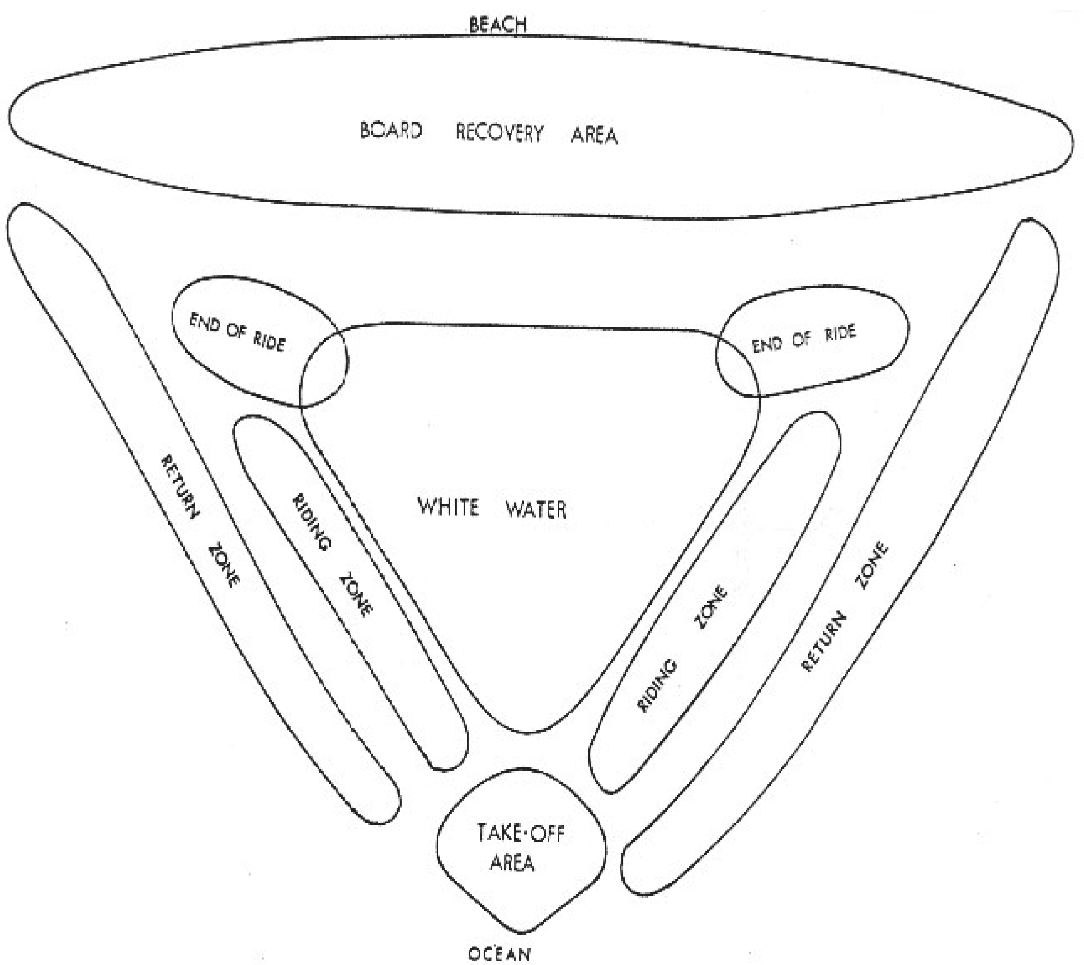


Figure 2.1. Schematic of a typical surf break (after Moffatt & Nichol, 1981).

A surfing wave is primarily the result of an incident wave being transformed by the bottom into a wave having characteristics desirable for surfing. Breaking is not a prerequisite for surfing, although the majority of surfing waves break. However not all breaking waves are surfable.

Construction projects in the past have in many cases resulted in the destruction or partial destruction of prime surfing areas. The elimination of surf sites decreases the surfing potential and tends to cause overcrowding of the remaining sites. Overcrowding increases the frequency of injury and decreases the enjoyment of the sport.

The purpose of a study undertaken by Walker from 1971-4 was to define the important surf parameters which are required to produce a desirable surf site and to describe the relations between a surf site and the environment. It was hoped that this work would be of use in designing construction projects which are compatible with existing surfing activities and in creating or enhancing surf sites.

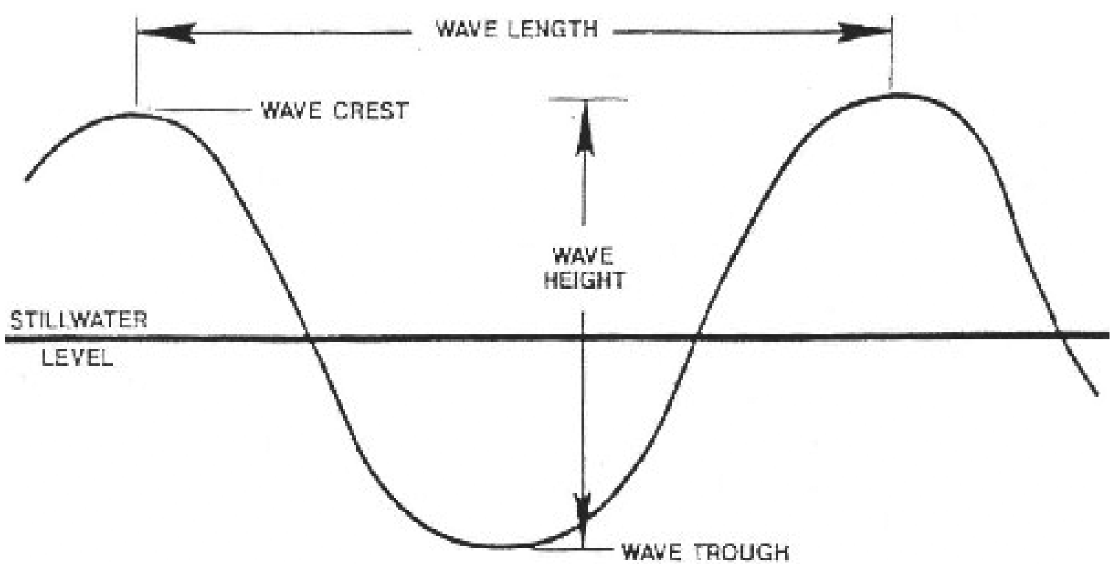
2.1.2 WAVE GENERATION AND CLASSIFICATION OF OCEAN WAVES

Waves are undulating forms that move along the surface of the ocean. They may exist on the interface between any two fluids of different density, however this review will deal solely with those that travel on the surface between the ocean and atmosphere. While any kind of disturbance in the water is likely to generate waves, there are three prime natural causes: wind, earthquakes, and the gravitational pull of the moon and the sun.

Wind waves are the most familiar kind and are of the most importance to this study. The size and variety of the waves raised by the wind depend on three factors: the velocity of the wind, the distance it blows across the water, and the length of time for which it blows (Bascom, 1980). Moreover, the character of the waves change markedly as they move away from the winds that created them.

The earthquake mechanism is simpler in that rapid motion of the sub-sea rock disturbs a mass of water and in regaining equilibrium, the water surface oscillates up and down and sends out a series of seismic sea waves, collectively called a *tsunami*. Tides, which are a special kind of very long wave, are caused by the earth's rotation beneath great bulges of water raised by the combined gravitational fields of the moon and the sun.

In order to classify waves, it is necessary to introduce various terms used to define waves. As shown in Figure 2.2, the wave crest is the highest point of a wave and the wave trough is the lowest point of a wave. The wave height, *H*, is defined as the vertical distance from trough to crest, whereas wave amplitude, *a*, is the distance a wave moves the water above or below mean sea level. Wave amplitude is hence equal to half the wave height. The wavelength, *L*, is the distance measured from any point on one wave to the equivalent point on an adjacent wave, for example from crest to crest or trough to trough. Wave period, *T*, is defined as the time it takes for one wave to pass a specified point. The frequency, reciprocal of wave period, is the number of waves passing a specified point in a given unit of time, commonly expressed as waves per second. The propagation rate of waves, or celerity, is the velocity at which they travel (Bascom, 1980 and Ingmanson &Wallace, 1985).



WAVE PERIOD IS THE TIME REQUIRED FOR SUCCESSIVE CRESTS
TO PASS A STATIONARY POINT

Figure 2. 2. Wave characteristics.

Several types of water waves may be identified depending on their mode of generation and propagation. The emphasis here is on progressive ocean surface waves. These are most commonly classified on the basis of wave period, *T*, or the equivalent frequency, *f*. Kinsman (1965) proposed a spectrum of ocean surface waves, shown in Figure 2.3. This figure suggests that wind-driven surface gravity waves, with periods from 1 to 30 seconds, contribute most of the ocean's wave energy. Consequently, these waves are of primary concern in coastal and offshore engineering and it is wind-driven gravity waves that form the basis of a regions 'wave climate'.

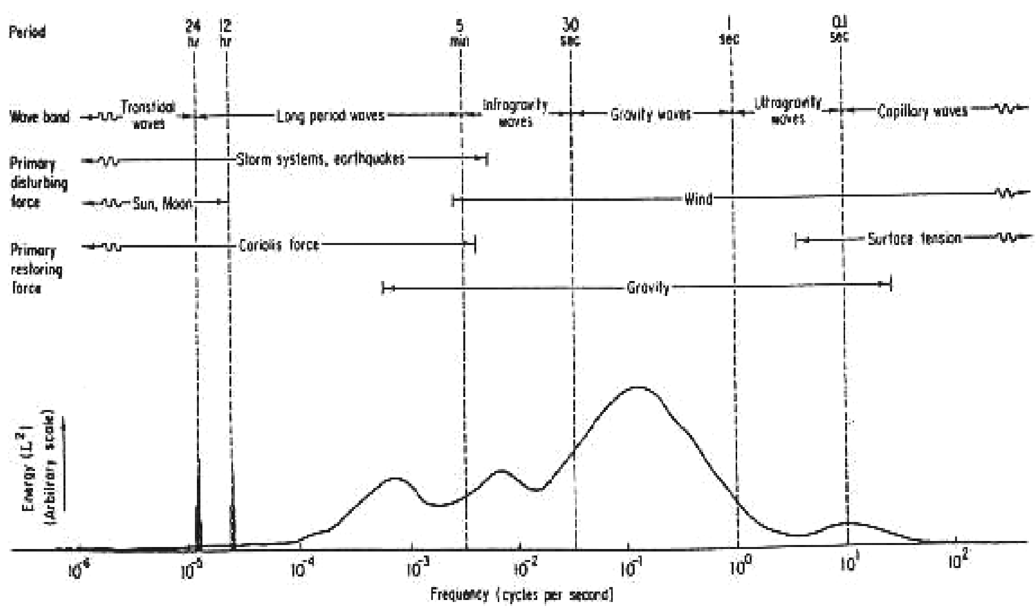


Figure 2.3. Approximate distribution of ocean surface wave energy (after Kinsman, 1965)

2.1.3 WIND WAVES

For the purposes of coastal engineering, wind-driven surface gravity waves can be divided into two categories, namely *storm waves (sea)* and *swell*. Sea refers to waves which are still being generated or maintained by the wind, and are therefore within the confines of the *fetch* or storm zone.

The fetch is the distance of ocean over which the wave generating wind blows. The term *swell* is applied to waves that have left the fetch, sorted themselves out according to period, are dispersing across the oceans to some distant shore and are no longer subjected to significant wind action (Silvester, 1974). Sea waves tend to have shorter wavelengths and periods, and are generally steeper than swell waves. A sea appears ‘complex and confused’ whereas a swell is more regular with successive waves having rounded crests of similar height.

2.1.3.1 Seas (Storm waves)

The term *sea* refers to those waves that are under the direct influence of the wind. These waves tend to have peaked crests and smooth rounded troughs. The sea surface undulation in a fetch consists of many waves of differing height and length. Each component, particularly the small-period ones, are being built up to a maximum steepness until breaking occurs.

Some energy is thus dissipated, and some is fed into longer waves, near whose crests these events take place (Silvester, 1974). The residue of the small wave is rebuilt to breaking point once more. Other waves of similar period are being formed and enlarged by wind pulsations, shear-flow or sheltering effects, as well as the energy transfer from the breaking of still smaller waves. The combination of all these wave components make up the random fluctuations of the stormy sea surface. The resultant major waves are therefore steep in character, since the ratio of height to apparent wave length is great (Silvester, 1974).

Another feature of storm waves is their asymmetrical shape. Due to the pressure of the wind, and the non-linearities in the water particle motions as maximum steepness is reached, the wave becomes steep fronted or tilted forward. The extra steepness, plus the momentum transferred through breaking, causes the waves to travel at slightly higher speed than the theoretical value for a sinusoidal wave of very small height.

The generation of waves over the fetch results in waves with differing directions. The closer the celerity of a wave is to the wind velocity, the more aligned the wave is to the wind. The slower or shorter waves on the other hand will be more oblique (See Figure 2.4). These shorter waves however are the ones which are built up in the fetch more quickly. As they become steep enough for the wind to promote breaking, they add momentum to the longer waves which are more or less aligned with the direction of the wind. Thus whilst the shorter waves are angled greatly to the wind, the longer waves deviate only slightly from the wind or fetch alignment.

Figure 2.4. Typical crest plan of waves along the length of a fetch (after Davis, 1974).

2.1.3.2 Swell

As has already been noted, waves of any particular period in the fetch will be travelling in many directions. The shorter waves have a wider fan of operation than do the longer ones, which are more closely aligned with the mean wind velocity. Waves in the fetch which have short wave lengths interfere with one another, dissipate rapidly, and break on the crests of larger waves. Consequently, they tend to die out soon after leaving the region of a storm. Other waves tend to lose height and sort themselves out according to wavelength, and hence period, in a process called *dispersion*. As the newly formed swell moves from a storm region, the packet of waves spreads out. Waves with longer wavelengths move more rapidly than waves with shorter wavelengths and are the first to reach land. Once generated, these waves continue to move in the same direction and so traverse the oceans in *great circles* until a land mass, and hence change of depth, is encountered (Silvester, 1974).

2.1.4 WAVE THEORIES FOR REGULAR WAVES

A complete analytical description of surface gravity waves is not possible due to non-linearities, their apparent random behaviour, and the three dimensional characteristics of water waves. However a number of wave theories have been developed, on the basis of various assumptions, which are satisfactory for use in coastal engineering. These may be broadly classified as small amplitude (linear), and finite amplitude (nonlinear) wave theories. Linear wave theory is commonly known as Airy Wave Theory. Nonlinear wave theories include Stokes, Gerstner, Trochoidal, Cnoidal and Solitary Wave Theory.

In 1802, Franz Gerstner of Czechoslovakia produced the first rather primitive wave theory. He described how water particles in a wave move in circles, and he pointed out that those in the crest of a wave move in the direction of wave advance and those in the trough move in the opposite direction. Gerstner noted that before returning to its original position, each water particle at the surface traces a circular orbit, the diameter of which is exactly equal to the height of the passing wave. He observed that the surface trace of a wave is approximately a trochoid, the curve described by a point on a circle as the circle is rolled along the underside of a line. Presumably he knew that if the wave height is small compared to the length, as it is for most water waves, the shape of the trochoid approaches that of a sine curve.

Such was the theoretical beginning, from which followed development of a number of satisfactory linear and non-linear wave theories, named above.

Airy wave theory is the simplest theory and is used widely in coastal engineering. It is best suited to describing gravity waves travelling in deep, offshore waters, whereas the non-linear theories become more applicable in the nearshore region. In applying Airy wave theory, the following assumptions must be made (CERC, 1984):

- The wave amplitude is small compared to water depth and the wave form is invariant in time and space;
- The wave being considered does not interact with any other water motions;

- Waves are two-dimensional;
- The fluid is ideal (ie. homogeneous, incompressible and inviscid);
- Surface tension can be neglected;
- Coriolis effect can be neglected;
- Pressure at the free surface is constant and uniform; and
- The sea bed is a horizontal, fixed, impermeable boundary (therefore the vertical velocity at the bed is zero.

The following outline of basic Airy wave equations provides insight for periodic wave behaviour in general. For linear wave theory, the water surface elevation is given by:

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t) \qquad (1)$$

where H is the wave height, $k = 2\pi / L$ is the wave number (L is the wavelength), ω *(= 2π/T)* is the angular frequency, x is the horizontal spatial coordinate and t is time. The fundamental equation underlying linear wave theory is the *dispersion relation*

$$\omega^2 = gk \tanh(kh) \qquad (2)$$

where h is the water depth and g is the gravitational acceleration (9.81 m/s^2). Consequently, the general expression for wavelength is:

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \qquad (3)$$

The general expression for phase velocity or wave celerity is:

$$C = \frac{L}{T} = \frac{gT}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \qquad (4)$$

As previously mentioned, water particles at the surface move in a circular path as a wave passes. At the surface, the diameter of this path is equivalent to the height of the wave. The diameter of the orbital paths decreases with depth until there is no motion. The depth at which no motion takes place is equal to _ of the wavelength. The motion in the orbits is in the direction of wave propagation (Davis, 1987). The decrease in orbital diameter is such that for each 1/9 of a wavelength increase in depth, the diameter of the orbital path is halved.

It is possible to consider three categories of waves depending on their size relative to water depth. These are deep water waves, transitional/intermediate waves, and shallow water waves. Deep water waves are those with water depth greater than _ of the wavelength. There is no interference from the sea bottom with the orbital motion within the waves. A shallow water wave is one in water shallower than 1/20 of the wavelength. At such depths, the waves are markedly deformed by the interference with the bottom and may break. In between these are the transitional or intermediate waves.

The expressions developed in Airy wave theory can be simplified for the cases of shallow water (*h/L<1/20*) and deep water (*h/L>1/2*). For instance, Eqn. 3 simplifies to:

$$L_S = T\sqrt{gh} \qquad \textit{shallow water} \qquad (5a)$$

$$L_0 = \frac{gT^2}{2\pi} \cup 1.56T^2 \qquad \textit{deep water} \qquad (5b)$$

For intermediate depths (*1/20 < h/L < 1/2*), the general equations need to be applied. An approximation to Eqn. 3 which facilitates the calculation of L is:

$$L \cup L_0 \sqrt{\tanh\left(\frac{2\pi h}{L_0}\right)} \qquad \textit{intermediate water} \qquad (5c)$$

Consequently:

$$C \cup \frac{gT}{2\pi} \sqrt{\tanh\left(\frac{4\pi^2 h}{gT^2}\right)} \qquad \textit{intermediate water} \qquad (5d)$$

The characteristics derived by the linear theory above imply small amplitude waves and a sinusoidal profile. Employment of this simplified form permits the use of strong mathematical tools such as Fourier analysis. More complex systems can be considered as summations of several sinusoids. However ocean waves are not infinitely small in amplitude in deep water and, as they arrive in the shallower depths, steepening introduces distortions in the surface profile and the orbital paths of particles. The linear theory is then no longer applicable.

Gerstner (1802) was the first mathematician to tackle this problem, and his solution applies strictly to deep-water conditions, however it was Stokes in 1880 who first put the analysis in the modern form now accepted. Many other workers have been active in this area, deriving slightly different equations depending upon the boundary conditions assumed. A detailed discussion of the non-linear theories can be found in Kinsman (1965) or Silvester (1974). The applicability of the different wave theories according to criteria set by Dean (1970) is summarised in Figure 2.5 below.

Figure 2.5. Zones of application of wave theories according to criteria by Dean, 1970.

2.1.5 IRREGULAR WAVES (REAL OCEAN WAVES)

The characteristics of wind generated ocean waves are governed by the wind velocity, the duration of time during which it blows and the extent of open water across which it blows (fetch length), as well as the existing sea state (Bascom, 1980). Due to the high variability of these factors, ocean wave fields are extremely irregular, consisting of waves with a range of heights, periods and directions. The wave theories previously discussed all describe regular waves, which are waves with a constant height, period and direction, and thus they cannot be used to adequately describe the irregularity of a real sea state.

There are hence two techniques used to analyse irregular waves; *wave-by-wave analysis* (a time domain approach) and *spectral analysis* (a frequency domain approach).

In wave-by-wave analysis, individual waves in a record are isolated using the *zero-downcrossing* or *zero-upcrossing method* to determine representative wave parameters. This time-domain method identifies waves by successive transitions of the water-surface elevation across the mean water level (IAHR, 1989). Figure 2.6 indicates the definitions used for the down-crossing method.

Figure 2.6. Definition of zero-downcrossing waves (after Massel, 1996)

Using spectral analysis, the wave record is considered to consist of an infinite number of component waves. The wave statistics are established on the basis of the energy distribution of these component waves (Horikawa, 1988).

To apply the basic equation of wave dynamics to real ocean waves, Sverdrup and Munk (1947) introduced a descriptive sea state parameter termed the *significant wave height*. The significant wave height, H_S, is defined as the mean of the highest one third of waves present in the sea at any given time (Davis, 1987). The average wave period of this highest one third of waves is termed the *significant wave period,* T_{Hs}. It is commonly thought that visual estimates of ocean wave heights and periods are good approximations of H_S and T_{Hs} (Silvester, 1974; Khandekar, 1989).

2.1.6 WAVE SHOALING AND WAVE BREAKING

2.1.6.1 Wave Shoaling

As swell waves approach land, the depth of water decreases and the waves change from deep-water waves to shallow-water waves. As the leading waves interact with the shallow bottom, the speed of the waves decrease due to drag effects. Succeeding waves, which are still travelling in deeper water, tend to pile up behind the leading waves and the wavelength of the waves decreases. Hence there is a related increase in the wave height.

An explanation of this growth of shallow water waves involves the transfer of energy from one form to another. As the wave speed decreases, the wave's kinetic energy decreases. In accordance with the conservation of energy, the loss in kinetic energy appears as potential energy, which is proportional to height (Igmanson & Wallace, 1985 and Bascom, 1980). This process by which the wave celerity, height and length alter is called shoaling.

2.1.6.2 Refraction, Diffraction and Reflection

When waves approach the shore, they undergo refraction, diffraction and reflection. Refraction of waves is the bending of wave fronts due to the effects of shallow water and it's influence on the speed of wave propagation. When one part of a wave reaches shallower water before another, the part impeded by the shallow water is slowed relative to the other. The wavefront moves more slowly than the part of the wave still in deep water and bends to fit the shore. This occurs when waves travel at an angle to underwater contours, with the variation in the depth felt by different parts of the wave causing the crest to bend toward alignment with the contours.

Diffraction is the bending or spreading of waves around objects such that energy is transmitted behind a barrier, much in the way that sound travels around a wall from one room to another. As waves pass a barrier, some of their energy is transmitted along the wave, thus producing small waves behind the barrier.

Another property that waves have in common with light rays, is that they can be reflected with little energy loss from vertical walls, jetties, or other similar structures. Beaches also present barriers to the progression of waves, and reflect wave energy. Most of the wave energy is dissipated over and absorbed by the beach area, so that the percentage of energy that is reflected is low. The amount of reflected energy is proportional, for those composed of sand-sized sediment, to the steepness of the beach.

2.1.6.3 Breaker Criterion

When the orbital paths of water in a wave begin to interact with the bottom (at a depth approximately _ the wavelength), the changes in the waves outlined above take place. As the wave moves into shallow water, the orbits are somewhat flattened to an elliptical shape and eventually show only a back and forth motion. As the waves "feel the bottom", the speed of the waves decrease, causing their wavelength to also decrease. The overall result is a slowing and a steepening of the wave, an increase in wave height, and a decrease in wavelength, though the period remains constant.

A condition for wave breaking occurs when the particle velocities of the wave crest exceed the velocity of wave propagation (Stokes, 1847). As the wave moves into progressively shallower water, the surface orbits begin to move faster than the wave propagation velocity. Eventually the wave steepens beyond the limits of wave stability and it breaks. The theoretical limits of wave stability are a steepness or height-length ratio of 1:7 and a 120° angle below the water surface (Figure 2.7).

Figure 2.7. Limits for wave stability (after Davis, 1987)

Different wave theories predict the condition for breaking at slightly different limits. The most commonly employed condition for breaking, from McCowan (1894), is:

$$H_b = 0.78 d_b$$

where H_b is the breaker height, and d_b is the breaking depth. Other investigators have employed various theories and have obtained different criteria for breaking, ranging from $H_b = 0.73 d_b$ (Laitone, 1963) to $H_b = 1.0 d_b$ (Dean, 1968).

Since wave theories are not generally valid near the breaker zone and the above criteria were developed for limiting waves travelling over a horizontal bottom, the reliability of these limits is questionable. Galvin (1969) reviewed data from several wave flume investigations and developed the following empirical relationships, which include the effect of beach slope, m:

$h_b / H_b = 0.92$ when m is steeper than 14.3, and

$h_b / H_b = 1.4 - \left(6.86 / m \right)$ when m is flatter than 14.3.

Weggel (1972) developed the following breaker criterion which also include the effect of the bottom slope, referred to in this case as *tan* β. The occurrence of wave breaking in design studies was in accordance with this criterion.

$$H_b / h_b = b - aH_b / gT^2$$

in which

$$a = 43.8\left[1 - \exp\left(-19.5 \tan \beta\right)\right]$$

$$b = 1.56 / \left[1 + \exp\left(-19.5 \tan \beta\right)\right]$$

where H_b is breaker height, h_b is breaker depth, g is gravity and *tan* β is beach gradient.

2.1.6.4 Breaker Type

Breaker-type is also an important factor in surfing. Breaker-type is a classification of the wave profile during breaking. Patrick and Wiegel (1954) classified breaker type as spilling, plunging and surging. They observed in the field that breaker type depended primarily upon beach slope, represented by *m*, and the deepwater wave steepness. They determined spilling breakers occur for large values of H_0/L_0 on flat slopes, surging breakers occur for small values of H_0/L_0 on very steep slopes, and plunging breakers occur between the two extremes.

Galvin (1968) introduced the collapsing breaker type as an intermediate form of breaker between plunging and surging waves (See Figure 2.8). Galvin defined two parameters, the "offshore parameter" and the "inshore parameter", to classify breaker type, expressed in terms of the beach slope and wave steepness. Transitional values were found to be:

surging-collapsing if $\frac{H_0}{L_0 m^2} < 0.09$

plunging if $0.09 < \frac{H_0}{L_0 m^2} < 4.80$

spilling if $\frac{H_0}{L_0 m^2} > 4.80$

for the offshore parameter, and

surging-collapsing if $\frac{H_b}{m L_0} < 0.019$

plunging if $0.019 < \frac{H_b}{m L_0} < 0.427$

spilling if $\frac{H_b}{m L_0} > 0.427$

for the inshore parameter.

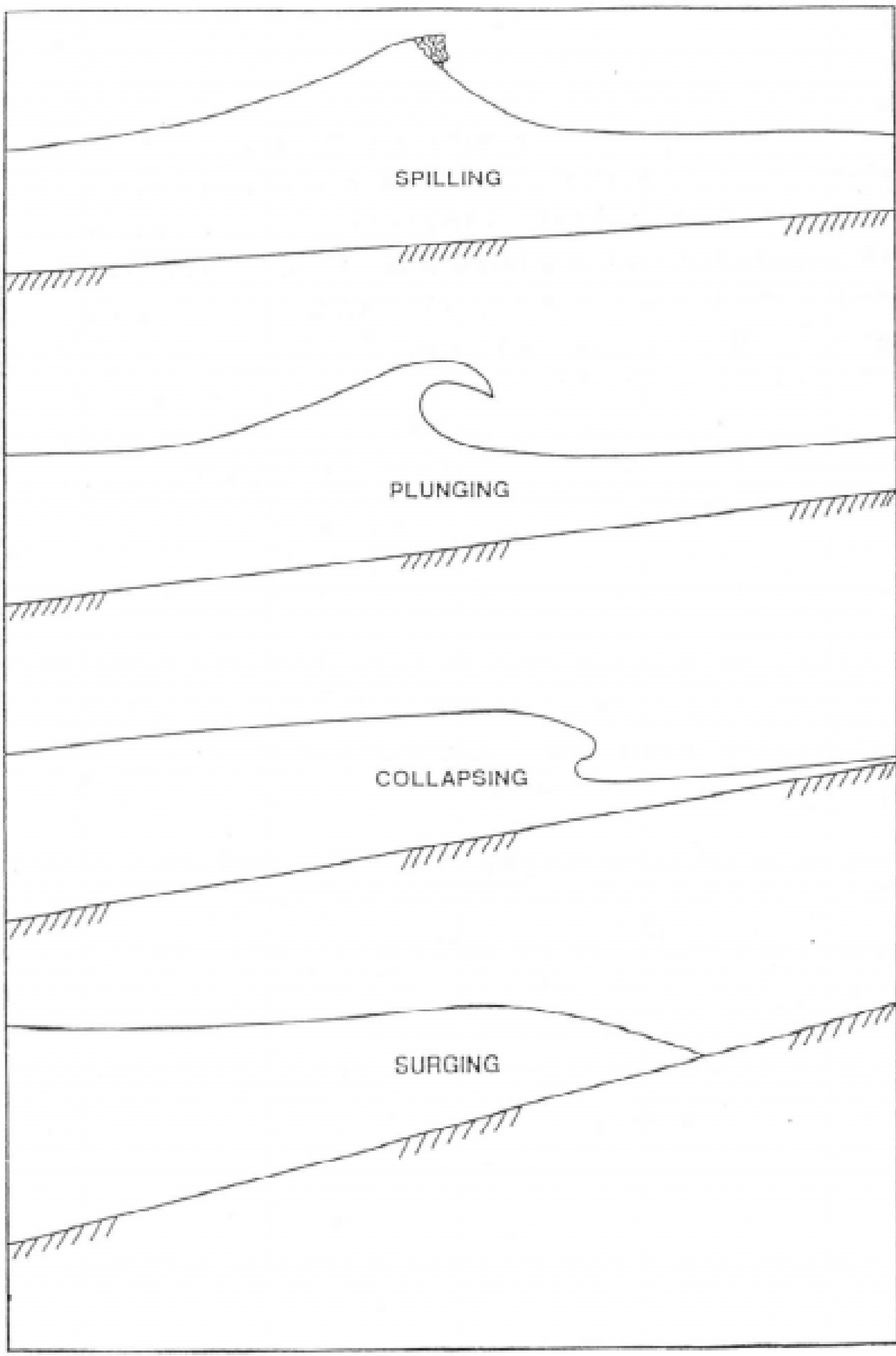


Figure 2.8. Breaker type classifications.

Battjes (1975) extended the usage of the Iribarren number, developed by Iribarren and Nogales (1947) for use as a breaking criterion, to describe breaker type. This commonly used breaker type descriptor is now also referred to as the *surf similarity parameter*, ξ, defined as:

$$\xi = \frac{m}{\left(\frac{H}{L_0}\right)^{1/2}}$$

where H is wave height, m is beach slope and L_0 is the offshore wavelength. This is also still known as the Iribarren number, with the terms commonly being used interchangeably. Battjes converted the transition values of Galvin to values of ξ_0 (or I_0), the offshore surf similarity parameter, resulting in:

surging or collapsing if	$\xi_0 > 3.3$
plunging if	$0.5 < \xi_0 < 3.3$
spilling if	$\xi_0 < 0.5$

Battjes defined an inshore parameter:

$$\xi_b = \frac{m}{\left(\frac{H_b}{L_0}\right)^{1/2}}$$

and by re-analysing the Galvin data, the following transitional values were determined:

surging or collapsing if	$\xi_0 > 2.0$
plunging if	$0.4 < \xi_b < 2.0$
spilling if	$\xi_b < 0.4$

These ranges for the inshore and offshore Iribarren number, and hence surf similarity parameter, are shown in Table 2.1, along with colloquial surfing terminology used to describe these wave types.

Table 2.1. Breaker type classifications and colloquial terminology.

IRRIBARREN NUMBER	BREAKER TYPE	SURFING TERMINOLOGY
$I_b < 0.4$ $I_o < 0.5$	spilling	"mushy"
$0.4 < I_b < 2.0$ $0.5 < I_o < 3.3$	plunging	"tube or hollow"
$2.0 < I_o$ $3.3 < I_o$	surging or collapsing	"cruncher"

A qualitative description of wave breaking is given by Bascom (1980) in which it is concluded that spilling breakers also exhibit a plunging motion, just on a smaller scale than is observed with typical plunging breakers. This results in the division between spilling and plunging breakers being a subjective one. Further detailed observations were made by Bascom of wave shape, jet evolution and collision, the resulting vortex and turbulence which led to the discovery of a secondary wave, generated from the jets collision, which propagates forward with the incident wave.

For the design of the Cables Station Artificial Surfing Reef, a gently plunging wave, tending to spill at higher tides, was chosen as the most suitable breaker type for surfing.

The effect of wind on breaker characteristics was studied in the laboratory and in the field by Galloway, Collins and Moran (1988), leading to the conclusion that light to moderate strength offshore and onshore winds promote plunging and spilling waves respectively, with extreme strength winds having the reverse effect. Offshore winds move the breaking point inshore, onshore winds move the breaking point seawards, with the result being an increase in the surfzone width by up to 100% to allow for wind effects.

2.1.6.5 Criterion for a rideable wave

According to Walker (1974) and Dally (1989), the qualitative definition of 'surfable' is a wave on which a surfer can maintain a mean speed (termed 'board speed') that is as fast or faster than the rate at which the point of incipient breaking translates along the wave crest (termed 'peel rate'). If the breaking segment of the wave overtakes the surfer, the wave 'closes out' and becomes unsurfable. Figure 2.9 shows the breaking sequence of a wave. In the most basic sense, it is the joint statistical climate of attainable board speed and peel rate that determine the surfing climate of a particular beach.

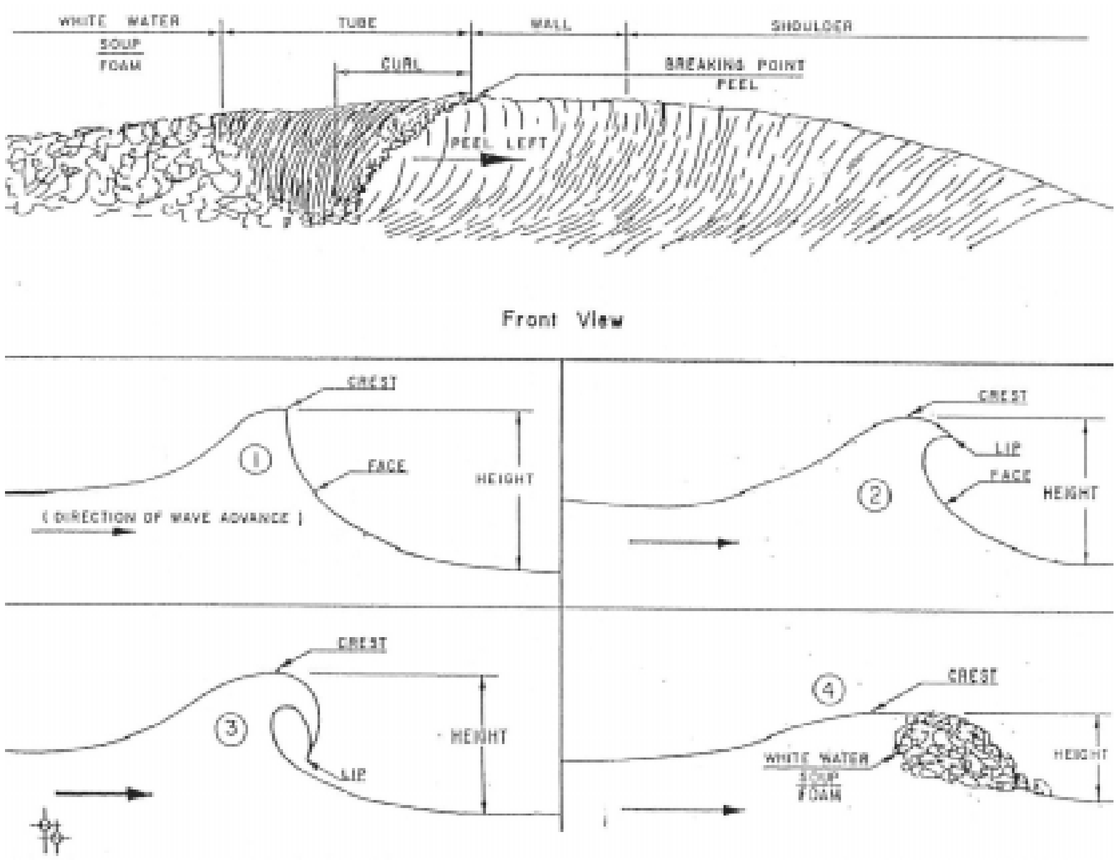


Figure 2.9. Breaking sequence for a wave and the associated terminology.

BREAKER TYPE

As outlined above, breaker type is a very important aspect of a wave's surfability. Spilling and plunging waves are able to be surfed. Spilling breakers are surfable, but not as desirable as plunging breakers. Collapsing breakers, or 'dumpers', are unsurfable and can in fact be quite dangerous to surfers.

BOARD SPEED

Attainable board speed is a function of the size and shape of the face of the breaker, the weight of the surfer, and the board characteristics (Dally, 1990). For a given board shape and surfer weight, the board speed can be inferred by using the wave height at incipient breaking (H_b) to quantify the size and the Iribarren Number (or surf similarity parameter) to represent the shape of the wave face.

Using aerial photographs, Walker (1974) was able to infer mean board speed from estimates of the peel rate of the waves that were surfed, and found maximum speeds on the order of 12 m/s. As part of the Lyons (1992) study into the design of an artificial surfing reef, board speeds of surfers at Trigg Beach, Perth, were measured using a police radar gun and were found to be around 8 m/s.

PEEL RATE AND ANGLE

Of particular interest to the surfer is the rate of lateral propagation of the peel, called the peel rate, V_p. The general objective of surfing is for the surfer to move parallel to the advancing wave crest, attempting to keep ahead of the peel. This concept is illustrated in Figure 2.10, where the wave velocity vector, V_w, is orthogonal to the crest, the peel velocity, V_p, is oriented parallel along the wave crest, and the surfer velocity, V_s, is the resultant velocity of the surfer relative to a coordinate system fixed on the ocean bottom.

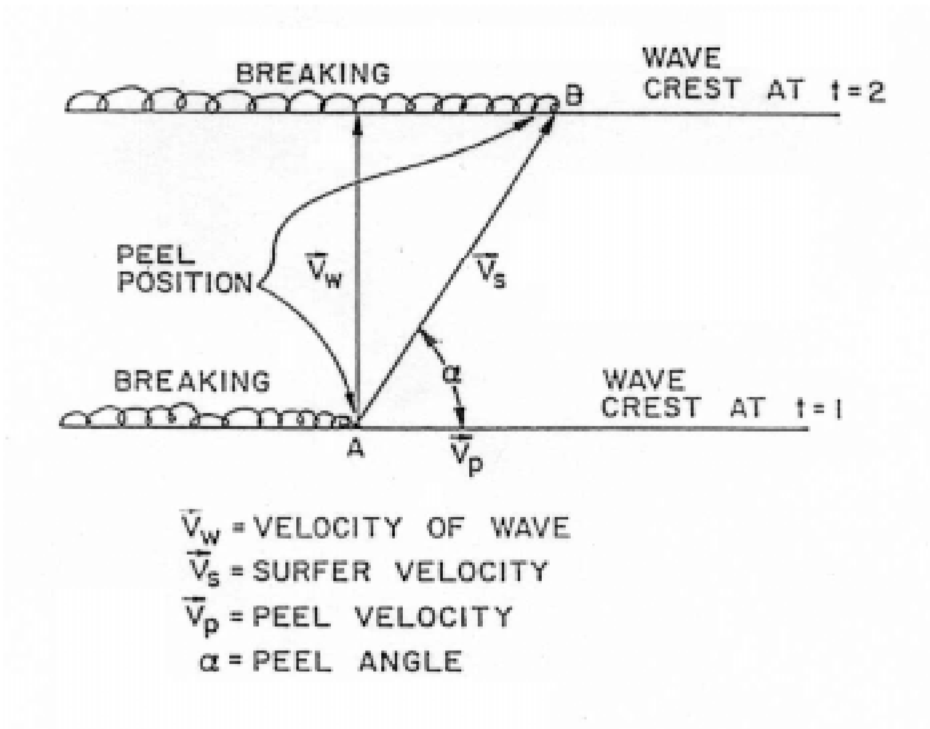


Figure 2.10. Peel parameters (after Walker, 1974).

The angle subtended between the surfer velocity vector, V_s, and the peel velocity vector, V_p, is the peel angle, α. The surfer velocity, V_s, is an average velocity which a surfer must attain to remain with the peel. A surfer generally manoeuvres under and over this velocity but must, on average, maintain the surfer velocity to successfully ride the wave (Walker, 1974).

LENGTH OF RIDE

The length of ride provided by a wave is a key parameter in determining the capacity of a site. Takeoffs generally take from 2-5 seconds, depending on the wave size and breaker type (Walker, 1997). In a typical head-high wave, length of takeoff could be about 20 metres, with the ride then being anything from an exhilerating takeoff to a long ride of one minute. The capacity of a site can be enhanced by having long rides to both the right and the left.

The above parameters help determine the class of the surfer and type of surfing practiced at a surf site. The breaker height, breaker type, and peel angle are the most important parameters in describing the surfing wave (Walker, 1974). Surfing conditions are further classified by parameters such as the length of the ride, the surfer velocity, variability of the peel rate, wave height distribution, waiting time between sets, number of rides per set, number of rides per wave, the arrival rate of surfable waves, the number of surfers, the skill level of the surfers and the water surface and wind conditions.

As part of the study by Walker (1974) conducted in Hawaii, observations of wave height and period, bottom slope, peel angle, surfer velocity and breaker type were made at many surf sites. Walker then developed a plot of wave height versus peel angle, with isolines of surfer velocity, V_s, drawn over the top of this using the equation:

$$V_S = V_W / \sin\alpha$$

where

$$V_W = 1.25\sqrt{gh} = 1.25\sqrt{gH_b}$$

Also plotted on this figure are subjectively-developed categorisations of surfer skill level to indicate the zones of peel angle and wave height under which surfers of different experience prefer (See Figure 2.11). Walker emphasises that the categories do not clearly differentiate from one another and that there is considerable overlap.

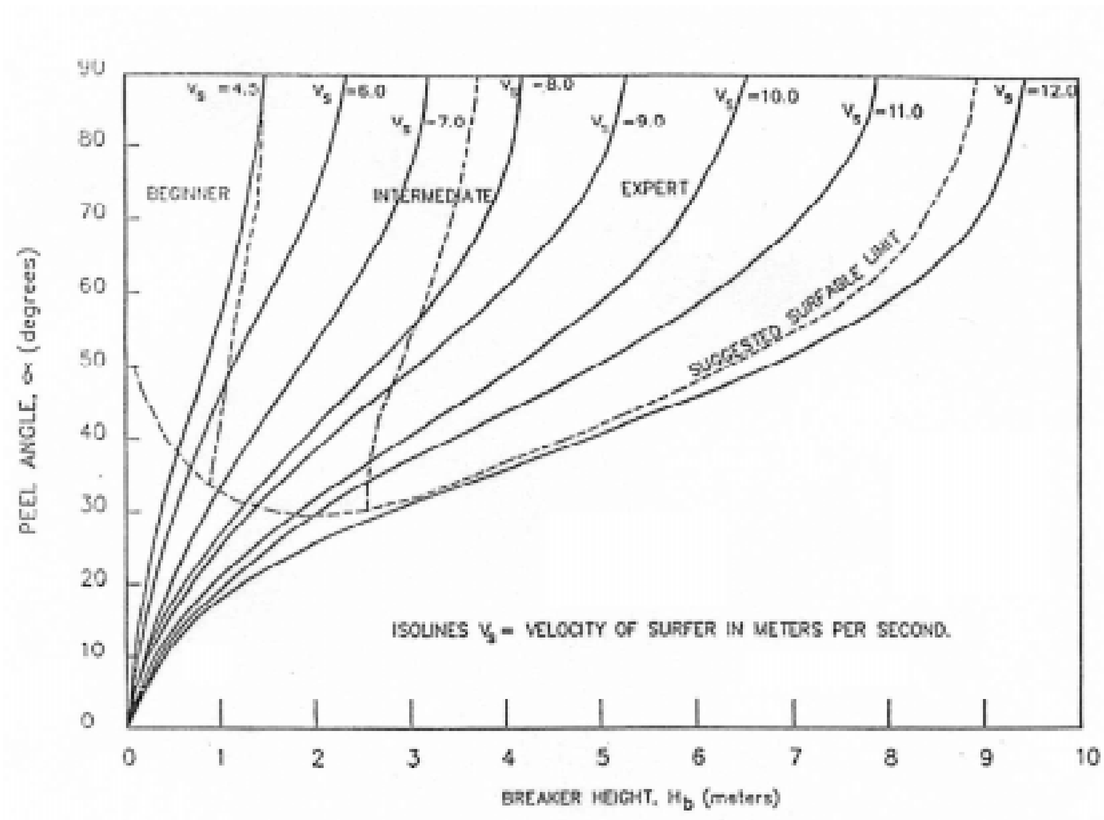


Figure 2.11. Surfer ability classifications: the Walker Diagram (after Walker, 1974).

Surfer skill levels were divided into three categories; beginner, intermediate and expert. The beginners tend to ride smaller waves and less acute peel angles. The intermediate or typical surfer overlaps into the beginner region and rides up to about 12 foot surf (~3.7 metres). Experts ride the larger surf with more acute peel angles. A lower limit has been hypothesised as a suggested surfable limit based on observations at some sites with fast peel rates such as Pipeline, Sunset and Ala Moana in Hawaii, some of the best surf sites in the world.

A minimum peel angle of 30° at about 8 foot (~2.44 metres) surf is postulated. The minimum peel increases with increase in wave height due to surfer velocity limitations imposed by drag on the surfboard. The minimum peel on the smaller waves is seen to increase due to the lesser amount of potential energy available to propel the surfboard. These classifications developed by Walker (1974) are still commonly used in surfability studies and haven't been modified from the original form.

A wide degree of scatter in peel angle is observed for any given surf site, even under similar conditions. This is attributed by Walker to the wave direction variability and the distribution of wave energy over the shoal. A peel angle of about 50° is typical according to studies of many sites. This yields a surfer velocity approximately 30% greater than the wave velocity at breaking.

A relevant point was made by Hurst (1996) with regard to the Walker skill level limits outlined above. He points out that Walker's skill level limits should be studied in the context of the state of surfing in 1974, in that since this time, several significant changes to board design and style have resulted in faster surfboards. This means that the suggested limits may be conservative by today's standards. Other types of surf riders are satisfied with different breaker types. For example, the invention of the body board has made waves more accessible to some surf riders who are satisfied with fast breaking, hollow waves. Similarly, slower craft such as the long-board and the wave ski are often well suited to spilling breakers (Hurst, 1996).

2.1.7 LONG-PERIOD SEA-LEVEL FLUCTUATIONS

Water level fluctuations have a significant influence on wave breaking in that waves need to 'feel the bottom' to begin breaking. If water levels are high, the depth of water encountered at a location is greater then under mean sea-level conditions, hence shoaling isn't as effective because interaction of the wave with the bottom is more limited. Conversely, if water levels are lower than mean sea level, the tendency to break is enhanced because the wave experiences shallow water earlier such that shoaling is more extensive.

Sea-level records have been collected at the Port of Fremantle since 1896. The Port of Fremantle is a fairly minimal distance from the Cables Station site, and hence the tide levels recorded at Fremantle are applicable to this region. Long-period sea-level variations may be identified in these records, including a distinct tidal signal and several non-tidal constituents. The average mean sea-levels have been found to be 0.3 metres higher in winter than in summer (Steedman, 1982). The overall sea-level range is small, with a maximum range of 2.04 metres observed over the period of 1896 to 1968 (Hegge, 1994).

Although short-period wind waves contribute most of the ocean surface's wave energy, long-term sea-level variations in the Perth region contribute to controlling wave shoaling and breaking, nearshore processes and beach morphology. The following outlines the characteristics of the most important long-period sea-level fluctuations in the Pert coastal waters.

2.1.7.1 Tides

The tides in Perth coastal waters are amongst the smallest in the world, are predominantly diurnal (one tide per day), with a mean daily range of only 0.55 metres. The maximum spring tidal range at Fremantle is 1.2 metres. Steedman (1982) found that semi-diurnal tides occur for up to six days following new and full moons. The tidal and non-tidal, long-period sea-level fluctuations in the Perth region are of the same order of magnitude and as such, sea-level predictions based on astronomical tides alone are of limited accuracy.

2.1.7.2 Seiches

Seiches are long-period standing waves formed in enclosed or semi-enclosed basins that can be caused by sudden changes in atmospheric pressure or winds (CERC, 1984). In the coastal waters of Perth, seiching is frequently observed at periods of around 30 minutes and 2.8 hours (Lemm, 1996). The line of reefs and islands off the Perth coast form an inshore basin, in which 30 minute oscillations are maintained with heights of approximately 0.1 metres (Allison *et al*, 1980; Steedman, 1982). The seiching with the 2.8 hour period may be attributed to the resonance of the coastal waters over the entire width of the continental shelf and have heights of the order of 0.3 metres (Steedman, 1982).

2.1.7.3 Storm Surges

Storm surges are associated with transient storm events and manifest as a change in sea-level. This is an abnormal rise of the water level, resulting principally from the atmospheric pressure and winds associated with storms. The frequency and intensity of storm surges in the Perth region has a seasonal cycle which peaks in winter (Allison *et al*, 1980). The Fremantle sea-level variations due to atmospheric conditions was found by Steedman (1982) to normally be around ± 0.3 metres, however severe storms may cause sea-level changes of up to 0.7 metres.

It is to be emphasised that storm surges have high spatial variability due to factors such as bathymetry and shoreline aspect. With regards to the impact on Perth metropolitan beaches, the timing of surges in relation to tides, and other causes of sea-level fluctuations, is crucial. A storm surge occurring at low tide has much less impact than a surge which coincides with high tide and severe wave conditions.

2.1.7.4 Continental Shelf Waves

Continental shelf waves are caused by the periodic passage of synoptic scale anticyclonic pressure systems. Waves of periods of 1 to 365 days with heights of up to 0.5 metres propagate southward along the Western Australian coastline and may contribute to sea-level fluctuations at Fremantle (Provis and Radok, 1979).

2.1.8 NEARSHORE PROCESSES

Kempin (1952) found that longshore movement of sand along the Perth metropolitan coastline occurs in both northerly and southerly directions, depending on the season and weather conditions. However, he suggested that the *net* movement of sand along the metropolitan coast is from south to north.

In summer, sand is primarily shifted northwards as a result of sea-breeze induced longshore sediment transport (Masselink and Pattiaratchi, 1996). In winter, southward sediment transport may be driven by winds and waves approaching from the northwesterly quadrant. Silvester (1961) claimed that the southerly sediment movement is rather limited because of the short duration of winter storm wave conditions.

Several areas along the Perth coastline have problems with beach erosion, often due to coastal structures which have been developed. Erosion at Cottesloe main beach was investigated by Kempin (1952) and Silvester (1961), and it was suggested that the construction of the Fremantle Moles has been responsible for the disruption of the longshore sediment transport regime. An accumulation of sand between Fremantle North Mole and Leighton Beach (north of Fremantle) has resulted from the mole's construction, with sand transported into this region essentially trapped. This has prevented sand from being returned to the more northern beaches via the northerly summer drift and as a result, beaches between Cottesloe and Swanbourne are frequently eroded.

Along the more northern beaches, similar processes may be active on a smaller scale adjacent to coastal structures (*eg* City Beach) and nearshore reefs (Bowyer, 1987). Sections of the coast where longshore sediment transport remains uninterrupted seem to be relatively stable.

The nearshore processes and sediment transport regime at the Cable Station site is treated in more detail in Section 2.2.3.6.

2.2 Artificial Surfing Reefs

The following sections will address specific aspects associated with artificial surfing reefs and the development of this technology. The studies which culminated in the construction of the Cable Station reef will also be outlined as a basis from which to assess the performance of the artificial reef.

2.2.1 HISTORY OF ARTIFICIAL SURFING REEFS

In 1969, *Surfer Magazine* published an article by Dr Richard Grigg titled "Artificial Reefs, a Plan for Multiple Use" which proposed construction of a surf site as a multiple purpose project that would be used for surfing, diving and shore protection. This concept was adopted by the Los Angeles District Corp of Engineers for a project at Royal Palms Beach, Point Fermin, however the project was not continued and the reef not constructed. Palmer and Walker (1970) proposed the creation of an artificial surfing reef, this time as part of the Honolulu runway dyke in Hawaii, again however the reef never eventuated.

In August, 1971, *International Surfing* described a sand bag reef at Hermosa Beach, California, constructed by Hoppy Swarts. The reef extended 100 feet seaward, and was 50 feet wide at the base. It was reported that the 'reef' created surfable waves, however it was also reported that the sandbags scoured into the beach due to lack of toe and underlayer protection.

Dr. James (Kimo) Walker, then of the University of Hawaii, studied the characteristics of surfing waves in Hawaii in the early 1970's. This was an extensive State of Hawaii funded project, aimed at describing surfing resources for their preservation, enhancement and creation. These studies are summarised in *Look Laboratory Report TR 73-30, University of Hawaii* under the 'Recreational Surf Parameters' program.

The report was divided into six major categories, the first being a description of the wave, wind, bathymetric and social environment of the Hawaiian study region. The second section was a description of wave transformations pertinent to surfing and the third presented the observations of the study surf sites. The fourth area of focus was presentation of a general concept for a surf site, derived from analytic consideration and field observations. The fifth section provided an example of applications of the results of the study to the design of a coastal structure with preservation of a surf site as a design criterion. The final section summarised the comprehensive recommendations for the preservation, enhancement, and creation of surf sites.

The three year investigation included detailed measurements of the bathymetry of Hawaiian surf sites, observation of bottom conditions, and time sequenced aerial photographs of waves and surfer paths that could be imposed over the bathymetry. The study also used three dimensional wave basin tests to study wave transformations in the breaker zone and to look at how reefs of various sizes and shapes may influence waves. This study focused on the wave transformations and how surfers use a site.

Although the study was based exclusively in Hawaii and the surrounding islands, several important conclusions were drawn which apply to the creation and preservation of artificial surf sites in general. The Walker study is considered to be one of the first comprehensive studies aimed specifically towards the preservation, enhancement, and creation of surf sites. John Kelly (1973) presented the social aspects of surfing in a companion study, ‘Surf Parameters, Final Report, Part II, Social and Historical Dimensions’.

Dr. Richard Silvester (1975) was commissioned by the West Australian Surf Riders Association to prepare a report on the feasibility of constructing artificial reef sites on the coast for ‘surfing with boards’. The research and proposal were presented in his report ‘Synthetic Surfing Sites’. This work included details of wave characteristics, site and reef characteristics, environmental aspects, research requirements, costs and recommendations.

His concept was to construct the reef from sand-filled polyethylene bags. The reef would extend 150 feet (~46 metres) seaward, and be 30 feet (~9.2 metres) wide. However, the proposed reef idea was not constructed. In his report, Silvester stressed that he felt a rock armoured reef would present safety hazards.

Detailed studies were conducted to construct a surf site in Hawaii as a result of a court settlement associated with the construction of a cooling water discharge facility at Kahe Point on Oahu. Walker (unpublished, 1976) conducted three dimensional wave flume studies of a reef that would replace a surf site that was destroyed by the discharge facility. The reef planform extended 200 feet (61 metres) seaward and was about 150 feet (46 metres) wide.

Two dimensional hydraulic model studies were conducted by Dr. Fred Raichlen (1976) of Cal Tech to determine the stability of the reef materials. He found, in agreement with Silvester (1975), that an armour layer of large rock could prove to be a hazard. It was believed that large storm waves could break over the reef and dislodge individual stones. The stones that were dislodged in the model rolled on top of the reef, thereby presenting an underwater obstruction.

Rather than expose surfers to this risk, Walker modified a breakwater armour unit called the Tribar by cutting the top legs off the unit and angling the bottom legs such that they would interlock with adjacent units. This proved to be a feasible concept for a reef to be constructed from a trestle, however local environmentalists were concerned that the reef would cover bottom habitat where local fishermen caught squid. The project did therefore not proceed and the $250 000 funding was diverted to the State Parks system to enhance coastal access on the Waiamea coast.

In 1981, Moffatt & Nichol Engineers prepared a feasibility study for an artificial surfing reef at Oceanside, San Diego County, California. The study was undertaken for the Los Angeles District Corp of Engineers following a proposal to control beach erosion that may have degraded existing surfing conditions at this site.

In another study, the Corp of Engineers dredged 115 000 cubic metres of material out of a shoal in Dana Point Harbour, California, and placed the material east of the harbour. The material placed beside the harbour as a reef shoal reportedly created surfing conditions over the 'reef'. However no documentation is available regarding the configuration of the reef and its effects on surfing. Waves apparently eroded the shoal and hence it stopped producing surfable waves. According to Pratte (1987), construction of this same harbour destroyed several surf breaks.

Surfers at Port Hueneme, California, recognised that every two years the Corps of Engineers disposed bypassed sand on Ormond Beach. The concept of disposing the sand to form a spit was developed, in the hope that the spit would form a temporary point break. In 1987, the concept was tested and favourable surfing conditions were created, however strong surf rapidly washed the spit away.

In June, 1988, the Government of Western Australia (WA) formed the Artificial Surfing Reef Committee (ASRC) to investigate the construction of artificial surfing reefs in the Perth metropolitan area following submissions since the early 1970's from sporting organisations such as the WA Surf Riders' Association; the Professional Surf Riders Association; the Surf Life Saving Association; as well as private industries associated with beach recreation and members of the surfing community. In 1989, after detailed studies of the wave and wind climate, support services, facilities and public access at all possible metropolitan sites, the ASRC recommended that the artificial surfing reef be constructed in the area known as *Cable Station*, South Cottesloe, which is less than 15 kilometres southwest of the Perth CBD.

The WA government, through the Ministry of Sport and Recreation then provided funding for engineering investigations and preliminary design. These studies were undertaken by the Department of Marine and Harbours and the University of Western Australia, as well as private engineering consulting firms. The details and results of these studies will be outlined in subsequent sections of this report.

In 1994, the ASRC and the Ministry of Sport and Recreation received expressions of interest from suitably qualified coastal and construction engineers for a

Also in 1994, the ASRC submitted a comprehensive report to the WA government on their findings, summarising site selection, reef design, construction, environmental impacts and partial costing for the Cables Station Artificial Surfing Reef. Many studies of the wave climate, environmental impact, design optimisation and construction details were undertaken in the succeeding years which are also detailed in following sections.

In January, 1999, construction of the Cables Station Artificial Surfing Reef commenced, making it the first artificial reef of it's kind, designed with the specific goal of enhancing and creating a surfable wave. At the time of writing (October, 1999), the construction of the reef has been deemed as essentially complete, with some optimisation of the reef structure necessary.

Developing parallel to that of the Cable Station Artificial Surfing Reef has been several other artificial surfing reef designs in locations such as California, New Zealand and the Gold Coast in Queensland, Australia.

With funding from Chevron Oil Company administered by the California State Coastal Conservancy, the Surfrider Foundation is proposing to construct an artificial surfing reef north of Chevron's El Segundo refinery. The project is a mitigation commitment required by the California Coastal Commission to restore recreational surfing resources damaged by the construction of a jetty at the refinery. Tom Pratte (then president of the Surfrider Foundation), with great forethought, added a clause to a permit required by Chevron from the California Coastal Commission (1983), stating that if the jetty caused deterioration of natural surf quality in the area, Chevron would actively be involved in it's renovation.

The proposed reef will be constructed of 10 to 20 large geotextile fabric bags containing a total of 3830 cubic metres of sand. The 'Chevron-shaped' reef will be approximately 2.15 metres in height and 46 metres long on each wing, and will be located 90 metres offshore. It will be situated on 840 square metres of subtidal sand flats at a depth of 4.6 metres below mean sea level. The top of the reef will be at least 0.6 metres under the surface even at extreme low tides. The temporary reef will have

Construction of an artificial surfing reef at Narrowneck, Queensland, began in August, 1999. It has been designed by Prof. Kerry Black and a team of students from the University of Waikato, New Zealand. The reef consists of two parts, the northern part will form a right break, while the southern will form a left break. The entire reef would fit into a square 600 metres by 350 metres and will range in depth from about 1 metre to 10 metres below low tide level.

The reef has not only been designed for surfing purposes, but also as a shore protection structure to maintain a widened beach profile which has been proposed to be created through sand nourishment on Surfers Paradise beaches. The area previously experienced large littoral drift and as such, the reef structure is needed to provide coastal control. The reef begins approximately 150 metres from the shore and will involve about 300 sandbags being positioned according to design. These sand bags will come in 6 different sizes ranging from 160 to 300 tonnes. The actual bags will be placed into position first, after which they will be pumped with sand by a dredge.

Prof. Kerry Black is also involved in designing three artificial surfing reefs to improve surfing conditions at New Plymouth, Mt Wanganuai and Gisbourne in New Zealand. Black and the research group from the University of Waikato have also developed a numerical model that can be used in the design of artificial surfing reefs.

2.2.2 CABLE STATION ARTIFICIAL SURFING REEF

2.2.2.1 Project Initiation

In June, 1988, the Government of Western Australia (WA) formed the Artificial Surfing Reef Committee to investigate the construction of artificial surfing reefs in the Perth metropolitan area. Various Governments in WA had been approached over a period of many years prior to this for the construction of a reef, with requests emanating from sporting organisations such as the WA Surf Riders Association, industries associated with beach recreation, community members and individual surfers, as well as the Surf Life Saving Association. All were concerned with the difficulty of finding appropriate and consistent surf, the competition for that surf, and hence the concern for public safety with such crowding issues at Perth beaches. There were also financial incentives, with consideration of tourism, industries related to surfing, and professional surfing events.

One of the earliest reports on synthetic surfing sites in Western Australia was undertaken by Dr. Richard Silvester for the WA Surf Riders Association, who was then of the Department of Civil Engineering at the University of Western Australia. This 1975 study included the feasibility of constructing artificial sites for surfing with boards, preliminary surveying, investigation of environmental problems and proposed actions to overcome them, estimated costs of construction, and how it was proposed to be financed.

Silvester was first approached with the idea of the proposed reef being constructed from rubble materials, a suggestion he immediately discounted on the basis of instability and danger to surfers. However, after investigations of a strong, yet flexible polyethylene sheet that could be welded together, the concept of a massive elongated bag was borne. Silvester recommended that, before full scale application, that there be some research to test the concept, the material, the towing technique and general operations, as well as the influence of such reefs on the surrounding sea bed. Silvester believed that many artificial surf sites were going to be needed in the future for the expanding aquatic sport of surfing.

He forecast that for multiple installation of artificial surfing sites in the future, a long term research program would be necessary, involving scale models and theoretical analyses.

The major conclusions that Silvester drew from his study included the following:

1. There is a strong case for investigating the possibility of providing artificial surf sites on the Western Australian coast within easy access of metropolitan areas.
2. Good surfing conditions are produced by high waves breaking at sharp angles to bed contours, so resulting in reasonable wave celerities and peeling rates.
3. A synthetic reef should employ shoaling and reflection of waves to optimise the breaker, whilst at the same time, provide a nearby channel for access to the starting area.
4. Materials for a submerged mound should be stable under conditions of swell or storm waves and not provide a hazard to board riders
5. A solution worthy of study is a sausage-type reef consisting of a skin of polyethylene sheet available in reasonable length, width and thickness, for filling with sand and withstanding the wearing and weathering conditions of the coastal region.
6. The orientation and location offshore of such a mound should be examined in a pilot study to test its wave breaking characteristics and influence on the surrounding sedimentary bed.

To the knowledge of the writer, these pilot tests of the polyethylene reef were never performed or documented, however, Silvester's contributions were substantial in that the study initiated research and interest in artificial surfing reefs and demonstrated that the idea was a real engineering possibility.

The *Terms of Reference* laid down for the Artificial Surfing Reef Committee with regards to construction of an artificial reef was to undertake the following tasks:

1. An assessment of the present and future needs of surfing
2. Advice on the existence and success of such reefs elsewhere in Australia
3. Recommendation on the engineering aspects of artificial reef construction
4. Recommendation on the possible metropolitan artificial reef locations
5. Assessing the impact on the environment of the establishment of an artificial reef at the possible locations
6. Costing of the above
7. Other related matters

The ASRC initially gathered as much relevant information as possible, achieved in a number of ways including written submissions, oral submissions, site inspections and literature searches. Two outstanding submissions, amongst many, were received at this time, one from the City of Perth, and the other from Mr Mike Crawford who was an engineer at the Waterways Commission of WA at the time.

The submission from the City of Perth (1988) pertained to the matter of 'the considerable conflict that exists between fishermen and surfers at both the northern and southern groynes at City Beach', with the major problem being the number of surfers and swimmers requiring hooks to be removed from their flesh. It was felt that establishing an artificial reef in a suitably accessible location might provide a sufficient attraction to the surfers to reduce their demand on the groyne areas. In this light, it was suggested that the location of any such reef should be in close and functional proximity to:

1. A significantly large surfing population;
2. Appropriate support facilities such as parking, refreshment outlets, spectator vantage points and the like;
3. A range of secondary schools who may be contemplating including surfing as part of the elective sports curriculum;
4. A Surf Life Saving Club who would be able to provide safety, rescue, education

The City of Perth requested access to the findings of the Committee with respect to the establishment of an artificial surfing reef in the proximity of Floreat Beach or City Beach. At present there are no plans for artificial reefs at such locations, however the findings of the ASRC and studies which were performed as part of the Cable Station reef project will be useful in any future feasibility studies for artificial reefs along the Perth coastline.

The submission made on the feasibility of artificial surfing reefs by Crawford (1988) covered many aspects of the artificial reef issue in detail. He pointed out the problems and injuries associated with the number of surfers at Perth metropolitan surf sites. Crawford had himself been surfing for 20 years and also had the advantage of being a civil engineer with coastal engineering experience. He estimated the number of consistent average quality waves in Perth to vary from about 3 sites in mid-summer to 4 or 5 in winter, with about 11 other breaks existing, however considered to be substandard surfing sites. Crawford noted that the main beneficiaries of an artificial surfing reef would include; surfcraft riders, tourism, swimmers, Surf Life Saving Clubs, the Government, the surfcraft industry and the construction industry.

The issue of public liability and the possibility of litigation in regard to injuries at Perth metropolitan beaches was used as an argument for surfboard crowd control and surfing break construction, as part of a public liability risk reduction strategy.

An important inclusion in the study was a preliminary engineering assessment of existing surf breaks along the Perth metropolitan coastline. This was necessary to form an understanding of what conditions are required for good surf in Perth and to help with future assessments of the best location for an artificial reef (See Table 2.2). A preliminary assessment of what is required for the success of an artificial reef was also included in the Crawford submission, including size and shape, construction materials and suggestions for hydraulic modelling and prototype testing.

Table 2.2. Assessment of Perth's surfing beaches (after Crawford, 1988)

The government, having a duty of care to provide safe recreational facilities, and sponsorship from private organisations, were outlined as the most likely sources of funding for such a project. The Crawford submission was a good conceptual start and included a useful analysis of the quality of Perth's surf breaks and their potential as artificial reef sites.

From research into desirable wave characteristics and the outcomes from public submissions, the ASRC was of the opinion that the wave characteristics which should be promoted by the artificial surfing reef were as follows:

1. Left and right hand break.
2. Surf should work with swell sizes ranging from 0.5 metres to 3.5 metres.
3. Peel angle for design should be 45 degrees, on the basis that 30 degrees is appropriate for beginners, and 60 degrees is desirable for professional boardriders.
4. Wave steepness should be such that *plunging* is common.

2.2.2.2 Site Selection

A visual inspection of all metropolitan sites and support services, and review of the assessments submitted by Crawford, resulted in the compilation of a matrix summary of wave attributes and support services for all the sites under consideration (ASRC, 1994). The investigating committee recognised that the development of an artificial reef or series of reefs to provide new surf sites might also provide a tourist destination in an area that presently lacked a focusing feature. Careful siting and construction of an artificial reef and associated onshore facilities might produce surfing conditions suitable for surfing contests of an international level which could be held during the day or night (ASRC, 1994).

While the primary intention was to provide waves for surfing, the investigating committee felt that the reef had the potential to serve as a beach protection structure and to provide a marine habitat. The reef could be used for diving and/or fishing when surf conditions are calm and unsuitable.

It was decided by the ASRC that the ocean contours and existing reef formation at Cable Station, south of Cottesloe, make it an ideal location for a submerged artificial surfing reef. Two existing peaks in the reef, which were separated by relatively deep water, were thought to be able to be enhanced by an appropriate structure to create a left and right hand break which would be operational for the greater part of the year. The Cable Station area had also been noted as being subjected to little sand movement and minimal swimming, fishing and other non-surfing use. The location of Cable Station is shown in the figure below.

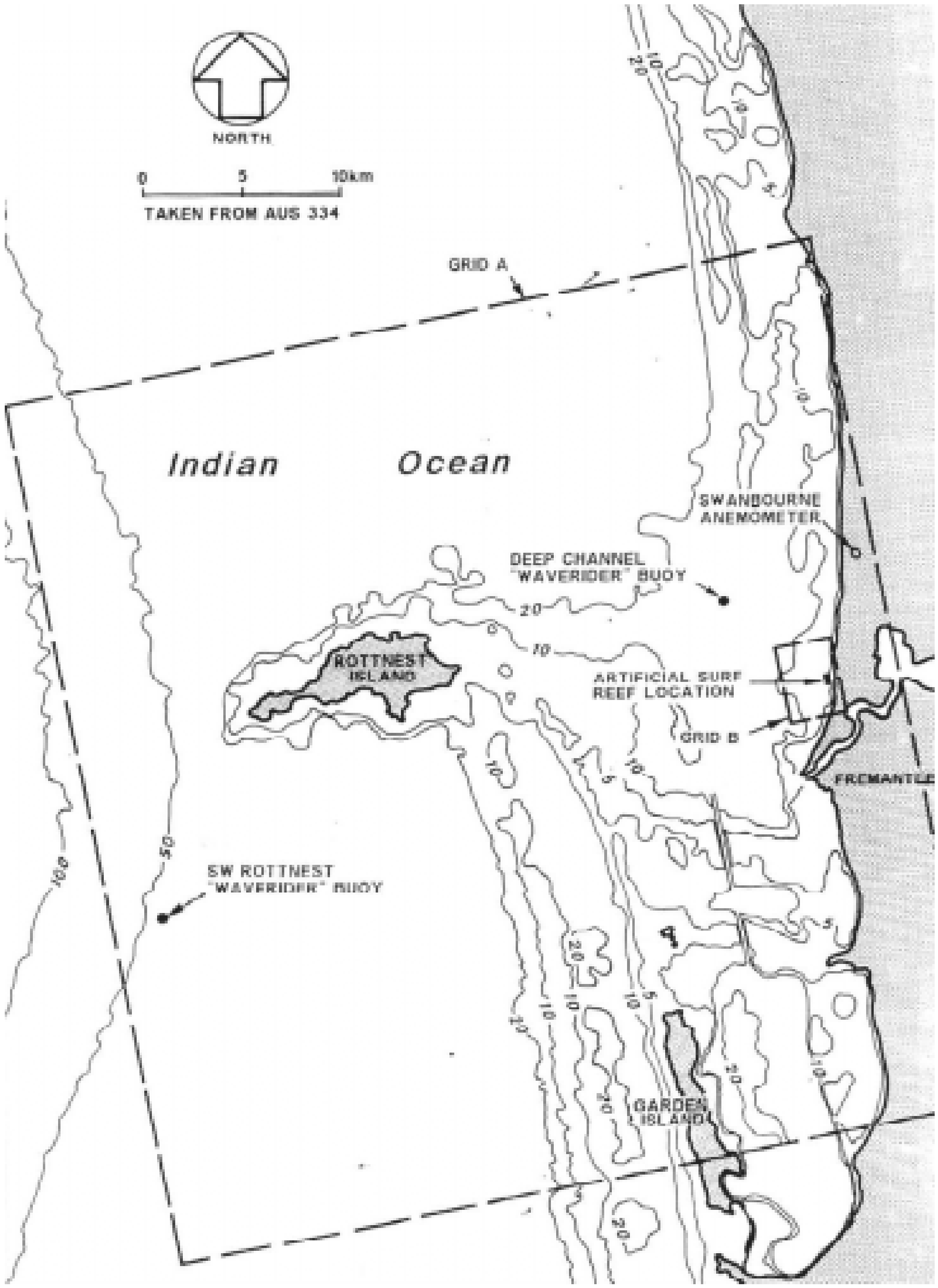


Figure 2.12. Location along the Perth coastline of the Cable Station artificial reef.

The committee noted that, although the area experiences a lot of swell in summer and winter, and the wave looks promising, it rarely breaks properly (ASRC, 1994). The likelihood of obtaining a good wave was greater at low tide. Cable Station was also known to work particularly well after winter storms when northerly swells had created an offshore bank.

The Cable Station site, also known colloquially as *Cables*, is readily accessible by public transport via the Wellington Street Train Station, which the ASRC thought would make it attractive to many younger surfers, particularly those living south of the river who cannot find transport to the popular breaks at Trigg and Scarborough.

In their determination that Cables be the preferred site for the first metropolitan artificial surfing reef, the committee were aware of the work of Silvester (1975) who found that large depressions in the seabed offshore were gradually migrating landward in this area, which indicates a loss of sand available for the creation of natural breaks for surf.

Hence the Cable Station location was chosen as the site for the first artificial surfing reef on the Perth coast (and in the world), with the view that it would enhance and protect the existing break, increase the frequency and quality of breaking at the site, and secondarily provide a diving and/or fishing area when surf conditions are calm.

2.2.2.3 Design Studies

The Department of Marine and Harbours was designated to handle the necessary engineering for the project and were assisted in the design aspects by the Centre for Water Research at the University of Western Australia. The work by the Centre for Water Research was completed in two main stages.

Firstly a series of experiments were conducted in a 50 metre long wave flume to determine the optimal two dimensional bottom profile, specifically for a surfing break, in a wave climate typical of the Cable Station location. This study was undertaken by Mark Button (1991) as an undergraduate engineering honours dissertation under the supervision of Drs. Charitha Pattiaratchi and David van Senden of the Centre for Water Research.

The second stage of the experiments were conducted in a 40 by 40 metre wave basin to determine the three dimensional plan shape of the reef, which defines the length of the ride, peel angle and the optimum orientation to incoming swells. This second study was undertaken as an undergraduate pass project by Matt Lyons (1992), under the supervision of Dr. Charitha Pattiaratchi. The outcomes of the design studies have been reproduced for publication by Pattiaratchi (1997a).

BUTTON STUDY (1991)

Until the time of the 1991 Button study, breaking wave experimentation had typically been conducted on beaches of constant slope. However, in nature, beaches are made up of any number of sections with varying slope with no two beaches ever being the same (Button, 1991). The course of laboratory experiments undertaken in this study aimed to quantify the effect of complex bathymetry on breaking wave characteristics. The knowledge gained would then be used to optimise the design of the Cable Station Artificial Reef.

All of the tests undertaken by Button were conducted in a wave flume at the Coastal and Hydraulic Engineering Laboratory located in Floreat Park, Perth. The wave flume was 50 metres long, 1.5 metres wide, with a water depth of up to 1.2 metres. A glass wall section 3 metres long was built into the side of the flume to allow a visual description of breaking waves. The waves were generated by a digitally controlled, hydraulically actuated, vertical paddle wave generator. Three different beach slopes were used during the course of the experiment, which covered a total of 214 individual tests. Figure 2.13 shows the three different slope configurations used in the experiments.

In general, the experiments indicated that a complex bottom profile effects both wave shoaling and breaking shape characteristics. When a steeper section is placed in an otherwise plane beach, there is a decrease in wave shoaling (Button, 1991). The effect of complex bathymetry is that wave breaking characteristics become dependant on wave size rather than wave steepness. The effect is minimal when $H<0.3h$, however increases to eventually dominate breaking as wave height exceeds $0.3h$.

To optimise breaking wave height and wave shape in the design of an artificial reef for surfing, it was deemed necessary to keep the beach slope approximately constant (Button, 1991). It was found that a constant 1:20 sloped bathymetry was requisite to produce a surfable plunging wave for the range of wave heights and periods maximum of one design wave height vertically and located in at least 1.5 times the design wave height of water.

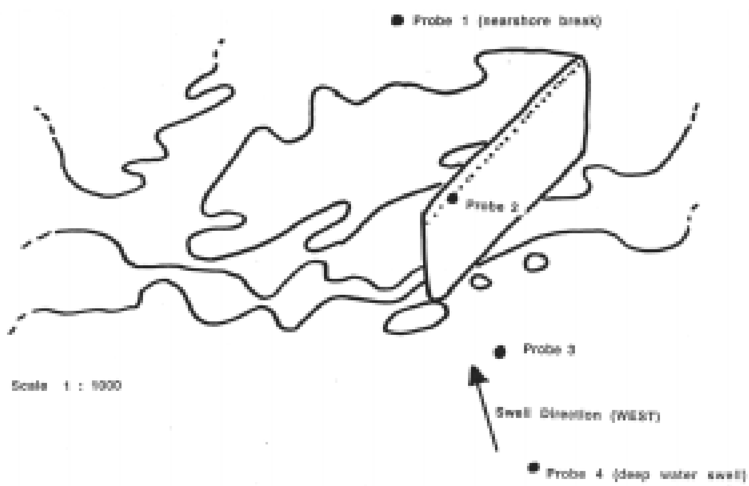
Figure 2.13. Slope configurations tested (after Button, 1991).

LYONS STUDY (1992)

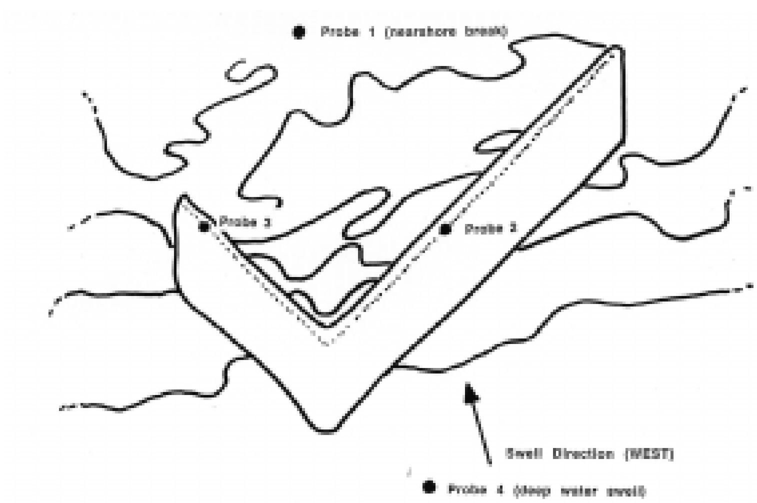
As a basis for the Lyons study, 1992, a gently plunging wave, tending to spill at higher tides, was chosen as the most suitable breaker type for surfing. All testing for this study was also undertaken at the Coastal and Hydraulic Engineering Laboratory. The basin used was approximately 40 metres square with a depth of 0.5 metres.

The waves were generated by a wave paddle, approximately 12 metres long, which produced monochromatic regular oscillatory waves onto the model at a preset wave height and period. Wave conditions for testing the various reef designs were chosen according to the conditions present at Cable Station. The swell conditions chosen were 0.5, 1.0, 1.5 and 2 metres, and each of these swells was tested with varying wave periods of 8, 10, 12 and 14 seconds (Lyons, 1992). Thus a matrix of sixteen wave conditions were recorded for each of the three reef designs and for the existing reef model. Figure 2.14 shows the three different reef designs tested.

Reef Design 1:



Reef Design 2:



Reef Design 3:

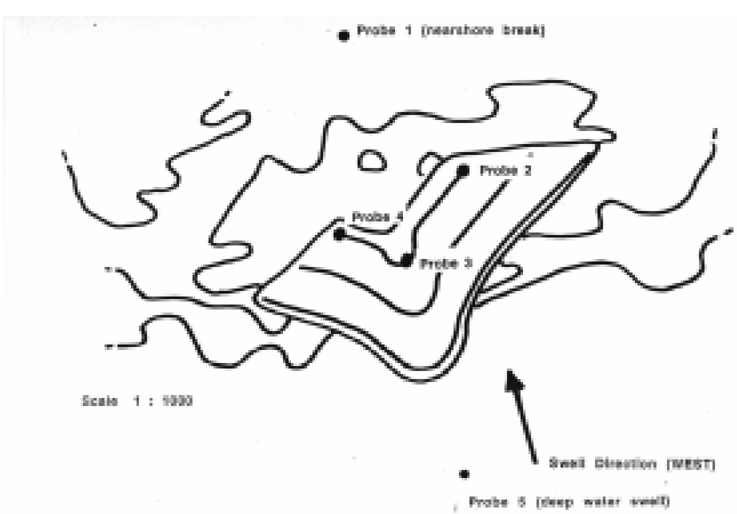


Figure 2.14. Alternative reef designs tested (after Lyons, 1992).

A model of the existing reef was constructed at a scale of 1:40. It covered a prototype area from the shoreline to the 7 metre depth contour offshore (approximately 350 metres), and about 600 metres in the longshore direction, centred on the existing reef. The sea level elevation was set at the average tide level of 0.78 metres for all tests (Lyons, 1992). Experiments were made on the effect of the reefs on the sand movement patterns in the nearshore zone. Beach sand, crushed macadamia shell and a mixture of these two substances were used to model sediments.

Swell direction was taken to be predominantly from the west, however some testing on peel angle and peel rates were carried out using swell direction variations of 10 degrees south and 10 degrees north of west.

The depth of water over the reef determines the range of wave heights which will break over the reef (Lyons, 1992). It was taken to be desirable to transform swell conditions above 1 metre into good surfing waves, concentrating on the range from 1 to 2 metres. The minimum depth of the reef was concluded to be 1 metre below Datum tide level, which would correspond to the reef being 1.78 metres deep at the break point at an average tide level. Even at low tide, the reef should therefore not bare, and there should be sufficient depth for surfers to fall in the water without striking the bottom any more than they would on a natural surfing break (Lyons, 1992). Another consideration in the reef design was to maximise the use of the existing reef in the design to minimise the overall quantity of material to be used for construction.

A constant peel angle of approximately 45 degrees was considered to be the best design peel angle for the reef. This, with a total of 20 degrees swell direction change, results in a range of peel angles between 25 degrees and 65 degrees. This gives a wide range of peel rates and would produce surfing waves for a variety of skill levels. A summary of the characteristics and results for each of the reef designs is shown in Table 2.3.

Table 2.3. Summary of reef design characteristics (after Lyons, 1992).

The final chosen design (Design # 3) was involved extension of the existing 3 metre contour out into deeper waters and then creating a 1:20 slope back up the existing reef to produce a left and right hand plunging breaker. Included in the design was a slightly less than 1:20 slope on the point (seaward extent) of the reef (See Figures 2.15 and 2.16, plan view and cross section).

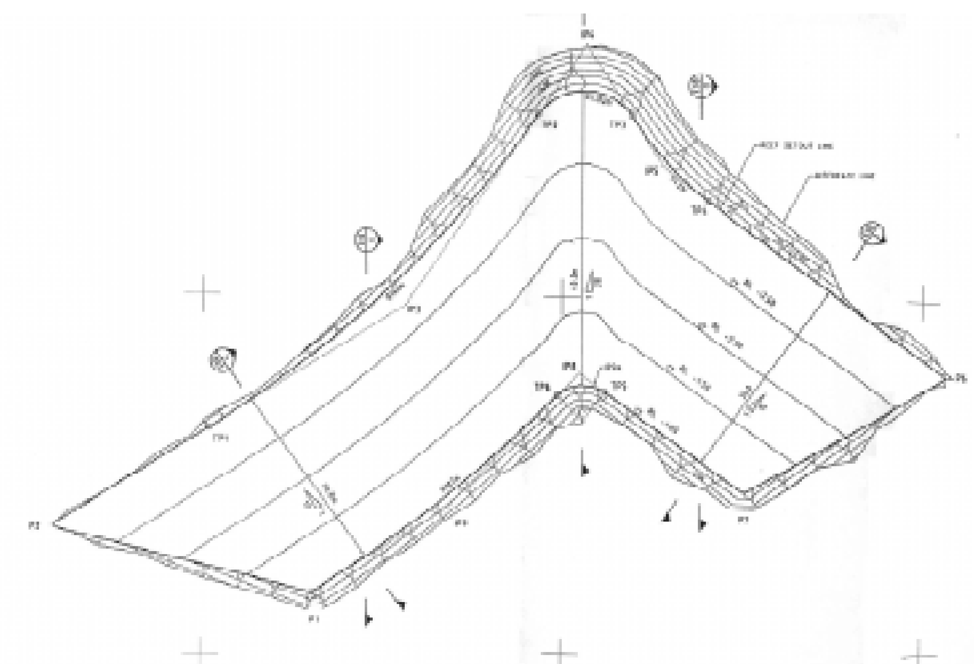


Figure 2.15. Plan view of the chosen reef design.

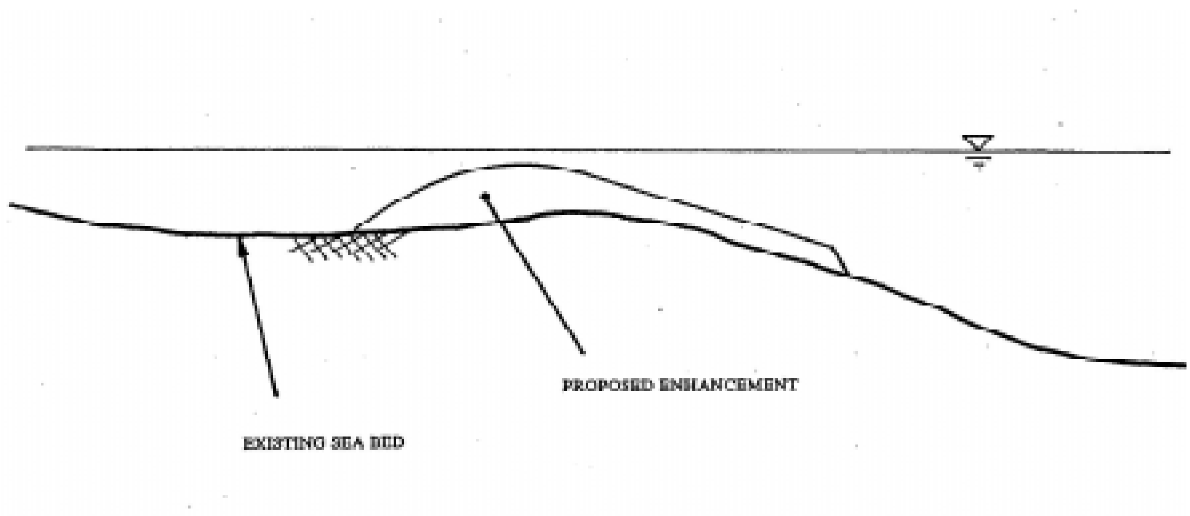


Figure 2.16. Section profile of the chosen reef design (after Lyons, 1992).

This design, as opposed to earlier tested designs had a much larger shoaling area so that the approaching waves don't experience a sudden change in depth, and means that wave shoaling over the reef is much more extensive. Another advantage of this design was its use of the existing reef. The artificial extension hugs the existing reef for the most efficient use of material and also utilises the existing reef in the wave break (Lyons, 1992). From a 2 metre incident swell, the results showed that up to a 4 metre plunging wave was produced on the right hand break, and 3.2 metre plunging waves on the left hand break. The reef design also induces enough shoaling for waves to break under swell conditions as small as 0.5 metres at mid-tide, which was a vast improvement on previous designs.

Hence, the proposed artificial reef comprised of a boomerang shaped submarine rock structure. The overall length from north to south is approximately 140 metres, while the maximum width is about 70 metres. The artificial reef was proposed to be located about 275 metres offshore, with the structure constructed on the existing reef in 3 to 6 metres depth of water. The new structure, when completed, would be between 1 and 3 metres below the average tide level (Alan Tingay and Associates, 1995).

During the study, it became apparent that it would have been easier to design a surfing reef on uniform topography, as the location of the artificial reef in relation to the existing reef bathymetry was a critical factor which determined whether a surfable wave could be maintained over a prescribed distance (Lyons, 1992; Pattiaratchi, 1997a).

Even though the existing reef and the headland are rocky, the effects of the reef on sediment transport in the region still needed to be considered. The use of sand and crushed macadamia shell as model sediments proved to be ineffective in modelling the influence of the new reef on sediment movement. With experiments such as those performed by Lyons, problems arise from not having the sediment to scale with the model, thus causing inaccurate results.

By analysis of video recordings taken during the experiments, scoured areas, resulting sediment movement and current directions gave a rough estimate of the sediment movement. Figure 2.17 shows the current flow around the reef when Design No. 2 was tested. It also shows the predicted sediment movement at the site, working on the assumption that sediment is actually present at the site. On the rare occasion that sediment is located in the area, it is expected to result in the formation of a sand bar point directly in front of the reef, and transportation of sediments both in a northerly and southerly direction onto beaches in the proximal area (Lyons, 1992). The presence of an artificial reef at Cable Station should tend to reduce the wave energy reaching the mainland and therefore act to preserve the existing point.

The method and materials used in construction of the artificial reef are outlined in Section 2.2.2.8 of this report.

Figure 2.17. Current behaviour and predicted sand movement.

2.2.2.4 Perth Wave Climate

In Crawford's 1988 submission to the ASRC, he took the first look at the Perth metropolitan area's wave climate in relation to the feasibility and siting of an artificial surfing reef. Hegge (1994), as part of his study on the environmental effects of the proposed reef, also had a general look at the prevailing weather conditions and wave climate along the Perth metropolitan coast.

Port and Harbour Consultants (PHC) conducted a preliminary assessment of the wave climate at Cable Station during 1989. Their findings were based on a one year hindcast data set for the offshore region, transformed to the near vicinity of the site in approximately 8.6 metres of water. The study produced total sea states at the site, which were reported as the combined conditions of swells, offshore seas and local seas affecting Cable Station. These results did not include an assessment of individual wave trains, winds or other variables which may make an individual event more or less surfable. Also, it should be noted that this hindcast study was for one year only and may not reflect a true average statistic for the Cable Station site.

This study suggested that the peak period corresponding to the 50% exceedence level was 7-8 seconds, with the period band being wider toward the low period end in summer due to prevalence of the sea breeze. Significant wave heights were found to be larger during winter than summer, with the 50% exceedence values being approximately 1.3m and 1m respectively. Annually, nearly 50% of wave heights are between 1m and 2m at the site. The most common sea-state annually was estimated to be H_S: 0.5-1.5m and T_S: 7-10s. During summer, the window is H_S: 0.5-1.3m and T_S: 4-10s, while in winter H_S: 0.6-1.7m and T_S: 7-11s.

A concerted effort into quantifying the wave climate off the Perth coast was undertaken by Lemm (1996). Previous to this study, local wave conditions for the coastal waters of Perth had generally been limited to site specific studies. Hence the principal aim of his study was to provide a detailed description of the Perth offshore wave climate, achieved by analysing non-directional wave data collected over the period of 1993-1996, in 48 metres of water, southwest of Rottnest Island. A high quality (97% coverage) 30-month data set from the period between March 1994 and August 1996 was analysed by Lemm in detail to provide a reliable, quantitative and qualitative summary of offshore wave conditions for Perth coastal waters.

Lemm (1996) described the offshore wave climate of Perth to be energetic and variable, with a distinct seasonality which largely reflects the nature of the local wind regime. During summer, sea breeze generated, moderately energetic seas make a significant contribution to the total offshore wave energy (Lemm, 1996). In winter, frequent and intense storms generate high energy waves.

The offshore wave climate of Perth is thus characterised by a shift from predominantly low period (< 8 s) seas in the range of 1-2 metres during summer, to generally high period (> 8 s) swell and storm waves of 1.5-2.5 metres in winter (Lemm, 1996). The offshore wave conditions have been found to be much more variable in winter than in summer, with July being the most energetic month, having a mean significant wave height (H_S) of 3.0 metres. February is the 'calmest' month, with a mean H_S of 1.5 metres. A background swell above 0.5 metres, generated distantly in the Indian and Southern Oceans, is present year-round (Lemm, 1996).

Lemm's (1996) quantitative analysis of storms showed that extreme wave conditions for offshore Perth had been previously underestimated. Earlier local studies provided 100-year design-wave values of approximately 7 metres. However, over the 30 month study period assessed, eight storms with maximum significant wave heights (peak H_S) greater than 7 metres were observed, the largest of which had a peak H_S of 8.6 metres. The 1-year and 100-year offshore design wave estimates provided were 7.7 metres and 10.8 metres respectively. The analysis also showed that storms are most frequent and intense during the month of July. Lemm (1996) also found, from the 30-month data set, an annual increase in the number of severe storms, peaking in 1996.

The two dominant short-term features of the Perth offshore wave climate are diurnal summer sea breeze cycles and transient winter storm events (Lemm, 1996). These summer sea breeze cycles are characterised by the daily superposition of energetic seas on a background swell field. A typical Perth winter storm is characterised by a rapid transfer of energy from lower to higher wave periods, followed by a more gradual dispersion of energy which results in a 'confused' sea state with waves spread over a broad range of periods (Lemm, 1996).

The prevailing direction of wave climatic components off Perth are distinctly seasonal. Swell waves have been noted to arrive at Perth mainly from the south-southwest in summer and from west-southwest in winter. This clockwise shift in incident direction is caused by the south-to-north displacement of the extra-tropical low pressure region, which generates swell far out in the Southern and Indian Oceans summer and west in winter, corresponding to the change in modal wind direction. This modal wind direction is southerly in summer due to coastal sea-breezes, and westerly in winter due to synoptic-scale pressure gradients (Lemm, 1996).

As waves travel into the shallower inshore waters of Perth, they are modified by a number of processes. The waves are refracted due to changes in bathymetry and diffracted by exposed reefs and islands. Rottnest and Garden Island, in particular, have significant sheltering effects on the inshore wave field (Lemm, 1996). Waves have also been found to break or partially reflect along the line of shallow reefs extending along much of the Perth coastline.

These processes lead to wave height attenuation, the degree of which varies considerably along the shore because of the high variability in incident wave direction, bathymetry and sheltering by exposed reefs and islands. Attenuation factors have generally been found to lie in the range of 0.4-0.6, though in the lee of islands may be as low as 1% of the offshore wave energy. The wave period generally remains constant as waves travel inshore (Steedman, 1981).

The *Cables Station Artificial Surfing Reef Wave Climate Study* was undertaken by MP Rogers and Associates (MRA) in 1998 for the Department of Transport. They were required to complete a detailed wave climate study of the proposed reef site with the primary purpose of quantifying the occurrence of surfable conditions at the site (See also Section 2.2.2.7).

Based on observations of passing ships and various wave measurements, MRA (1998) report the deepwater wave climate off Fremantle to be dominated by the following:

SWELL WAVES

- Originate from distant storms in the Southern and Indian Oceans,
- Summer swell typically 1-2m height, 8-16s period, from the WSW (240-250°),
- Winter swell typically 1-3m high, 10-18s period, from approximately W (255-265°),
- Sometimes during winter and spring, the swell wave heights can exceed 4m.

SEAS GENERATED BY WINTER STORMS

- H and T of these waves vary markedly from storm to storm,
- Often the wave heights exceed 4m and peak spectral wave T can reach 6-8s.
- Severe storms: deepwater H_S can reach 7m and can include swell components of 4-5m,
- Direction of approach can range from northwest to southwest during the passage of a storm.

SEAS PRODUCED BY THE SEA BREEZE

- The sea-breeze is a diurnal cycle which is most prevalent in summer.
- Generation of these sea-breeze waves is limited by the offshore extent and duration of the sea-breeze system.
- Typical height range of 0.5-1.5m, peak spectral period from 3-6s.
- Wave direction dominated by the direction of sea-breeze, so generally arrive from the southwest.

As these waves travel towards the shore, they are greatly affected by the nearshore bathymetry and the reefs. Waves travelling to the coast around Fremantle are modified by the following physical processes:

- Reflection off reef faces,
- Depth limited breaking on the reef tops and shallow areas,
- Diffraction through the gaps in reefs,
- Attenuation due to hydraulic turbulence as the waves travel over the reefs and other areas of shallow water,
- Refraction and shoaling.

These processes act to varying degrees, and significantly modify and attenuate waves as they approach the coast (MRA, 1998). The higher frequency waves generated in local storms and by the sea-breeze are less affected by refraction and aren't necessarily well aligned with the coast. However, the low frequency swell waves are greatly affected by refraction and the crests in shallow water generally become well

The astronomical tides in the Fremantle region are predominantly diurnal and are relatively limited in range. The typical daily range is around 0.5m during spring tides and around 0.2m during neap tides. The tides have the following characteristics:

- Mean Low Low Water (MLLW) ~ 0.5m above Chart Datum
- Mean Sea Level (MSL) ~ 0.7m above Chart Datum
- Mean High High Water (MHHW) ~ 0.9m above Chart Datum

For their wave transformation modelling, MRA used the finite difference model 2GWAVE to establish the wave climate at the site and assess the improved surfability with an artificial reef in place. Details of their results can be found in Section 2.2.2.7 of the current report.

2.2.2.5 Management and Construction

In December, 1993, the ASRC called for expressions of interest for the construction of an Artificial Surfing Reef at Cable Station, Cottesloe. The purpose of this was to evaluate costs and construction techniques. It was felt that, in view of the technical nature of the submissions and the need for expertise beyond the wider Committee, that a sub-committee be formed to assess the validity and strength of the construction submissions. Specifications for the construction and criteria were issued to all interested parties.

Detailed construction design was undertaken by Nello Siragusa of the Department of Transport in 1995-96. Project management of the reef design was awarded by the Department of Transport to Egis consulting in 1997, who then prepared a construction tender document for a lump sum contract which went out to construction companies for tender in July 1998. This called for submissions from the tenderer of such things as a complete schedule of prices, a draft construction plan, preliminary safety plans and financial details amongst others.

This document also contained a *Scope of Works*. This included an outline of works to be completed with the project defined as being to construction artificial surfing reef at Cables, using stable material, to the dimensions, lines, levels and slopes specified. It was determined that the most appropriate material to be used is granite stone, with sand to be placed over the top of the reef at the completion of construction if so directed by the Superintendent. The sand would be placed in order to fill voids in the reef. Local government restriction prevent stockpiling or the operation of a plant on the South Cottesloe foreshore, therefore the material was to be transported to the reef site using a dumping barge. It was envisaged that the material would be transported from Fremantle Port, due to its proximity to the reef site. However it was left open for the Contractor to nominate to use any Port (Egis, 1998).

The basic outline of the phases of construction was as follows. The granite stone material and sand were to be quarried and carted to the nominated Port by the contractor. Once there it would be stockpiled into separate stockpiles for each Class of stone and sand. Table 2.4 shows the median unit mass and the estimated quantities required for each of the granite Classes and for the sand. A barge would then be loaded by the contractor, ensuring no rock or sand falls in the water at the berth. This sand and rock (and the required personnel) would then be transported to the construction site by the barge and the stone would then be placed on the seabed according to the dimension, lines, level and slopes specified in the design (Egis, 1998).

Table 2.4. Estimated quantities of the specified classes of granite stone required for constuction (after Egis, 1998).

Stone sizes were to be placed according to this specification and be placed such that the voids between the stones be minimised. The two classes of stone to be used were represented as *reef stone* (Class II, 1.5 tonne unit), and *perimeter armour* (Class I, 3.0 tonne unit). This reef stone was to comprise the main body and crest of the reef, and the perimeter armour was to surround the reef stone.

Upon completion of the placement of all the rock to the satisfaction of the Superintendent, the contractor was to place a layer of sand over the completed reef. The sand would be placed to fill the voids below the top layer of the reef stones and between the stones forming the upper surface of the reef (Egis, 1998). Drawings of the general arrangement plan, set out plan, and cross sections for construction can be found in Appendix A1.

In 1998, the submission from WA Limestone won the artificial reef construction job, with construction being undertaken via use of a barge transporting the granite stone material from Fremantle Harbour.

2.2.2.6 Design Optimisation

Two main design reviews have been conducted for the Cable Station Artificial Reef design. The first of these was conducted by Clive Neeson for the Department of Transport in January of 1998. The other, also commissioned by the DOT, was undertaken by Port and Harbour Consultants (PHC) in June, 1998. The wave climate study by M P Rogers and Associates of October 1998, outlined above, also brought up some artificial reef design issues.

NEESON, 1998

The Neeson report was generally found to be fairly lacking in its review findings, was poorly structured and poorly referenced, with a lack of hard evidence to back up many of the claims. Generally there was a strong leaning towards the use of numerical modelling in preference to physical modelling, without outlining specific improvements that this may make on the reef design. Documented information is interspersed with subjective observations which don't appear to be backed up by evidence. However, there are some points of interest and importance to be drawn from the review, including aspects of the design which require improvement.

This design review process was to take the following form:

- Review of all data, documentation, experiments, results, conclusions etc. which had led to recommendation of the current prototype.
- Identification of any outstanding work

- Preliminary comments on the design.
- Identification of resources and expertise to perform the design verification.
- Survey of the latest developments and resources in artificial reef design.
- Recommend a strategy and program for the design verification process.
- Documentation of all of the above as a reference for the design verification and engineering.

Neeson claimed that his report documented completion of this design review process and provided a comprehensive reference for the whole design process. The writer feels these claims were an exaggeration, since aspects of this design review, as outlined above, were left unfulfilled or unsatisfactorily completed. The document does not provide a 'comprehensive reference for the whole design process', as it omitted several aspects of the design development and previous works undertaken.

The total project requirement and scope was fairly well defined by Neeson, identifying some outstanding work required to optimise and finalise the design. Neeson looked at the previous wave climate studies for the area and concluded that further work was still required, including:

1. Qualification of the wave climate at the Cable Station site for wave height, period and directional variation.
2. Run refraction/diffraction model to 4 km offshore to determine the natural focusing effects of near-reef bathymetry.

Studies of this nature have since been undertaken by Port and Harbour Consultants, and M P Rogers and Associates, as outlined in Section 2.2.2.4.

For an artificial reef, a feasibility study is necessary to determine the project viability. Neeson suggested that a feasibility study should encompass the following sub-modules:

1. Economic analysis
2. Environmental and social impact study
3. Potential amenity value assessment
4. Assessment of suitable locations

The environmental and social impact study and the economic analysis were recognised as being complete, and are outlined in this report in Sections 2.2.2.7 and 2.2.2.9, respectively. The amenity value assessment, as outlined by Neeson, included expected use by surfers and potential amenity value for other groups. At the time of Neeson's assessment, only the Hurst study on surfability had been conducted, however since this time, two other studies have looked at the increase in surfability which should result from construction of the reef (See Section 2.2.2.7).

Neeson suggested that there should also be consideration of the artificial reef's use by other parties such as windsurfers and divers. This potential for other uses was considered in the Alan Tingay and Associates (AT&A) report of 1995 (See Section 2.2.2.9). A public opinion assessment in the form of the survey conducted by AT&A concluded that the public in general approved of the project, however some local residents feared a reduction in the value of their land.

PORT & HARBOUR CONSULTANTS, 1998 (June)

Several design issues were raised in this study undertaken for the DOT. During the study, PHC received revised design drawings of the reef, which revealed that the design reef is somewhat altered from the physically modelled reef in that the reef will not be grouted and is to consist of large armour rocks. These construction details for the reef were outlined Section 2.2.2.5.

The grading information for the proposed construction materials indicated that rock would not be well graded, being between 0.5t and 2.5t in size for the main part of the structure. This would result in a highly permeable structure. From this proposed grading, PHC identified two separate issues:

- Energy loss due to friction and porosity;
- Effective upper reef level, as experienced by the waves.

Both bottom friction and seabed porosity act to absorb wave energy, and thus reduce wave height, as waves pass over surfing reefs. The issue of determining an effective upper reef level was identified as being critical to the performance of the reef. Voids present in the structure would lower the effective upper surface below the design line.

Due to these issues, it was felt that the design reef performance might differ from that of the physical model. They concluded that for the structure to perform as expected, the reef should be built such that all material below the design line is well packed.

The design provided for use in the PHC study included a slight curvature in the right hand break, concave in the sense of an observer standing offshore. This would actually help the wave to closeout, by directing the breaker path towards a smaller peel angle. Such a feature was not present in the physical model and the possible straightening of this arm was a suggested topic of investigation.

PHC pointed out that the reef alignment was based on the assumption that the mean wave direction is 270°. The desire of the project was to optimise the surfability of both the left and right breaks under most of the expected swell conditions, and hence they suggested that a more accurate study of the wave climate at the site should be undertaken to look at minor variations in the wave direction, allowing for further optimisation of the reef alignment.

This aspect was investigated in the M P Rogers & Assoc. (MRA) study of October, 1998, and the modelling appeared to indicate that most of the swell waves arrive at the reef site from 270 to 285° and not the 260 to 280° tested in previous studies. In light of this, they suggested that it may have been appropriate to slightly adjust the orientation of the reef. However, this was not found to be feasible, in that adjustments in the orientation of the reef would be very difficult due to the pre-existing reef bathymetry and would increase the tendency for the waves to closeout (Charitha Pattiaratchi, *pers. comm*).

PHC also looked at the width of the takeoff zone in the design. The modelling results suggested the takeoff zone could be up to 8 metres in width. Should this be considered to be too narrow to accommodate multiple surfers, the design offers the potential to widen this region by widening the reef apex.

To provide a more accurate assessment of the potential increase in surfability at the site, PHC suggested that a hindcast study providing joint occurrence of all issues affecting surfability including swell, seas, winds and tides should be undertaken. This need was fulfilled in the MRA study in October of that year (See Section 2.2.2.8).

2.2.2.7 Environmental Concerns

The need for studies into the environmental effects of the proposed artificial surfing reef was identified early in development of the Cables Station Artificial Surfing Reef. In Crawford's 1988 submission to the ASRC, he identified that an artificial reef or any other modification to the offshore environment would have an impact on the physical and biological environment. Crawford suggested that the overall effect would be benign, however recommended that an opinion be sought from an accepted authority. It was also thought that a new artificial reef might enhance the environment, with a beneficial effect on biota, however there would be some accretion and erosion of the seabed in the vicinity of the reef which would need to be investigated.

In their 1994 submission to the Minister for Sport and Recreation, the ASRC identified environmental considerations to be investigated further. The site selection of Cable Station was restricted to where reef development presented minimal possibility of influencing coastal erosion, either local or remote. The Committee was also aware that reef construction could have a positive impact on the shoreline and enhance deposition.

The metropolitan beach coastline consists of sandy beaches or cliffed headlands from Port Beach in the south to Mindarie Keys in the north. The substrata is mostly Tamala limestone overlaid with ancient dune structures (ASRC, 1994). The section of beach of which Cable Station is part of is characterised by rocky outcrops and shallow rock platforms. Data provided on shoreline changes in the metropolitan area over the past 10 years indicates that the Cable Station location is one of the most stable in the metropolitan area.

The beach at Cable Station is not presently suitable for other activities, such as fishing or swimming, due to the difficult access and rocky foreshore. It is expected that any additional sand deposits which may result from construction of the artificial reef would actually make access easier.

The proposal for an engineered surf reef at Cable Station was submitted to the Environmental Protection Authority (EPA) and in 1991, the EPA decided that the proposal would be assessed at informal level. Dr. Des Mills of the Department of Environmental Protection (DEP) was invited onto the ASRC and identified several environmental considerations arising in relation to the proposed reef and recommended that the specialist sub-committee address these aspects.

This specialist sub-committee included Dr Nello Siragusa (then with the Department of Transport), Dr Ian Eliot (Department of Geography, UWA) and Dr Charitha Pattiaratchi (Centre for Water Research, UWA). This sub-committee was to consider and report on the following; "Within the general context of the littoral drift/beach alignment issues in the Cottesloe/Fremantle section of the coastline:

- provide an evaluation of the long term changes to littoral drift/beach alignment due to the presence of an artificial reef;
- provide an evaluation of the short and long term changes to littoral drift/beach alignment due to the proposed construction options;
- provide an evaluation on the future stability of the rocky coastline at the point of access to the reef, the success of past remedial measures, and the issue of a steep access ramp."

The advice from the DEP, and the criteria placed on the artificial reef proposal, was as follows;

- an artificial reef should use construction materials which are essentially non-toxic to marine organisms;
- construction materials should be placed only on the reef and seabed areas supporting commonly found and colonising marine biological communities;
- construction methods should only affect common marine communities which can readily recolonise and recover;

- short and long term changes to the littoral drift arising from the construction method or the presence of an artificial reef itself should not lead to long term erosion of beaches;
- stability of the foreshore should be maintained.

The DEP considered that an artificial surfing reef proposal meeting these criteria would be environmentally acceptable.

HEGGE, (1994):
In September, 1994, Dr. Bruce Hegge of the Department of Geography, UWA, produced a study on the anticipated impacts of the proposed reef. In August of that year, Peter Browne-Cooper of the DEP had requested an expanded statement on the anticipated environmental impacts of the Cables reef, within the general context of littoral drift and beach alignment issues for the Cottesloe to Fremantle coastline.

Hegge (1994) outlined the fact that no artificial reefs had been placed in the natural environment in the past, however, analogues existed through the construction of offshore breakwaters to protect shorelines. Offshore breakwaters had been constructed at Kwinana and Quinns Rock on the Perth metropolitan coastline and in both instances they were close to the shore and resulted in shoreline accretion immediately shoreward of the breakwaters.

The inshore topography of the Perth metropolitan coast has a complex topography of limestone ridges and depressions, formed from lithified Pleistocene marine and aolianitic calcarenites of the Tamala formation, which is very resistant to erosion (Hegge, 1994). The calcarenite outcrops are a series of shore-parallel reefs and islands that result in the significant dissipation of offshore wave energy by up to 40%. Hence wave energies along the mainland shoreline are generally low. The offshore reefs function as breakwaters that shelter the coast and contribute, through wave refraction, to the development of sediment accumulation forms at the shoreline (Hegge, 1994).

The proposed location of the artificial reef is atop a Pleistocene limestone ridge and limestone of the Tamala formation. This limestone provides a stable base for the steep cliffs to the south of Cable Station and provides good protection to the backshore during beach erosion events. A thin veneer of Holocene sand overlays the calcarenite along the coast adjacent to the Cable Station reef. These sands are principally composed of calcium carbonate grains of marine origin, intermixed with a small proportion of quartz and heavy mineral grains (Hegge, 1994). They are part of the sediment in circulation within the Cottesloe-North Fremantle sedimentary cell. The sediment in this cell is periodically supplemented with dredge spoil from the vicinity of the Fremantle Harbour.

The summer sea-breeze system has been noted as a very important part of the coastal weather of the metropolitan coastline. The sea-breeze is associated with strong northward flowing longshore currents and is an important mechanism for the northward transport of sediment along the coastline. Hegge noted that the predominant swell direction along the Perth metropolitan coastline is from the west-south-west and this drives a northward littoral drift along most of the Perth coastline. However, refraction of swell around Rottnest Island gives rise to a preferred southward drift along the shoreline between Cottesloe main beach and Leighton beach. During summer though, the sea-breezes can override this southward drift and induce a net northward drift of sediment along this beach sector (Hegge, 1994).

Swell waves, which prevail during summer, cause an onshore movement of sediment and general beach accretion. Winter storms often produce large storm waves which arrive from the north-west, which can supplement the prevailing southward littoral drift along the Cottesloe-Leighton shoreline. These winter storms are generally accompanied by the removal of sediment from the beach and the formation of nearshore bar features. The beach sediments are thus cycled between the beach and the nearshore bar from summer to winter. The net direction of sediment drift along the Cottesloe-Leighton shoreline also appears to shift seasonally from northward in summer (driven by sea-breezes) to southward during winter (driven by wave refraction and north-westerly storm systems) (Hegge, 1994).

The beach at Cable Station is relatively narrow with very little sediment contained exhibits the classical seasonal oscillation between onshore and offshore as described above. Any net removal of sediment from this region could present problems in eroding the toe of the slope adjacent to Marine Parade and Curtin Avenue. However, the location of the shoreline at Cables has remained stable since the early 1940's, which may be partly attributed to the presence of the offshore reef system (which dissipates wave energy) and the resistance of the limestone which underlies the beach sediments along this section of the coast (Hegge, 1994).

Laboratory studies of the artificial reef show that the zone immediately shoreward of the surfing reef will experience reduced wave energy due to dissipation across the surfing reef (Lyons, 1992; see Section 2.2.2.3). As a result, it is expected that sediment may accumulate in this shadow region (Hegge, 1994). This would also be associated with localised scouring of sediments from the shoreline laterally adjacent to the surfing reef due to the circulation pattern associated with waves breaking over the reef (See Figure 2.17)

From the above considerations, Hegge concluded that the most likely impact of the surfing reef on the shoreline would be accretion on the beach section directly onshore of the surfing reef as predicted in the laboratory, and that no long term shore line change would be anticipated due to the resistance of the underlying limestone to erosion.

To accommodate the anticipated increased usage of the Cable Station area, Hegge asserted that it would be necessary to upgrade the existing access through the dunes and the car-park facilities. There is a necessity at this site to stabilise the dunes and restrict future access to the dunes.

Hegge (1994) also suggested the construction of a low (10-20cm) bund across the shore limestone to facilitate access to the artificial surfing reef, since access to the surf break is presently hindered by the rough limestone rocks that underlie the shoreline. He anticipated that this low rounded embankment would not inhibit the littoral drift of sediments.

It was predicted that any detrimental environmental impacts of the artificial surfing reef, if any, would be the result of increased beach usage rather than directly attributable to the surfing reef itself. The problems associated with this increased beach usage and need for access to the reef could be readily mitigated with adequate planning and management.

ALAN TINGAY & ASSOCIATES, (1995):
The study by Hegge (1994) mainly addressed the effects of the proposed reef on sand movements at the Cables location. Another environmental study was undertaken by Alan Tingay & Associates (AT&A) in 1995 for the Ministry of Sport and Recreation, which also looked at the biological and social impacts of the reef. The AT&A study supports the decision by the EPA that the reef doesn't involve sufficient environmental implications to warrant formal assessment, and concluded that the artificial reef is not likely to cause any significant environmental impacts.

The limestone reef which existed at the site supported a relatively simple biological community of turf algae and some kelp on elevated limestone pinnacles. AT&A thought it probable that the new reef would actually increase biological diversity in the area as it would provide more ecological niches than were previously available.

AT&A agreed with the conclusions of Hegge (1994) that the artificial reef is unlikely to have any significant effect on the beach as it is a relatively small submerged structure that is unlikely to affect the major coastal processes that occur in the area. At most, they thought the reef might create a slight wave shadow inshore which would tend to reduce sand erosion from the beach, and if this occurred it would be a positive benefit, as the beach currently erodes back to bare rock in winter.

A biological survey of the pre-existing reef and seabed, from beyond the reef to the shore, was conducted on the 30th of August, 1995 as part of the AT&A study. They assessed the general biological features of an area of approximately 9 hectares. Details of this study of marine fauna and plant communities can be found in the 1995 report. The marine survey recorded a variety of fauna including fish, starfish, mussels, sea urchins, sea anemones, and various species of sponges and ascidians.

However no rare or unusual animals were sighted, nor were rock lobsters recorded during the survey.

AT&A considered that the impacts during the reef construction phase would depend to a large extent upon the construction method employed. Transportation of construction materials via a barge would result in minimal disturbance beyond the reef site, although suspended sediments were expected to drift inshore and settle onto nearby plant communities (AT&A, 1995). In contrast, the other option, to create a temporary causeway to the reef site, would have resulted in significant local direct disturbance to sea-grass and other marine communities.

The placement of rock to form the artificial reef would effectively eliminate the existing plant and resident marine fauna of the part of the reef which was directly impacted. More mobile species such as fish would not be effected. They concluded that the plant communities on the pre-existing reef were not diverse and comprised mainly small algae, and furthermore, a more diverse community of marine organisms could be expected to colonise the new reef as a result of the wider range of habitats provided by the broken rock.

The study concluded that the environmental impacts of the artificial reef and it's construction would be minimal, however felt it would be appropriate to monitor the extent of the environmental change if the project proceeded. In particular, specific monitoring studies of the inshore *Amphibolus antarctica* seagrass meadows and of the artificial reef itself were recommended.

2.2.2.8 Assessment of Surfable Days (predicted)

Several studies including an assessment of surfable days at Cable Station, both before artificial reef construction and after, have been undertaken. The results of these assessments have been used for comparison with the observed days breaking and surfability determined as part of the performance monitoring undertaken for this thesis.

LYONS (1992):

The first initial look at surfability, in terms of wave breaking, was undertaken as part of the artificial reef design by Lyons in 1992. In order to assess which of the three proposed design possibilities best enhanced the breaking conditions at Cable Station, tests of wave breaking under a matrix of swell and periods was undertaken for each reef design (See Section 2.2.2.3).

The chosen design produced a ‘good, clean, plunging breaker’ for both the left and right hand breaks. This design had a much larger shoaling area than the others such that the approaching waves did not experience a sudden changes in depth, which meant that wave shoaling over the reef was much more extensive.

The chosen artificial extension hugs the pre-existing reef for the most efficient use of material, but also uses the pre-existing reef in the wave break (Lyons, 1992). Lyons claimed that it extended the surfers ride, on the right hand break, from 50 metres (the length of the artificial capping) to almost 80 metres under 2 metre swell conditions, due to continued breaking on the natural reef at the end of the artificial reef arm.

Modification of the take-off point of the previous reef design meant that a peak was produced on approaching waves, which would be clearly visible and ideal for surfers catching the waves (Lyons, 1992). On the point of the reef, the design included a slightly less than 1:20 slope, which resulted in the production of a less violently plunging wave with spilling occurring under larger swell conditions, making the take off much safer for surfers.

Off a 2 metre swell, up to 4 metre plunging waves were produced on the right hand break, while up to 3.2 metre waves were produced on the left hand break in the laboratory tests. The reef was also found to induce enough shoaling to cause waves to break under swell as small as 0.5 metres at mid tide.

Lyons concluded that this reef design would significantly improve the quality of surfing waves at the Cables site, would break in almost all swell conditions in a manner favourable to surfing and would enhance the nearshore wave breaks. Figure conducted on Reef Design 3. This plot indicated that the chosen design would cater for all skill levels.

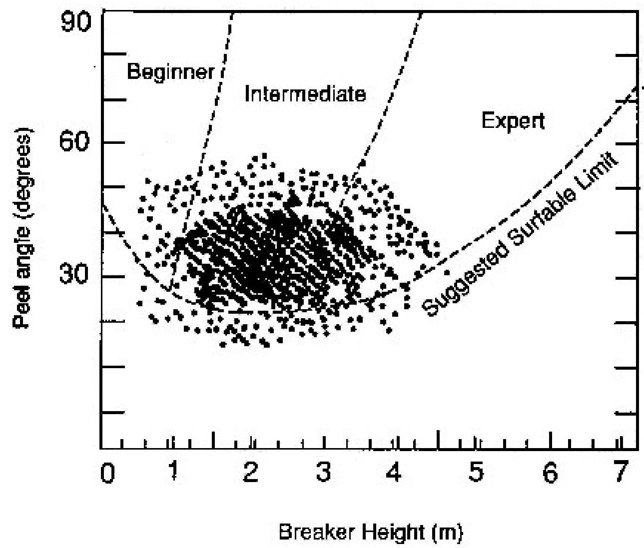


Figure 2.18. Walker diagram, showing skill levels expected to be catered for by the proposed reef (after Lyons, 1992).

HURST (1996):

In 1996, Paul Hurst performed surfability modelling of the Perth metropolitan coastline as an honours project at the University of Western Australia under the supervision of Dr. Charitha Pattiaratchi of the Centre for Water Research. Hurst developed a multipurpose numerical method of obtaining important wave parameters at the shoreline and from this, assessed the surfing potential of several beaches along the Perth coastline. The methods adopted in the project allowed him to assess the feasibility of the Cables Station Artificial Surfing Reef in terms of surfability.

The project involved using the numerical model RCPWAVE (Regional Coastal Processes Wave) to transform offshore wave data to the nearshore. RCPWAVE is a linear wave propagation model designed by the US Army Corp of Engineers Shore Restoration and Protection research program in 1986 and was chosen because of its relative simplicity and allowance for large inputs, which were characteristic of the project. Most important physical processes regarding wave propagation are considered in this model.

The main RCPWAVE procedure will do the following:

- Refract the waves using Snell's Law
- Check if the waves break
- Iterate for the wave heights along each row
- Iterate for the wave angles along each row
- Set the shoreline boundary

The output from running RCPWAVE is a matrix of all the wave heights and angles throughout the bathymetry grid. Although the RCPWAVE program could have been used to obtain the breaker heights at the shoreline, it was only used to obtain wave parameters at 400 metres from the shoreline, because:

1. The 100x100m bathymetry used resulted in poor resolution at the shoreline,
2. The linear shoaling theory adopted by RCPWAVE underestimates the breaker height.

From 400 metres offshore to the shoreline, a shoaling procedure was adopted by Hurst which used higher order shoaling theories. The shoaling wave theory of Shuto (1974) was used, and the waves were transformed to breaking using the breaking wave theory developed by Weggel (1972).

The shoaling program had to be further modified for the Cables artificial reef site, as this location needed to be treated differently from the beach locations. On a beach profile, a wave will ultimately break, as the water depth diminishes to zero at the shoreline (Hurst, 1996). An offshore reef however, will only have a breaking wave if the reef is sufficiently shallow. Thus the shoaling program needed to specify if the waves broke or not.

Using the results from RCPWAVE and the shoaling program, surfability was assessed at each location. Three different surfability measures were used at each site, as outlined in the following:

METHOD 1 – Breaker Height (H_b) and Iribarren Number (I_b)

The criteria for a surfable wave was set at H_b > 1.5m, and I_b > 0.3, hence if the daily method was used because Dally (1989) had used this method in a similar study. The main assumptions were:

- A wave is surfable regardless of peel rate.
- Breaker geometry is not affected by other factors such as wind.
- Less steep spilling waves are not surfable.

<u>METHOD 2 – Breaker Height and Wind Direction</u>

The local wind behaviour, neglected in Method 1, is an important consideration in surfability measurement, as it significantly affects breaker type. Surfing is favourable with offshore winds. The second method employs this factor combined with the breaker height as a measure of surfability. The Iribarren Number at break point has been omitted because the local wind significantly affects the breaker type and as such the method assumes that all breaking waves, of sufficient height, are surfable provided the wind is offshore. An offshore day was classified as a day which experienced offshore winds for a period of greater than or equal to 2 hours, during daylight.

<u>METHOD 3 – Breaker Height and Wind Modified Iribarren Number</u>

Based on the experimental data obtained by Baker and King (1995), Hurst developed a third method where breaker height, Iribarren number and local winds were included. This method involved the calculation of a modified Iribarren number which included the wind effects. Depending on the strength of the wind and the direction, the Iribarren number at break point will be increased for an offshore wind and decreased for an onshore wind.

Baker and King (1995) represented the experimental data as a graph, which was used by Hurst for his project. The scale of the model used by Baker and King was 1:50, thus a 2m/s wind in the model was effectively ~14m/s (= 2x√50) on the coast. The daily average winds for 1995 were compared with the values on the graph to check which category the local conditions were in. The percentage of plunging breakers in this category were compared with the percentage of plunging breakers under zero wind and hence a multiplying factor was derived.

Therefore this multiplying factor was applied to the daily average Iribarren number; with offshore wind multiplying factors being greater than one and the onshore multiplying factors being less than one.

Hurst (1996) suggested that the third surfability method conceptually provides the best measure to quantify surfability of a surfing location, concluding that the results gained from this method were strongly supported by observation.

Hurst (1996) undertook predicted surfability studies for the artificial reef and found that the Cables reef would provide a significant increase in the number of days on which the breaker height exceeds 1.5 metres. If the new reef were in place, Hurst found that there would have been waves breaking over the reef on 252 days during 1995, with a total of 149 days having breaker heights over 1.5 metres. The pre-existing reef had been found to produce breaking waves only 31 days of the year, all of which were of heights over 1.5 metres. From these statistics alone, Hurst found that the new reef would provide an average five-fold increase in the number of surfable days.

The number of surfable days in the year, as tested by the three different methods for both the existing and artificial reef's, are shown in Table 2.19. For the artificial reef, Method 3 gives 88 surfable days in the year. This is not a large reduction from Method 1, indicating that the typical plunging breakers that are produced over the new reef have reasonably large Iribarren numbers (Hurst, 1996).

Before

Cables (before)	days			Percentage			
	S1	S2	S3	S1	S2	S3	Breaker ht. Average
summer	0	0	0	0.00	0.00	0.00	0.00
autumn	2	0	2	2.17	0.00	2.17	0.17
winter	10	1	9	10.87	1.09	9.78	1.19
spring	6	0	6	6.59	0.00	6.59	0.32
	18	1	17	4.93	0.27	4.66	0.42

After

Cables (after)	days			Percentage			
	S1	S2	S3	S1	S2	S3	Breaker ht. Average
summer	17	5	12	18.89	5.56	13.33	0.97
autumn	16	6	14	17.39	6.52	15.22	1.42
winter	58	18	42	63.04	19.57	45.65	2.98
spring	32	2	20	35.16	2.20	21.98	1.59
	123	31	88	33.70	8.49	24.11	1.70

Table 2.19. Summary of Cables Station surfability: before and after artificial reef construction (after Hurst, 1996)

The surfability of the pre-existing reef is limited by the lack of swell that it receives. An improvement in the shape of the reef will cause a larger percentage of waves to break. The dependence of the surfability on swell is apparent in Table 2.19, which shows that that the surfability is approximately doubled in winter due to the increase in breaker heights.

In addition to these three introduced surfability methods, the Cables reef was also assessed by Hurst using the Walker (1974) surfability limits. Using the RCPWAVE output of wave angle at 400m depth, a breaker angle was devised by Hurst assuming that the reef angle on the left and right breaks of the new reef was 45°. Due to the significant refraction of the waves around Rottnest, the majority of the waves approached from the northwest, regardless of the swell incident angle (Hurst, 1996).

The results indicated that the left break would be more challenging as it peels at a smaller angle, hence at a greater rate.

Hurst's analyses showed that a significant proportion of breakers fell into the "intermediate" category on both the left and right breaks. On the right break, there was a large number of waves the suit "expert" surfers, due to the large size of the breaker only, *not* due to a fast peel rate. On the left break, a significant proportion fell in the "intermediate" category, however when the breaker height increases (even with a similar peel rate) the lefts become unsurfable (Hurst, 1996).

Similar data was plotted for the pre-existing Cables reef. Due to the depth of the pre-existing reef, the only waves that broke over the reef were large. The left break at Cables was unsurfable due to the small peel angles and hence large peel rates causing the waves to close out. The pre-existing right had a satisfactory peel angle, on average about 60-70°, however the size of the waves required for breaking meant that the surf was classified as being for "expert" surfers.

Since Hurst's study was not only of the Cable Station location but also the other main surfing sites in the metropolitan area, he was able to compare the surfability of the then proposed Cables reef with that at other sites. One problem Hurst encountered was comparing reef breaks with beach breaks regarding the relative surfabilities of reef break waves and beach break waves. A fourth way of ranking was hence considered with the only reef break, Cables, being assigned with more realistic constraints.

A reef break with similar breaking height and Iribarren number to that of a beach break will be more popular with surfers because it will peel at a favourable rate and every wave will break around the same place, whereas Perth's beach breaks often close out (Hurst, 1996). Onshore wind conditions also tend to be not as devastating on the surfability of a reef break as on a beach break. For use of comparison with beach breaks only, Hurst increased the relative surfability of the reef break by using criteria of $H_b > 1$m instead of 1.5m.

Using this alternative criteria, Cable Station would rank around third out of the main Perth metropolitan breaks, behind the Trigg to Brighton beach breaks.

PORT AND HARBOUR CONSULTANTS (June, 1998):
Included in the design review conducted by Port and Harbour Consultants (PHC) was an assessment of improved surfability for the Cable Station artificial reef. This was conducted for dual purpose of verifying the previous physical modelling work and extending the result data based at the prototype scale (PHC, 1998). This was achieved through the use of two distinct numerical modelling packages: MIKE 21 NSW, a nearshore spectral wave transformation model, and RCPWAVE, as detailed above.

Overall, the results of both studies suggested that the reef as modelled will provide a significant improvement to the surfability at the site. This is expected due to an improvement both in breaking wave quality and in the frequency of surfable waves at the new break. PHC found that, based on the past wave climate study at the site and neglecting the influence of wind speed and wind direction, up to a five-fold increase in the occurrence of surfable conditions at the reef is expected, compared to the pre-existing bathymetry. This is in agreement with the outcomes of Hurst outlined above.

PHC summarised the reef performance as providing good quality surfable waves at most tide levels for sea states in excess of 1 metre significant wave height, with the occurrence of surfable waves increasing dramatically as H_s increases. Over the wide range of parameters investigated, breaking waves with a wave height of 1.5 times the offshore incident wave (in approximately 9 metres of water) may be expected, with good plunging 'tubes' forming (PHC, 1998). It was found that these waves would tend to spill as the wave height increases. These estimations were made neglecting the identified issue of reef porosity, discussed in Section 2.2.2.6 of this thesis.

It was observed that the increase in wave steepness prior to breaking was gradual enough to suggest that there will be sufficient time for a surfer to catch the wave prior to wave breaking (PHC, 1998). Following this, they predicted that the surfer may expect a 'challenging' ride of up to 70 metres, depending on the incident wave conditions. For a 1.5 metre wave, rides of 30m and 50m were predicted for the left

Walker criteria plots and surfability matrices (Figure 2.20) were developed by PHC and are good indicators of the improved surfability with the artificial reef in place. According to the criteria set by Walker, the proposed reef should offer a wide range of conditions for the intermediate or expert surfer, which rarely occurred at the pre-existing Cables reef.

PHC found that it was difficult to present the large number of parameters in one format to define improved surfability. Therefore much effort was put into this area of the study and Figure 2.20 was developed for this purpose, where the improved surfability can be clearly seen. This figure represents a matrix rating formed for each bathymetry and direction case, based on a notional 'acceptable' performance.

For each combination of wave height and period, the performance of each water level case was assessed and rated positive if breaking waves with peel angles greater than 30° formed and the minimum ride length was 10 metres. Positive performance for each of MLLW, MSL and MHHW were rated at 1, 2 and 4 points respectively to give a spectrum from 0-7 which included all possible successful combinations. For example:

1 = surfable only at MLLW

3 = surfable at MLLW and MSL

7 = surfable at MLLW, MSL and MHHW (all cases).

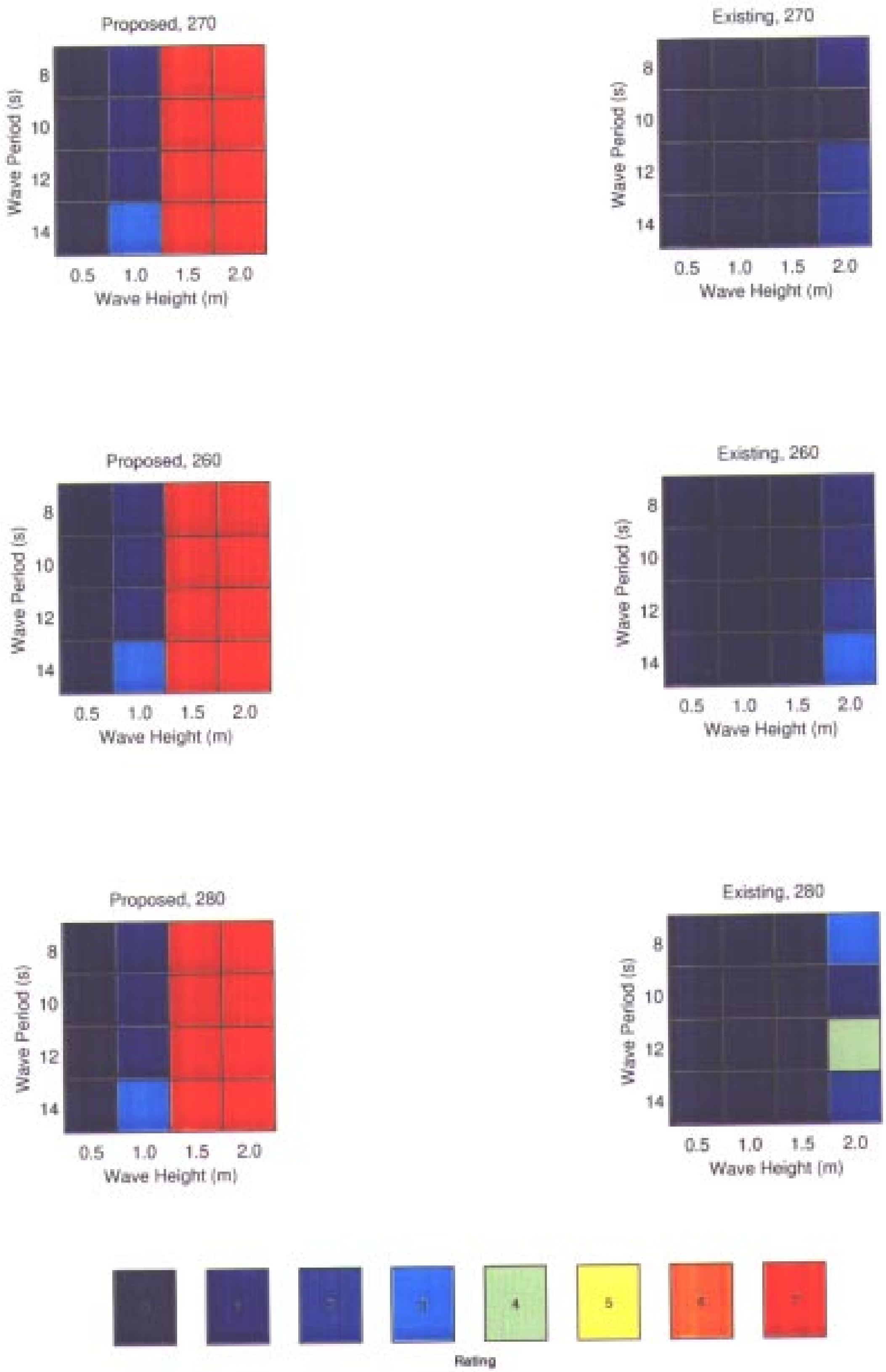


Figure 4.20. Surfability predictions made by PHC (1998).

The colour coded matrices of Figure 2.20 demonstrate the significant improvement with the artificial reef in place. At all water levels, the proposed reef as modelled provided surfable waves with good ride lengths for 1.5m and 2m incident swells. For the artificial reef, the results were the same for each of the incident direction cases (260°, 270° and 280°). Contradicting the results of the design study of Lyons (1992), PHC found that the reef would not produce surfable waves under any water level conditions for a 0.5m incident swell. They also found that 1m waves generally required low water levels to be effective. These assessments have been partly disproven during the current study, as shown in Section 4.3.

MP ROGERS & ASSOCIATES (October, 1998):
The DOT engaged M P Rogers and Associates (MRA) to complete a detailed wave climate study for the artificial reef site. The primary purpose was to quantify the occurrence of surfable conditions at the proposed reef site, with the required outcome being the number of days per year on which useable, surfable waves should occur. They had only 3 weeks in which to complete the study meaning that assessment could only be made with a proven wave model and readily available data.

In assessing the times when the new reef would be surfable, the criteria for surfable conditions needed to be extended from the PHC work to cover the complete range of wave conditions and water levels that can be encountered at the reef location. For example, water levels up to the Highest Astronomical Tide, which is 0.4 metres higher than the MHHW level used in the PHC study, can be experienced at the site. Meteorological effects and the general effects of the Leeuwin Current can also add to the total water level at the site.

It was deemed reasonable to assume that waves larger than those tested by PHC would be surfable at slightly higher water levels. Therefore the MRA study was based on the PHC water level and wave condition surfability results, together with some extrapolation for higher water levels and wave heights. These criteria for wave and water level are plotted in Figures 2.21 below (MRA, 1998).

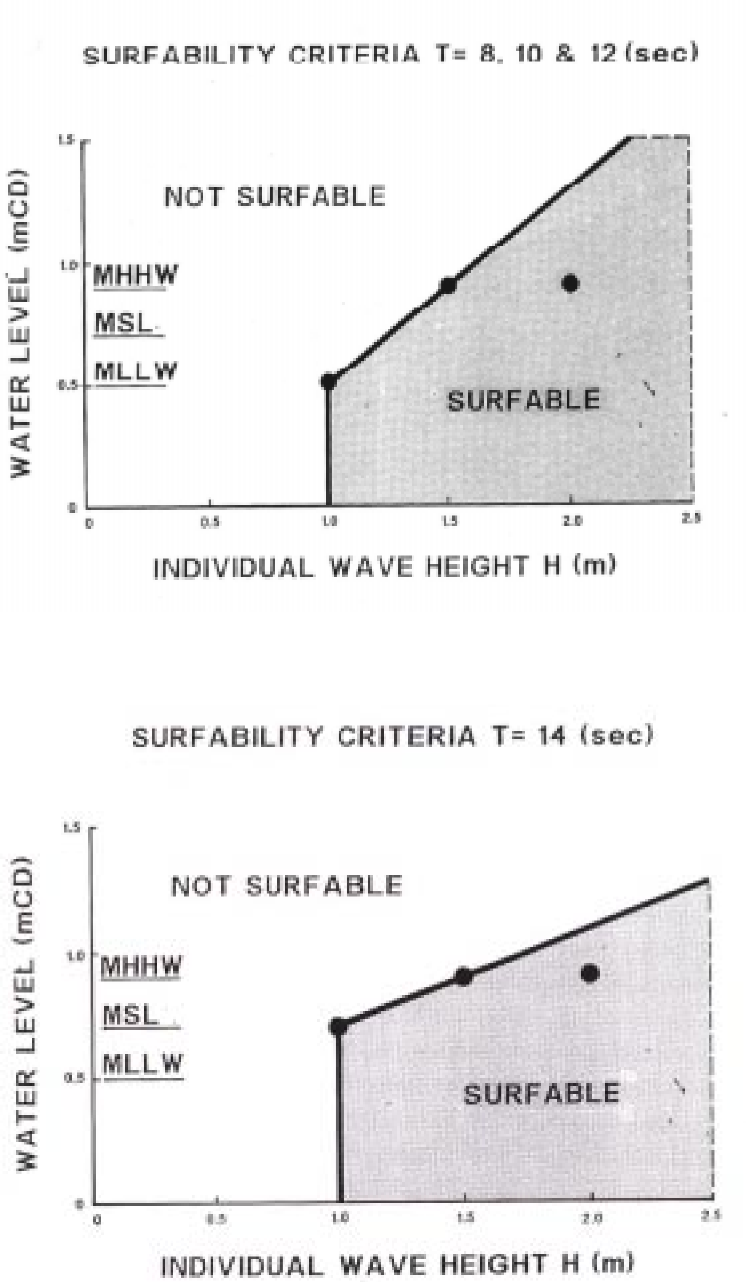


Figure 2.21. Water level and wave criteria used in the MRA surfability assessment (after MRA, 1998 and PHC, 1998).

The computer model used for this study was 2GWAVE, which is a finite difference model that accounts for the following wave transformation processes:

- Spectral refraction and shoaling,
- Wind forcing,
- Dissipation due to bottom friction and white capping,
- Deep and shallow water breaking,
- Non-linear wave-wave interactions.

2GWAVE has been extensively tested in the Fremantle area and proven to be reliable (MRA, 1995). In order to verify that the wave model was correctly modelling the wave field for the main conditions experienced at Fremantle, simulations were conducted including the following:

- Swell verification event,
- Winter storm verification event, and
- Land/Sea-breeze verification event.

The assessment of days with surfable conditions in 1994 to 1998 was made using the following criteria (the details of which can be found in the MRA report):

- Wave height, wave period and water level requirements in about 9 metres of water west of the proposed reef site which create conditions suitable for surfing on the reef as determined by PHC (1998).
- Onshore component of the wind speed being less than 6 m/s (which includes all offshore winds).
- The T_Z (mean period) of the total spectra being equal to or greater than 6 seconds.
- The time of day being between half an hour before sunrise to half an hour after sunset.

The conditions at the proposed reef location were assessed using the following:

- The Waverider Buoy measurements at Deep Channel for 1994 to 1998 provided by the DOT.
- The transformation of wave conditions (H_S swell, T_P swell and T_Z total) from the Deep Channel site to the location 200 metres west of the artificial reef site as calculated by 2GWAVE.
- Individual waves for the PHC criteria being 1.4 times H_S to provide about 3 surfable days every 20 minutes.
- The water level records from Fremantle Fishing Boat Harbour for 1994 to 1998 provided by the DOT.
- The wind records from the Swanbourne anemometer for 1994 to 1998 provided by the Bureau of Meteorology.

Every 20 minutes, the conditions were assessed for the suitability for surfing. Whenever there were conditions suitable for surfing for 1 hour or more during daylight hours, the day was classed as being suitable for surfing (MRA, 1998). For each month that sufficient data was available, the number of days of surfable conditions was calculated and the results are summarised in Table 2.5.

Table 2.5. MRA assessment of the days with surfable conditions for the Cable Station artificial surfing reef (after MRA, 1998).

Month	Year 1994	1995	1996	1997	1998	Average 1994/98
January	n.a.	0	1	1	0	0.5
February	n.a.	1	1	0	1	0.75
March	n.a.	0	0	0	0	0.0
April	n.a.	0	0	0	1	0.25
May	n.a.	2	2	0	1	1.25
June	n.a.	4	3	2	5	3.5
July	n.a.	11	10	10	8	9.75
August	n.a	20	12	9	6	11.75
September	17	11	8	10	n.a.	11.5
October	10	2	7	6	n.a.	6.25
November	3	3	2	1	n.a.	2.25
December	3	0	1	2	n.a.	1.5
Full Year	n.a.	54	47	41	n.a.	49.25

Notes: 1. The Deep Channel wave data was available from August 1994 to August 1998 inclusive. Months and years where significant periods of wave data at Deep Channel was not available have been marked n.a..

The overall average, from the four years assessed, of the number of surfable days in a year was 49.25. The analysis was also completed for two other cases to test the sensitivity of the result to minor levels of error in the assessment technique. The first test hypothesised that the PHC assessment of wave heights necessary for surfable conditions was 15% too low, or alternatively, that the assessment of the wave height at the reef site in the MRA report was too high by 15%. Such an error would decrease the average number of surfable days by about 26 days.

The second test presumed the opposite, ie. wave heights necessary estimated too high or wave height predicted at the site actually too low, resulting in an increase in the average annual surfability by 23 days.

This sensitivity analysis showed that the number of surfable days is very sensitive to slight variations in wave conditions and assessment criteria. Consequently, MRA claimed that the assessment of the average annual number of surfable days per year should be taken as 50 days with a likely error band of ±20 days. In addition, it is likely that variations from year to year could be in the order of 10 days (MRA, 1998).

The study also showed that surfable conditions would be infrequent during summer and autumn. On average, for each surfable day in summer or autumn, there was estimated to be around 3 hours of surfable conditions. Most of the surfable days occurred in winter and spring, with an average of around 4.5 hours of surfable conditions on the days that were classed surfable (MRA, 1998).

2.2.2.9 Social and Economic Aspects

The 1995 Alan Tingay & Associates study, mentioned in Section 2.2.2.7 of this report with respect to environmental concerns, also contained a social appraisal of the artificial surfing reef. The study involved research into the social context, recreational uses of the marine and coastal sectors (including offshore and onshore activities), community attitudes and social impacts of the proposed artificial reef at Cable Station. This included a limited survey of people living to the south of Warton Street in South Cottesloe and others who had expressed an interest in the Cable Station Beach area. The object of this survey was to gain an indication of coastal use and community attitudes to coastal development in the area.

In summary, the survey sought to assess the following:

- Current recreational activities at Cable Station Beach.
- The adequacy of existing facilities at Cable Station Beach.
- The views of residents regarding what facilities should be established.
- Whether coastal land immediately north of the Vlamingh Memorial is regarded as

- Other locations which were considered suitable for the development of facilities.
- Potential attendance at future surfing events, whether extra facilities were provided or not.
- General comments related to the artificial surfing reef, the development of onshore facilities, etc.

The study suggested that the social implications of the artificial reef will depend on the level of use by surfers and the related need for coastal facilities to cater for visitors. In the past, the main offshore activities have been surfing, swimming, boating, fishing and scuba/skindiving. Onshore, the Cables Station area is well used as a dog beach. The Vlamingh Memorial is the dominant cultural feature at Cable Station Beach, located approximately 100 metres south of the intersection between Marine Parade and Curtin Avenue. The memorial was dedicated on the 5th of January, 1974, to mark the 275th anniversary of the landing of Willem de Vlamingh on the WA coast in 1697, and attracts some tourists to the site.

The artificial reef will not prevent pre-existing recreational activities at Cable Station Beach from occurring, except possibly for offshore fishing and diving, which may be limited by the presence of an increased number and frequency of surfers (AT&A, 1995). However, it is thought that the new reef may provide a more interesting location for diving than previously encountered.

For most of each year, the number of visitors to Cable Station Beach is not likely to be substantially greater than in the past. However, if organised surfing competitions are held on the artificial reef, the number of visitors over short periods of a few days may be substantial. Accommodating this potential increased level of use would require onshore coastal developments such as carparks and public facilities (AT&A, 1995). The report from AT&A suggested that with sensitive design, such developments could substantially enhance the area.

In 1996, Reark Research undertook an economic analysis of the artificial surfing reef for the Ministry of Sport and Recreation. The report details the findings of a qualitative investigatory search by Reark Research and McIntyre Management and reef. The major objective of the research was to 'analyse the revenue producing potential and scope of likely products, services, merchandising, sponsorship and licensing opportunities flowing from the artificial surfing reef'.

The research demonstrated a high level of awareness, knowledge of, and interest amongst potential users, retailers of surfing equipment and accessories, and potential corporate sponsors. Although Reark Research found an initial inclination amongst those interviewed to 'sit on the fence' until the reef concept was proven, they were able to identify some potentially lucrative direct and indirect economic outcomes from the construction of the artificial reef.

The suggested means of managing the direct revenue that would be generated was the establishment of a charitable fund, however the writer feels that any revenue would be most suitably focused into coastal protection and rehabilitation projects. Their cost:benefit analysis, based on speculative but nonetheless what they considered conservative assumptions from tourism statistics, indicated an economic benefit to Western Australia of approximately $6.3 million (indirect economic impacts). The direct revenue raising opportunities that were explored by the study included:

- Naming rights
- Advertising and merchandising royalties
- Event sponsorship
- Fundraising from surfers, and
- Formation of a construction consortium.

The economic benefit analysis itself ignored the additional social benefits to the active board riders and the total surfing community in WA, such as reduced crowding, fewer injuries, more competition opportunities and increased interest from the government and the public in surfing.

2.2.3 SUMMARY OF ARTIFICIAL SURFING REEF BACKGROUND

The idea of creating artificial surfing reefs has existed for a long time. Developing parallel to the plans for Cable Station Artificial Surfing Reef were other artificial reefs at locations such as the Gold Coast, Queensland and in California, USA.

The demand for an artificial reef in Perth was due to competition between users and overcrowding of surfers at the few good locations. This lack of consistent surf along the Perth metropolitan coastline is due to the low wave energies incident on the coast because of the protection provided by an extensive chain of offshore reefs.

In 1988, the Government formed the Artificial Surfing Reef Committee to assess the feasibility of constructing an artificial reef in the Perth metropolitan area. The site selected for this reef was Cable Station, South Cottesloe. This site was chosen because of the lack of existing beach use, stability of the coastline, existance of carpark facilities and public transport to the area, an appropriate wave climate and a pre-existing reef that it was felt could be enhanced to provide an improvement in surfability.

The design chosen was a Boomerang shaped reef, with physical modelling predicting a ride of 50-80 metres on the right break, and 30-40 metres for the shorter left arm. It was thought that the reef would cater for a broad range of surfer abilities from the beginner to the expert.

A salient (accumulation of sediment) was expected to form in the shadow region immediately shoreward of the reef due to the dissipation of wave energy across the reef providing shoreline protection.

Surfability predictions made by MRA (1998) under strict criteria for wave shape, wave height, water level and wind conditions suggested a likely improvement in surfable days from around 5-7 days per year to 50 days under the influence of the proposed artificial reef.

Biological activity on the pre-existing reef was expected to be heavily impacted during the construction phase, however it was expected that the artificial reef would probably provide more ecological niches at the site and hence eventually increase biological activity at the Cable Station location.

3 Methodology

This section outlines the data collection, processing and analysis techniques employed in this study. Data analysis, after initial processing, was carried out using MATLAB, a high level, vector-oriented, mathematical programming language developed by 'The MathWorks Inc.'. Many aspects of the reefs performance were assessed during this study, using both field measurements and data collected specifically for this purpose, and using data and images recorded by other sources for the Department of Transport.

3.1 Wave data for Cable Station

Wave data was collected via deployment of two wave measurement devices in the vicinity of the Cables artificial reef location. A pressure sensor was placed at the inner apex of the reef to record non-directional wave height measurements at a likely break point on the reef. An S4 current meter was placed at a depth of approximately 8 metres, directly offshore of the reef to record incident wave data. This measured both the fluctuations in hydrostatic pressure, to determine wave statistics, and the direction of incoming waves, at 2 Hz for 20 minutes each hour. Figure 3.1 shows the locations where these wave measuring devices were deployed.

Figure 3.1. Locations of the S4 and pressure sensor deployment at Cable Station.

3.1.1 WAVE MEASURING DEVICES

3.1.1.1 Pressure Sensor

Plate 3.1 shows the pressure sensor which was deployed at the inner apex of the artificial reef. This device measures the changes in hydrostatic pressure caused by variations in the height of the overlying water column due to the passage of waves. A pressure sensor alone is a non-directional device and records a time series which can be analysed for height and period statistics only. The pressure sensor was weighted with a large lead weight to ensure it remained in place on the reef during the recording period.

3.1.1.2 S4 Current Meter

The S4 current meter, as shown in Plate 3.2, measures both the pressure signal, and the u and v components of water movement to give wave directions as well as the wave statistics that can be provided by a pressure sensor alone. For this study, the S4 was mounted in a frame measuring 2m x 2m x 1.5m. The lower corners of the frame were weighted with lead bars to ensure the frame would remain in position after placement offshore of the artificial reef at the 8 metre depth contour.

3.1.2 DATA COLLECTION TECHNIQUE

After several unsuccessful attempts, the pressure sensor and S4 current meter were deployed on the 3rd of August, 1999. They remained at the site until collection on the 1st of September.

The pressure sensor was located at the inner apex of the reef, as shown in Figure 3.1. This location was pinpointed by the presence of the cut-off base of a pylon which was present at this location during the construction phase. A dive boat was used to approach the site from the seaward side, as attempts to deploy the sensor with divers leaving from the shore had failed. A large flotation buoy was used to float the pressure sensor to the location and it was then lowered into position using a system of ropes. The pressure sensor collection was also undertaken by divers leaving from the diving vessel to retrieve the device, roping the pressure sensor to the flotation buoy, and swimming it seaward to the dive boat. Both processes of deployment and collection were complicated by the shallowness of the area due to the artificial reef, and due to the swell that was incident on the reef.

The S4 was deployed in approximately 8 metres depth of water, directly seaward of the reef. The frame and current meter were lowered over the side of the dive vessel down to the bottom of the water column using a system of ropes. Divers went down to assure that the frame was still upright upon reaching the bottom.

At the end of the data collection period, the S4 and frame were collected, using the dive boat and removing the weights whilst in the water to allow the frame to be lifted into the vessel.

3.1.3 DATA PROCESSING

After collection, it was discovered that the pressure sensor had only collected two days worth of data, while the S4 had worked for the entire deployment period. Any sequence of observations made through time, such as those recorded by these devices, may be referred to as a *time series*. The data records that were collected are time series' of the water surface elevation measured at a fixed location. These time series' are stochastic, discrete, uniformly sampled and of finite length. In this study, the time series records were processed using spectral analysis, a frequency domain approach.

Spectral analysis can be used to decompose a time series into it's constituent frequency components and hence different frequency bands can be isolated. In particular, the method permits sea and swell components of the wave field to be separated. In this investigation, data records were transformed from the time domain to the frequency domain using Fast Fourier Transform (FFT).

Application of the FFT requires that the time series satisfies the following conditions:

- The time series must be *stationary*. This means that the series must have no long term trend in its mean or variance,
- The number of data points in the series should be a power of 2,
- The discontinuous 'end points' of the series should be tapered

The time series' were detrended before applying FFT to ensure stationarity of the water surface elevation signal, which involved fitting and then subtracting a linear trend from each data record, a process which is undertaken using MATLAB. The length of the data record from the S4 in this study was a power of 2, containing 2048 points ($N = 2^{11}$). This record of 2048 points was split up into 2 sets of 1024 (2^{10}) points which were used to develop spectrum averages.

The FFT applied to the time series and the resulting spectral density function or 'power spectrum' could then be used to extract various frequency domain wave parameters. It should be noted that the data were sampled at a rate of 2 Hz, so the lowest resolvable frequency, or *fundamental frequency* was $f_f = f_s / N$ = 1/1052 Hz. The highest resolvable frequency, or *Nyquist frequency*, was $f_c = f / 2$ = 1Hz. So the range of periods that could have been resolved by the application of the FFT was 1-1052 seconds.

The main parameters of interest generated by this analysis were:

- *Significant wave height (H_S)*: an estimate of the average height of the highest 1/3 of waves in a record (metres). Visual estimates typically estimate this measure of this wave height.
- *Significant wave period (T_S or $T_{0,1}$)*: this is a measure of the average period of the highest 1/3 of waves in the series (seconds).

3.1.4 DATA ANALYSIS

The results gained from data processing were then used to make comparisons between the wave statistics found offshore at Cables Station with the wave climate recorded at Deep Channel, Cottesloe. This was of importance because previous design, surfability and environmental studies for the Cables artificial reef had been based on this data and hence it was valuable to compare the two sites. A shoaling coefficient was determined between Deep Channel and Cables via the following:

shoaling coefficient = $Hs_{S4} / Hs_{deep\ channel}$.

Analysis was also performed to attain the shoaling coefficient across the artificial reef, ie. between the S4 and the pressure sensor. This was determined via:

shoaling coefficient = *Hs* / *Hs*

3.2 Breaking wave data

3.2.1 OUTLINE OF PROCESS

The data collected for analysis of the surfability of the artificial reef site, and the conditions under which breaking occurs, was in the form of still images of the reef, recorded by an Axis web camera located on the roof of the Family and Children Services' McCall Centre building in Cottesloe. This location is indicated on Figure 3.1. The images recorded by the camera are posted on the World Wide Web, and update approximately every minute.

The archives of these images from February to August were made available by the Department of Transport for processing. For every day of records over this period, the times when the images showed the artificial reef site breaking were recorded. These breaking incidences were then marked over the top of plots of swell wave height, swell wave period, water level and Iribarren number, for analysis of the conditions required for breaking.

After general trends had been identified, instances when these trends were not adhered to were checked to see why this was. This involved further analysis of the plots previously mentioned and also referring back to the relevant web cam images. Wind data from the Swanbourne Anemometer was also assessed to note the effects of wind on wave breaking at the reef.

3.2.2 RECORDING DEVICE (COAST CAM)

As stated, the images used for breaking wave analysis were captured from an Axis web camera located on the roof of the Family and Children Services' McCall Centre building, located on Curtin Avenue, South Cottesloe, across the road from the Vlamingh Memorial (Plate 3.3). From this location, the web camera image looks out at the site of the reef over a small park (See Plate 3.4). The beach region at Cables is not captured in the image, though part of the shorebreak can be seen. Waves breaking over the actual artificial reef area can easily be identified.

The images are posted on the World Wide Web by the Coastal Data Centre, a DOT initiative that provides the public with Western Australia's tide and wave data. The images on the web update automatically approximately every minute. Live 'Coast Cams', like the one at Cable Station, are also located at Marine House (Fremantle), Cottesloe Beach and Swanbourne Beach. The URL for this site is: http://www.coastaldata.transport.wa.gov.au/coastcam.

3.2.3 RECORDING TECHNIQUE

All images were recorded by the Axis web cam as outlined above, however the recording technique, in terms of frequency of recordings, changed part way through the study period of February to September. From February to the 8th of July, images were recorded at partly random intervals. The basic pattern was that approximately every 10 minutes, recordings were made every few seconds for around a minute. This was by no means a constant pattern, with jumps of 15-20 minutes at a time being common.

From the 9th of July onwards, the camera was set to record an image every minute. This was a more regular monitoring method, however didn't record consecutive images over a few seconds as the previous method had.

Obviously, wave breaking could not be identified after dark, hence the times for recording starts and finishes were set at just before and just after sunset respectively. This was deemed to be acceptable for examining wave breaking as it was assumed that, because no lighting for night surfing was available, no surfing would be undertaken outside of these hours.

3.2.4 ANALYSIS METHOD FOR BREAKING AND SURFABLE DAYS

For every day between February and August, 1999, for which images had been recorded, the times at which waves were breaking in an image were noted. A wave was considered to be breaking in an image if there was whitewater present in the form of a breaking wave.

This first stage of analysis was only indicating whether a wave was breaking on the reef, not whether it was considered to be surfable. A second stage of the analysis involved estimates of the surfability of waves, which was a very subjective analysis, as the definition of *surfable* varies from individual to individual. Surfable days were assessed using by:

- the presence of people out surfing on the reef (which could be seen in the web cam images), or
- visual assessment that the wave size and shape would be conducive to surfing.

Some days in the February to August period had no images recorded due to problems with the web camera. For the same reason, some days had late recording starts, or recording would stop at some time during the day. To ensure that interpretation of the days breaking would not be misleading due to these errors with the camera, the dates on which the web camera stopped working, started late, or didn't work at all, were recorded. If it was deemed very likely that a wave would have been breaking on the reef during these camera failures, the day was counted as having breaking waves. It was felt that this approximation would result in less error in the assessment of days breaking and surfability than if the failure days were discounted.

3.2.5 OTHER DATA REQUIRED

Swell wave height, swell wave period, water level data and wind data were also required for the analysis of conditions under which waves break on the artificial surfing reef. This data was also provided by the Department of Transport.

Wave conditions were obtained from the Datawell Waverider Buoy located at 'Deep Channel', which is offshore from Cottesloe. The location of this buoy is shown in Figure 3.3. The 0.9 metre diameter Waverider measures wave height by measuring the vertical acceleration of the buoy. The discrepancy between the movement of the Waverider and the movement of the sea surface is small. When a moored Waverider follows the waves, the force of the mooring line will change. This force is produced by the changing immersion of the buoy, resulting in a maximum error of 1.5%. Figure 3.2 shows a diagrammatical representation of the Waverider Buoy.

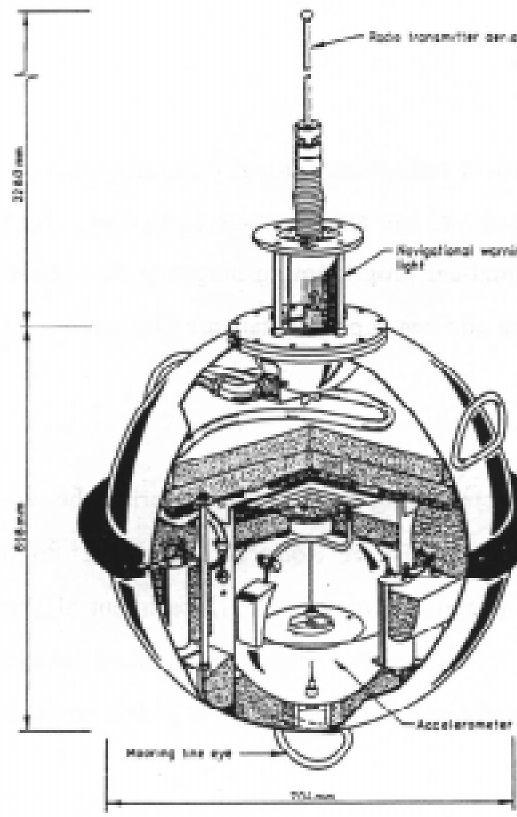


Figure 3.2. Waverider Buoy located at Deep Channel, Cottesloe (adapted from Dept. of Construction, 1977).

With decreasing wave length, the buoy will not follow the wave amplitude if the wavelength is less than 5 metres (wave period below 1.8 seconds). If the wave length is less than 2.5 metres (wave period 1.25 seconds), the buoy's response decreases quickly.

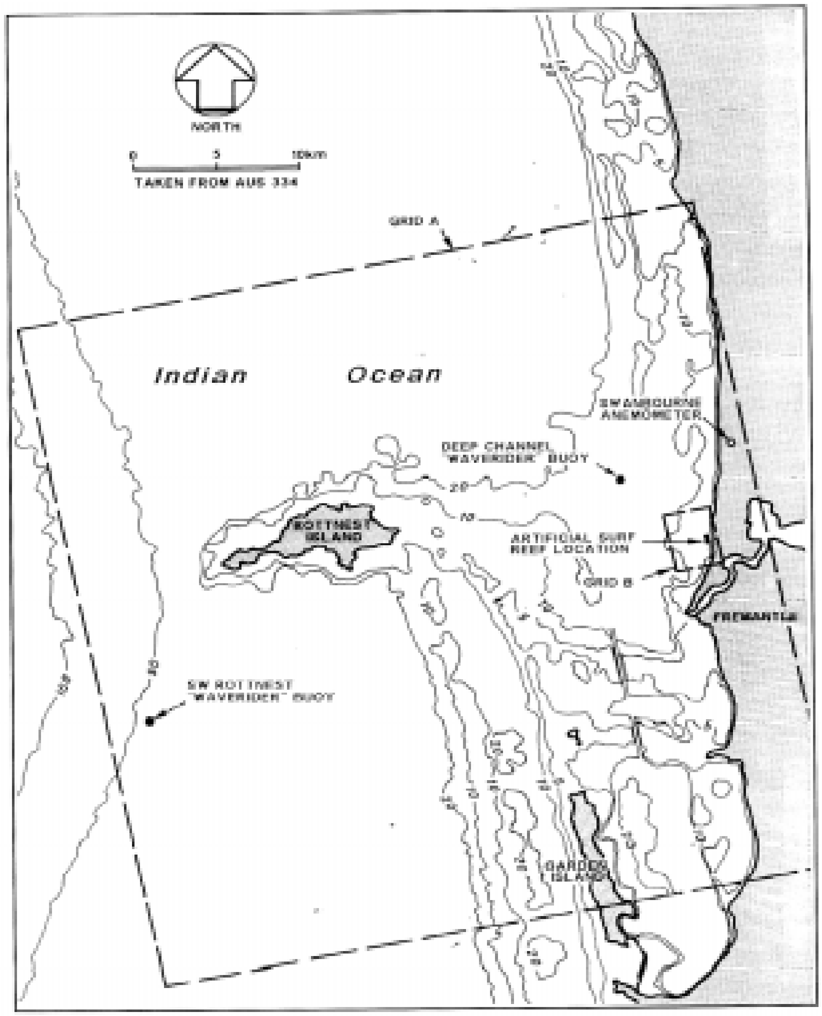


Figure 3.3. Location of the Deep Channel Waverider Buoy off Cottesloe.

The data acquisition system consists of a standard Pentium PC and a Datawell receiver. The dimensions of the receiver are 15cm x 40cm x 50cm. Measurements of water surface elevation via the Waverider Buoy are taken every 20 minutes at a rate of 1 Hz for a period of 8 mins 32 secs (512 data points) and are transmitted to the receiver on shore.

To identify defective records, the Department of Transport employs a set of fifteen quality assurance routines. Faulty records are flagged to facilitate manual inspection or omission at a later stage. The time series recorded by the Waverider Buoy at Deep Channel are analysed via spectral analysis by the Coastal Data Centre (DOT). Results of this analysis are posted on the web in terms of significant wave heights and mean wave periods for the swell, seas and total sea state components of the signal from Deep Channel, Cottesloe.

The Fremantle water levels used for this analysis were provided by the Maritime Division of the Department of Transport. Wind data recorded by the Swanbourne anemometer was analysed to determine the onshore/offshore component of the winds. The data as provided contained the wind speed (knots) and wind direction. This was converted into an onshore/offshore component as follows:

onshore/offshore wind component = wind speed x (- sinα),

where α = wind direction (taken as degrees from north). The calculation adopted the convention that onshore winds are generally taken as being in the +ve direction, while offshore winds are taken as –ve. Data for analysis of the effects of wind was only available for July and August, however this was sufficient to note the apparent trends associated with wind effects.

3.2.6 DATA PROCESSING FOR CONDITIONS WHEN SURFABLE

Plots were made of swell wave height, swell wave period and Fremantle water level versus time for the period of February to August for which data was available. These plots were developed using MATLAB, the scripts for which can be found in Appendix A2. Night time was indicated on these plots using grey bars, such that only daylight hours would be tested for wave breaking conditions.

Marked on these plots of wave and water level conditions were the times of the day at which wave breaking had been recorded. A plot of offshore Iribarren number versus time was also made with wave breaking times overlain. The offshore Iribarren number was calculated via:

$$I_0 = \frac{m}{\left(\frac{H_0}{L_0}\right)^{1/2}}$$

$$I_0 = \frac{m}{\left(\frac{H_0}{1.56T^2}\right)^{1/2}}$$

substituting *m (slope) = 0.05*,

$$I_0 = \frac{0.0625T}{\sqrt{H_0}}$$

Also marked on the plots were times when the reef was considered to be surfable according to the criteria described in Section 3.2.4.

These plots were then used to analyse the specific conditions, or combinations of conditions, under which wave breaking and surfable waves would occur. Frequent reference back to the web camera images was also required for this analysis. The onshore/offshore components of the wind for July and August were used to assess the wind's effects on breaking conditions at Cable Station.

3.3 Annual Tidal Patterns

A very basic analysis of the annual pattern which tide levels follow was made for use in analysis of breaking wave conditions, as discussed above. Since lower tides allow for greater shoaling under smaller swell conditions, the time of occurrence of Low Low Water (LLW) is an important annual trend to understand. In analysis of breaking wave occurrences, this tide level fluctuation can be used to explain why, in some cases when the reef wouldn't be expected to break, it actually does break and vice versa.

The WA Tide Predictions booklet, produced with the assistance of the Department of Transport Maritime section, was used to establish this yearly trend in water level fluctuations. The tidal predictions for 1999 contained within the booklet are based on the predictable position of the sun and moon, and the average meteorological conditions that may be expected. The times predicted for High High Water (HHW), Low Low Water (LLW), Low High Water (LHW) and High Low Water (HLW) were entered into an Excel spreadsheet. Plots were then produced of the times of HHW and LLW versus day of the year to establish the general trends.

3.4 Peel angle and rate

The peel angle and rate are essential parameters in assessing what ability level of surfer the reef is suitable for. Hence measurements of the peel angle and rate were approximated for the Cable Station artificial reef.

3.4.1 DATA COLLECTION TECHNIQUE

A helicopter was used to take digital video footage and still photos from above the reef such that breaking could be viewed in plan view. This recording was made on the 17th of October using a Preston joy flight helicopter which leaves from the Swan River foreshore in east Perth. Several minutes of footage were taken while the helicopter circled around the Cables reef site.

3.4.2 ANALYSIS OF FOOTAGE

The footage taken during the helicopter flight was analysed to determine the approximate peel angle that was observed on the 17th of October. A schematic diagram showing definitions of peel angle and peel rate is shown in Figure 2.10, in Section 2.1.6.5 of this report. The position of the wave crest at two different times in the helicopter footage was used to assess the peel angle of the right and left hand breaks.

3.5 Beach Width data

In order to look at the effects the reef is having on the deposition and erosion of sediment on the beach in the vicinity of the reef, measurements of the beach width have been made. These measurements should be incorporated into a long term monitoring program.

3.5.1 BEACH MEASURING TECHNIQUE

Three different locations were chosen for the beach measurements;

1. Slightly south of the artificial reef
2. Slightly north of the artificial reef
3. Cottesloe main beach (slightly south of the Surf Life Saving building)

The first two of these locations have been surveyed by the DOT and the points from which to take measurements were already present.

Every 2 weeks, at each of these locations, the width of the beach, from the chosen reference point, was measured. Beach measurement was undertaken at approximately midday on each of the monitoring dates. Some weeks, poor weather conditions meant that measurements had to be pushed back one or two days. The monitoring dates are shown in the table of beach monitoring results (Table 4.?).

The width of the beach was measured from the reference point to the point where the heavier material was being deposited by waves. These measurements were made using a retractable metal tape measure. Measurements were taken from the 20th of July to early October, 1999.

3.5.2 DATA ANALYSIS

Plots of beach width versus time were developed for each of the three sites. It should be noted that the actual beach widths may have been wider than these measurements because they were taken from a benchmark location. Weekly changes in this parameter is what is important, not the absolute values.

3.6 Qualitative Observations

The writer undertook many visits to the reef site, both on shore measuring the beach or checking surf conditions, and in the water skin diving over the reef. Many qualitative observations were hence able to be made. Observations were noted and photographs were taken as evidence. Several points of concern were raised on visits to the reef site, as will be noted in the discussion.

3.7 Middleton Beach (Feasibility study)

A feasibility study into constructing an artificial surfing reef at Middleton Beach in Albany was also initiated during this study. The bathymetry of the offshore region at Middleton Beach was quantified by recording bathymetry readings from a grid of 500 by 500 metre cells throughout King George Sound (off Middleton Beach) to an offshore depth of approximately 50 metres. These bathymetry measurement were recorded in an Excel spreadsheet for analysis as part of a future study.

Plate 3.1. Weighted pressure sensor deployed at Cable Station reef; inner apex.

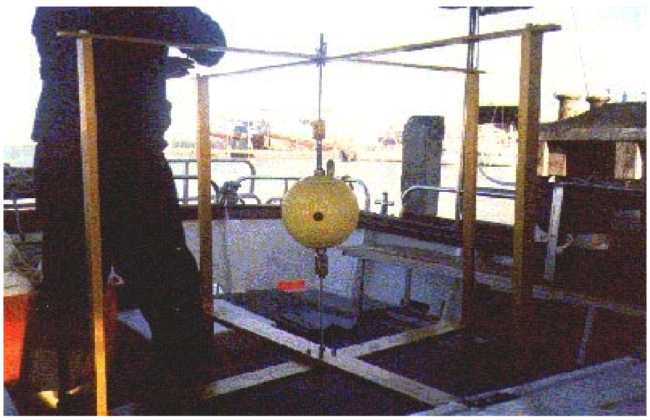


Plate 3.2. S4 current meter and frame, before weights were attached to each of the corners.

Plate 3.3. Axis web camera located at the Family and Children Services' McCall Centre

Plate 3.4. View recorded by the web cam at Cable Station (after DOT, 1999)

4 RESULTS AND DISCUSSION

4.1 Introduction

This thesis covers a wide range of aspects associated with performance monitoring of the Cable Station Artificial Reef. The incidence of wave breaking and the conditions under which this occurs was a major part of this design monitoring. The beach width results will be useful if included in future monitoring programs, however on their own they give little indication of the changes which may be occurring due to the artificial reef. Qualitative observations associated with the reef have also been included as they are of future monitoring importance.

This assessment of the performance of the artificial reef is of significant importance in that the reef is the first of it's kind in the world. Cable Station is the first artificial reef constructed specifically for the purpose of recreational surfing and as such it's performance will be noted by designers of artificial surfing reefs in the future. This area of coastal engineering is rapidly expanding, with projects already being initiated in places such as California, USA; the Gold Coast, Australia; and at several locations in New Zealand. The success of Cable Station Artificial Surfing Reef and these other frontrunners in artificial reef technology will influence the directions in which this technology progresses in the future.

The aspects of the reef's performance which have been examined include:

- occurrence of wave breaking over the reef
- conditions under which wave breaking occurs (including swell height and period, water level and Iribarren number)
- shoaling coefficient over the reef
- wave climate at the Cable Station artificial reef site
- effects of the reef on sediment erosion/deposition in the area (beach width monitoring)
- peel angle and peel rate being produced by the reef
- detrimental effects on the shore and dune areas in the form of erosion (qualitative)
- biological activity on the new artificial reef (qualitative)

4.2 Wave Climate at Cable Station

4.2.1 ASSESSMENT DATA

The following assessments of the wave climate present at Cable Station were made using the following:

- data from deployment of an S4 current meter and pressure sensor at the artificial reef from the 3rd of August to the 1st of September, 1999;
- data from the Waverider Buoy permanently located at Deep Channel, Cottesloe;
- water level records measured at Fremantle Harbour.
- wind data from the Swanbourne anemometer.

4.2.2 RESULTS OF FIELDWORK

The S4 current meter that was deployed in 8 metres of water directly offshore from the reef recorded data over the entire deployment period of 28 days, however collection of the pressure sensor revealed that it had recorded only 2 days of data. As such, the analyses of the wave climate at Cables was focussed on the data collected by the S4, although the 2 days of data from the pressure sensor was also considered. The significant wave heights and periods determined over the recording period for each of the recording devices are shown in Figures 4.1 and 4.2.

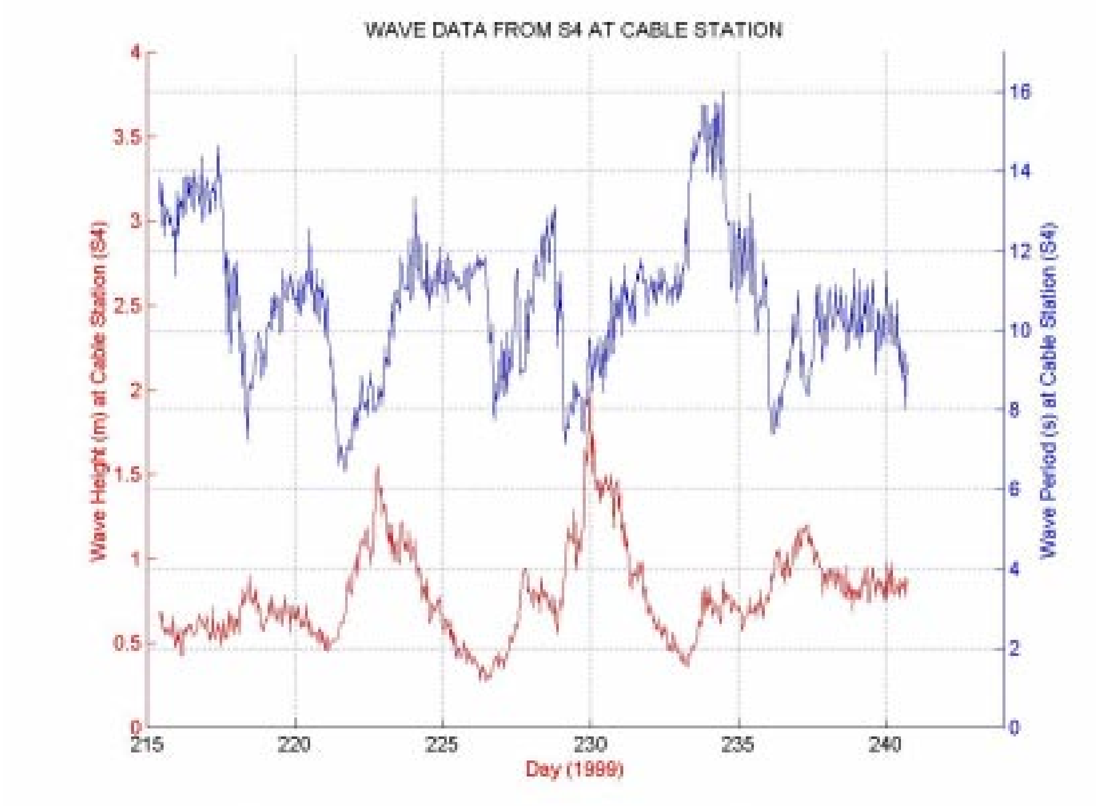


Figure 4.1. Wave data measured by the S4 current meter located in 8 metres depth offshore of the reef.

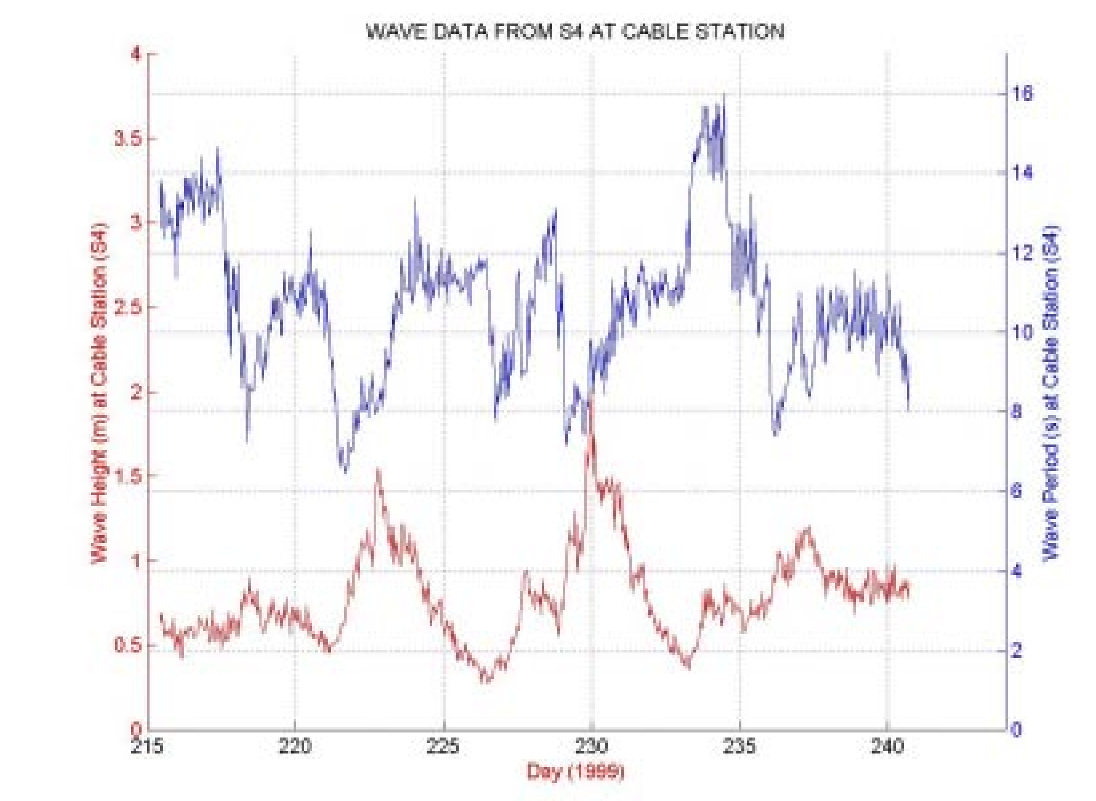


Figure 4.2. Wave data measured by the pressure sensor located at the inner apex of the reef.

4.2.3 ANALYSIS OF DATA

Three aspects of the wave climate at Cable Station were assessed during this study;

- Comparison between the wave climate at Cable Station and that at Deep Channel, Cottesloe;
- Wave shoaling over the artificial reef (limited due the problems associated with the pressure sensor recording device); and
- Assessment of wave conditions likely to be conducive to surfing at Cable Station.

4.2.3.1 Wave climate: S4 versus Deep Channel

Comparison of the wave heights measured at Cable Station (S4) and those recorded by the Waverider Buoy at Deep Channel, Cottesloe indicated that the wave heights experienced offshore at Cable Station are very similar to those recorded at Deep Channel. This can be seen in Figure 4.3 which gives a time series of the significant wave heights from both locations. The Deep Channel Buoy did not record any data from about day 222 to day 225 and on days 239 and 240, therefore these periods were omitted from the assessment as they appear misleading on Figure 4.3. When these areas of the plot are ignored, it can be noted that there are only slight deviations between the wave heights measured at the two locations.

When the significant wave period at each of these locations are compared (see Figure 4.3), the trends in the period are virtually identical, however the values appear to be out by approximately 2-3 seconds. This may indicate that the spectral analysis technique used by the Coastal Data Centre to analyse the time series recorded at Deep Channel differs from that used in this study to analyse the S4 current meter data. This was concluded, rather than assuming different wave conditions, because the period of swells incident on the Perth metropolitan coastline do not differ significantly along the coast, and especially not between areas close in proximity to one another.

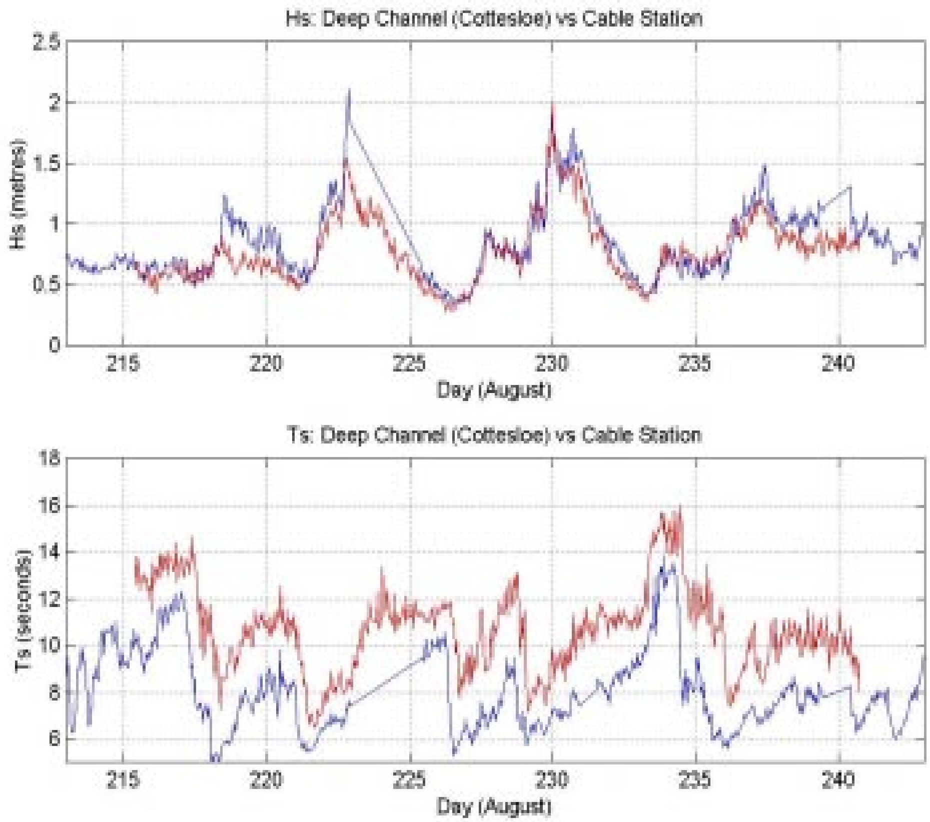


Figure 4.3. Comparison of significant wave heights and periods from the S4 current meter and Deep Channel, Cottesloe.

It is concluded that the wave climate measured at Deep Channel, Cottesloe is very similar to that recorded offshore of the Cable Station Artificial Surfing Reef. This was a very useful discovery because, although the S4 was only temporarily deployed at Cable Station, the Waverider Buoy at Deep Channel permanently records wave conditions. This means that, in the future, wave conditions incident on the Cable Station artificial reef can be well approximated by the data recorded at Deep Channel.

The data recorded at Deep Channel was also the source of wave climate data used in the design of the reef and the many assessments of the proposed reef that followed. The conclusion that the wave conditions incident on Cables are very similar to those at Deep Channel means that the reliability of the design studies and other assessments are further validated.

4.2.3.2 Shoaling over the artificial reef

The results of physical modelling undertaken by Lyons (1992) as part of the reef design study were used to estimate the predicted shoaling coefficients for the artificial reef. For each of probes 2 to 4, located on the right arm, inner apex, and left arm respectively, wave heights measured at the probe under 4 different swell scenarios were recorded. From these results, Figure 4.4 was developed, which shows calculated shoaling coefficients for each sensor under a matrix of 16 different swell height and period conditions. This shoaling coefficient was calculated using;

$$\textit{shoaling coefficient} = H_{SENSOR} \div H_{INCIDENT}$$

The shoaling coefficient measured on the physical model varied under different swell conditions. In general, the larger swells appeared to have smaller shoaling coefficients under the four periods tested. The mean shoaling coefficient that can be estimated from these plots is approximately 1.5. Hence, assuming the prototype works according to the physical model results, a shoaling coefficient of around 1.5 can be expected on the artificial reef under mean conditions.

The data recorded by the pressure sensor deployed on the reef as part of the field measurements, was very limited, with only 2 days recorded. This corresponded to a period of low incident swell (Figure 4.2), which meant that an approximation of a shoaling coefficient over the artificial reef would have limited value due to the possible lack of accuracy and validity (due to the lack of data). Figure 4.5 compares significant wave height and period measured at the offshore location and the inner apex of the reef. Visual estimates of a shoaling coefficient from this data give a range of around 1 to 1.25. Since the swell was very low over this period and there was little data recorded, it is not likely that this estimate is a good indication of the shoaling that takes place over the artificial reef.

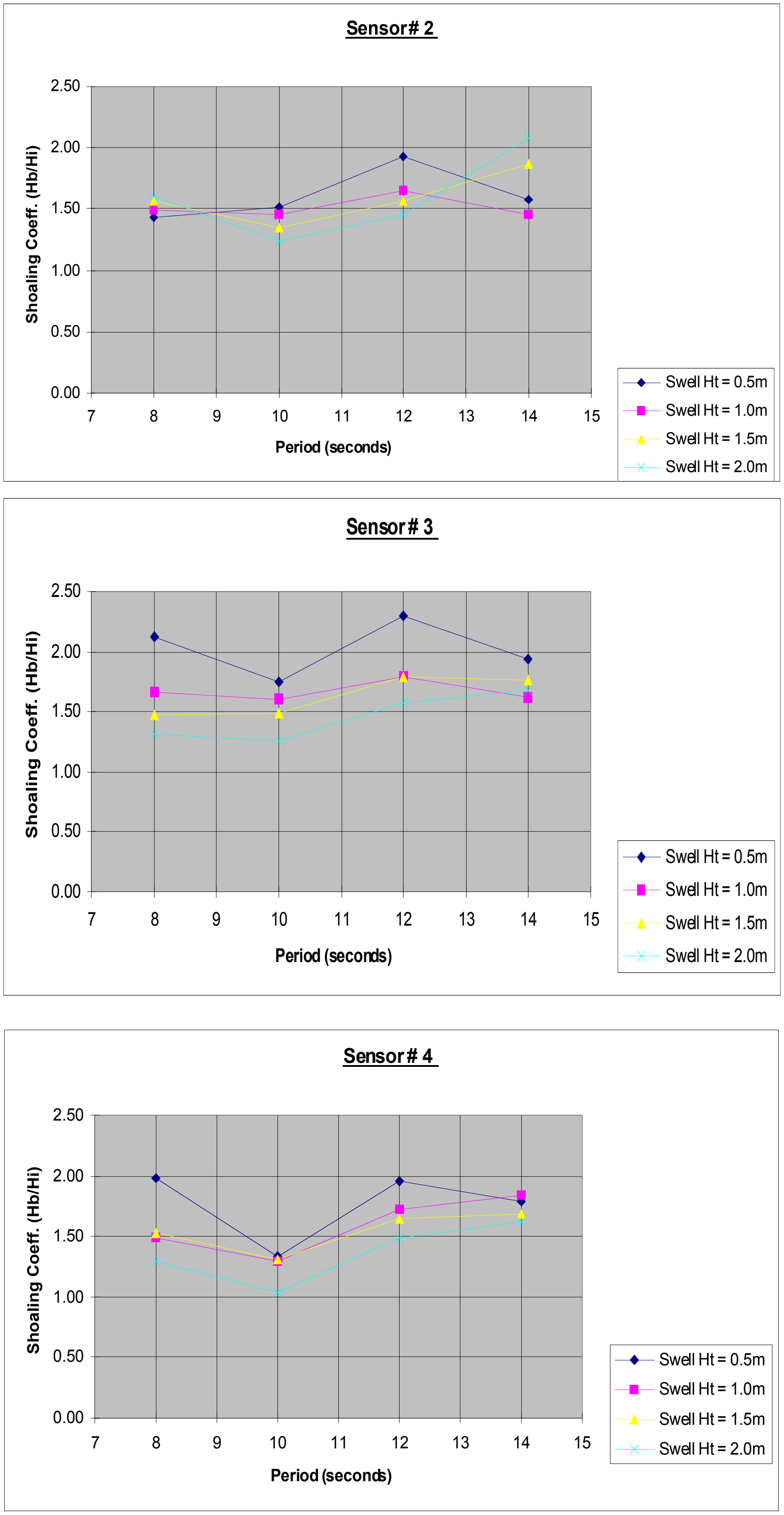


Figure 4.4. Shoaling coefficients determined from the design study (adapted from Lyons, 1992).

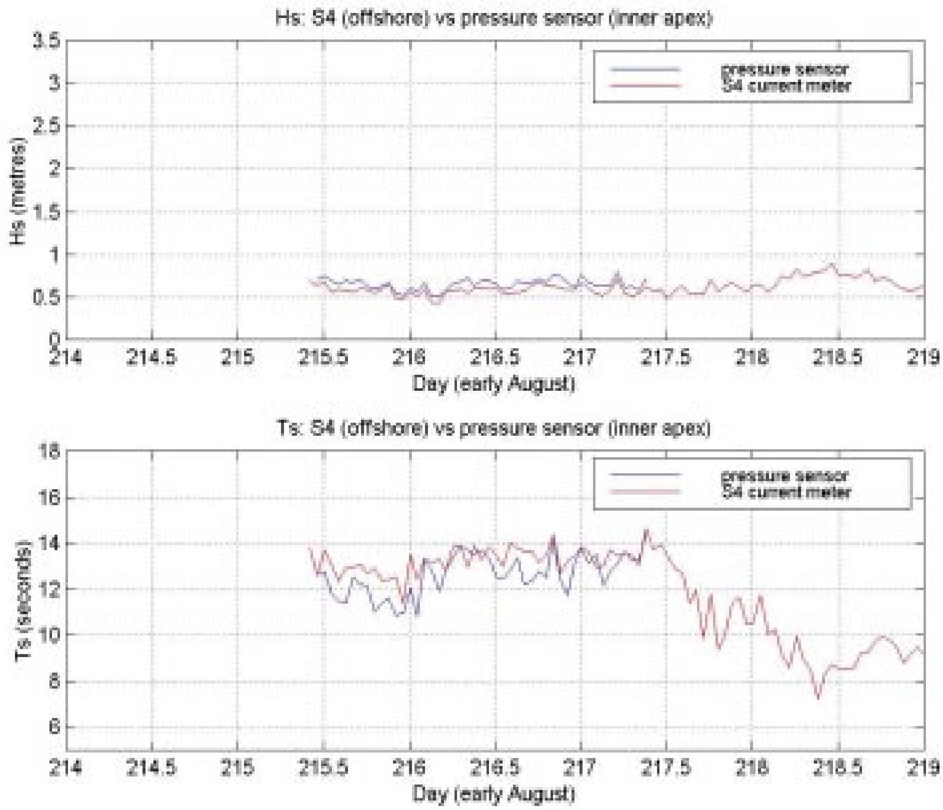


Figure 4.5. Significant wave height and period recorded by the pressure sensor and S4 current meter.

Further monitoring of the shoaling over the artificial reef should be undertaken in the future due to the absence of reliable or extensive data being used for the approximations in this study. From observations of waves breaking over the reef, it is suggested that it would be more effective to place a pressure sensor on both the left and right arms of the reef to enable more realistic estimates of the shoaling coefficient. It may not be necessary to deploy the S4 offshore again, due to the discovery that the wave data recorded at this location is very similar to that recorded at Deep Channel, Cottesloe.

4.2.3.3 Occurrence of best conditions for surfing

Some general observations have been made from the data in relation to the occurrence of the most conducive conditions for surfing. According to general observations and past research into surfable conditions, large wave heights and low water levels appear to be provide the best conditions for surfing. Large wave heights provide a more challenging and powerful wave for the surfer, while low water levels allow for better breaking conditions as the wave can 'feel' the bottom more effectively.

Figure 4.6 is a plot of wave heights from the Deep Channel Waverider Buoy and Fremantle water levels over the period of February to September, 1999. The relationship between the wave height and water level is clearly evident, with large drops in the water level occurring directly after the peaks in the wave height time series.

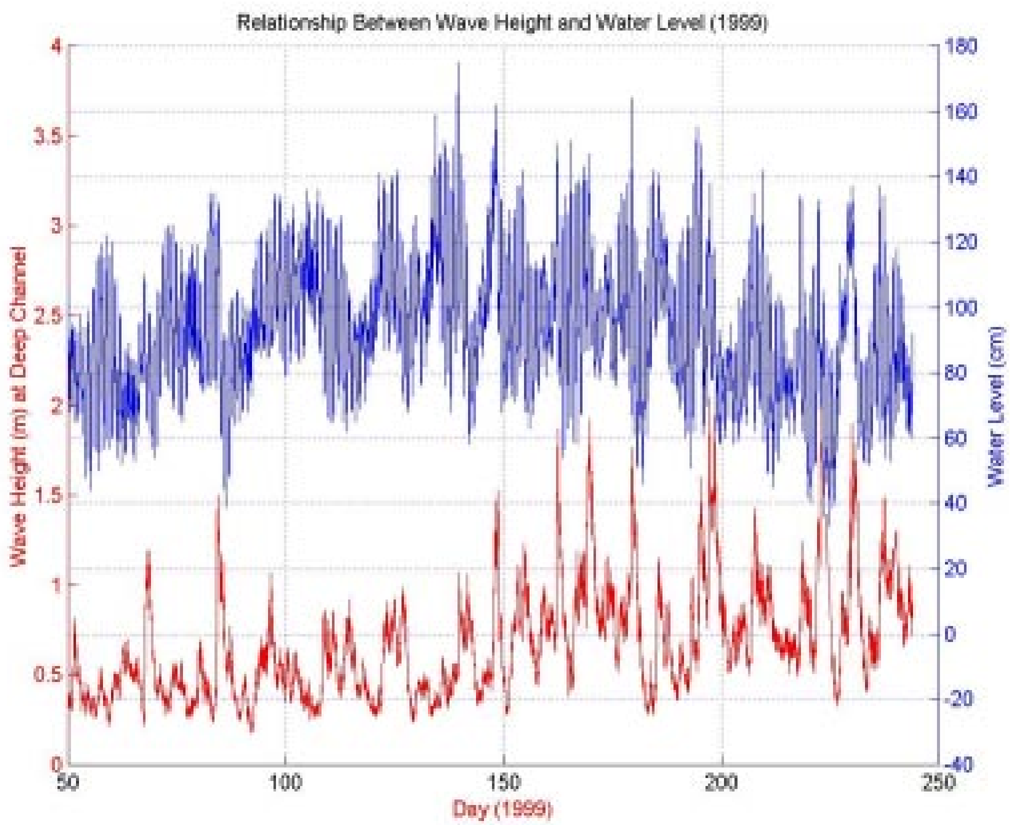


Figure 4.6. Relationship between incident wave heights and water level in the Cables region.

This can be explained by the occurrence of low pressure systems, manifesting as mid-latitude storms, passing across the Western Australian coastline in an easterly direction. Large incoming swells are associated with these storm fronts, with incident swells reaching up to 2.5 metres at Deep Channel. As a low pressure cell passes over the coast, the water level is elevated. When the low pressure system has passed over the coast, the high pressure cell which follows it then depresses the sea level, indicated in these plots by the low water levels at Fremantle following the peaks in the incident swells. Large incident swell heights can persist for some time after storm fronts have passed through the region, and hence can coincide with the drop in water level associated with the high pressure systems.

When this meteorological low water event coincides with an astronomical low tide, the water level is depressed even further, maximising the potential for surfable waves to be produced by a reef break such as Cables, which is designed to work best at low water levels (Lyons, 1992).

Hence, the best conditions for surfing along the Perth metropolitan coastline are likely to occur following the progression of a storm front (low pressure system) across the coast, and during tidal water when the tide cycle for that day is at low tide. Under these circumstances, the water level will be at a minimum and the incident wave height will still be large due to remnant effects of the storm.

4.3 Breaking Waves

4.3.1 INTRODUCTION

Cables Station artificial reef was designed specifically for the purpose of generating a breaking, surfable wave for recreational use. Therefore assessment of the occurrence and surfability of waves breaking on the reef is of high priority in this performance monitoring study. Comparison of the observed wave breaking on the reef during the February to August period with the predicted wave breaking at the site has been undertaken and is outlined in the following section.

4.3.2 RESULTS OF DATA PROCESSING

The web cam images were analysed for both days breaking and surfable days, as described in Section 3.2. The results of this image processing can be found in Figures 4.? to 4.? for February to August respectively. These figures contain time series' of swell height, swell period, Iribarren number and Fremantle water level over the month being considered. Overlain on these time series are red stars that indicate times when waves were observed to break on the reef. On the time series' of Iribarren number, a purple dot indicates that the web camera failed to record images on that particular day (all day).

The green bars which are present on the upper parts of the Iribarren time series' indicate the days in the month that were considered to have surfable conditions. It should be noted that, while a day may have had waves breaking on the reef, this did not necessarily mean that the day in question was surfable (see section 3.2 for details).

Table 4.1 contains the *monthly* counts of days breaking and days surfable (as defined in Section 3.2.4) for the artificial reef. The predicted surfabilities, as assessed by M P Rogers and Associates (see section 2.2.2.8) are also contained in this table to allow comparison. Figure 4.7 provides a visual description of these differences.

Table 4.1. Monthly observations of days breaking and days surfable.

MONTH	OBSERVED		PREDICTED
	Days Breaking	Surfable Days	M P Rogers & Assoc. (1998)
January			0.5
February	1	0	0.75
March	3	3	0
April	3	3	0.25
May	11	7	1.25
June	28	24	3.5
July	27	18	9.75
August	29	22	11.75
September			11.5
October			6.25
November			2.25
December			1.5

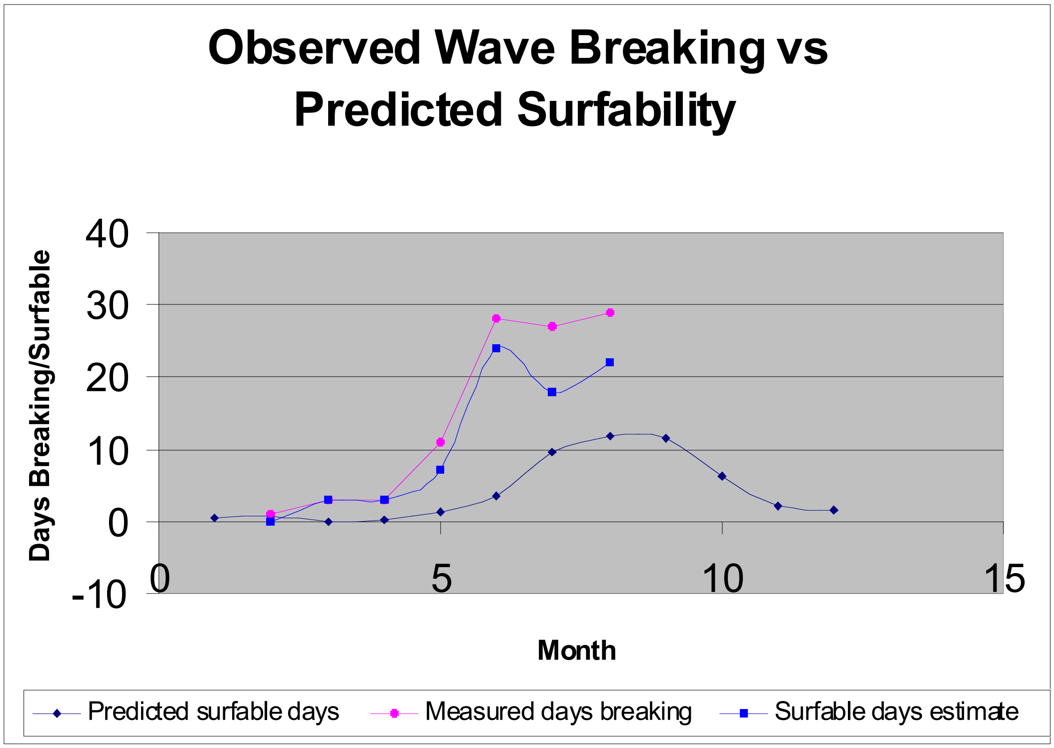


Figure 4.7. Comparison of observed with predicted breaking characteristics.

Table 4.2 contains *seasonal* counts of days breaking and days surfable to allow comparison with the predicted surfability assessments made by Hurst in 1996 (see section 2.2.2.8).

Table 4.2. Seasonal observations of days breaking and days surfable.

SEASON	OBSERVED		PREDICTED			
	Days Breaking	Days Surfable	MRA (1998)	HURST (1996)		
				Method 1	Method 2	Method 3
Summer			2.75	17	5	12
Autumn	17	13	1.5	16	6	14
Winter	84	64	25	58	18	42
Spring			20	32	2	20

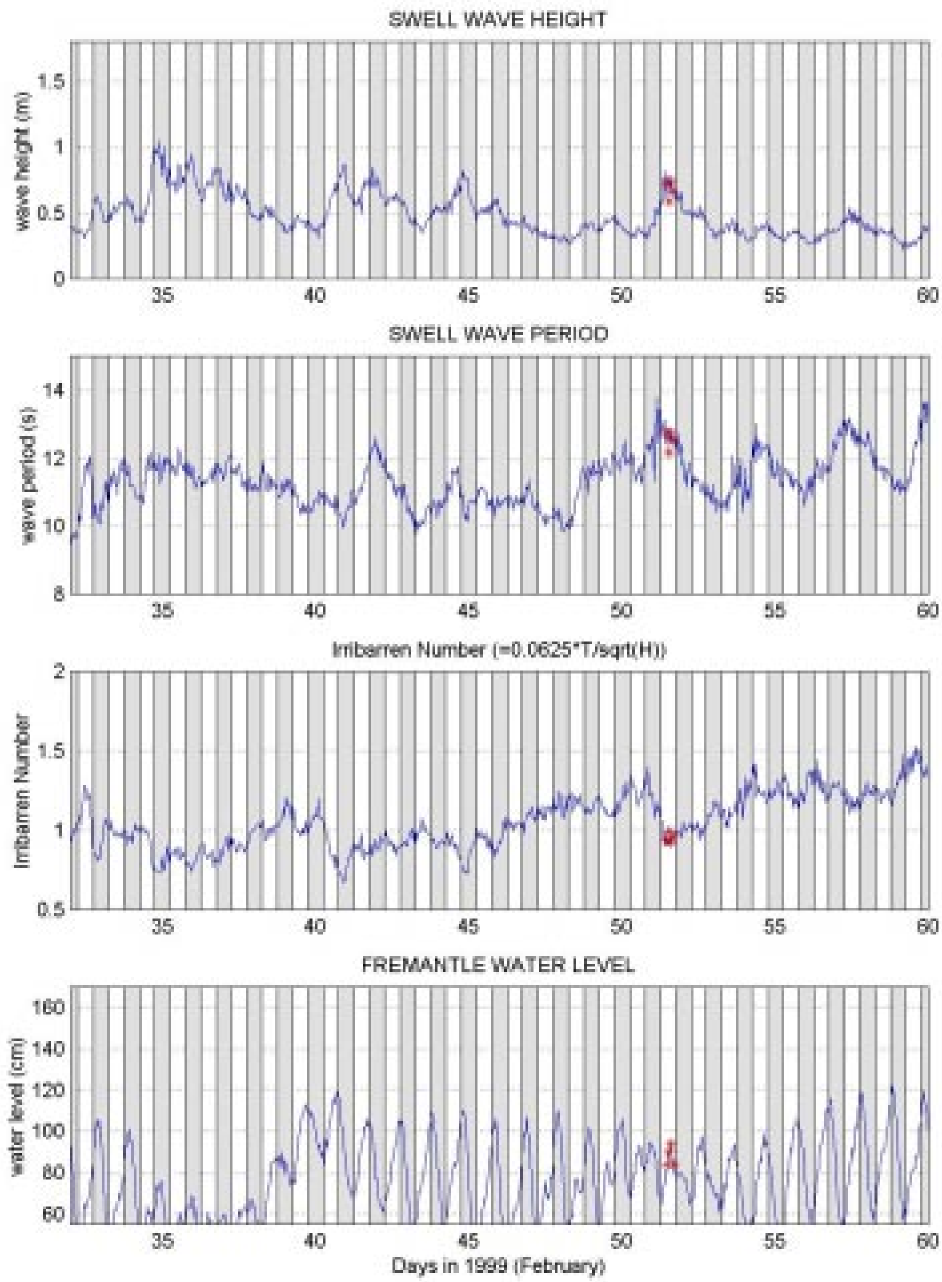


Figure 4.8. Observations of days breaking and days surfable: FEBRUARY (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

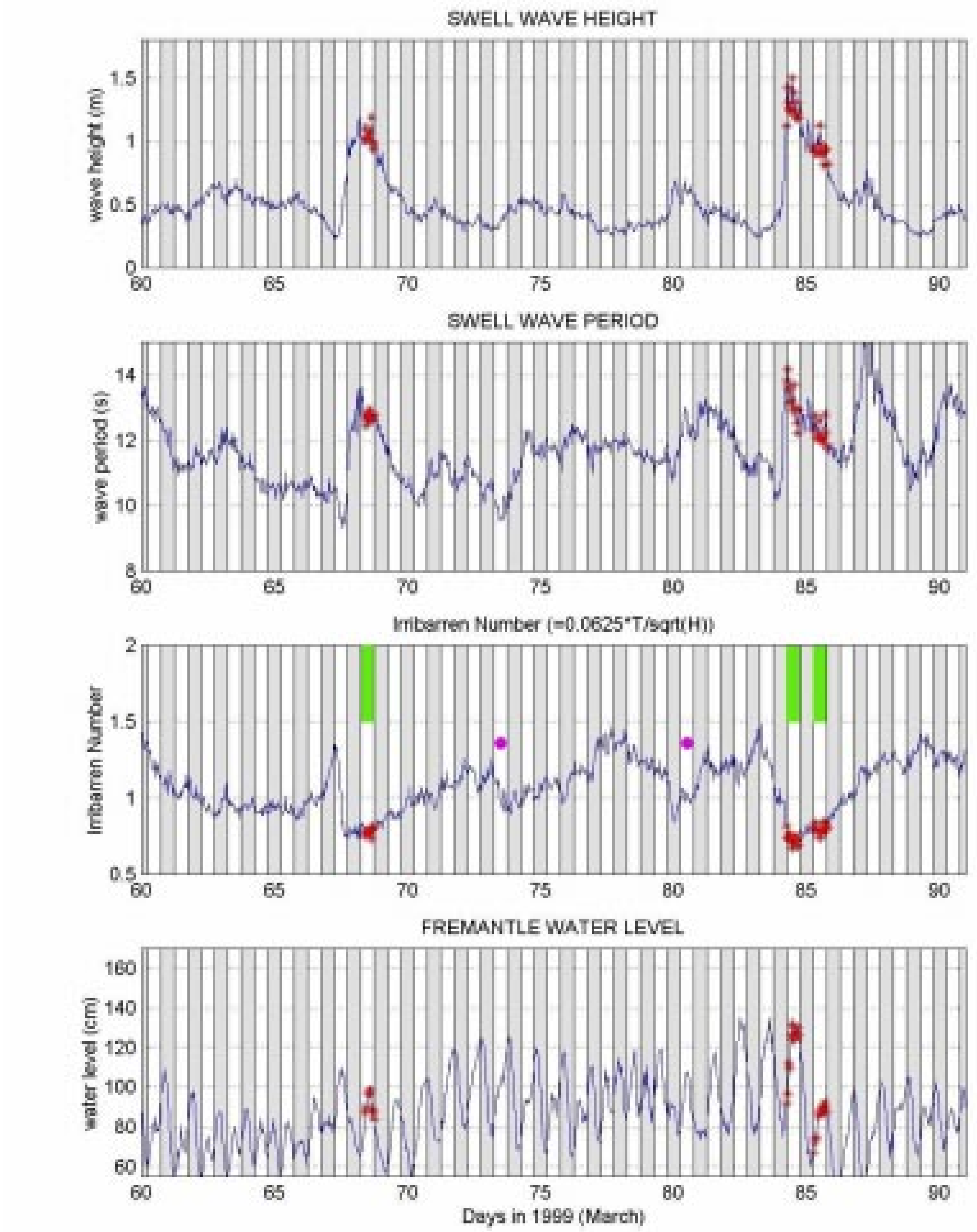


Figure 4.9. Observations of days breaking and days surfable: MARCH (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

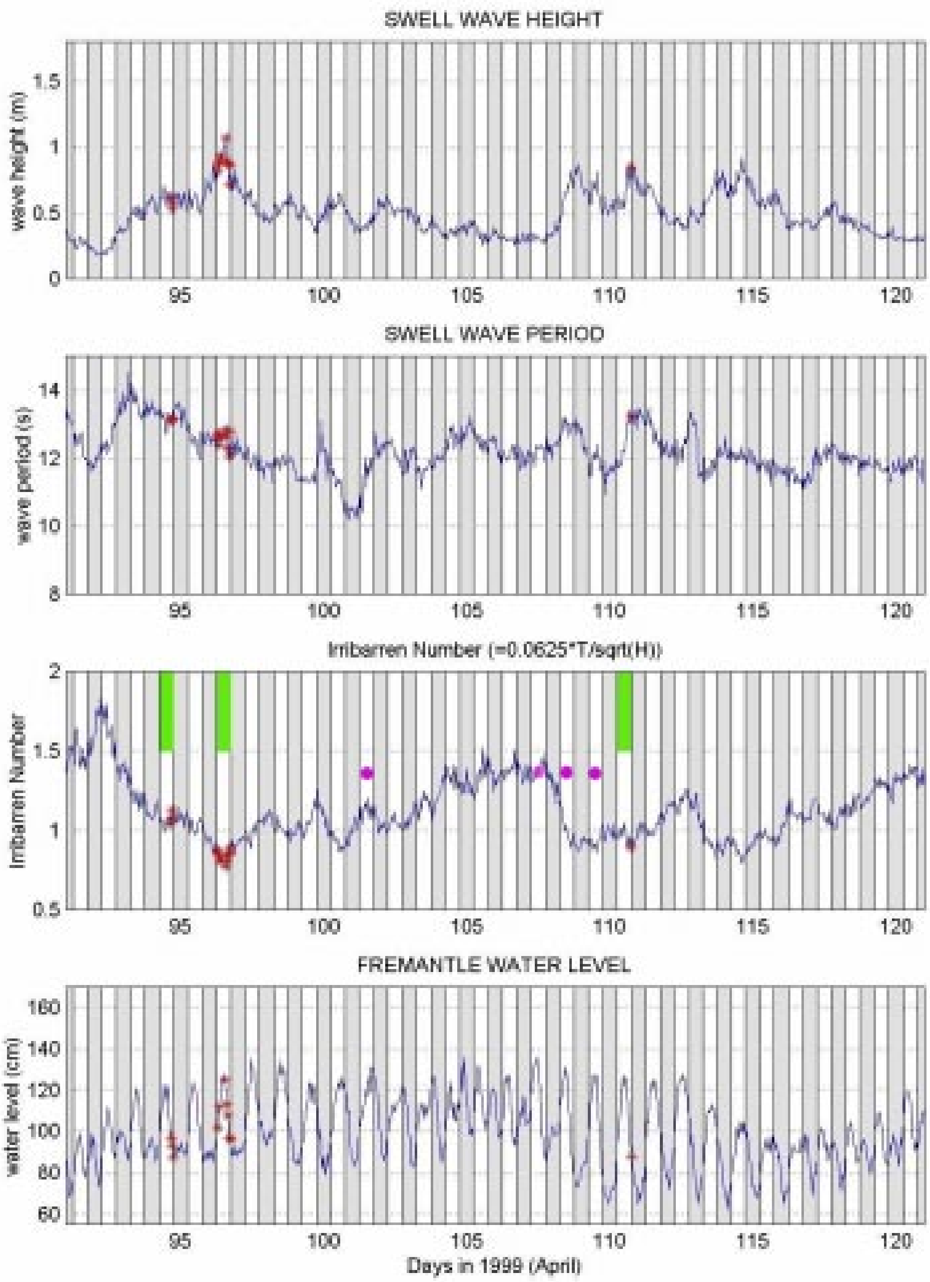


Figure 4.10. Observations of days breaking and days surfable: APRIL (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

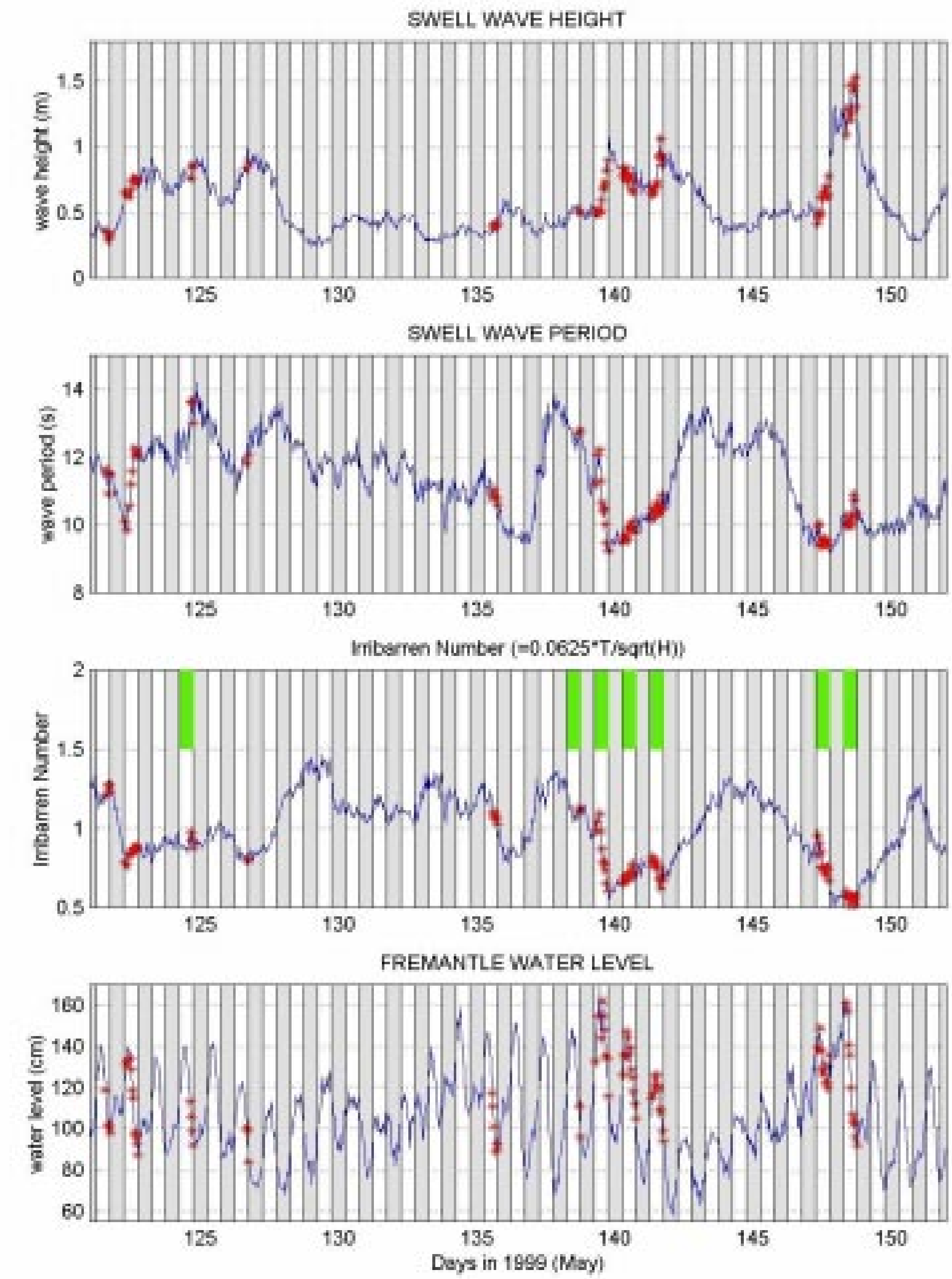


Figure 4.11. Observations of days breaking and days surfable: MAY (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

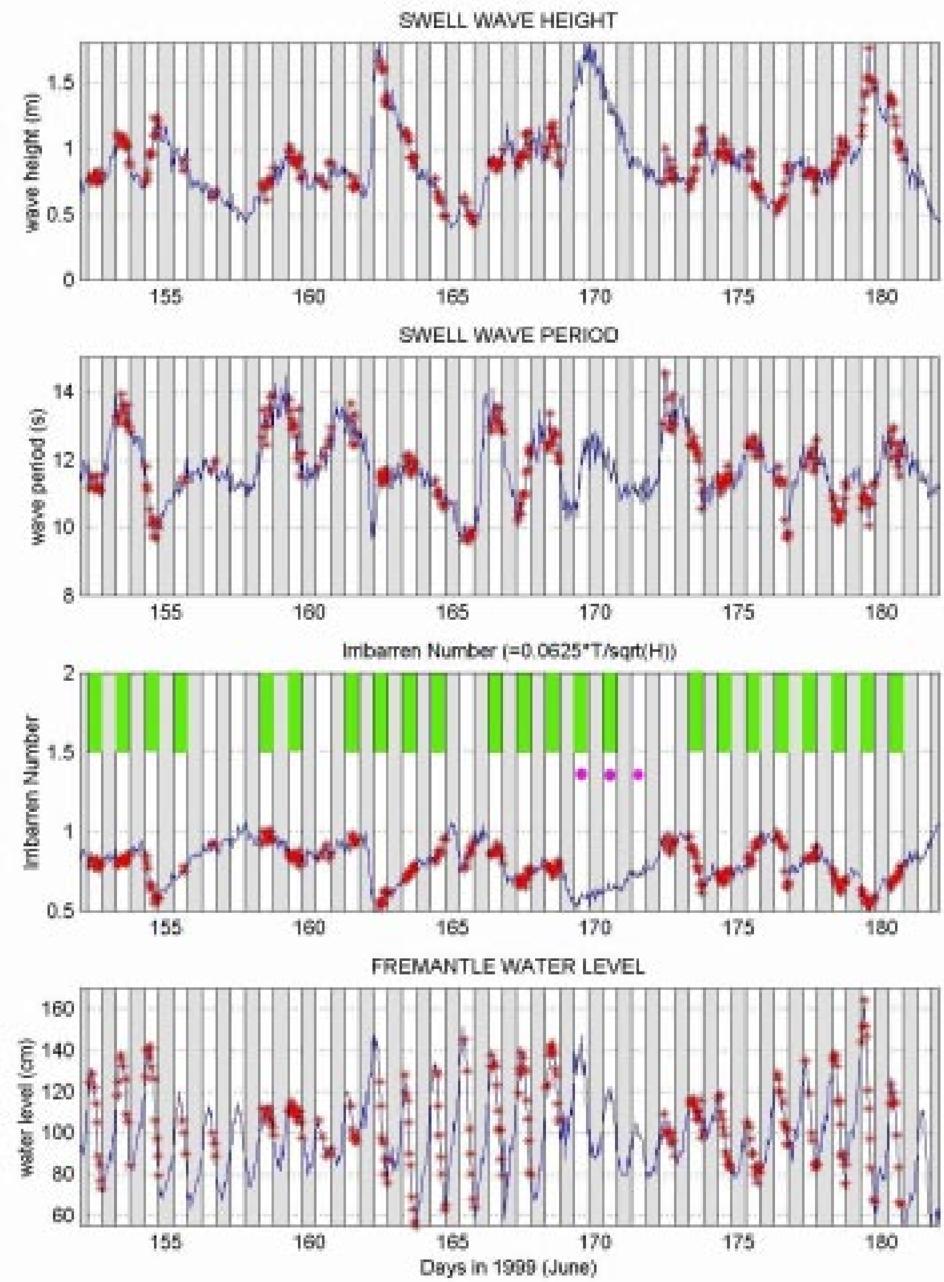


Figure 4.12. Observations of days breaking and days surfable: JUNE (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

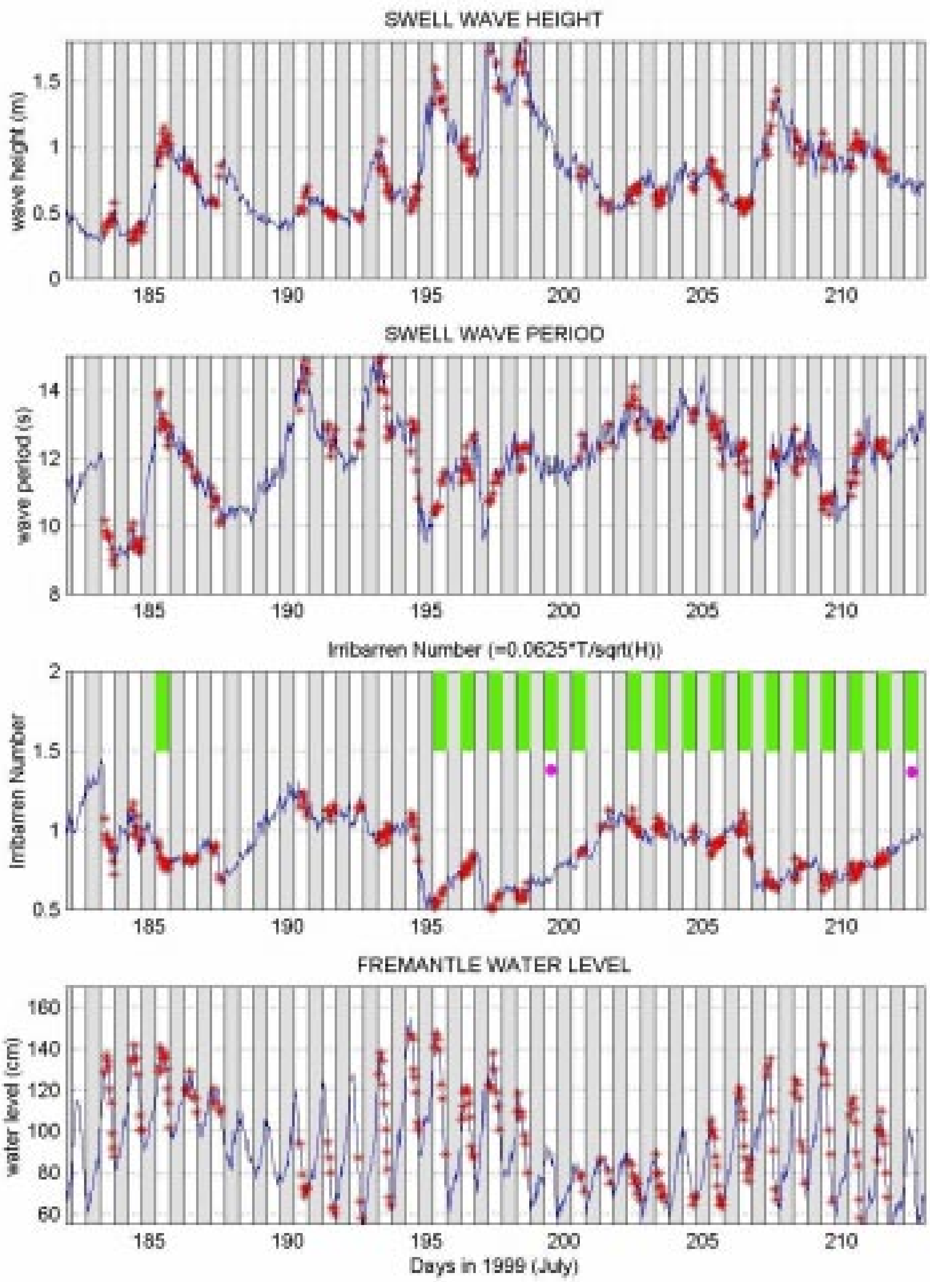


Figure 4.13. Observations of days breaking and days surfable: JULY (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

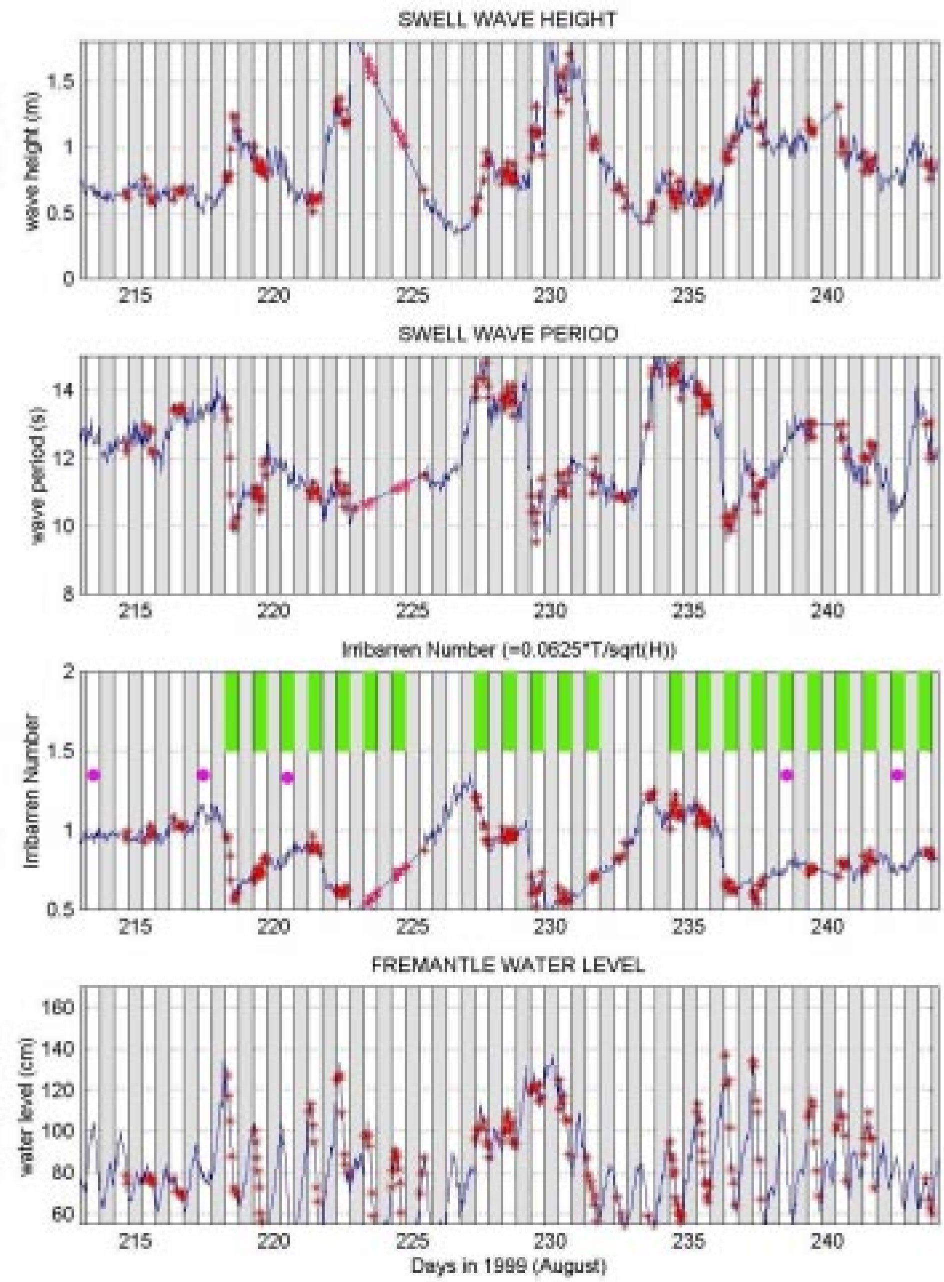


Figure 4.14. Observations of days breaking and days surfable: AUGUST (1999).

Note: red star = breaking; green bar = surfable; purple dot = camera failure (all day).

4.3.3 DISCUSSION OF WAVE BREAKING AND SURFABILITY

Predictions of wave breaking made by Hurst in 1996 were of 252 days breaking and 139 days breaking with wave heights greater than 1.5 metres. The observations of wave breaking made in this study are likely to have included waves breaking with wave heights less than 1.5 metres, therefore a count greater than 139 days was expected. Alternatively, the count of 252 days for the year was likely to have included waves smaller than those counted as the lower limit for wave breaking during the current study, due to the small scale of the images that were assessed. This implies that if the reef is working to design, the days breaking observed for this year should be somewhere in the range of 139 to 252 days.

From the numbers of days breaking over the February to August period, it would suggest that the number of days breaking over the artificial reef for the current year would be in the upper half of this range. If it is also taken into account that construction of the reef was incomplete for half of the study period, it becomes clear that the Cables artificial surfing reef is breaking as well as or better than was predicted.

The observed surfability of the reef far exceeds the predictions made by MRA in 1998. However, this is most likely due to the strictness of the assessment criteria used by MRA, as opposed to the subjective observations made in this study. Assuming that the observed surfability is a significant over-prediction of the surfability of the new reef, even a reduction by a factor of 2 still results in the observed surfability being equal to or greater than the predictions made by MRA (1998).

The observed surfability should also be compared to the predictions made by Hurst (1996) using the three methods outlined in Section 2.2.2.8. The observed surfability for autumn and winter closely approximated the predictions of Method 1, were significantly larger than for Method 2 and were slightly greater than estimates made using Method 3. In the Hurst (1996) study, he concluded that Method 3 was the most likely of the methods to provide good predictions of surfability, and as such it can be concluded that the Cable artificial reef is more surfable than predicted by Hurst (1993).

From the comparison of the reef surfability with these two predictive studies, it can be concluded that the reef is working as well or better than expected, depending on the level of validity that the subjective observations are given.

The surfability of the Cable Station surf site, as opposed to the artificial reef alone, would be greater than that determined above. A shore break exists at Cable Station which is also popular with surfers in the region. This was often surfed in preference to the artificial reef in the early stages of construction as the shore break was generating more rideable waves. The shore break also now produces larger wave conditions than previously due to the focusing effects of the artificial reef.

4.3.4 ANNUAL TIDAL PATTERNS

A qualitative analysis of the seasonal fluctuations in the tidal regime in the vicinity of Fremantle has been undertaken to provide an understanding of the underlying water level trends which affect wave breaking at the Cables reef site. This analysis aided in establishment of the conditions under which the artificial reef at Cable Station is most likely to generate breaking waves, as discussed in Section 4.3.5 below.

The water level, due to tidal and meteorological fluctuations, is a very important factor affecting the occurrence of wave breaking and the form of these breaking waves. The tides in the Perth coastal waters are amongst the smallest in the world. They are predominantly diurnal (one tide per day) with a mean daily range of only 0.55 metres and a maximum spring tidal range of 0.8 metres at Fremantle. Semi-diurnal tides occur for up to six days following new and full moons.

Tidal and non-tidal sea-level variations are of the same order of magnitude in the Perth region. Consequently, sea-level predictions based on astronomical tides alone are of limited accuracy. The tidal predictions used for this analysis were based on the predictable positions of the sun and moon (astronomical), and also on the average meteorological conditions that may be expected.

Figures 4.15 and 4.16 show changes in the time of occurrence of Low Low Water (LLW) and High High Water (HHW) respectively. Also shown on these plots are the predicted water levels for the LLW and HHW occurrence over the year.

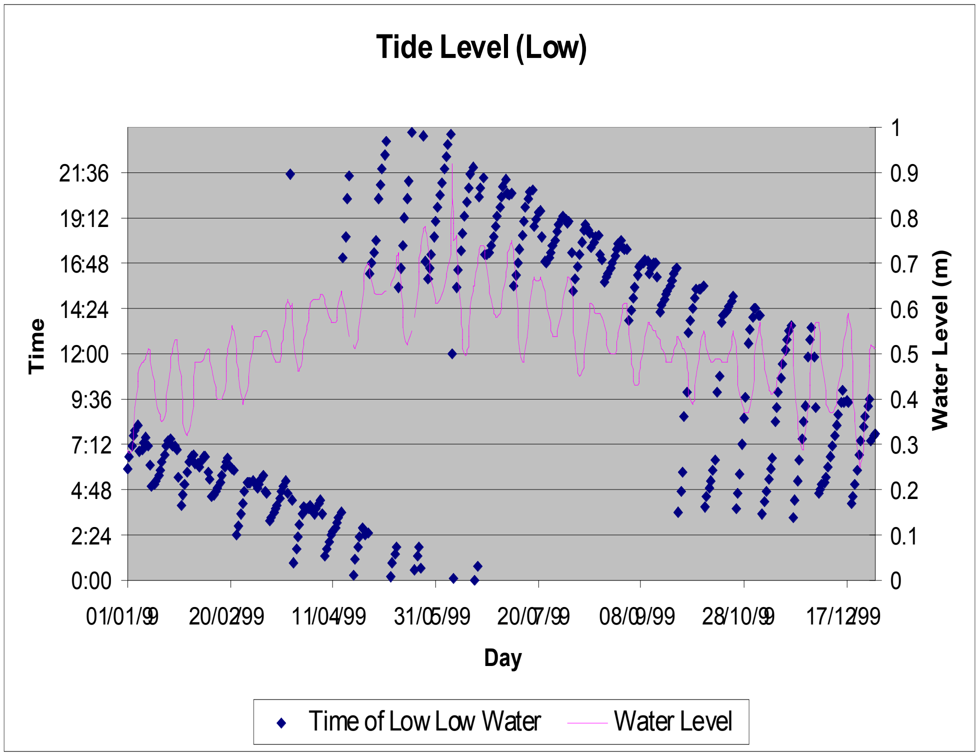


Figure 4.15. Annual tidal patterns: Time and water level for Low Low Water (LLW)

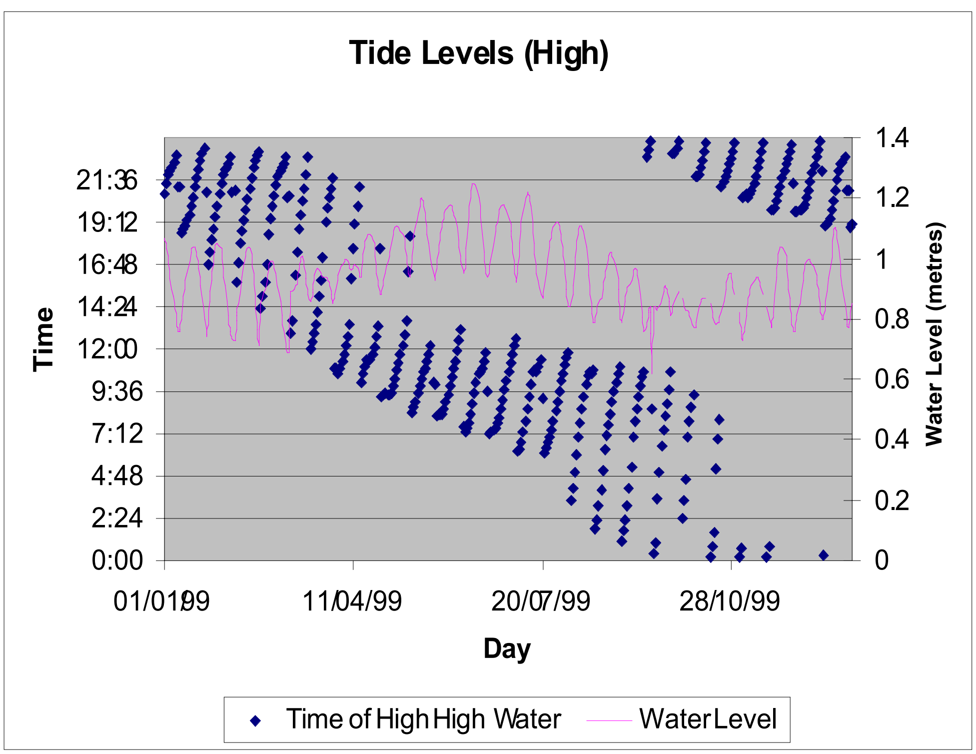


Figure 4.16. Annual tidal patterns: Time and water level for High High Water (HHW)

Over summer, the lowest water level in a day generally occurs in the morning. Superimposed over the seasonal trend is, of course, the higher frequency fluctuations in time of low tide due to the phase of the moon. Hence at the start of summer, LLW can occur anywhere between 4am and around 12 noon, depending on the phase of the moon. As summer progresses, the occurrence of LLW becomes progressively earlier in the day. At the onset of winter, the time of LLW is late at night, progressively becoming earlier in the evening.

So it can be concluded that the best tide conditions for a breaking wave to be generated are late to early morning for summer and autumn respectively, and in the evening and afternoon for winter and spring. This implies that, assuming a fairly constant swell for the day, surfers would encounter the best waves in the afternoon in winter, and in the morning in summer.

However, this is a conclusion relating to the time that *peak* tide level conditions occur on a particular day, depending on the season. It needs to be emphasised that Perth's tides are sometimes diurnal and at other times semi-diurnal, meaning that a secondary low tide sometimes occurs. Therefore, low tides are possible at times of the day other than those of LLW outlined above, such that water level conditions are again conducive to surfing. Low water levels are also often experienced due to meteorological effects, such as continental shelf waves.

In winter, the difference between LLW and HLW is fairly negligible, so there is good water levels conducive to breaking waves both in the early evening (LLW), and early in the morning (HLW). In winter, the occurrence of HLW is generally before 5-6am, implying that surfing feasibility is light limited at this time. Therefore, as previously concluded, the peak conditions for surfing in winter occur in the late afternoon to early evening.

In summer, LLW and HLW generally differ by 0.2-0.3 metres, so there is a considerable difference in conduciveness to breaking waves between the two low tides. HLW during summer occurs in the late afternoon, suggesting that conditions could again be conducive to surfing at this time, depending on the other relevant hours due to the later sunsets that occur in summer, meaning that this occurrence of low water level would be beneficial to surfability of the waves.

The occurrence of High High Water (HHW) follows, obviously, the opposite of this trend, with the largest high tide occurring at night in summer and in the morning in winter, producing water level conditions which are less conducive to wave breaking.

The aforementioned trends have merely been used as an indication of the occurrence of best tide conditions over the annual cycle. There is much variability in the suggested patterns and hence the assumptions are to be interpreted in a qualitative manner.

Continental shelf waves, as described in section 2.1.7.4, are also an important form of long-period sea-level fluctuations that have an impact on wave breaking along the Western Australian coastline. They can have amplitudes of between 0.5 and 1 metre and hence are of comparable magnitudes to the tidal ranges outlined above. They are caused by the periodic passage of synoptic scale anticyclonic systems down the coastline and have significant effects on wave breaking when they occur.

4.3.5 CONDITIONS REQUIRED FOR BREAKING

From the plots that were developed which overlay the days breaking and days surfable over the swell height, swell period, Iribarren number and water level, the conditions under which breaking and surfable waves were produced were assessed (See Figures 4.8 to 4.14.)

It was found that surfable waves could be produced on the reef even under swell conditions as low as 0.5 metres. This observation contradicts the findings of the 1998 PHC study into the surfability of the proposed reef, which claimed that the reef wouldn't produce surfable waves under swells of 0.5 metres, even at Low Low Water (LLW). The reef was actually designed to produce surfable waves from 0.5 metre swells, so this discovery verifies this aspect of the design. Relatively low water levels are however required for surfable waves to be produced from 0.5 metre swells.

The most distinct trend that became apparent was that breaking generally occurs when the Iribarren number is less than one. This is clearly visible on the plots of May, June, July and August. On rare occasions, breaking was observed for Iribarren numbers of slightly greater than one, however for surfable conditions, there is a distinct upper limit at an Iribarren number of one. It is therefore necessary to understand the factors that are required for a low Iribarren number.

As shown previously (Section 3.2.6), the Iribarren number is directly proportional to wave period and inversely proportional to the square root of the wave height. This suggests that a swell with a large wave height and/or a relatively low period is likely to produce a surfable wave (ie. high wave steepness).

Days for which the 'Iribarren number less than one' rule was violated were assessed to further quantify the conditions required for surfable waves. This included assessment of both:

- days when the Iribarren number was less than one and the reef didn't produce surfable waves; and
- days when the Iribarren number was greater than one and surfable waves were still produced.

Wind speeds and directions from the Swanbourne anemometer were available for July and August. Figures 4.17 and 4.18 provide plots of wind speed and direction and the wind speed component perpendicular to the shoreline. These were used to assess the influence of onshore and offshore winds over the July-August period.

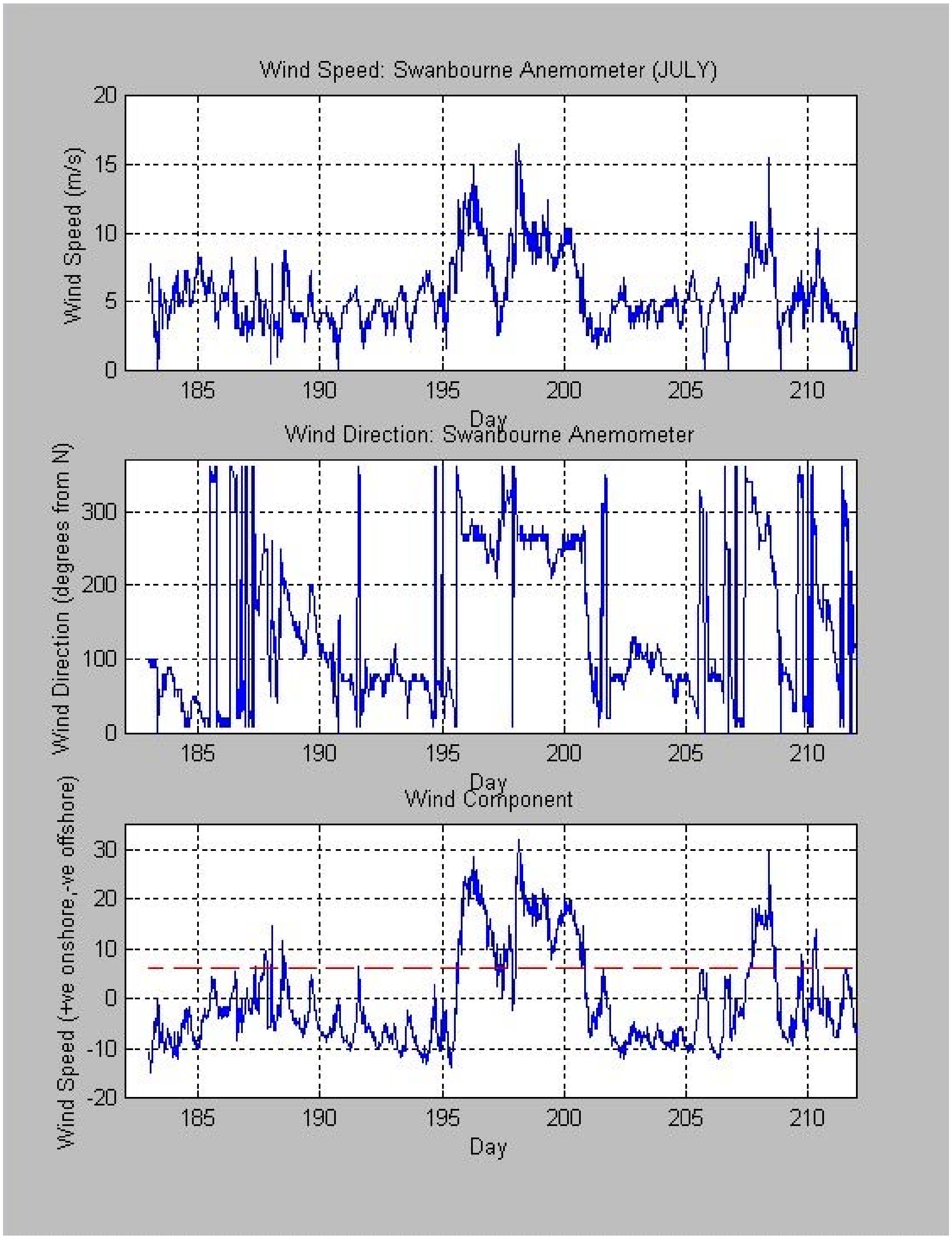


Figure 4.17. Wind data: JULY (Swanbourne anemometer)

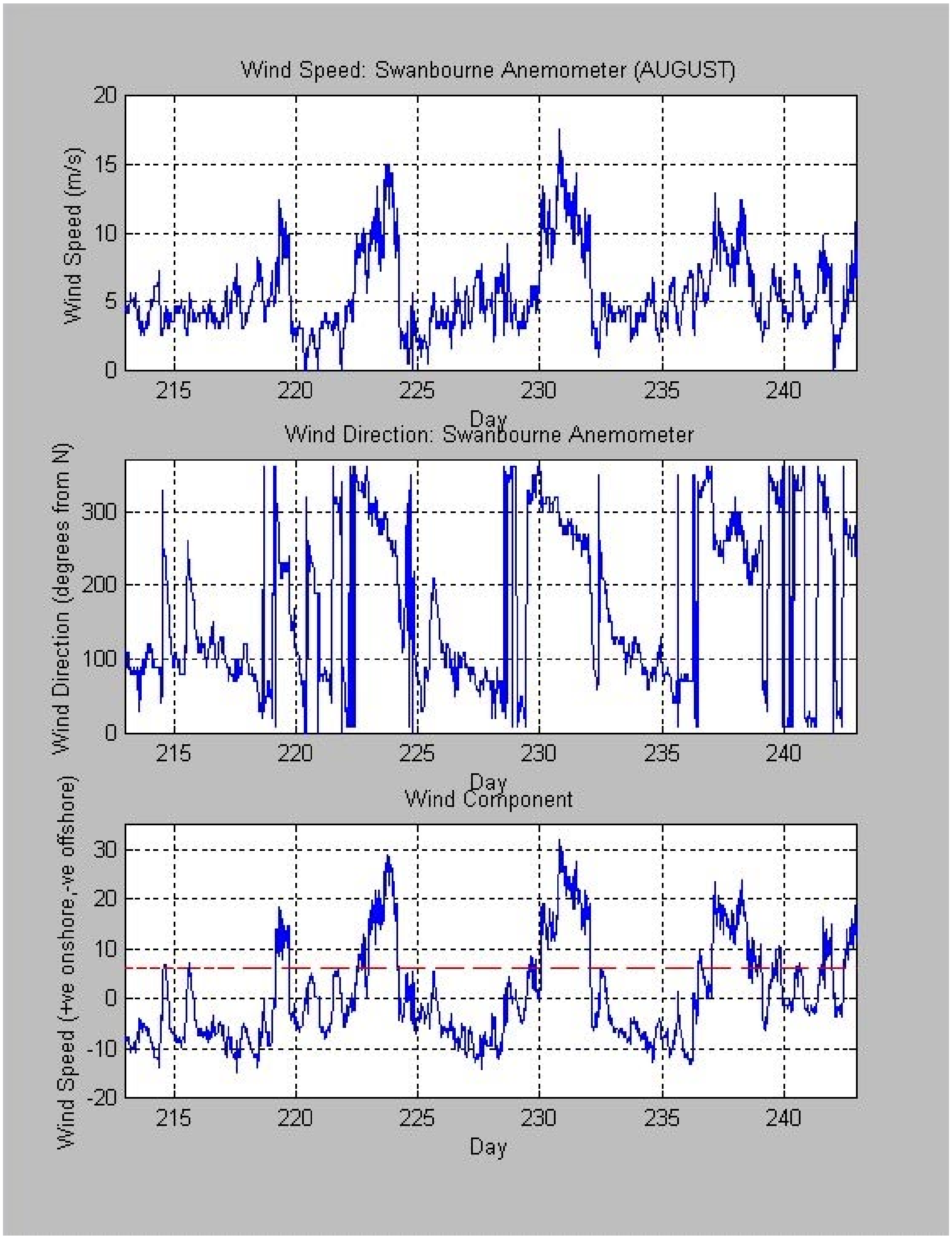


Figure 4.18. Wind data: AUGUST (Swanbourne anemometer)

When the Iribarren number was less than one and the reef break wasn't surfable, it could often be attributed to the presence of high water levels. An example of this is the 2nd of May when, even though the Iribarren number was 0.75, the reef was not surfable due to high water levels. It was often observed over winter period that breaking would not occur in the morning due to high water levels, whereas conditions in the afternoon were conducive to surfing. This can be related back to the annual tidal patterns study (Section 4.3.4), which showed that LLW occurs in the late afternoon to early evening during winter.

For the July-August records, if wave surfability was not being impeded by high water levels, the onshore/offshore component of the wind was checked to see whether onshore winds were causing the lack of surfable conditions. For example, Day 232 (August 20th) had an Iribarren number of approximately 0.6 for most of the day and yet was observed to be unsurfable. The water level was very low and hence could not be used to explain this anomaly. When the wind data was checked, it was found that there was a very strong onshore wind this day that rendered the waves unsurfable. Past studies have shown that an onshore wind of greater than 6m/s is not conducive to producing surfable waves (Baker & King, 1995).

Working backwards from this logic, days when the onshore winds were greater than 6m/s were checked for surfability. A few of the days with these onshore winds were unsurfable even though the Iribarren number was less than one. However for the majority of the July-August period when onshore winds occurred, there was also a significantly large incident swell (winter storm conditions), such that the break was still surfable.

The conditions under which surfable waves occur at Cable station are very inter-dependent, working relative to one another. However, some general conclusions about the conditions conducive to surfing can be made:

- Iribarren number < 1 (large swell height, relatively low period, ie. high steepness);
- Lower water level;
- Onshore component of winds < 6m/s;

- If swell < 0.5 metres, relatively low water is required for surfable waves.

The study hence produced a useful predictive tool in determining whether the artificial reef will be breaking under a given matrix of wave, water level and wind conditions.

4.4 Peel Angle at Cable Station

The images shown in Plates 4.1 and 4.2 were recorded from a helicopter circling over the Cables reef on the 17th of October, 1999. Observations of wave breaking made during this flight indicated that both the left and right hand break were working well. Swells of around 1 metre were incident on the reef at the time when aerial footage was recorded, with well formed, surfable waves breaking on the reef. Several people were surfing on reef on this occasion and appeared to be attaining suitable board speeds when riding the waves.

The peel angle observed was estimated at approximately 45 degrees. The shoaling coefficient over the artificial reef has been predicted in the past as being about 1.5, therefore the assumption of the breaker height on the reef of around 1.5 metres seems reasonable. From these estimates, the surfer ability classification from Walker (1974) that would apply on this day, would be intermediate level.

This estimate was an approximation on a single day under a certain set of wave conditions and as such further testing of the peel angle and rate will be required in the future under a range of different conditions to establish the surfer abilities which are being catered for on the artificial reef. It would be conducive to this analysis to have a pressure sensor on the reef over the period when these peel angles are being recorded in order to quantify the breaker heights occurring with the measured peel angles. From this, a Walker diagram could be developed showing the range of breaker heights and peel angles being generated by the artificial reef.

4.5 Beach Width

Table 4.3, shown below, displays the dates and measurements of the beach monitoring undertaken in this study, while Figure 4.19 outlines visually the fortnightly variation in beach width for the 3 sites in question. The beach widths measured at Cables north, Cables south and Cottesloe main beach showed little trend other than the expected seasonal increase in beach width due to sand accumulation towards summer (lower wave energies) and the offshore movement of sand, and hence erosion of the beach, in winter.

Table 4.3. Beach width measurement results for Cables N, Cables S and Cottesloe.

DATE	BEACH WIDTH (metres)		
	Cable Station (S)	Cables Station (N)	Cottesloe
20/07/99	10.6	18.9	23.3
03/08/99	11	18.5	27
20/08/99	10.4	21	27.5
31/08/99	9	19.25	30.5
15/09/99	11	20	29
29/09/99	11	20.5	32.5

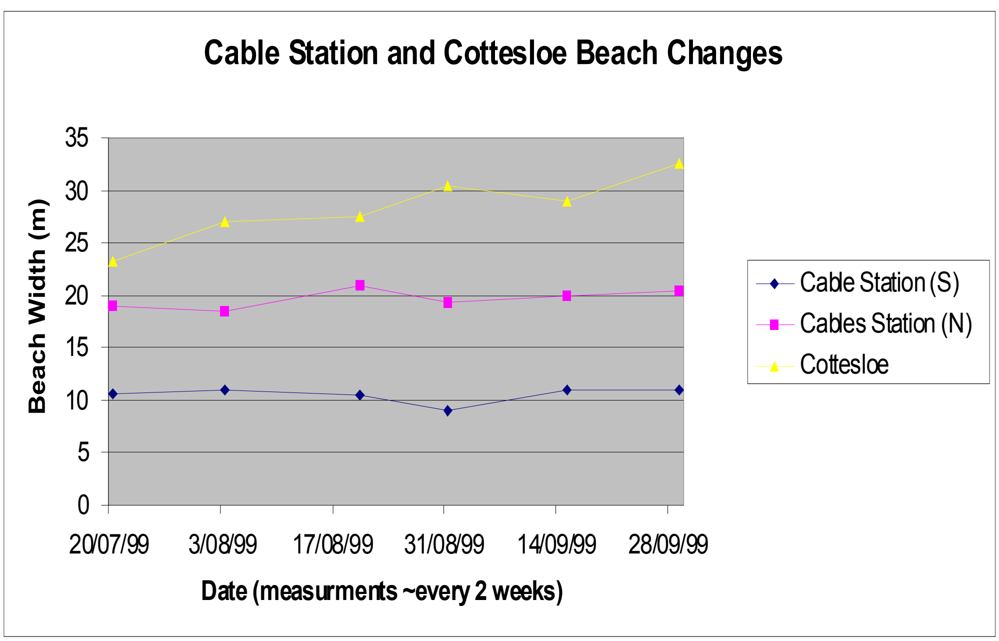


Figure 4.19. Plot of beach width changes for the three measurement sites

The beach monitoring was initiated on the Tuesday the 20th of July, in the middle of winter, so there was hardly any beach width to measure due to winter storms carrying beach sediments offshore. Unfortunately, it appeared that the fortnightly measuring from this time onwards was coinciding with the cycle of cold fronts and storms passing across the coast. As such, the beach was basically non-existent at the Cables south location for each of the beach measurements.

At Cables south, the beach width hence remained fairly constant at around 10 or 11 metres, except on the 31st of August, when the beach was at it's minimum width of 9 metres. Though the beach width varied little over this period, the underlying rocky calcarenite foreshore became more exposed over the monitoring period.

At the Cables north location, there was a very slight increase in beach width over the study period, from 18.5 metres to around 21 metres. Converse to the rocky exposure that occurred to the south of the reef, the Cables north site became less rocky on the foreshore over the monitoring period. This was possibly due to the fact that the southern monitoring location appeared to receive higher wave energies at the shore than at the Cables north location, which appears to be fairly well sheltered.

A shorebreak exists in the vicinity of the Cables south location, were waves reform after breaking on the artificial reef. The waves break close to the shore, and hence the wave energies received at the shoreline are fairly high. The Cables north location is north of the rocky point which exists immediately shoreward of the artificial reef, and there appears to be some energy dissipation occurring in the vicinity of this site. This is most probably due to energy loss due to waves breaking over the rocky reef outcrops in the nearshore region.

Another possible reason for this accumulation to the north of the point and slight erosion to the south of the point could be due to the southward sediment transport initiated by winter storms. During winter (the period over which beach measurements were made), winds associated with the approach of mid-latitude depressions are initially from the north, and increase in strength while shifting to the northwest. Sand hence moves south during winter as a result of the southward-flowing currents

The rocky headland at Cables would act like a small breakwater, trapping sediment to the north and inducing the subsequent erosion on the southern side.

The Cottesloe main beach location experienced a fairly steady increase in width from around 23 metres to 32 metres. This increase could again be due to the increase in beach widths which occur towards summer as the incident wave energies decrease. However this accumulation may also be interpreted as further evidence of the effects of the northwesterly storms in winter, in that the groyne present at Cottesloe to the south of the measurement point would act to trap the southward sediment transport. This pattern of sediment accumulation to the north of headlands/groynes and erosion to the south can be observed in Plate 4.3, an image recorded in October of 1999.

The beach width measurements made over the monitoring period at all three locations cannot, at this stage, be used to draw any conclusions about the effects the artificial reef is having on sediment accumulation and erosion. The data should, however, be included into an ongoing beach width monitoring program at these sites. If this monitoring is undertaken for several years, any significant changes in the beach width between years would be observable, rather than simply noting the fluctuations due to the seasonal sediment movement regime.

It was predicted in environmental studies (Section 2.2.3.6) that the zone immediately shoreward of the surfing reef will experience reduced wave energy due to dissipation across the surfing reef, and as a result, sediment may accumulate in this shadow zone. In light of this prediction, it may be worthwhile to add an additional beach surveying site directly shoreward of the artificial reef, as the current sites are slightly north and south of this location.

4.6 Qualitative Observations

The following observations and concerns were noted by the writer over the study period of January to October, 1999. Although these observations are subjective in nature, the points raised are important when considering the performance of the reef and the effects it's presence is having on the local environment, both in and out of the water.

4.6.1 DUNE EROSION & ENVIRONMENTAL CONCERNS

The lack of proper public access to the Cable Station Beach has been observed as a major problem at the reef site. This lack of formal access points is creating a significant coastal erosion problem at Cable Station due to the public accessing the artificial reef by climbing down the face of the steep dunes at the site. This is causing degradation and erosion of the dunes, and is destroying the vegetation that was previously present stabilising the face of the cliff.

The landforms and geomorphology present at the Cable Station site consist of the degraded surfaces of the Spearwood Dunes (AT&A, 1995). Behind the beach south of the Vlamingh Memorial, there is a steep cliff which rises from about 3 to 10 metres AHD. Considerable quantities of building rubble and fill have been deposited on this cliff in places. At the top of the cliff, the ground has been levelled across to the eastern side of Curtin Avenue. Further north in the vicinity of the Vlamingh Memorial, the landform is more natural and comprises a small section of steep dunes behind the beach, with peaks up to about 14 metres AHD and swales, or depressions, at about 6 metres AHD.

A carpark is present south of the Vlamingh Memorial, hence extending south of the Cable Station Artificial Surfing Reef site, and an access route is present at the northern extent of this area. This access is very degraded and the fence which lined the access route, to keep people out of the dunes to the north of the carpark, has now fallen over. The lower part of the access route is precarious during winter when only rocky outcrops are present rather than a beach. A drop of about 1.5-2 metres to the beach level is present at the lower end of this access route which is difficult to manoeuvre down whilst carrying a surfboard. Surfers hence don't appear to use this as the main access route, preferring to make their way down the face of the cliff/dune that exists in front of the carpark.

Significant amounts of vegetation have been destroyed and bare sediment is now present in previously vegetated areas, leaving the dunes prone to water and wind erosion. This can be seen in Plate 4.4 showing a typical 'access point' used by surfers and other visitors to the Cables site. Around 10 or more of these eroded 'access points' exist on the cliff face immediately in front of the carpark at Cables.

An access route is planned for this location, however due to community objections, the construction has been delayed. While public facilities including picnic tables and shelters have recently been provided at the site, there has been no work done on improving the beach access. The demand for access to the beach is going to increase further still as summer approaches, therefore it is imperative that planned access ramp be provided for surfers and the general public to access the artificial reef site as soon as possible.

If plans are initiated for other artificial surfing reefs in the future, the provision of public access facilities, if not already present, should be one of the first stages *prior* to construction of the reef. People are always interested in something that is new and different, even before completion, and as such an increase in visitors to a site should be accepted as an expected outcome to be included in planning schemes.

4.6.2 BIOLOGICAL ACTIVITY ON THE REEF

From observations of the biological activity on and around the reef made during several dives undertaken before and after construction, it would appear that the artificial reef has not had any significantly detrimental effects on the reef ecosystem. Even during the construction phase, the reef was host to a range of fish species, and a range of aquatic flora was establishing on the reef.

However, future studies of the aquatic flora and fauna at the Cable Station site will be required to ensure that the reef is not having a detrimental effect on the ecosystem in the area. These studies can then be compared with the baseline study undertaken by Alan Tingay & Associates in 1995 to assess any changes that have taken place at the site.

4.6.3 PROBLEMS WITH THE REEF'S CONSTRUCTION

During the construction of the Cables reef, 'holes' or 'gaps' in the reef which were as yet not filled with granite stone according to the design specifications caused wave breaking to be irregular over those sections (See Plate 4.5). This was to be expected early during the construction phase, however occurrences of these irregularities were also noted towards the end of the initial construction phase.

These problems with breaking form, due to irregularities in the reef surface, indicate how adherence to specified design is imperative in the construction of artificial reefs. Most of the holes that were identified in the reef have since been filled by WA Limestone, the company contracted to construct the reef to design specifications. From observations of wave breaking, both at site and from web camera images, these irregularities in wave breaking appear to have been mostly fixed. Plate 4.6 shows a recent image recorded by the web camera showing a well formed, plunging breaker.

4.6.4 CURRENT STATE OF THE ARTIFICIAL REEF

At the time of writing, the artificial reef is considered by the project managers from Egis Consulting to be approximately 95% complete. More rock is required to fill any ‘holes’ that still remain in the reef to ensure that the artificial reef corresponds to the design as closely as possible.

To date, approximately 10 243 tonnes of rock has been placed at the site. This amount is greater than the original quantity of 8 750 tonnes quoted in the construction tender document developed by Egis in 1998. The computer models that predicted the amount of rock required were based on a survey taken on a 2 metre grid. The model assumed that the surface of the pre-existing reef at the site was flat between the survey sites, however the pre-existing reef was actually not smooth like that modelled, rather it’s surface is very irregular in terms of elevation. Therefore the model appears to have underestimated the amount of rock required for the reef construction, however it was the best estimate that could have been made with the available data.

Another reason for the greater quantity of rock required may be from some rock loss due to material rolling off the reef or scattering on the seabed after placement. This is a feasible possibility because of the nature of the method of rock placement, via a front end loader from a barge.

The Department of Transport concluded that it wouldn't be necessary to place sand over the artificial reef after rock placement, as had been initially planned. The funding that had been set aside for this sand placement was hence available for other uses and a reef extension was extended to allow for a longer ride on the right hand (southern arm) section of the reef. It was initially thought that the left arm of the reef would benefit most from this extension, as the right arm was already designed to be bigger than the left. However, it was found that any extension to the left arm was not beneficial because the bathymetry in that region would cause the wave to close out anyway.

The feasibility of extending the right break was then investigated. This was deemed feasible in the sense that the wave wouldn't close out like the left break. However the construction company WA Limestone concluded that they couldn't get the barge they had been using into that area due to the depth of water. This decreased depth is because of presence of the artificial reef. It was decided that WA Limestone would bring in a smaller barge to undertake the right break extension for a slightly increased charge. The proposed reef extension is shown in Figure 4.20 below.

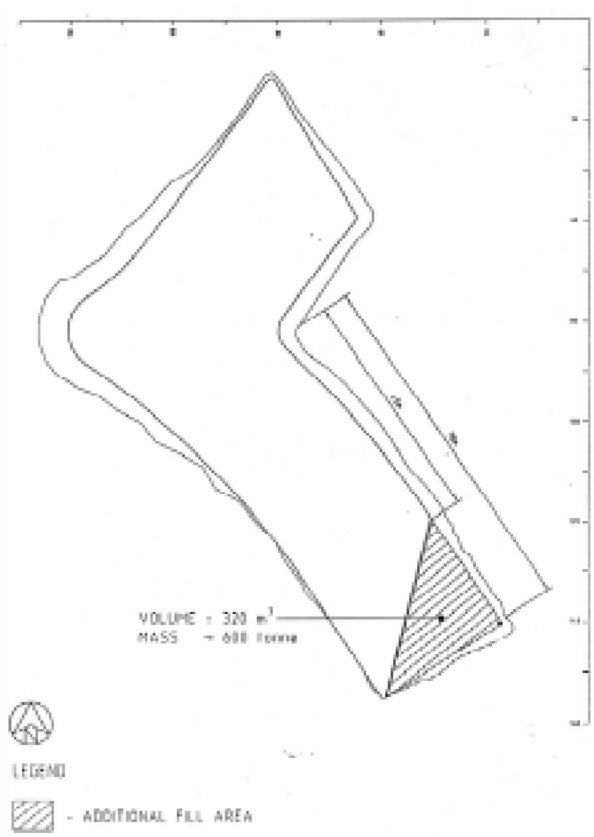


Figure 4.20. The proposed extension of the right arm of the artificial reef.

At present, 60 tonnes of a proposed 600 tonnes, have been placed as part of the reef extension. As with the original sections of the artificial reef, the larger Class 1 armour units would be placed on the perimeter of the extension, with Class 2 rock filling in the interior areas.

Therefore, in total, 10 303 tonnes of rock has been placed to form the reef to date, including the original Scope of Work and the reef extension. The remaining construction work is likely to be recommence during November (1999).

Plate 4.1. Observation of peel angle from helicopter (17/10/99).

Plate 4.2. Observation of peel angle from helicopter (17/10/99).

Plate 4.3. Erosion and deposition pattern along Perth's southern beaches due to winter storm events.

Plate 4.4. Coastal erosion at the Cable Station site due to lack of access facilities.

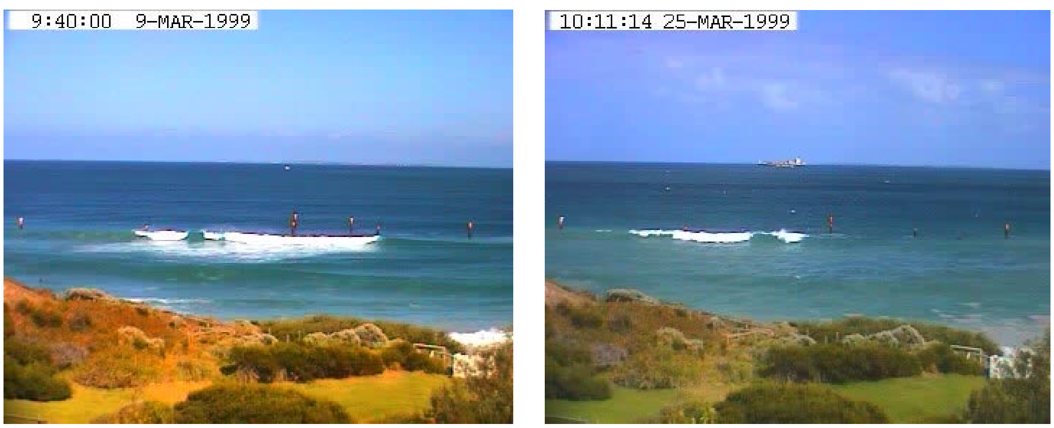


Plate 4.5. Problems encountered with the shape of waves breaking on the reef.

Plate 4.6. Current wave breaking form, after infilling of holes in the reef (after DOT, 1999)

5 CONCLUSIONS

The performance monitoring of Cable Station Artificial Surfing Reef involved assessing many aspects of the reef's performance in order to conclude whether the reef is working as desired and whether it is having a detrimental environmental impact. The artificial surfing reef is a world first, the success of which will surely have an impact on the design and construction of such reefs in the future.

It is concluded from the studies undertaken for this report that the Cable Station reef is working to design and is performing as well, or better than, predicted. The occurrence of wave breaking on the reef is within the expected range, while the reef is surfable on more days than predicted by the surfability study undertaken by MRA (1998). This better than predicted surfability may be due to the subjective nature of the surfability observations as opposed to the strict criteria for surfability imposed in the MRA study. However, even if the observed surfable days are reduced by a factor of two, the reef is still more surfable than was predicted.

On the occasion that the peel angle was monitored, the reef was peeling effectively to the left and right, with a peel angle of approximately 45 degrees. Using a visually estimated breaker height, the day would be classed as being for an intermediate skill level, as dictated by the Walker criteria. There needs to be further investigations into the peel angles being produced on the reef to determine the range of surfer abilities that the reef is catering for.

The incident swell height measured at the 8 metre depth contour offshore of the Cables reef was virtually identical to that measured at the Deep Channel Waverider Buoy off Cottesloe during the August monitoring period. Therefore, in the future, Deep Channel data can be assumed to be a good estimate of the incident swell conditions at Cable Station. This is a useful conclusion because the Waverider Buoy at Deep Channel is a permanent wave climate recording device, and as such will

provide information for use in further studies at Cables Station, possibly alleviating the need to deploy further wave recording devices offshore at Cables.
Field experiments undertaken to determine shoaling over the reef were relatively unsuccessful due to failure of the pressure sensor 2 days after deployment. The 2 days on which data was recorded experienced very low incident swell conditions and the observed shoaling coefficient appeared to be as low as 1 to 1.25 over this period. Further monitoring will be required to attain an accurate estimate of the shoaling coefficient at the site, as outlined in the recommendations.

A qualitative analysis of the occurrence of conditions most likely to be conducive to surfing suggested that the best conditions occur after storm fronts have passed the Western Australian coastline. These low pressure systems cross the coast from west to east, allowing the water level to rise due to the low pressure experienced. Following these low pressure cells are high pressure systems which then depress the water level along the coast. Swell heights generally remain relatively large for some time after storm fronts pass the coast due to remnant effects of the storm, hence large swells and low water levels may be experienced. If this also coincides with the occurrence of low tide, the conditions are very favourable for the production of surfable waves.

The study of wave breaking and surfability of the reef produced a useful predictive tool for determining whether the reef will be working under a given matrix of wave, water level and wind conditions. The conditions of wave, wind and water levels under which surfable waves occur at Cable station are very inter-dependent, working relative to one another. If the offshore Iribarren number is less than one, which requires a large swell height and/or relatively low wave period, the reef will tend to break in a surfable manner. If the Iribarren number was less than one during the study period and the break was not surfable, either the water level was too high or the onshore component of the wind was greater than 6m/s. When the Iribarren number was less than one yet the reef was still breaking, this was attributed to the occurrence of extreme low water.

A 0.5 metre swell, in contradiction with predictions made by PHC (1998), can produce surfable waves on the artificial reef, though low water levels are required. Swells of less than 0.5 metres were found to not produce surfable waves.

The artificial reef does not as yet appear to have affected the deposition and erosion regime in the reef vicinity. The expected accumulation of sediment in the shadow region immediately shoreward of the reef has not been observed. Future monitoring will be required to assess whether this salient is forming due to the reef. The trends that were apparent in the fortnightly beach width measurements taken during this study followed the erosion and deposition pattern that occurs along the Perth coastline due to winter storms. These northwesterly storms generate southward-flowing currents which transport sand from north to south along the coast. The rocky headland at Cables would act like a small breakwater, trapping sediment to the north and inducing the subsequent erosion on the southern side.

Dune erosion has become a significant problem at Cables since the construction of the reef, due to access problems at the site. Surfers and other visitors to the site make their way down the front of the cliff to access the beach, causing degradation of the cliff/dune face. The access routes that are present in the vicinity of Cables are either precarious to traverse down with a surfboard or deemed too far away from the surf site. Provision of an access route should be undertaken before the onset of summer, when the numbers of visitors to the site is likely to increase.

Biological activity in the area doesn't appear to be impaired due the presence of the artificial reef. Although aquatic flora and fauna would have been destroyed or damaged during the construction phase, there is now a large amount of biological activity on the reef and recolonisation is taking place. A study should be undertaken in the future to make comparisons with the baseline study that was undertaken prior to reef construction.

The reef is currently deemed to be 95% complete (October, 1999) according to the original scope of works. Holes, or gaps, have been identified in the reef which need filling to ensure that the reef is completed according to design. Many of these have sand that was to be placed over the reef has been deemed unnecessary by the DOT. The funding that was available for this process is now going towards the construction of an extension of the right hand arm of the reef, with construction likely to be initiated in November, 1999.

The Cable Station Artificial Surfing Reef constructed in the first half of 1999 has been observed to be working according to, and in some aspects better than, design. The wave breaking and surfability appear to be better than predicted, while any environmental problems that have been observed are associated not with the actual artificial reef, but with the increased human traffic at the site.

6 RECOMMENDATIONS

The following recommendations for future work are made in regards to performance monitoring of the Cables Station Artificial surfing reef:

- Ensure that the reef construction is completed according to design, including filling of 'holes' identified on the reef, and construction of the reef extension.
- Undertake further field investigations into shoaling over the reef. It would be advantageous to place two pressure sensors on the reef, one on either arm, to enable better assessment of the shoaling coefficient at Cable Station.
- Continued monitoring of the peel angles being produced on the reef. The aerial footage taken of the reef to observe peel angles should coincide with times when a pressure sensor is located on the reef recording breaker heights. This would allow a Walker diagram to be developed to quantify the surfer abilities that are being catered for by the artificial reef.
- Fortnightly beach width monitoring should continue for several years to allow inter-annual comparison of beach changes, rather than simply noting the seasonal changes which take place at the site. The addition of a monitoring location directly shoreward of the reef may also be advantageous, as this is the area where a salient has been predicted to develop.
- A biological survey of the artificial reef should be undertaken and comparisons be made with the AT&A (1995) baseline study to quantify the biological impacts of the artificial reef.
- Another study relating to the surfability of the Cable Station artificial reef, after construction is deemed 100% complete, may be of value. The surfability observations would be less subjective if the site was visited and surfed each day, either by the researcher or designated representatives from the surfing community.
- The access route, which is already planned for the location, should be built as soon as possible to discourage further degradation of the cliff/dunes

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APPENDIX A1: Design Drawings

APPENDIX A2: Matlab Data Processing Files

```
% script used to create plots of days breaking with relation
% to swell height, swell period, Iribarren number and water level

load dch99.dat
load fre99c.dat
%load wavebreak.dat
%load tidebreak.dat


%February
%Day_Start=32
%Day_Finish=60
%March
%Day_Start=60
%Day_Finish=91
%April
%Day_Start=91
%Day_Finish=121
%etc…

xx=zeros(300,4);
for i=1:300
x1=i+0.75;
x2=i+1.25;
xx(i,:)=[x1 x1 x2 x2];
end
yy=[0 1.8 1.8 0];
cc=[0.9 0.9 0.9];

[m n]=size(dch99);
irrb1=zeros(m,1);

clf
st=sqrt(dch99(:,5));
for i=1:m;
irrb1(i)=0.0625*dch99(i,7)/st(i);
end

%Plot Swell Wave Height
subplot(411)
plot(dch99(:,1),dch99(:,5))
hold on
plot(wavebreak(:,1),wavebreak(:,5),'r*')
grid on
ylabel('wave height (m)')
axis([Day_Start Day_Finish 0 1.8])
% create grey bars for night
for i=1:300
fill(xx(i,:),yy,cc)
end
title('SWELL WAVE HEIGHT')

%Plot Wave Period
subplot(412)
plot(dch99(:,1),dch99(:,7))
hold on
plot(wavebreak(:,1),wavebreak(:,7),'r*')
grid on
ylabel('wave period (s)')
axis([Day_Start Day_Finish 8 15])
yy=[8 15 15 8];
```

```
for i=1:300
fill(xx(i,:),yy,cc)
end
title('SWELL WAVE PERIOD')

%Plot Irribarren Number
subplot(413)
plot(dch99(:,1),irrb1)
hold on
plot(wavebreak(:,1),wavebreak(:,11),'r*')
grid on
ylabel('Irribarren Number')
axis([Day_Start Day_Finish 0.5 2.0])
yy=[0.5 2. 2. 0.5];
for i=1:300
fill(xx(i,:),yy,cc)
end
title('Irribarren Number (=0.0625*T/sqrt(H))')

%Plot Water Level
subplot(414)
plot(fre99c(:,1),fre99c(:,2))
hold on
plot(tidebreak(:,1),tidebreak(:,2),'r*')
grid on
ylabel('water level (cm)')
xlabel('Days in 1999 (August)')
axis([Day_Start Day_Finish 55 170])

yy=[55 170 170 55];
for i=1:300
fill(xx(i,:),yy,cc)
end
title('FREMANTLE WATER LEVEL')

%
orient('tall')
print -dpsc mayi.ps
```

```
% script to create .dat file containing only the applicable
% data on days when the reef was working

load rytest.dat
load dch99.dat
load fre99c.dat

[r_m r_n] = size(rytest);
[d_m d_n] = size(dch99);
[f_m f_n] = size(fre99c);
wavebreak = zeros(r_m,d_n+1);
tidebreak = zeros(r_m,f_n);

d_i = 1;
f_i = 1;

% picks out wave heights and periods for times when the reef is
breaking
for i= 1:r_m
   while rytest(i,1) > dch99(d_i,1)
      d_i = d_i +1
      if d_i > d_m
         d_i = d_i -1;
         break
      end

   end

   if (dch99(d_i,1) - rytest(i,1) ) > (rytest(i,1) - dch99(d_i -
1,1))
      wavebreak(i,1:10) = dch99(d_i - 1,1:10);
   else
      wavebreak(i,1:10) = dch99(d_i,1:10);
   end

end

for i= 1:r_m
   while rytest(i,1) > fre99c(f_i,1)
      f_i = f_i +1
      if f_i > f_m
         f_i = f_i -1 ;
         break
      end

   end
% picks out water levels for times when the reef is breaking
   if (fre99c(f_i,1) - rytest(i,1) ) > (rytest(i,1) - fre99c(f_i -
1,1))
      tidebreak(i,:) = fre99c(f_i - 1,:);
   else
      tidebreak(i,:) = fre99c(f_i,:);
   end

end
%Iribarren calculation
st=sqrt(wavebreak(:,5));
for i=1:r_m;
wavebreak(i,11)=0.0625*wavebreak(i,7)/st(i);
```

```
% SCRIPT USED TO COMPARE SWELL HEIGHTS AND PERIODS AT DEEP CHANNEL
% WITH SWELL HEIGHTS AND PERIODS RECORDED BY THE CABLE STATION S4

clear all
load surfr
load asrwp

subplot(211)
plot(surfr(1,:),surfr(7,:))
axis([213 243 0 3.5])
hold on
plot(wavestat(1,:),wavestat(7,:),'r')
grid on
ylabel('Hs (metres)')
xlabel('Day (August)')
title('Hs: Deep Channel (Cottesloe) vs Cable Station')

subplot(212)
plot(surfr(1,:),surfr(3,:))
axis([213 243 5 18])
hold on
plot(wavestat(1,:),wavestat(3,:),'r')
grid on
ylabel('Ts (seconds)')
xlabel('Day (August)')
title('Ts: Deep Channel (Cottesloe) vs Cable Station')
```

```
% SCRIPT USED TO COMPARE WAVE HEIGHT AND PERIOD MEASURED BY S4
% AGAINST THAT MEASURED BY INNER APEX PRESSURE SENSOR
% (SHOALING OVER THE REEF)

clear all
load surfr
load asrwp

surf = surfr(:,1:47);
subplot(211)
plot(surf(1,:),surf(7,:))
axis([214 219 0 3.5])
hold on
plot(wavestat(1,:),wavestat(7,:),'r')
grid on
ylabel('Hs (metres)')
xlabel('Day (early August)')
title('Hs: S4 (offshore) vs pressure sensor (inner apex)')
legend('pressure sensor','S4 current meter')

subplot(212)
plot(surf(1,:),surf(3,:))
axis([214 219 5 18])
hold on
plot(wavestat(1,:),wavestat(3,:),'r')
grid on
ylabel('Ts (seconds)')
xlabel('Day (early August)')
title('Ts: S4 (offshore) vs pressure sensor (inner apex)')
legend('pressure sensor','S4 current meter')
```

```
% SCRIPT USED TO CREATE PLOT OF WIND CHARACTERISTICS FROM
% THE SWANBOURNE ANEMOMETER

clf
load m_9215.lst

Day = zeros(3636,1);
Month = [1 32 60 91 121 152 182 213 244 274 305 335 ];
windtime = zeros(3636,1);

for i=1:3636;
   MD = MOD(m_9215(i,1),10000);
   D = MOD(MD,100);
   M = (MD-D)/100;
   Day(i,1) = Month(M) + D;
   windtime(i,1) = Day(i,1) + ...
      (MOD(m_9215(i,2),100)+ ...
      0.6*(m_9215(i,2) - MOD(m_9215(i,2),100) ) )/1440;
end

speed=m_9215(:,4)*0.51444444;

subplot(311)
plot(windtime(:,1),speed(:,1));
axis([213 243 0 20])
grid on
xlabel('Day')
ylabel('Wind Speed (m/s)')
title('Wind Speed: Swanbourne Anemometer (AUGUST)')


subplot(312)
plot(windtime(:,1),m_9215(:,3));
axis([213 243 0 370])
grid on
xlabel('Day')
ylabel('Wind Direction (degrees from N)')
title('Wind Direction: Swanbourne Anemometer')

subplot(313)
wind = zeros(3636,1);
for i=1:3636;
   wind(i,1)= m_9215(i,4)*(sin((m_9215(i,3)*pi/180)));
end

plot(windtime(:,1),wind(:,1)*(-1))
axis ([213 243 -20 35])
grid on
hold on

limit = zeros(3636,1);
for i=1:3636;
   limit(i,1)= 6;
end
plot(windtime(:,1),limit(:,1),'r--')

xlabel('Day')
ylabel('Wind Speed (+ve onshore,-ve offshore)')
title('Wind Component')
```

```
% SCRIPT USED TO ASSESS THE RELATIONSHIP BETWEEN WAVE HEIGHT (DEEP
CHANNEL)
% AND WATER LEVEL (FREMANTLE DATA)

clf
load dch99.dat
load fre99c.dat


hl1=line(dch99(:,1),dch99(:,5),'color','r');
ax1=gca;
axis([50 250 0 4])
set(ax1,'XColor','r','YColor','r')
ylabel('Wave Height (m) at Deep Channel')
xlabel('Day (1999)')
title('Relationship Between Wave Height and Water Level (1999)')

ax2 = axes('Position',get(ax1,'Position'),...
   'YAxisLocation','right',...
   'Color','none',...
   'XColor','k','YColor','b');

hl2 = line(fre99c(:,1),fre99c(:,2));
axis([050 250 -40 180])
ylabel('Water Level (cm)')

grid on
```

```
% SCRIPT USED TO PLOT THE WAVE MEASUREMENTS RECORDED BY THE S4
% OFFSHORE OF CABLE STATION

wavestat=ones(31,608);

load asrwp
clf
subplot(411)
plot(wavestat(1,:),wavestat(3,:))
xlabel('Time (days)')
ylabel('Ts (s)')
grid on
axis([215 241 6 16])
title('CABLES ASR: AUGUST 1999')
subplot(412)
plot(wavestat(1,:),wavestat(7,:))
xlabel('Time (days)')
ylabel('Hs (m)')
grid on
axis([215 241 0.0 3])
subplot(413)
plot(wavestat(1,:),wavestat(29,:))
xlabel('Time (days)')
ylabel('Wave Direction')
grid on
axis([215 241 0 100])
 subplot(414)
 plot(wavestat(1,:),wavestat(5,:))
 xlabel('Time (days)')
 ylabel('Hmax (m)')
grid on
axis([215 241 0 3])
orient('tall')
print -dps asr99.ps
%!lpr -Plaser stw2.ps
```