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Research-Based Surfing Literature for Coastal Management and the Science of Surfing—A Review

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ABSTRACT

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Incorporating recreational surfing into coastal management practices is required to protect the seabed features and oceanographic processes that create surfing waves. A review of research-based surfing literature is undertaken to provide a summary of information available to assist in coastal management decision making around surfing breaks. The different categories of research-based surfing literature are identified as artificial surfing reef (ASR) design, ASR monitoring, ASR construction, ASR sediment dynamics, biomechanics, coastal management, economics and tourism, industry, numerical and physical modeling, surfers and waves, sociology, and physical processes. The majority of this research has been undertaken in the last decade, making it a relatively young research area. As a background for nonsurfing coastal researchers and managers, the characteristics of surfing waves and surfing breaks are described, referring to relevant literature. Wave height, peel angle, breaking intensity, and section length are identified as essential parameters to describe surfing waves. Existing surfer skill and maneuver categorization schemes are presented to show the relationship between surfers and surfing waves. The geomorphic categories of surfing breaks are identified as headland or point breaks, beach breaks, river or estuary entrance bars, reef breaks, and ledge breaks. The literature discusses the various scale bathymetric components that create these surfing breaks. Examples of modeling offshore wave transformations at Mount Maunganui, New Zealand, as well as the measurement microscale wave transformations at "The Ledge," Raglan, New Zealand, are presented to demonstrate surfing wave transformations.

ADDITIONAL INDEX WORDS: *Surfing breaks, surfing reefs, surfing wave parameters, wave focusing, coastal management.*

INTRODUCTION

A key reason that coastal management practices are needed is to minimize conflict between coastal space users (*e.g.,* boat users and surfers) and coastal sectors (*e.g.,* ocean recreation and port operations). Incorporating the sport of surfing into coastal management is a relatively new phenomenon that is gradually gaining attention because of the importance of surfing breaks to coastal communities (Lazarow, 2007; Nelsen, Pendleton, and Vaughn, 2007; Pratte, 1983, 1987; Scarfe *et al.,* 2009). Consideration in coastal management is required because historically there have been many surfing breaks altered or destroyed by coastal development. When surfing amenities are considered in coastal management projects, the process needs to include transparent scientific evidence.

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Presented at the 4th International Surfing Reef Symposium—Manhattan Beach, California (12–14 July 2005). Conference proceedings are yet to be published.

This paper comprises the introductory section of a comprehensive research effort (Scarfe, 2008) devoted to developing tools for the scientific management of surfing amenities. The research reviews the existing framework of knowledge around surfing research and provides definitions of key concepts for the larger body of work. References for research-based surfing literature are consolidated for those with an interest in the research and management of the coastline. In this context, research-based surfing publications explore the various characteristics of surfers and the surfing environment and industry. The first section identifies the different categories of research-based surfing literature. The second section explains the mechanics of surfing waves and surfing breaks from an oceanographic perspective. It discusses the physical processes occurring around surfing breaks, drawing from literature on the topic. This paper updates and expands on the work of Scarfe *et al.* (2003a) on surfing science, notably by adding a coastal management focus.

SURFING SCIENCE RESEARCH HISTORY

With the exception of the detailed foundation research by the University of Hawaii (Walker, 1974a, 1974b; Walker and

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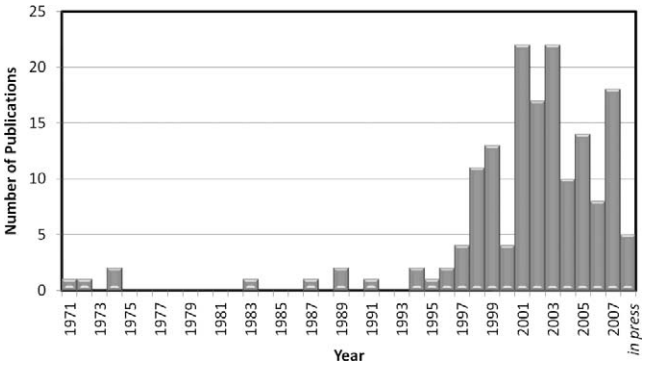


Figure 1. Number of research-based surfing publications identified for each year.

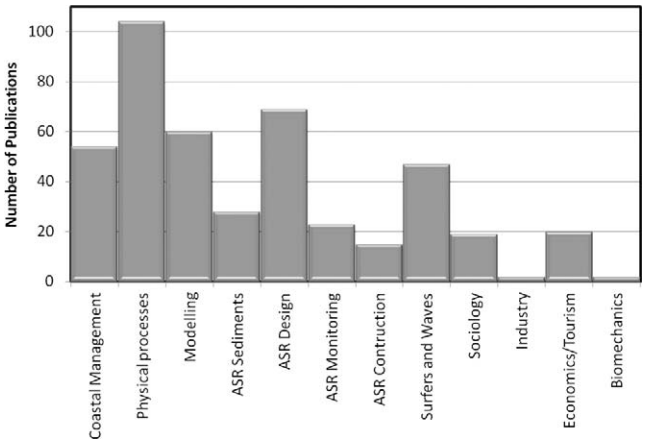


Figure 2. Number of citations for each research-based surfing literature category between 1971 and 2007.

Palmer, 1971; Walker, Palmer, and Kukea, 1972) and a few miscellaneous works (*e.g.,* Dally, 1989, 1991), most of the 63 scientific surfing publications identified by Scarfe *et al.* (2003a) were published in the last decade. The updated review presented here identified 162 research-based surfing publications, and it is evident from Figure 1 that the topic is only a recent focus in the coastal literature. This increase in surfing literature can be attributed not only to surfers trying to understand their environment, but also out of the need to have scientifically credible research to support the concerns of surfing communities that often arise during the coastal management process.

Research from the University of Hawaii identified many of the modern concepts and parameters that should be considered when studying a surfing break. One of the most important parameters used to describe surfing waves, the peel angle (α), came out of this research. Studies of Hawaiian surfing breaks using bathymetric charts, aerial photography, and various other techniques helped dissect the mechanics of surfing breaks. Much of the modern surfing research and literature on artificial surfing reefs (ASR) has come out of the Artificial Reefs Program (ARP) and subsequent research at the University of Waikato (*e.g.,* Andrews, 1997; Black, 2001a; Hutt, 1997; Mead, 2001; Moores, 2001; Sayce, 1997; Scarfe, 2002a; Splendelow, 2004). The use of modern scientific methods, especially numerical wave modeling, coastal geomorphology, hydrographic surveying, and photogrammetry, were invaluable for investigating natural surfing breaks, as well as predicting wave and sediment response to artificial surfing reefs. After achieving the main objectives of the ARP, the major findings were published in the *Journal of Coastal Research* Special Issue No. 29 (Black, 2001a), along with other surfing research undertaken around this time. Topics included relating waves to surfers (Dally, 2001a, 2001b; Hutt, Black, and Mead, 2001), relating surfing waves to surfing breaks (Mead and Black, 2001a, 2001b, 2001c), sediment transport and salient response to offshore reefs (Black and Andrews, 2001a, 2001b; Turner *et al.,* 2001), currents around reefs (Symonds and Black, 2001), and ASR design and construction (Black and Mead, 2001a; Jackson, 2001).

Five international surfing reef symposiums have been held since 1996. Not every conference seems to have produced a widely published proceedings, but the third conference in Raglan, New Zealand (Black and Mead, 2003) produced many editorially reviewed papers. Despite the lack of conference proceedings, each of the symposiums has brought together worldwide researchers on coastal engineering and management for surfing, resulting in an exchange of ideas. Also in recent years Delft University of Technology has published a series of Master's theses on designing ASRs for Dutch swell conditions (*e.g.,* Henriquez, 2005; Over, 2006; Poort, 2007; Trung, 2006; van Ettinger, 2005; West, 2002).

Concurrent to the aforementioned literature, attempts were made to build ASRs in El Segundo, California (Borrero, 2002; Borrero and Nelsen, 2003; Mack, 2003; Moffat and Nichol Engineers, 1989), Cable Station, Western Australia (Bancroft, 1999; Pattiaratchi, 2000, 2002, 2007), Narrowneck, Gold Coast (Aarninfkof *et al.* 2003; Black, 1998, 1999; Black, Hutt, and Mead, 1998a; Hutt *et al.,* 1998, 1999; Jackson *et al.,* 2007; Turner 2006), Mount Maunganui, New Zealand (Black and Mead, 1999a, 2007; Mead, Black, and Hutt, 1998a, 1998b; Mead *et al.,* 2007a; Rennie and Makgill, 2003; Rennie, Mead, and Black, 1998; Scarfe and Healy, 2005; Scarfe, 2008) and Opunake, New Zealand (Black *et al.,* 2004; Tourism Resource Consultants, 2002). The success of the reef projects has been mixed, but each reef has made significant advances in design and construction methods. For example, the complexity of the design and construction method, as discussed in Mead, Black, and Moores (2007), demonstrate significant improvements in the technology since the first attempt in El Segundo.

Many publications on surfing have reviewed the basics of surfing science merely as a background to their research methods. This enables publications to be read without a detailed background of surfing concepts. Although this has lead to repetition in the literature, especially in some of the Masters' theses, it has also resulted in some well-researched synopses on the formation of surfing waves and desirable wave characteristics for surfing. Noteworthy literature reviews are

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included in Bancroft (1999), Black (2001a), Couriel and Cox (1996), Hearin (2005), Henriquez (2004), Mack (2003), Mead (2003), Ranasinghe, Hacking, and Evans (2001), Scarfe (1999, 2002a), Scarfe *et al.* (2003a), Walker (1974a), Walther (2007), and West (2002).

CATEGORIES OF RESEARCH-BASED SURFING LITERATURE

People have initiated surfing research for a variety of reasons. They may simply be interested in understanding the surfing environment, or they may have been motivated to protect a local surfing break or manage a social issue surrounding surfing. Others may be looking to enhance surfing amenities in some way. This includes building ASR, incorporating surfing amenities into another coastal development project, or changing any factor that may improve the surfing experience (including toilets, access to surfing breaks, accommodation, parking, water quality, *etc.*). Given the significant volume of literature on surfing, it is difficult to summarize all of the work into a single research paper, and therefore various categories of surfing research have been created (Figure 2 and Table 1). It is important to appreciate the different categories of information available to make well-informed coastal management decisions.

The categories in Table 1 reflect the main themes apparent in the coastal literature. The literature reviewed has been incorporated into the categories to facilitate its accessibility to decision-makers and researchers interested in particular themes. Some publications (*e.g.,* doctoral theses or final ASR design reports) cover a variety of topics, traversing more than one category, and may therefore have multiple entries in Table 1. To be included, the publication needed to make a contribution to the topic. Only literature that has been cited and reviewed is included in Table 1.

The word "surfing" has been picked up and used in a variety of contexts (*e.g.,* Internet surfing), creating some difficulties when using Internet and library database searches for literature on recreational surfing. It is probable that research presented here has some bias in the distribution of article numbers (Figure 2) towards physical coastal scientific research because of the background of the authors and their familiarity with this field. Moreover, while the compilation is extensive, the logistics of obtaining some publications that may have been of some relevance means that the table is not exhaustive. However, Table 1 and Figure 2 do provide a comprehensive overview of the majority of research-based surfing literature and are indicative of the focus and gaps in the field.

Sociological surfing research is important because at many surfing breaks undesirable or antisocial relations exist between surfers as they compete for a finite number of waves. This is often caused by regular beach users attempting to protect their surfing breaks from outsiders and varied social science approaches have been used to analyze the issues. For instance, Ishiwate (2002) uses Hawaii as a case study to investigate the politics of surfing, including topics such as localism and hierarchies in the water. A more experimental approach was adopted by four-time world surfing champion Nat Young (Young, 2000) who concluded from a number of case studies that every surfer has experienced some form of aggression in the surf. It is important to understand some of the positive and negative cultural issues when planning and managing surfing amenities. However, this literature has not been extensively reviewed here because the broader research focus (Scarfe, 2008) is on oceanographic considerations for coastal management and surfing. For the same reason, the review of literature on the surfing industry and biomechanics is also limited.

In a detailed discussion, McGloin (2005) investigates the relationship between surfing and Australia's national identity, using interviews and literature as research tools. McGloin (2005) believes there has been a shift in ideologies as Australia's identity moves from being based on traditional images, such as bush pioneers and war heroes, to a surfing and beach culture. This cultural change is also identified by Lanagan (2002), who argues the physical act of surfing has been appropriated by business interests and turned into a commodity to make a profit from lifestyle clothing and accessories.

Surfing, while long considered by many as a fringe sport, has developed into a US$10 billion industry (mid-1990s) with over 10 million participants worldwide and a 12%–16% growth rate per annum in surfer numbers (Buckley, 2002a). McGloin (2005) estimated in 2001 that there were 2 million surfers in Australia alone. In another, McGloin (2005) calculates the global surfing industry to be worth $7 billion annually. Considering the economic value, surfing breaks clearly need to be considered in coastal management. Further evidence of the economic value of surfing is presented in ASR economic impact assessments (*e.g.,* Baily and Lyons, 2003; Raybould and Mules, 1999; Tourism Resource Consultants, 2002; Weight, 2003), a study of the value of a surfing contest (*e.g.,* Breedveld, 1995), and a calculation of the economic value of a surfing break (*e.g.,* Lazarow, 2007). Lazarow, Miller, and Blackwell (2007a) summarise various studies on surfing and economics, and note that little research on the social and economic benefits of surfing compared with that of recreational fishing, which historically has had much stronger focus in coastal management. To fill this void, Nelsen, Pendleton, and Vaughn (2007) and Lazarow, Miller, and Blackwell (2007b) provide methods to calculate the value of surfing breaks, which are subsequently applied to calculate the value of different surfing breaks in Australia and California.

Dolnicar and Fluker (2003) identify surf tourism as a prevalent and growing phenomenon, with only a few research investigations on the topic. They include Augustin (1998) who researched surfing resorts, Poizat-Newcomb (1999a, 1999b) who describes the genesis of surfing tourism, and also Buckley (2002a, 2002b) who investigates the impacts of surf tourism on Indonesia's economy. Surfing tourism is connected to the specific features of the natural landscapes and is largely separate from the cultures of the host communities but has strong economic links to the global fashion and entertainment industries (Buckley, 2002a). Yet in most countries, the strategic management of surfing breaks is not practiced at a government level, even though they provide social and recreational benefits, and support this growing industry. Even in places like Southern California, which is generally regard-

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Table 1. *Categories of surfing research-based surfing publications identified from the literature.*

Category	Criteria	References
Coastal management	Coastal management theory, protecting surfing breaks, recreational coastal amenities, environmental impact assessments, surfers, and coastal use conflict, examples of impacts to surfing breaks	Anon (1999, 2003); Andrews (1997); Anon (2003); Augustin (1998); Benedet, Pierro, and Henriquez (2007); Black (2001a, 2001b); Black and Andrews (2001a, 2001b); Black, Hutt and Mead (1998a, 1998b); Black and Mead (2001b); Borrero and Nelsen (2003); Buckley (2002a, 2002b); Challinor (2003); Chapman and Hanemann (2001); Corbett, Tomlinson, and Jackson (2005); Dally and Osiecki (2007); Farmer and Short (2007); George (2004); Jackson, Tomlinson, and D'Agata (2001, 2002); Lazarow (2007); Lazarow, Miller, and Blackwell (2007b); Luntz (2002); Mead (2001); Mead and Black (1999a, 2005); Mead, Black, and Hutt, (1998b); Mead, Black, and Scarfe (2004d); Mead *et al.* (2001, 2003a, 2004a, 2004b, 2004c, 2007); Mocke *et al.* (2003); Nelsen and Howd (1996); Nelsen, Pendleton, and Vaughn (2007); Nelsen and Rauscher (2002); Pratte (1983, 1987); Preston-Whyte (2002); Rennie and Makgill (2003); Rennie, Mead, and Black (1998); Scarfe and Healy (2005); Scarfe (1999, 2002a); Scarfe *et al.* (2003b, 2009); Schrope (2006); Walker and Palmer (1971), Walther (2007)
Physical processes	Oceanographic and sedimentary conditions around surfing breaks including artificial breaks, hydrography, measurement of physical processes, surfing science	Andrews (1997); Bancroft (1999); Battilio (1994); Beamsley and Black (2003); Benedet *et al.* (2007); Black (1998, 1999, 2001a, b, 2003); Black and Andrews (2001a and b); Black and Mead (2001a, b and 2007); Black, Mead, and Mathew (2001); Black *et al.* (1998a, 2001, and 2004); Borrero (2002); Borrero and Nelsen (2003); Buonaiuto and Kraus (2003); Button (1991); Caldwell (2005); Caldwell and Aucan (2007); Chong and Scarfe (2000); Couriel and Cox (1996); Dally (1989, 1991); Hearin (2005); Henriquez (2005); Hutt (1997); Hutt *et al.* (1998, 1999 and 2001); Kilpatrick (2005); Mack (2003); Mead (2001, 2003); Mead and Black (1999b, 2001a, b, c, d and 2005); Mead, Black, and Hutt (1998a, 1998b); Mead, Black, and Moores, 2007; Mead and Phillips (2007); Mead *et al.* (2001, 2003a, 2003b, 2004a, 2004b, 2004c, 2004d, 2007); Mocke *et al.* (2003); Moores (2001); Over (2006); Pattiaratchi (2000, 2002, and 2007); Phillips (2004); Phillips, Black, and Healy (2004); Phillips *et al.* (1999, 2001, 2003a, 2003b); Poort (2007); Pratte *et al.* (1989); Preston-Whyte (2002); Raichle (1998); Ranasignhe and Turner (2006); Ranasignhe, Hacking, and Evans (2001); Ranasignhe, Turner, and Symonds (2006); Rennie, Mead, and Black (1998); Sayce (1997); Sayce, Black, and Gorman (1999); Scarfe (1999, 2002a, 2008); Scarfe and Healy (2005); Scarfe *et al.* (2002a, 2002b, 2003a, 2003b, 2008, 2009); Spendelow (2004); Symonds and Black (2001); Trung (2006); Turner (2006); Turner *et al.* (2001); van Ettinger (2005); Vaughan (2005); Walker (1974a 1974b); Walker and Palmer (1971); Walker, Palmer, and Kukea (1972); West (2002); West *et al.* (2002)
Numerical and physical modelling	Modelling of theoretical and real surfing breaks	Beamsley and Black (2003); Benedet, Pierro, and Henriquez (2007); Black (1998, 1999, 2001b, 2003); Black and Mead (2001a, 2001b, 2007); Black, Hutt, and Mead (1998); Black Mead, and Mathew (2001); Black *et al.* (2004); Blenkinsopp (2003); Buonaiuto and Kraus (2003); Caldwell and Aucan (2007); Dally and Osiecki (2007); Hearin (2005); Henriquez (2005); Hutt (1997); Mack (2003); Mead (2001, 2003); Mead and Black (1999b, 2001b, 2001d, 2005); Mead, Black, and Moores (2007); Mead, Black, and Scarf (2004); Mead and Phillips (2007); Mead *et al.* (2001, 2003a, 2003b, 2004a, 2004b, 2004c, 2007); Mocke *et al.* (2003); Over (2006); Pattiaratchi (2007); Phillips (2004); Poort (2007); Raichle (1998); Ranasignhe, Turner, and Symonds (2006); Rennie, Mead, and Black (1998); Scarfe (2002a, 2008); Scarfe *et al.* (2003b, 2003c, 2008, 2009); Spendelow (2004); Symonds and Black (2001); Trung (2006); Turner *et al.* (2001); van Ettinger (2005); Vaughan (2005); Walker (1974); West (2002); West *et al.* (2002)
ASR sediment dynamics	Sediment and morphological response to an ASR	Andrews (1997); Atkins, Morris, and Bartle (2007); Black (1998, 1999, 2003); Black and Andrews (2001a, 2001b); Black and Mead (2001b, 2007); Couriel and Cox (1996); Hearin (2005); Hutt *et al.* (1998, 1999); Innes (2005); Mead *et al.* (2004b, 2004c, 2007); Meadger (2005); Mocke *et al.* (2003); Ranasignhe, Turner, and Symonds (2006); Scarfe and Healy (2005); Scarfe (2008); Spendelow (2004); Turner *et al.* (2001); Turner (2006)
ASR design	The design of ASRs	Andrews (1997); Anon (1999); Black (1998, 1999, 2001a, 2001b, 2003); Black and Andrews (2001a, 2001b); Black and Mead (2001a, 2001b); Black, Hutt, and Mead (1998a) Black *et al.* (2001, 2004); Blenkinsopp (2003); Borrero (2002); Borrero and Nelsen (2003); Button (1991); Couriel and Cox (1996); Hearin (2005); Henriquez (2005); Hutt (1997); Hutt *et al.* (1998, 1999); Jackson, Tomlinson, and D'Agata (2002); Kilpatrick (2005); Mack (2003); Mead (2001, 2003); Mead and Black (1999a, 2001a, 2001b, 2001c, 2001d, 2005); Mead, Black, and Hutt (1998a, 1998b); Mead, Black, and Moores (2007); Mead, Black, and Scarfe (2004); Mead *et al.* (2001, 2003a, 2003b, 2004a, 2004b, 2004c, 2007); Meadger (2005); Mocke *et al.* (2003); Moores (2001); Nelsen and Howd (1996); Over (2006); Pattiaratchi (2000); Pratte *et al.* (1989); Ranasignhe, Hacking, and Evans (2001); Ranasignhe, Turner, and Symonds (2006); Rennie, Mead, and Black (1998); Scarfe (1999, 2002a); Scarfe *et al.* (2002a, 2002b, 2003a); Symonds and Black (2001); Trung (2006); van Ettinger (2005); Vaughan (2005); Walker (1974); West (2002); West *et al.* (2002)
ASR monitoring	Monitoring of effects to surfing amenities, coastal stability, habitat, navigation, swimming safety	Bancroft (1999); Black and Mead (2007); Borrero (2002); Borrero and Nelsen (2003); Jackson, Tomlinson, and D'Agata (2002); Jackson *et al.* (2002, 2007); Mack (2003); Mead, Black, and Hutt (1998a); Mead, Black, and Moores (2007); Mead *et al.* (2004c); Pattiaratchi (2000, 2002, 2007); Ranasignhe and Turner (2006); Scarfe (1999, 2008); Scarfe and Healy (2005); Scarfe *et al.* (2002a; unpuslihsed data); Turner (2006)

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Table 1. *Continued.*

Category	Criteria	References
ASR construction	Construction techniques and tolerances	Black (2001b); Black, Mead, and Mathew (2001); Blenkinsopp (2003); Hearin (2005); Jackson (2001); Jackson *et al.* (2007); Jenkins and Skully (1994); Mead, Black, and Hutt (1998b); Mead, Black, and Moores (2007); Mead *et al.* (2004a, 2004b, 2004c); Pratte *et al.* (1989)
Surfers and waves	Describing waves, relating surfers to waves including skill levels, surfboard type, manoeuvres performed, surfability	Bancroft (1999); Battilio (1994); Benedet, Pierro, and Henriquez (2007); Black (2001); Black, Hutt, and Mead (1998a); Black, Mead, and Mathew (2001); Borrero (2002); Borrero and Nelsen (2003); Couriel and Cox (1996); Dally (1989, 1991, 2001a, 2001b); Hearin (2005); Henriquez (2005); Hutt (1997); Hutt, Black, and Mead (2001); Hutt *et al.* (1998, 1999); Jackson, Tomlinson, and D'Agata (2002); Kilpatrick (2005); Mack (2003); Mead (2001, 2003); Mead and Black (2001a, 2000c); Mead *et al.* (2003a, 2004a, 2004b, 2004c); Mocke *et al.* (2003); Moores (2001); Pattiaratchi (2002); Phillips *et al.* (2003a); Ranasignhe, Hacking, and Evans (2001); Scarfe (1999); Scarfe (2002a); Scarfe *et al.* (2002b, 2003a, 2003b); Symonds and Black (2001); van Ettinger (2005); Walker (1974a, 1974b); Walker and Palmer (1971); Walker, Palmer, and Kukea (1972)
Sociology	Sociological aspects of surfing including surfing culture, social protocols at surfing breaks, gender and surfing, localism	Augustin (1998); Buckley (2002a, 2002b); Ishiwater (2002); Lanagan (2002); Lazarow (2007); McGloin (2005); Nelsen, Pendleton, and Vaughn (2007); Ormon (2007); Osmond, Phillips, and O'Neill (2006); Poizat-Newcomb (1999a, 1999b); Preston-Whyte (2002); Rider (1998); Rennie, Mead, and Black (1998); Stedman (1997); Young (2000)
Industry	Surfing equipment and technology, merchandise, clothing, surfing films and magazines, marketing	Buckley (2002a, 2002b); Lanagan (2002)
Economics and tourism	Discussions on the economic value of surfing breaks, impacts of surf tourism on beach communities, the character or value of surf tourism	Augustin (1998); Baily and Lyons (2003); Breedveld (1995); Buckley (2002a, 2002b); Challinor (2003); Chapman and Hanemann (2001); Dolnicar and Fluker (2003); Lazarow (2007); Lazarow, Miller, and Blackwell (2007a and b); Lew and Larson (2005); McGloin (2005); Nelsen, Pendleton, and Vaughn (2007); Poizat-Newcomb (1999a, 1999b); Raybould and Mules (1999); Tourism Resource Consultants (2002); Weight (2003)
Biomechanics	Fitness, surfing techniques, sporting injuries	Sunshine (2003); Taylor, Zoltan, and Achar (2006)

ed as one of the main centers of modern surfing culture, and is home to many of the world's largest surfing companies, until recently surfers have had little political say in the management of their recreational space.

Large participation rates imply that in many locations surfing warrants funding and resources for research, resource management practices, and facility enhancement. For example, Bancroft (1999) estimated that 16% of the Western Australian population (300,000 people) surfs, which must have a significant social and economic impact. Lazarow, Miller, and Blackwell (2007b) estimate the global surfing population to be 18–50 million. Although not all countries have resource management frameworks that consider the economic effect of development (*e.g.,* New Zealand's Resource Management Act 1991), understanding the economics relating to surfing is important for political lobbying. If a surfing break is under threat from an activity, the economic benefits of the surfing break to the community can help to gain support for efforts to preserve the surfing location. This is iterated by Lew and Larson (2005) who note that information on the economic value of beach recreation is needed to make informed policy decisions. Economic analysis is also important for artificial surfing reef developments because it assists in evaluating benefits of a project. Although it is likely that more literature exists on surfing economics and tourism, the lack of abundance shown in Table 1 demonstrates a need to further this area of research. For example, Dyer and Hyams (2001) also noted that little research on surfing and economics exists in the United Kingdom, where a significant number of people surf despite the cold conditions and relatively poor quality surfing waves.

CHARACTERISTICS OF SURFING WAVES

Scarfe *et al.* (2003a) considered surfing waves and surfing breaks as distinct entities. Surfers can be related to surfing waves, and surfing waves related to surfing breaks. The parameters that describe surfing waves can be related to the skill level of surfers (Hutt, 1997; Hutt, Black, and Mead, 2001; Moores, 2002), and the types of maneuvers that they perform (Scarfe, 2002a; Scarfe *et al.,* 2002b). Thus the style and skill of surfers can be matched to a type of surfing wave. Similarly, the parameters of surfing waves can be related to the oceanographic and bathymetric features that comprise a surfing break. These basic concepts are pertinent when trying to determine changes to a surfing break from another activity, or trying to design an artificial surfing reef to match a particular type of surfer.

There is a need to scientifically quantify the impacts of an activity on a surfing break and to specify the design criteria for a surfing enhancement project. In the following section different wave parameters are identified that can describe surfing waves. To match surfers to surfing waves, existing schemes relating these parameters to surfing skill and maneuvers are discussed. Also the effects of wind are reviewed because it can have positive or detrimental impacts on breaking waves. Relating surfing waves and bathymetric features

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and wave transformation is dealt with separately in a later section.

Surfing Wave Parameters

Over the years, various surfing wave parameters have been used in the literature to scientifically describe waves. Because of the increasing number of terms used to describe waves, Scarfe *et al.* (2003a) argued that four main parameters can be used to discuss the general character of waves. Although more complex parameters and relationships between parameters exist (*e.g.,* Dally, 2001a, 2001b), for simplicity the following parameters are used to explain surfing waves transformations. The parameters are

- Breaking wave height (H_B);
- Wave peel angle (α);
- Wave breaking intensity (B_I);
- Wave section length (S_L).

Breaking Wave Height (H_B)

Breaking wave height (H_B) is a very important parameter because it dictates the skill level required to ride the wave. It can vary between wave sets and along the wave because of wave focusing, nonlinear wave interactions, and wind effects (*e.g.,* Scarfe, 2008). Measuring wave height can be subjective because different groups of surfers develop their own standards of measuring wave heights (Battalio, 1994). However, the measurement used by surfers may not actually have much relevance to the oceanographic measurement from the crest to the trough. For example, Caldwell (2005) and Caldwell and Aucan (2007) discuss the Hawaiian scale, which is approximately half the oceanographic height. They calibrated long-term observational data collected using the Hawaiian scale against measured deep water significant heights and showed that the oceanographic measurement was 1.36–2.58 times larger depending on the location.

For scientific surfing studies, the oceanographer's measurement is used because it can be measured by instrumentation. Because waves arrive in sets separated by lulls, and surfers generally ride the largest waves in a set, Hutt (1997) recommends using the average of the top 10% of waves ($H_{1/10}$) for surfing studies. The surfable limits of wave heights are identified by Mack (2003) as 1 to 20 m, although smaller waves can be ridden by highly skilled or lighter surfers. Developments in board technology and use of personal water craft for tow-in surfing have significantly increased the range of wave heights that can be ridden in recent decades.

Wave Peel Angle (α)

Wave peel angle (α) is perhaps the most critical parameter to determine whether a wave can be surfed, other than wave height. If a peel angle is not within a range that can be surfed, then the wave is said to be unsurfable. In fact, Scarfe *et al.* (2003a) state that the role of a surfing break is to increase peel angle to within surfable limits because low peel angles break too fast to surf. The difference between a surfable beach and a nonsurfable beach is often the peel angle. This parameter dictates the speed that the wave break point peels along the wave crest and is closely related to another parameter, peel rate. Peel angle is often preferred in the literature because it can be more accurately modeled than peel rate and is easily measured from aerial photographs (*e.g.,* Hutt, 1997; Walker, 1974a, 1974b) or oblique video images using more complex techniques (Scarfe, 1999, 2002a; Scarfe *et al.,* 2002a). Many of the core surfing science studies have used peel angles to define relationships between surfers and waves, or waves and bathymetry. It is important that future research recognizes the previous methodologies and parameters so that they can be compared. This concept was also noted by Lazarow, Miller, and Blackwell (2007b) for surfing economic studies.

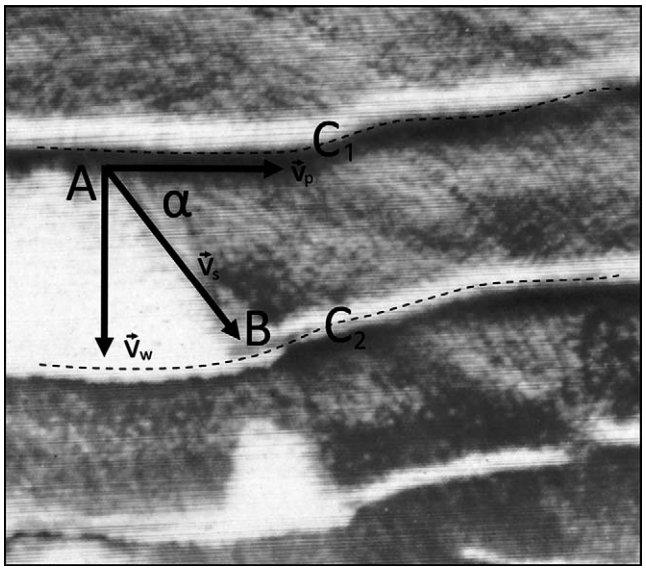


Figure 3. Wave peel angle (α), adapted from Walker and Palmer (1971).

Although most detailed studies identified in the *surfers and waves* category include some description of peel angles, it was first defined as "the included angle between the peel-line and a line tangent to the crest-line at the breaking point" (Walker and Palmer, 1971, p. 42). This definition is still accurate. In this context the peel line is the path of broken white water left after the wave breaks. Figure 3 shows an adapted figure from Walker and Palmer (1971) showing the parameters of a peel angle. At time 1, the wave break point position on wave crest, C1, is denoted by A. At time 2, the wave break point position on wave crest, C2, is denoted by B. As the wave crest C1 advances to position C2, a path of white water is left joining the breakpoints A and B. The peel angle is denoted by the angle α. At position A the wave has a velocity of propagation, $\vec{\mathbf{V}}_w$, which is perpendicular to the wave crest. The peel velocity, $\vec{\mathbf{V}}_p$, or peel rate, is the velocity the wave breaks, or peels, along the wave crest. Summing the vectors gives the resultant velocity vector, $\vec{\mathbf{V}}_s$, which approximates the surfer's speed if the surfer remains close to the wave break point.

A closeout is a wave where the wave crest breaks simultaneously and is said to have a peel angle of 0°. A closeout wave is only suitable for beginner surfers (Hutt, Black, and

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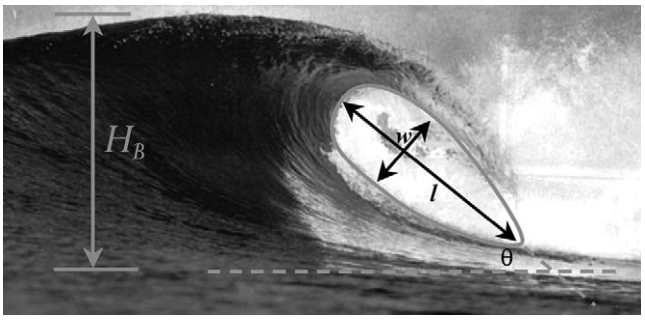


Figure 4. Wave breaker intensity (B_I) defined by the vortex ratio of w to l (after Mead and Black, 2001c).

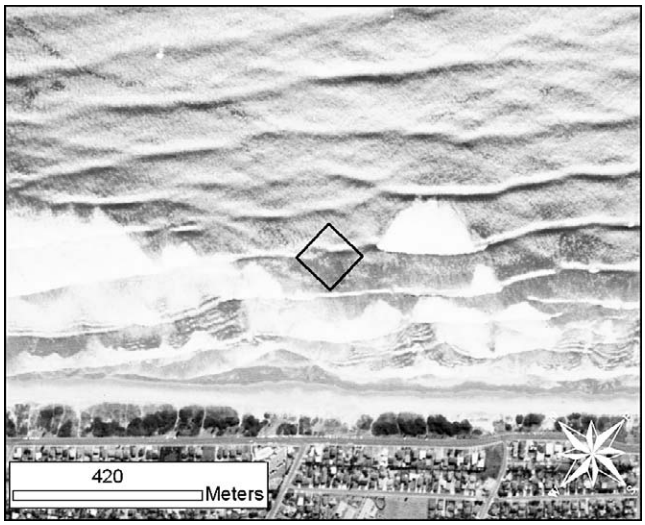


Figure 5. Aerial photograph around the Mount Maunganui ASR during a 1.5-m northeast swell showing broken wave crests and other nonlinear wave interactions (photo: 6 February 1990, 10:45 a.m.).

Mead., 2001) because surfers can only ride the broken wave white water, not the unbroken wave crest, which is not challenging for intermediate or advanced surfers. The peel angle in Figure 3 is approximately 52°, which is considered fast but surfable. Although peel angles can be too high to challenge more advanced surfers, high peel angles do not necessarily prevent surfers from riding waves, whereas low peel angles do.

Wave Breaking Intensity (B_I)

Waves break in spilling, plunging, collapsing, and surging forms (Komar, 1998), but surfers can only ride spilling and plunging waves. Plunging waves, colloquially termed by surfers as "barreling waves," need to occur consistently for a surfing break to be classed as what Mead and Black (2001a, 2001 b) term a "world-class" surfing break. Sayce (1997) coined the term "breaking intensity" (B_I) to describe the intensity at which surfing waves plunge. Mead and Black (2001c) used this concept to investigate the relationship between the open vortex shape (vortex ratio; Figure 4) and various parameters. The vortex ratio was calculated from surfing magazine photographs using measurements made with curve fitting routines written in MATLAB. A low vortex ratio is an extreme plunging wave and a high ratio is a mildly plunging wave. A linear relationship between the orthogonal seabed gradient was found that can be used to estimate the vortex ratio,

$$Y = 0.065X + 0.821,$$

where Y is the vortex ratio and X is the orthogonal seabed gradient.

Fairley and Davidson (2008) investigate the effect of steps in the two-dimensional profile of a surfing break on the quality of the surfing wave using wave flume experiments. Previous studies by Sayce, Black, and Gorman (1999) and Scarfe (2002a) at Raglan, New Zealand, show that steps in the profile can modify the wave breaker intensity. Fairley and Davidson's (2008) experiments involved inducing steps into the profile and observing the effects on the breaking intensity. Fairley and Davidson (2008) review wave breaking theory and conclude Mead and Black's (2001c) method provides a better prediction of wave breaking than the common coastal science methods such as the Iribarren number. Fairley and Davidson (2008) found inducing steps into the profile increases nonlinearities in the waves and observed that for extreme steps there was a transfer of energy to the higher wave spectrum, adversely affecting the "surfability" of the wave. The "surfability" of a wave represents the level of desirability to a surfer (Dally, 1989; Mack, 2003). Also the larger the steps, the larger the degree of uncertainty as to the type of breaking wave. They propose maximum steps in an ASR to be between 16% and 23% of the wave height.

Wave Section Length (S_L)

By the time a wave crest reaches a surfing break, it is sometimes bent or broken when the crest is viewed from an aerial perspective, with variation in height and angle along its length, as in the aerial photo shown in Figure 3 and Figure 5. This has been shown by Black *et al.* (2004) and Mead *et al.* (2004a) to occur when using Boussinesq modeling waves passing over complex reefs. The variations can be caused by a messy swell spectrum, local winds, bathymetric effects, nonlinear wave–wave interactions, and island sheltering. Although generally surfers desire waves that peel cleanly along the wave crest at a surfable speed, often waves break in sections with a length S_L. A surfing ride is actually made up of a variety of sections, breaking with varying H_B, α, B_I, and S_L throughout the ride. For example, small sections that break at once, with a peel angle near 0°, are not a problem for a surfer provided the surfer can generate enough speed to make it past the section to the unbroken wave crest. In fact, sections can be desirable for advanced surfers, and if the section has a high enough breaker intensity there is a chance of getting a barrel ride. The ability to negotiate a section is related to the surfer's ability to generate enough speed to make it past the section to the unbroken wave.

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	**Rank 2-3**	Beginning surfers able to perform basic manoeuvres. Soft breaking waves (spilling breakers). No vortex ratio.	Peel Angle (α) = 60-70°	Low gradient breaks
	**Rank 4**	Intermediate skilled surfers beginning to initiate and execute standard surfing manoeuvres on occasion. Steep faced, but rarely tubing: Vortex ratio 2.8-3.1	Peel Angle (α) = 55°	Bells Beach (Australia), Indicators (Raglan, New Zealand)
	**Rank 5-6**	Competent surfer able to execute standard manoeuvres consecutively and advanced manoeuvres on occasion. Some tube sections: Vortex ratio 2.2-2.8	Peel Angle (α) = 40-50°	Kirra Point, Burleigh Heads (Australia)
	**Rank 7**	Top amateur surfers able to perform consecutive advanced manoeuvres. Fast and hollow tubing waves: Vortex Ratio 1.9-2.2	Peel Angle (α) = 30°	Bingin, Padang Padang (Bali)
	**Rank 8-9**	Top world surfers able to perform consecutive advanced manoeuvres under extreme and dangerous conditions. Vortex ratio 1.6-1.9	Peel Angle (α) = <27°	Pipeline (Hawaii), Shark Island (Australia)

Figure 6. Reef design criteria adapted from Black and Mead (unpublished from 4th Surfing Reef Symposium proceedings) for relating surfing wave parameters to surfer skill level.

Winds

Wind generates surfing waves in distant locations, and when they arrive at a surfing beach, the wave period is often long (>8 second), which is favorable for surfing. Local winds can also play an important role in creating or destroying surfing waves (Pratte *et al.,* 1989). The ideal wind blows directly offshore and steepens the wave face causing plunging, or "barreling," waves at some surfing breaks. A light offshore wind is also said to groom the wave face to make it smoother (Schrope, 2006). Research by both Chen, Kaihatu, and Hwang (2004) and Feddersen and Veron (2005) found that an offshore directed wind will delay wave breaking by modifying the breaking-wave height to depth ratio γ_b, with the reciprocal being true for onshore directed wind. Feddersen and Veron (2005) also found that that γ_b can change by 100% and that waves breaking with offshore directed winds have greater breaking wave heights than for onshore conditions. Thus offshore winds increase the skill level required to surf a given wave. Onshore winds do not necessarily always lower the skill level required because the onshore winds often cause waves to break less predictably.

The delay in breaking caused by an offshore directed wind will reduce the water depth the wave breaks in, increasing the breaker intensity and probability of barrel rides. There will be a maximum offshore wind speed suitable for surfing, however, because the offshore wind will flatten a weak swell, or make it impossible to catch waves because surfers are blown off the back of the wave when trying to catch a ride. The maximum offshore wind speed was not found in the literature, but Mack (2003) suggested a directionless maximum wind speed of 5 m s^{-1}. Sometimes light local onshore winds can help slightly increase a small swell to a surfable height so the ideal wind condition is also dependent on the swell conditions. Cross-shore and strong winds generally detract from the quality of the surfing waves.

Relating Surfers to Waves

To understand waves at surfing breaks, or design an ASR, the waves need to be suitable for surfers. Not all waves are suitable for surfers of all skill levels, so from the earliest research this has been a topic of discussion. Walker (1974a) presented a beginner, intermediate, and advanced categorization scheme for skill level based on wave height and peel angle. Advances in surfer skill levels over time, as well as performance of surfboards required Hutt (1997) and Hutt, Black, and Mead (2001) to revisit the scheme for modern surfers. They also added a more quantitative 1 to 10 ranking system. Recently, Black and Mead (unpublished data[1]) incorporated breaking intensity into the scheme, which is shown in Figure 6. Another scheme that can be useful when dissecting a natural surfing break, or designing ASRs, was adapted from Scarfe *et al.* (2002b) by Scarfe *et al.* (2003a). The scheme, shown in Figure 7, does not include skill level but does relate surfing maneuvers to section length, peel angle, and breaking intensity for the first time.

Moores (2001) was the first to investigate sections and how they relate to the skill level of a surfer, including S_L. Using measurements from rectified video images, Moores (2001) found that the higher the surfer skill level, the longer the section that can be negotiated, mainly because of the surfer's ability to generate board speed. Thus investigations into sections are closely related to board speed, skill level, and peel angle. Both Dally (2001b) and Moores (2001) have investigated the speed of surfers. The outcome of Moores' (2001) investigation is shown in Table 2 and gives design criteria for the length of a section in an ASR. Scarfe (2002a) has also looked into sections but was more concerned with peel angles for different sections and how they influence the types of maneuvers surfers perform (Figure 7).

CHARACTERISTICS OF SURFING BREAKS

The role of a surfing break is to make the waves peel at a suitable peel angle (or rate) and breaking intensity for the size of the wave and the surfer style and skill level. In this section the different categories of surfing breaks and their characteristics are discussed first, followed by a brief overview of currents around surfing breaks. Two examples of physical processes occurring around surfing breaks are then presented to illustrate in more detail the character of surfing breaks and surfing waves.

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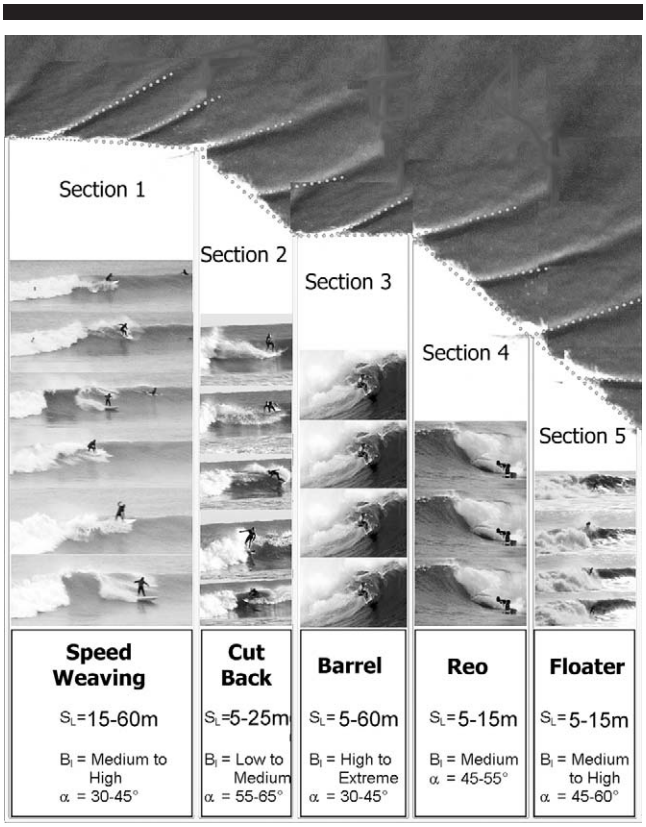


Figure 7. Possible configurations of wave sections suitable for different types of maneuvers. Adapted from Scarfe *et al.* (2002b).

Mead, Black, and Hutt (1998a) defined five geomorphic categories of surfing breaks and the following definitions have been adapted from Scarfe (1999). They are

- *Headland or point break*—Waves refract around a headland or point before breaking further around the headland or point. The refraction of the waves around the point or headland filters out high frequency waves leaving the longer period waves, which are more likely to be surfable. The wave direction at the surfer take-off zone is usually significantly different to the offshore direction. Examples include: New Zealand's Murdering Bay (Dunedin), and Raglan; California's Malibu and Rincon, and Kirra on the Gold Coast of Australia.
- *Beach break*—At a beach break, waves break in peaks along the beach caused by offshore wave focusing and nearshore sand bars and rips. Successive waves will break in different locations depending on the current beach state (*e.g.,* Wright and Short, 1984); offshore wave direction, height, and period; and wave peakiness. Often good beach breaks have control features offshore or nearshore that stabilize the position of sandbars or dictate wave focusing. Examples of beach breaks include the Gold Coast's D-Bar, and New Zealand's Tairua and Aramoana beaches. Tairua is investigated in Mead and Black (2001b) and surfing waves at Aramoana are numerically modeled in Scarfe *et al.* (2009).

Table 2. *Optimum artificial surfing reef design values of waves section for surfers of different abilities (adapted from Moores, 2002). Surfers with skill levels 1 and 2 cannot surf waves with sections because it requires the ability to generate speed (Hutt* et al.*, 2001).*

Surfer Ability	Wave Height (m)	Section Length (m)	Section Duration (m)	Section Speed (m s^{-1})
1 (low)	n/a	n/a	n/a	n/a
2	n/a	n/a	n/a	n/a
3	2.5	25	1	10
4	2.5	40	1.5	20
5	3	40	2.2	20
6	3	60	2.3	20
7 (high)	3	60	3	20

- *River or estuary entrance bar*—Interesting features and processes are required to create peeling waves, and river and estuary entrances often create good surfing spots. The ebb tidal delta, out flowing river sediment, and tidal currents all interact to sometimes make surfable waves. Tidal inlets are influenced by processes such as wave energy, tidal range, tidal prism, direction and rates of longshore sediment transport, sediment supply, and nearshore slope, and are subject to change (Fitzgerald, 1996). Changes to any of these factors can affect surfing conditions for the better or worse. In many locations around the world, river inlets have been jetted, and Scarfe *et al.* (2003b, 2003c) showed how this can create surfing breaks. Whangamata Bar (New Zealand), discussed in Scarfe *et al.* (2009), is an example of a high quality estuary entrance bar.
- *Reef breaks*—Many of the world's best surfing breaks are reef breaks because the reef provides more consistent wave breaking patterns and allows steeper orthogonal profiles than sandy surfing breaks. Various reefs are discussed in Mead and Black (2001b, 2001c) including Padang Padang (Indonesia), and Pipeline (Hawaii).
- *Ledge breaks*—Steep rock ledges interrupt wave propagation and create surfing waves breaking with the highest intensity. The waves come from relatively deep water into very shallow water, modifying the way that the waves break. Shark Island (Australia) is a ledge break and often ledge breaks are difficult to surf, except by body boarders.

Although these definitions are helpful for nonsurfers to understand surfing breaks, there are no clear boundaries between the different types. Sometimes surfing breaks fall under more than one category. For example, often good beach breaks have features, possibly reef, which control the sandbar shape and wave focusing. Sometimes a river bar blends in with a beach break, or a reef break has ledge sections.

Surfing Break Components

Ordinary waves are turned into surfing waves through the process of wave preconditioning and breaking. The preconditioning of waves has been discussed since the early Hawaiian research. Mead and Black (2001a, 2001b) identify several common components in "world-class" surfing breaks that either precondition or cause wave breaking. Identifying the component scale and configuration from detailed bathymetric

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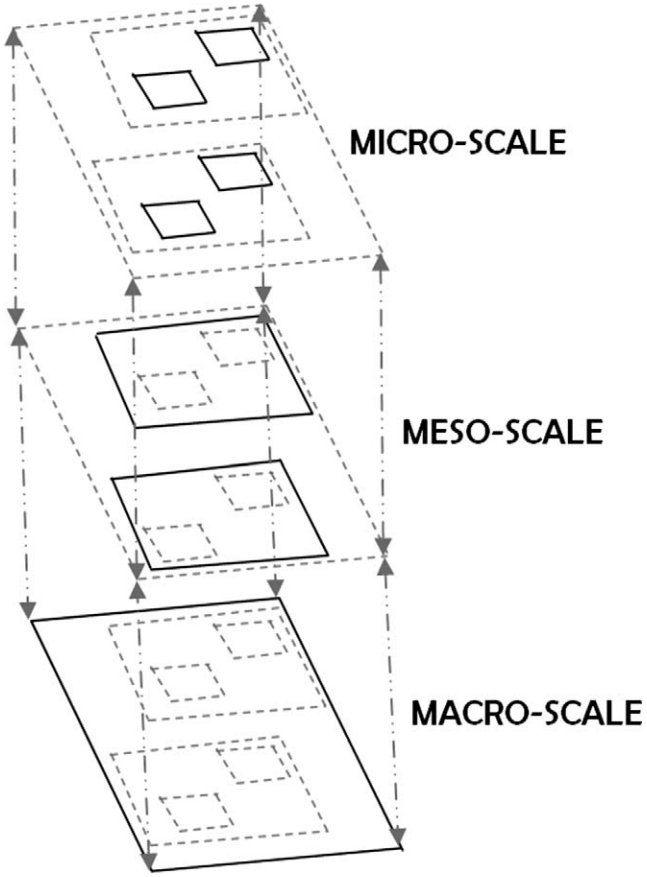


Figure 8. Schematic diagram of the different scale of surfing break components, super imposed on each other. From top, micro, meso, and macro scale components.

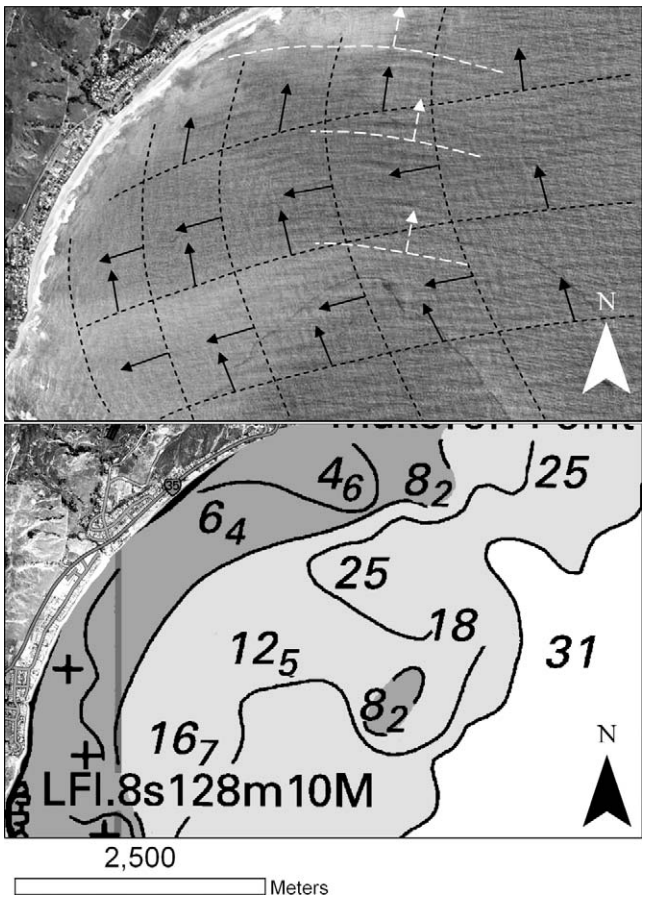


Figure 9. Advancing wave crests (top; black and white dashed lines; photography from www.google.com) from southerly and easterly sources converge creating wave nonlinearities and complex surf zone process conducive to a good beach surf break. Focusing over the offshore bank (bottom) further preconditions the waves. Top aerial photograph from DigitalGlobe, www.maps.google.com, and bottom navigational chart from Land Information New Zealand.

data and wave refraction analysis is essential for understanding how a surfing break works (*e.g.,* Beamsley and Black, 2003; Kilpatrick, 2005; Mead *et al.,* 2003b), identifying impacts of development on surfing breaks (*e.g.,* Scarfe *et al.,* 2003b, 2009), or designing artificial surfing reefs (*e.g.,* Mead, 2001; Mocke *et al.,* 2003; Scarfe, 2002a).

The meso-scale surfing reef components identified by Mead and Black (2001a) are ramp, platform, focus, pinnacle, wedge, ledge, and ridge. The components were subcategorized by preconditioning or breaking functions. Smaller scale components can exist on larger scale components (Figure 8), and this is explored in Scarfe (2002a) and Scarfe *et al.* (2003a). The way surfing reef components of varying scales are superimposed on each other is illustrated in Figure 8. The smaller scale components, termed microscale components, create wave sections. Common configurations of components identified by Mead and Black (2001b) show how surfable peel angles and breaking intensities are created by the different component configurations. The wave height during a surfing ride changes because of variations along the wave crest caused by wave focusing over bathymetric components and nonlinear wave–wave interactions.

A useful addition to the Mead and Black (2001a, 2001b) categorization method would be a categorization scheme relating common wave transformation patterns (*e.g.,* focusing, sheltering, wave–wave interactions) to the configuration of surfing reef components. In a surfing discussion, Benedet Pierro, and Henriquez (2007, p. 4) provide photographs of wave conditions that could be incorporated into such a scheme.

Wainui Beach, Gisborne (New Zealand), is one of New Zealand's premier beach surf breaks, and waves are affected by intersecting swells and nonlinear wave propagation over a shoal, or focus (Figure 9). This type of wave pattern producing good surfing waves is also identified at Ocean Beach, San Francisco (Battalio, 1994). The Raglan (New Zealand) surfing breaks, in contrast, require organized and unbroken wave crests approaching oblique to the coastline (Scarfe *et al.,* 2009). It is possible that the complex offshore wave transformations create the surfing bars and associated rips, which at times are significant in size at Wainui Beach. Modeling and further analysis of the beach is presented in Dunn (2001).

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The sandbars and rips then interact with the broken and focused wave crests creating surfing waves. Although nonlinear Boussinesq modeling of surfing waves is not uncommon (Beamsley and Black, 2003; Black and Mead, 2001a; van Ettinger, 2005), it is still an area that requires more discussion and experimentation. These types of wave interactions can create wave sections, and are referred to by Hutt (1997) as the "peakiness" of a swell. These processes are related to beach state (Wright and Short, 1984), which has been investigated around surfing breaks by Black and Mead (2007) and Scarfe *et al.* (2008), but is still poorly understood in relation to surfing. Intermediate beach states are likely to be best for surfing because of the more prominent surf zone features.

The orthogonal gradient has been the subject of research during surfing reef design projects because it is important for the wave breaking intensity. By varying the design of the surfing reef components, the orthogonal sea bed gradient can be altered to match the design criteria of a surfing reef. Mead (2003) shows predicted orthogonal seabed gradients for the proposed Lyall Bay (New Zealand) ASR. The orthogonal gradient will change with swell and tide conditions so it is a difficult task to design reef components that deliver expected breaking intensities for the most common wave conditions. As ASR technology improves, fine scale design parameters such as orthogonal gradient are likely to be subject to further research.

Currents around Surfing Breaks

Various researchers have physically or numerically modeled wave induced currents around theoretical ASRs (Black, 2003; Henriquez, 2004; Symonds and Black, 2001; Trung, 2006; van Ettinger, 2005). Currents around natural surfing breaks have received less attention. The only substantial work to date is by Phillips (2004), who studied currents and sediment transport around the Raglan headland surfing breaks. By repeatedly surveying a transect, collecting sediment, current and wave data, as well as wave and hydrodynamic modeling, Phillips (2004) identified cells of reticulating current pathways generated by wave-driven forces and bathymetric steering. The observed and modeled currents are related to sediment transport as well as surfing. The return cell circulation is very apparent when surfing the breaks and assists in returning surfers to the takeoff location at the end of a surfing ride. Studying natural surfing breaks, as done by Phillips (2004), has the benefit that empirical information about currents during different conditions is known by surfers. This provides a robust and additional data source for validation of model predictions of currents.

Henriquez (2004) states that considering currents is critical when investigating the surfability of a break. Currents can help make the surfing experience better when surfers use the currents to make paddling easier. They can also detract from the surfing experience by making it difficult to paddle, or even dangerous. They also interact with breaking waves, improving or detracting from the surfability of a surfing break. For example, currents associated with a rip provide a calm area to paddle through the surf zone. At many surfing breaks, especially during large swells, it would be difficult to ride the waves without utilizing currents to get into position to catch waves. Black and Mead (2001a) included a "paddling channel" between the arms of the Narrowneck ASR to minimize interference between waves of each reef arm, and to make it easier for surfers to return to the takeoff zone. Unfortunately the constructed reef shape did not match the design, and the success of the paddling channel is therefore unknown. Trung (2006) and van Ettinger (2005) tried to improve surfability of an ASR design by reducing currents over the reef with different designs. Morphological evidence of currents around a constructed ASR is included in Scarfe (2008).

OFFSHORE WAVE TRANSFORMATION AT MOUNT MAUNGANUI

Offshore wave focusing is known to affect inshore surfing conditions and has been investigated by a number of researchers (Beamsley and Black, 2003; Mead *et al.,* 2003b; Scarfe *et al.,* 2003b, 2009). Figure 10, from modeling by Scarfe (2008), shows how offshore islands, reefs, and the continental shelf affect the propagation of a monochromatic wave before reaching the Mount Maunganui beaches. The two offshore islands, and numerous reefs, transform waves to create variations in wave character along the shoreline. The ebb delta of Tauranga harbor has a significant focusing and rotating effect on the waves, creating the best surfing waves. Further east, waves focus to a lesser degree between Tay Street and Omanu beaches.

The offshore islands not only shelter wave energy, but also focus, rotate, and break wave crests. The aerial photograph in Figure 5 shows the broken, rotated, and focused wave crests, which create the peeling waves surfed at the Mount Maunganui beaches. The observed wave patterns are caused by the wave and wind process occurring over the varying scale bathymetric components. Wave focusing has also been predicted for the beaches by Spiers and Healy (2007) using refraction modeling. Bands of coarse sediment, or "sorted bedforms," identified using side scan by Spiers and Healy (2007) were considered to be a result of wave focusing, with the larger waves eroding away finer sediments (Spiers and Healy, 2007). These were observed in multibeam backscatter imagery by Scarfe (2008) in water depths around 8 m (MSL). The bands were depressed below the ambient seabed by 0.10–0.30 m. Analysis of multibeam backscatter as an indicator of focusing is a new area of surfing research, and it is expected that geomorphic indicators (from side scan, backscatter, shoreline, or bathymetry analysis) could be used with numerical modeling to relate wave focusing and bar formations to the surfability of a beach.

MEASURING MICROSCALE WAVE TRANSFORMATION AT "THE LEDGE"

The Raglan headland, New Zealand, more fully described in Hutt (1997), Moores (2001), Phillips (2004), Sayce (1997), Scarfe (2002a), and Scarfe *et al.* (2009) is made up of a reef and boulder shoreline with a sandy offshore platform below about 5–6 m (MLW). The headland hosts seven high quality surfing breaks. A survey by Scarfe (2002a) utilized accurate RTK GPS water level corrections (Scarfe, 2002b) and showed

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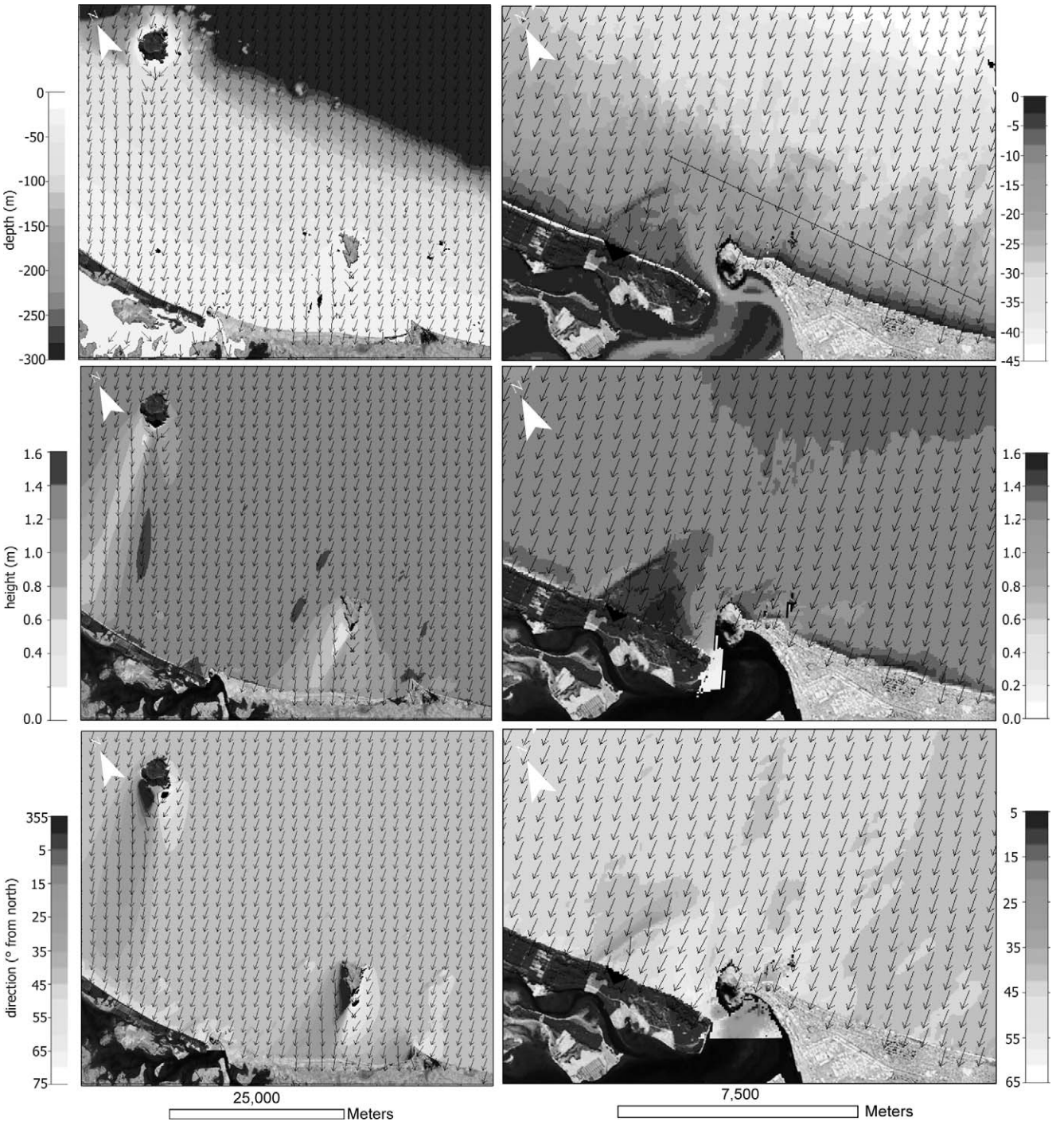


Figure 10. Effect of bathymetry and offshore islands on wave heights and angles for a surfing wave event on the Mount Maunganui (New Zealand), ASR from Scarfe (2004; 4 October 2006, 8 a.m.). **For a color version of this figure, see page 665.**

smooth sand preconditioning components, and a complex, undulating shallow-water wave breaking and focusing reef system. This enables the measurement and analysis of wave parameters at Raglan's premier barreling wave location called "The Ledge" to be undertaken. The classic barreling waves occur only occasionally, and generally the waves break with a lower breaking intensity not suitable for barrel rides, linking up with the next surfing break called Manu Bay.

Since the initial research of Walker (1974a), photogrammetry has been an important tool in scientific surfing studies.

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Figure 11. Barrelling surfing ride from video at "The Ledge" (Raglan), at 12:34 p.m., 30 July 2001 (after Scarfe, 2002a).

During Walker's (1974a) research, bathymetric survey was overlaid with aerial photos and surfer locations to understand the surfing breaks. Hutt (1997) also used aerial photographs to study the Raglan surfing breaks. Aerial photographs can be used to measure directly wave peel angles, track the path of surfing waves relative to bathymetric contours, position surfing takeoff zones, count surfer numbers, estimate wave direction and refraction patterns, as well as derive wave orthogonals for calculating wave breaking intensity. The first discussion on the more involved oblique measurements of surfing waves was by Scarfe (1999), where low cost "off-the-shelf" video cameras were researched to enable measurement of surfing parameters. Moores (2001) was the first to actually apply an oblique rectification technique to surfing studies. Subsequently, Scarfe (2002a) applied complex oblique photogrammetric techniques to video images at "The Ledge."

Figure 11 shows video frames from Scarfe's (2002a) measurement of breaking wave paths. Wave peel angles and peel rates were calculated by combining the break point locations with numerical modeling of wave orthogonals. Video frames for every second are plotted over the bathymetric features and are shown in Figure 12. From here the breaking behavior of individual waves can be related to the bathymetric features, surfer skill, and types of maneuvers performed. Modeling by Scarfe (2002a) shows that waves focus onto the ledge and sections with dramatically different wave crest angles

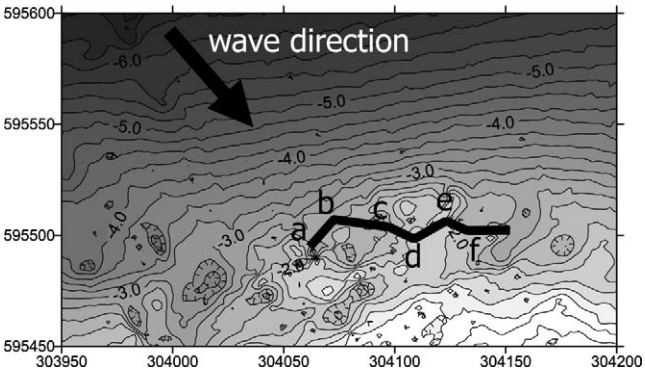


Figure 12. Path of breaking wave and peel angles for surfing wave in Figure 11 (after Scarfe, 2002a).

(>15°). Waves at "The Ledge" were measured by Sayce (1997) and found to be 9% larger than the wave height just offshore of the surfing break. To ride a wave at "The Ledge," surfers essentially take off at the end of a barreling closeout section. They are able to come out of the barrel section because the peel angle dramatically increases (22° to 69° in the modeled scenario) to a surfable peel angle.

Figure 13 shows an orthogonal profile through the "The Ledge." The offshore profile in Figure 13 shows a similar pattern to many other surfing breaks found in the literature, namely the convex profile that becomes steeper in shallow water. Often in the case of reef surfing breaks, the profile is undulating, affecting how the wave breaks for different oceanographic conditions. Scarfe (2002a) found that "The Ledge" profile is made of varying gradients that affect the breaking intensity (Figure 13). This was also observed in profiles by Mead (2001) of Kirra, and by Vaughan (2004) of "Whangamata Bar." This complicates the application of Mead and Black's (2001c) B_I formula, indicating the need for more research in this area to incorporate the effect of multiple seabed gradients on the vortex ratio. However, the simple breaking intensity equation from Mead and Black (2001c) still

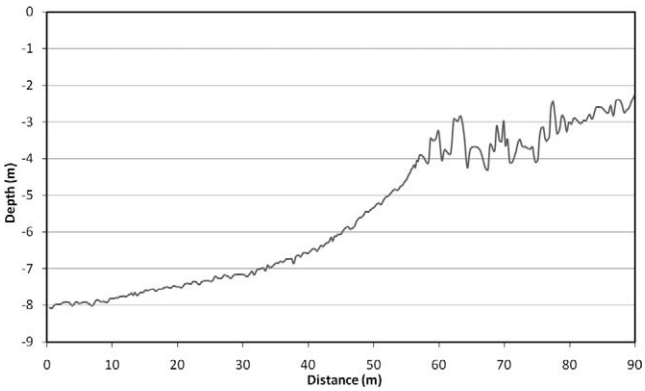


Figure 13. Orthogonal profile of "The Ledge" (adapted from Scarfe, 2002a).

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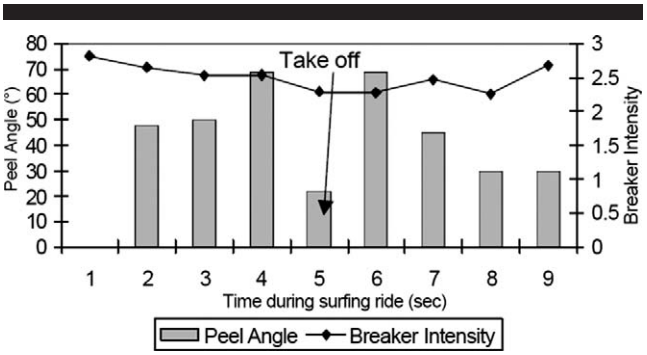


Figure 14. Peel angles and breaking intensity during the surfing ride shown in Figures 11 and 12.

Table 3. *Peel angles and peel rate during the surfing ride shown in Figures 11 and 12 (from Scarfe, 2002a).*

Time (s)	Peel Angle (°)	Peel Rate (m s^{-1})
1	0	14.4
2	48	11.2
3	50	15.2
4	69	10.5
5	22	16.2
6	69	9.7
7	45	9.8
8	30	6.7

gives a gross estimate of the hollowness of a surfing wave for a given beach gradient.

The peel angles, breaking intensity, and peel rates were shown to vary through the surfing ride. The variations are presented in Figure 14 and Table 3 and can be used to understand the microscale changes occurring during wave breaking. The microscale changes can be then related to bathymetric components and other oceanographic processes during the design or monitoring of an ASR, or while assessing the impacts of a coastal activity on surfing amenities.

DISCUSSION

Black *et al.* (2001b) defined the key goal of surfing reef studies as classifying and numerically ranking surfing wave parameters so that they can be systematically incorporated into artificial surfing breaks. Because every wave is different, and the seabed that comprises a surfing break is often mobile, there are still many unknowns about small scale, or temporal processes. However, the main processes have been identified and researched, sometimes in a lot of detail. The physical processes that differentiate wave transformations at surfing breaks from ordinary beaches are concluded to be reasonably well known, making a significant contribution to this goal. The next frontier for surfing research, discussed by Scarfe *et al.* (2009), involves maximizing the surfing amenities of coastal projects by incorporating surfing into coastal resource management, as well as minimizing negative effects of coastal engineering on surfing amenities. To achieve this goal, coastal managers and scientists need examples of methods used to study surfing breaks, and various methods are included in the reviewed literature. More importantly, standardized techniques are required to be applied when incorporating surfing into coastal management.

The method used to assign categories to each paper presented in Table 1 and Figure 2 allowed a publication to be assigned to more than one category. Papers often include some information on physical process, and this explains why this topic has the most publications. A lot of focus has also been put into the design of ASRs rather than the construction, shoreline response, or monitoring of ASRs. This may be a reflection of the maturity of ASRs as a research topic. ASR design received considerable attention because ASRs need to be designed before they are constructed. As more reefs are built and design questions are answered, it is likely that the volume of research on how they are constructed and results of monitoring performance will increase.

Although Figure 2 shows several publications on coastal management and surfing, the core topic of many of the publications included in this category are not all specifically for coastal management and surfing. Often the publications discuss topics such as problems with coastal development or engineering, environmental impact assessments for ASRs, or managing the effects of surfing tourism. The papers still contribute to the topic of how we should manage surfing amenities in some way, but it is not the sole focus of the research. There is urgent need for research on how to manage issues relating to surfing to avoid the problems associated with coastal engineering structures identified by Scarfe *et al.* (2009). To this end, economic research to support a surfer's mandate in coastal management needs more attention in the peer-reviewed literature, and the recent *Shore and Beach* journal (Walther, 2007) contributes to this goal. More research on how to calculate the value of a surfing break, economic benefits of ASRs, and the total value of the surfing industry would help gain support for surfing in coastal management. Many of the papers identified may not withstand strong academic criticism because of the location of the publication (*grey literature*), or detail of the study.

Beach Morphology

Considerable research now exists on beach and surf zone processes, yet there remains little specific research on surfing waves at beaches. Although surfing at beaches has been discussed (*e.g.,* Beamsley and Black, 2003; Kilpatrick, 2005; Scarfe and Healy, 2005; Scarfe *et al.,* 2009; Walther, 2007), empirical studies of surfing beaches are rare. The beach state, categorized by Wright and Short (1984), is expected to be very important for surfing, and it is likely that certain beach states are more likely to create surfing waves. Extremely dynamic beaches may have better or worse surfing conditions depending on previous swell events, seasonal variations in sediment supply, and wave climate, and even interdecadal trends such as the southern oscillation index (SOI), and these oceanographic features will influence beach state.

Henriquez (2004) stated that waves that form surfable peel angles when breaking along sandbars are what create surfable beaches. After years of discussions with surfers by the

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authors, many of them also believe that good sandbars create good surfing conditions. However, research by Scarfe and Healy (2005) at Mount Maunganui and Scarfe *et al.* (2009) at Aramoana, New Zealand, show that these surfing breaks are relatively free of surf zone features that would cause peeling waves, putting this commonly held belief in doubt. Refraction modeling by Dunn (2001) for a coastal erosion study at one of New Zealand's best surfing beach breaks, Wainui Beach, also supports the hypothesis that offshore wave focusing is often the controlling process for good surfing conditions at a beach.

Scarfe *et al.* (2003a, 2003b) state that for waves to peel suitably for surfing there needs to be a gradient in the wave height and/or contours oblique to the incoming wave crests. It is likely that at different surfing breaks the contributions of offshore processes or nearshore focusing and wave breaking features (bars or rips) to create peeling waves varies. For example, an ebb-delta focuses and breaks waves at the "Whangamata Bar" (Scarfe *et al.,* 2009) but offshore focusing will also make a contribution to the surfability of the beach. At Aramoana, offshore focusing and wave–wave interactions play more of a role in the creating of the surfing waves than the nearshore wave breaking features.

CONCLUSIONS

During this review the main drivers for the development of scientific surfing research have been discussed. These include incorporating surfing into coastal engineering (*e.g.,* ASRs) and protecting existing surfing breaks. Different types of research-based surfing literature are identified and 162 citations are categorized in Table 1. The findings show that the physical processes around surfing breaks are well researched. Physical and numerical modeling of surfing waves has featured often in the literature, including analysis of existing surfing breaks. Although ASR design has received a lot of attention, the construction, monitoring, resource management process, or beach response to a reef have not been covered in as much detail. As a result, when coastal conflict occurs near surfing breaks, surfing amenities often suffer. What is lacking is specific literature on how to manage coastal conflict issues around surfing breaks (*e.g.,* Scarfe *et al.,* 2009). More research on economics, sociocultural issues, coastal management, and the oceanographic effects of coastal development on surfing is required if the world's natural surfing breaks are to be preserved.

Surfing has been scientifically explained by breaking the topic into surfing waves and how they relate to surfers, and surfing breaks and how they relate to surfing waves. Breaking wave height (H_B), wave peel angle (α), wave breaking intensity (B_I), and wave section length (S_L) are four surfing wave parameters that can be used to describe surfing waves. Other parameters exist, but these ones are favored to maintain consistency in the literature. The effect of local winds at a surfing site is briefly discussed, and although wave–wind interactions have been researched in the oceanographic literature, surfing wave–wind interactions have not been the topic of specific research.

The different types of surfing breaks are presented, and literature on the bathymetric components of surfing breaks and their effect on surfing waves has been reviewed. Two examples of natural surfing breaks are presented to further illustrate how surfing waves form and how they can be analyzed. To better understand ASR design, as well as surfing breaks in general, we recommend that more research on beach morphology and surfing be undertaken.

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