ADDRESSING THE INTERNATIONAL RIP CURRENT HEALTH HAZARD

A Dissertation

by

SARAH MARGARET TRIMBLE

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Christopher Houser
Committee Members,	Christian Brannstrom
	Michael P. Bishop
	Anthony Filippi
	Ryan Ewing
Head of Department,	David Cairns

December 2017

Major Subject: Geography

ABSTRACT

Rip currents are concentrated seaward flows of water originating in the surf zone of beaches that are responsible for hundreds of injuries and fatal drownings worldwide annually. Calculating the exact number of deaths is hindered by logistical difficulties in collecting accurate incident reports, but the estimated annual average is about 59 in the United States (US), 53 in Costa Rica, and 21 in Australia. Previous research shows rip drownings are caused by a combination of personal and group behaviors with the physical environment. The co-incidence of a rip and swimmers, the 'hazard,' results from gaps in knowledge and in communication: we do not know how to accurately predict rip currents, and existing scientific understanding hasn't fully infiltrated the practiced knowledge of the general public or policy makers designing beach access.

This dissertation presents five papers examining the geophysical and social causes of rip-related deaths. Paper 1 reviews present rip current knowledge. Paper 2 demonstrates a novel method for mapping bathymetry within rip channels – topographic low spots in the nearshore resulting from feedback amongst waves, substrate, and antecedent bathymetry. The location and orientation of rip channels are investigated in Paper 3, which analyzes the degree of anisotropy in bathymetric surfaces. Paper 4 builds on rip detection by evaluating beachgoer knowledge alongside rip presence to evaluate physical environment control on swimmer exposure. Finally, because current research demonstrates lifeguard presence is a highly effective mitigation against drowning, Paper 5 identifies one way communities may fund beach lifeguard programs. Thus, the dissertation provides both cutting edge methods to improve prediction and warning systems with the geocomputation demonstrated in papers 2 and 3, and it provides more affordable short-term mitigation practices in papers 4 and 5, for increasing safety by designing and building geomorphologically informed beach access and funding lifeguard programs.

As a whole, the dissertation evaluates both human and physical geographies of rip currents, a naturally occurring phenomenon that becomes hazardous when entered by vulnerable individuals. Results can inform policy makers of a range of rip fatality mitigation methods: developing frequent nearshore maps to observe rip channel behavior, automating the detection of rip channels, designing beach access controls informed by morphology, and funding lifeguard programs.

DEDICATION

To my dear friends black coffee and straight bourbon, for keeping me focused during early mornings and inspired through late nights.

ACKNOWLEDGEMENTS

I owe tremendous thanks to several institutions and individuals who supported me during my dissertation work, and without whom this project could not have been completed. Chris, Rob, and countless fellow graduate students have shaped the thought processes and helped guide the tumultuous brainstorms that led to this completed document.

On a more personal note, I would like to say thank you to my pops: who still loves me unconditionally, even when Rush Limbaugh says he should not. I am also grateful to my mum, who taught me to do no harm, but also to take no …“shirt” (whether she meant to or not). To Michael and Lindsay, I am still thankful for your endless patience. And to Andy: without you, I probably would have finished an entire year earlier, but then all the following years would have been without you, too. I’m so glad we’re on this path instead. Thank you for flying to Australia.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee chaired by Dr. Chris Houser [advisor] while in the Department of Geography at Texas A&M University and through his transition to Dean of the Faculty of Science at the University of Windsor. Additional committee members included faculty from Texas A&M University: Dr. Christian Brannstrom, Dr. Michael P. Bishop, and Dr. Anthony Filippi of the Department of Geography, as well as Dr. Ryan Ewing of the Department of Geology and Geophysics.

All work for the dissertation was completed by the student, under the advisement of the committee members. Pete Chirico of the US Geological Survey provided data and impactful ideas critical to developing the methodology outlined in Paper 2. Dr. Michael P. Bishop wrote the software program that produced the anisotropic indices analyzed in Paper 3. Fellow Texas A&M University graduate students Dr. Phillipe Wernette, Andrew Evans, and Eric Guenther often provided valuable feedback during methods development for all sections. Dr. Robert Brander, of the University of New South Wales, helped collect data critical to Papers 2, 3, and 4; all analysis was completed by the student with assistance in data preprocessing provided by Dr. M. Jak McCarroll and Ben Van Leeuwen while they were at the University of New South Wales. Interviews discussed in Paper 5 were collected with the help of graduate student Andrew Evans and undergraduates Stephanie Reyes, Marian Gomez, and Garrison Goessler while they were enrolled at Texas A&M University.

Funding Sources

This work was made possible in part by the National Science Foundation and the Australian Academy of Science, which together provided the East Asia and Pacific Summer Institute fellowship (Award #1515522) that funded research and data collection in Australia used in Papers 2, 3, and 4. The dissertations' contents are solely the responsibility of the author and do not necessarily represent the official views of these awarding offices.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

1. INTRODUCTION

Rip currents are concentrated flows of water directed away from the beach and through breaking waves. They are part of naturally forming circulations that result from certain combinations of wind, wave height (as well as wave period), and variations in alongshore bathymetric features - including hard, engineered structures. These currents were first named in an English language peer-reviewed journal in 1941 (Shepard et al. 1941) and have become the subject of an increasing number of studies as rip currents have become recognized as a global public health hazard. Because rip currents occur on beaches all over the world and can flow 2 ms^{-1}, they do sometimes carry unsuspecting swimmers into deep waters, leading to thousands of rescues and hundreds of fatal drownings worldwide each year. A probable cause of rip current related injuries (and deaths) are communication gaps between scientists, policy makers, and the beach going public; knowledge gaps persist because of communication barriers, and because coastal geomorphology theory isn't fully resolved regarding the transformation of nearshore bars (and the subsequent development of rip currents) as beaches shift between Wright and Short's (1984) beach types. The dissertation here presented closes some of these knowledge gaps within coastal geomorphology and provides options for closing communication gaps between scientists and the vulnerable public. The research presented here encompasses five papers, where each of the four papers beyond the literature review (which is the first paper) evaluates a specific element of either the physical formation of currents or the human behaviors that lead vulnerable swimmers toward rip current locations.

First, a literature review consolidates seven decades of rip current research (Paper 1). This review is meant as a comprehensive text detailing the present knowledge base of coastal geomorphologic and social science theory regarding rip current formation and human interaction. Paper 2 presents a new method for mapping rip current locations in bathymetric models developed from Digital Globe WorldView multispectral imagery; because rip currents form in specific bathymetry types, improving mapping of this coastal zone increases available options for mapping rip current locations. Bathymetry is calculated from 8-band multispectral imagery captured by the Digital Globe WorldView3 (WV3) satellite and field measurements of depth, resulting in maps of the nearshore at an intermediate, rip-prone beach. In the following section (Paper 3), bathymetric models serve as input to anisotropic index analysis where results suggest there is a characteristic scale that can be used to identify topographic rip currents forming alongshore on open sandy beaches. The combined results from these papers could improve rip current location prediction models. Next, discussion shifts to the influence beach access controls have on the distribution of vulnerable swimmers within a single beach (Paper 4), because the geomorphologic influences which generate regularly-located rip currents on certain beaches may also lead developers to inadvertently build public beach access points in the same alongshore locations as rip currents. Controls include rip channel location, beach access points, and environmental factors favored by swimmers. Results reveal why and how people select a swimming location within a rip-prone beach and can be applied to improving beach access design and warning sign placement. Finally, in Paper 5, analysis of a town in a middle income country reveals one model by which communities can develop and maintain a lifeguard program to keep swimmers safe from these hazards. The last section provides a brief summary of the conclusions relevant to the entire dissertation.

2. LITERATURE REVIEW

2.1 Introduction

In 1941, several scientists working at the Scripps Institute published a paper in the *Journal of Geology* which was the first to define, for scientists, a coastal phenomenon long acknowledged by surf lifesavers and ocean swimmers (Shepard et al. 1941). At the time, there was still debate regarding the origin of the return flow of water and kinetic energy away from the shore, but it was hypothesized that a flow must develop to counterbalance the widely observed and predominant shoreward motion of waves, surface flow, and debris. Previous models had proposed that a vertical gyre existed and that a strong (possibly even violent) near-bed seaward flow must exist beneath the surf zone. This would account for colloquial accounts of swimmers being pulled beneath breaking waves on some coasts, but even older papers had already been published in the renowned journal of *Science* challenging this idea of "dangerous undertow," though these had not proposed that the rip current might be the mystery return flow needed to resolve circulation models (Craig et al. 1925, Jones 1925). What sets the 1941 paper apart is a clear definition of the term *rip current* as a concentrated, seaward flow of water that cuts breaking waves and as distinct from either "sea pusses," "rip tides," or "violent undertow," all terms which had historically been used with indistinct definition by the public and by some scientists (Shepard et al. 1941). This defining paper clarified that rip currents are neither purely surficial currents nor restricted to bed-level flow. To contradict previous conjecture, observations were collected and used to define that these currents:

- Exist vertically through the water column (to varying degrees of strength);
- Cannot exist without sufficient onshore-directed breaking wave activity;
- Are easier to observe from higher and more vertical vantages;

- Can vary in color and other aspects of appearance;
- Are a global phenomenon (Shepard et al. 1941)

In this and other early papers, scientific instrumentation limits hindered scientists' ability to collect quantitative data to aid in rip currents' description and definition. As instrumentation improves and an increased number of experiments are conducted globally, rip currents are understood increasingly well. In general, they are presently reported as ranging from a few to > 100 m in length, < 5 to 30 m in width, and speeds from 0.5 to more than 3 ms^{-1} (Brander 1999).

Rip currents are an object of scientific inquiry for multiple reasons: (i) surf zone circulations are, in some cases, still difficult to measure and evaluate (leading to gaps in knowledge) and (ii) rip currents are an international health hazard responsible for hundreds of rescues, injuries, and fatal drownings worldwide every year (Houser et al. 2017). Since Shepard et al. research has tended to focus on either the purely geomorphological and physical properties of rip currents' role in surf zone circulations *or* on the present state of public risk, awareness, and safety education campaigns regarding the health hazard posed by rip currents. In this review, these qualities are not treated as separate but as completely intertwined. Rip currents are presented here as a naturally occurring physical phenomenon which represents a hazard to public health only when the right knowledge gaps, physical conditions, and social conditions are all present (Figure 1). Several papers already published by the author (of which some are included in the dissertation) address some of the knowledge gaps which generate this risk, including new methods to mitigate the hazard.

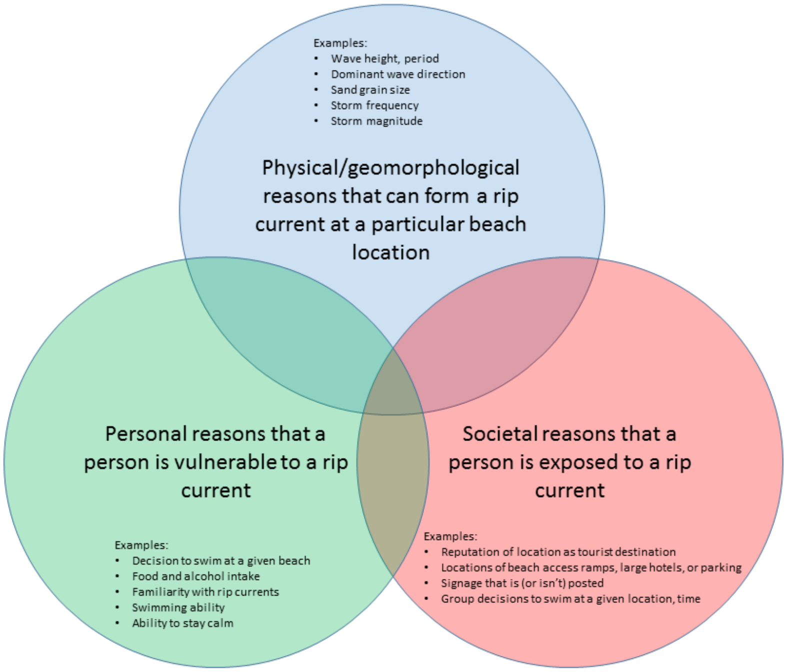

Figure 1 The rip current can become a public health hazard when three conditions are present.

2.2 The role of rip currents in surf zone circulation

In general, rip current circulations develop when incident wave angles and coastal morphology interact to create variation in wave height and wave breaking alongshore, which in turn generates a spatial imbalance in radiation stress and, therefore, pressure gradients (Haller et al., 2002; Castelle et al. 2016). These variations in stress manifest along the beach as spaces of "higher wave 'set-up' (higher waves, more intense breaking) and lower 'set-up' (lower waves, less intense breaking)" (Castelle et al. 2016). Maximum rip current speeds are generally observed during a falling tide, when interaction between breaking waves and bathymetry is greatest (Aagard et al., 1997; Brander, 1999; Austin et al., 2010, 2014; McCarroll et al., 2014b; Scott et al., 2014; Pitman et al. 2016).

This circulation system is initiated as incident waves shoal and break on nearshore sandbars, creating wave set-up landward of the breaking zone. Shoaling is the change in height and shape of the wave that occurs as waves interact with the seafloor; waves break when this shape collapses. Wave set-up is the increased water level against a shoreline, the result of the accumulated momentum and mass of water cast onto the beach by a breaking wave. Waves break at different locations alongshore as the result of refraction, the process of waves slowing over shallow areas and retaining speed over deeper areas (Davidson-Arnott 2010). Wherever wave breaking varies alongshore, wave set-up will vary, and a longshore pressure gradient will develop that funnels water offshore through breaks or low points in the nearshore sandbars. This longshore gradient can result from an alongshore variation in wave breaking resulting from the presence of sandbars (Sonu 1972; Wright et al. 1979; Wright and Short 1984), hard structures (Gensini and Ashley 2010), or alongshore variability in the incident wave field (Bowen 1969). The focused return flow of water back through breaking waves is what we call a rip current (Davidson-Arnott 2010).

Rip currents are an end member of a suite of nearshore circulation patterns that include meandering currents and alongshore currents, that are controlled by the angle of wave incidence and the alongshore variability of the nearshore morphology. In the absence of an alongshore variation in nearshore morphology, near-normal wave incidence forces a bed-return flow (i.e. undertow) that is replaced by a quasi-steady alongshore current as the angle of wave incidence increases. Near-normal waves approaching an alongshore variable nearshore morphology force a closed rip circulation characterized by a narrow seaward flowing current that extends from the inner surf zone through the line of breaking waves (Brander 1999; Brander and Short 2000; Sonu, 1972; MacMahan et al. 2006; Short 2007). The closed rip circulation can either be symmetrical with two opposing circulation cells that occupy half of the shoal and channel or asymmetrical with the current occupying one rip channel and one shore-connected shoal. The rip circulation is replaced by a meandering alongshore current as the wave field becomes increasingly oblique to the shoal (Sonu 1972; MacMahan et al. 2010; Houser et al. 2012).

Not every beach has a morphology prone to the formation of rip currents and it is possible that the potential for rip currents to develop can vary alongshore, through the tidal cycle, or following storms. In 1984 Wright and Short published their article “Morphodynamic variability of surf zones and beaches: a synthesis” in which they set the standard for classifying sandy beaches around the globe for the next three decades (and counting). Using 2-dimensional transect observations from 26 beaches around Australia over the years 1979-1982, they determined 6 primary beach states: dissipative, reflective, and four distinct intermediate stages between these two end-member states (Figures 2.2 and 2.3). The two opposite ends of this spectrum, dissipative and reflective beaches, do not have morphologies that create semi-permanent rip currents.

Dissipative beaches are so named because their long gentle slope dissipates wave energy well before it can break on the beach; this also means they are typically too gently sloped for rip current formation, although flash (short, hydrodynamically driven) rip currents have been observed. On the other end of the spectrum, reflective beaches are very steep and lack the sandbars that might generate the necessary alongshore variation in wave set-up for rip current development. Depressions in elevation on these beaches tend to be associated with cusps (which can sometimes form small ‘swash rips’).

It is the middle category between these two, the intermediate beaches, which can develop a variety of three-dimensional bar structures, and are prone to rip currents under the right wave condition. Intermediate beaches themselves come in four subcategories of morphology, determined by the shape and location of the nearshore bar, as well as tidal range and average wave climate. These are the: longshore bar-trough (LBT), rhythmic bar-beach (RBB), transverse bar and rip (TBR), and low tide terrace (LTT; Wright and Short 1984; Figure 2.2 and 2.3). Each of these four intermediate states is characterized, to varying degrees, by the presence of rip channels.

For intermediate states, rip channels are an identifying form; they develop between breaks in the sandbar as it moves toward (accretes) or away from (erodes) the beach face. These are called accretional rips and erosional rips, respectively. Accretion rips are perhaps the most dangerous because they are associated with a beach's smaller wave conditions during a recovery period following a storm or other large wave action (Short 1985). Because wave energy is decreasing at this time, these are the rip current conditions during which the water may look the safest. The dissipating wave energy moves the sand bar back toward the beach face, and the returning water flow will favor channels forming in breaks in the bar. Accretion rips are associated with crescentic bars, rhythmic bar and beach, and transverse bar and rip states (Wright and Short 1984). These rip currents can vary in width, up to 10s of meters across, and can last up to several days or even weeks if favorable conditions persist (Wright and Short 1984; Short 1985). Erosional or flash rips form when wave conditions increase suddenly, such as during a storm. As waters rise over an existing transverse bar and rip state, the sharp increase in wave energy causes surf zone circulations that include rip currents. These rip currents then move the bar rapidly offshore to a depth where the larger waves first begin to shoal, or 'touch' bottom (Short 1985). Erosion rip currents can be more than several 10s of meters wide but will disappear as quickly as they formed, lasting only a few moments or at most a few days (Short 1985).

Rip currents can also be topographically controlled, such as those that form along jetties or piers, but these are not associated with any particular beach state. Some rip currents, called ‘mega-rips’ form only during extreme wave events and occur primarily on embayed beaches. These mega-rips are actually topographically controlled erosion rips that form from a complex interaction between headlands and wave refraction that “prevents the development of the fully dissipative state” (Short 1985). They form at largely spaced scales, typically one rip current for the entire embayed beach or about 1 km apart, and can flow several 100s of meters out to sea (Short 1985).

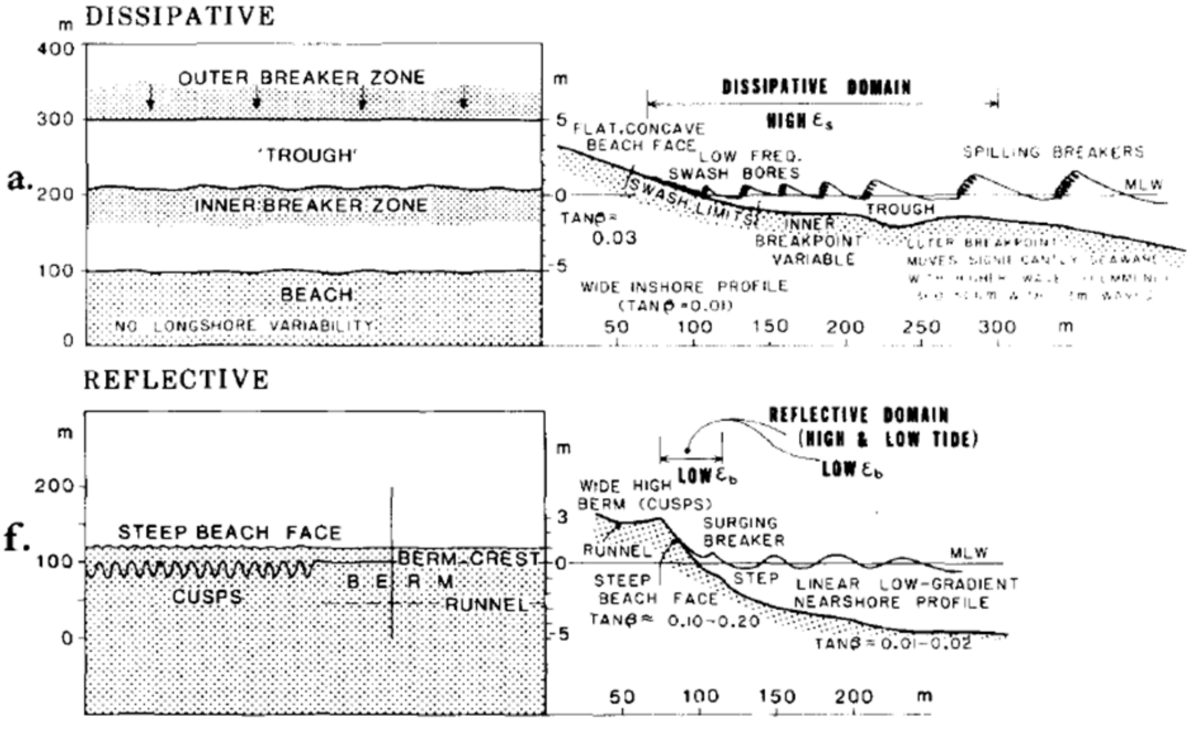

Figure 2 Wright and Short's (1984) two end member states, dissipative and reflective.

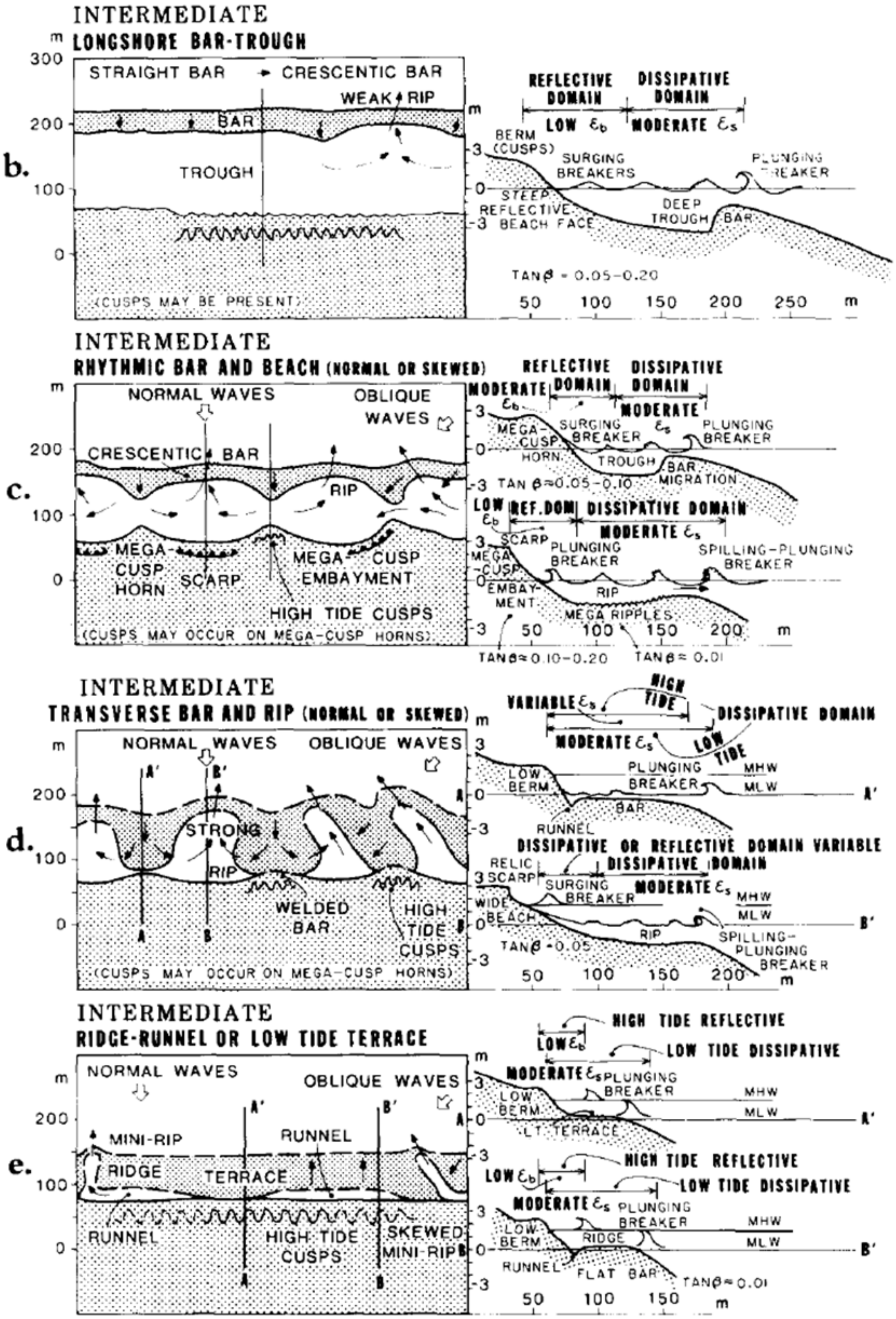

Figure 3 Wright and Short's (1984) intermediate beach states.

The present knowledge gap in the Wright and Short (1984) system of beach states lies in understanding how the 3-dimensional bar morphology develops as the bar moves landward on a large scale. At the time Wright and Short (1984) completed their study, 2-dimensional profile transects and qualitative observation of alongshore changes were the limits of possible data collection because spatially or temporally dense 3-dimensional observations were not possible in the 1980s. The authors recognized this in their concluding paragraphs, by stating that "predictability is certain to be improved progressively through continued observation, data collection, and analyses" and that "[e]xtension of the predictive models [to a global scale] will require more intensive use of remote sensing data" (1984, pg. 116). Instruments, technology, and computation power have since experienced rapid advancement and this study seeks to fulfill Wright and Short's call for remotely sensed, global confirmation of their beach state evolution predictions while focusing on the modern need for improved rip channel observation, modeling, and prediction.

Table 1 Conditions which can form rip currents, all of which can vary, depending on the angle of wave approach (Castelle et al. 2016). The center column lists the most common expression of the conditions which create rip currents; at right are listed the less common, but possible, expressions of rip current morphology.

Conditions	**Typical**	**Possible**
Beach morphology	Alongshore, three-dimensional variability	Can be planar
Channel morphology	Distinctly deep channels, which can form along hard structures or along unrestricted, sandy coasts	Can be indistinct, as in the case of "flash" rips
Life-span	Persistent in occurrence and location	Can be transient, short-lived, as with "flash" rips
Speed	Maintain a mean flow	Can be unsteady
Length	Confined within the surf zone	Can extend well beyond the breakers, as with "mega" rips

Recent publications have further developed the categorization of rip currents observed globally. The formation of rip current circulations in the surf zone is an inherently complex process that can be generated by an array of conditions, outlined in Table 2.1 and described in detail in a recent review of rip current studies published since 1941 (Castelle et al. 2016).

At present, no singular rip current classification system is in widespread use, though several attempts to create one have been published (Short 1985, 2007; Dalrymple et al. 2011; Leatherman 2013). This publication will employ terminology as defined by the most recent and most comprehensive classification, described by Castelle et al. (2016). These categories are, however, not entirely discrete. It is possible to develop multiple rip current types on the same beach, even simultaneously and adjacent to each other. It is also possible to have rip currents which reflect more than one type; examples include boundary-channel rip currents or channel-flash rip currents (Castelle et al. 2009).

Rip currents can be described by four general categories; photographs and bathymetric profile examples are provided in Figure 2.4. One rip current type is so small it may be called a mini-rip (e.g. Russell and McIntire 1965) or a swash rip (Dalrymple et al. 2011); these form in the center of small cusps (10 m wide curved slopes) on steep beaches and do not persist far enough past the swash zone to pose a great hazard to beach goers (Masselink and Pattiaratchi 1998; Castelle et al. 2016). The remaining three categories are purely hydrodynamic rip currents, which lack morphologic controls; bathymetric rip currents, which exist because of surf zone and/or inner shelf morphology; and boundary rip currents, which exist largely due to rigid boundary structures. Each of these categories can also be subdivided into at least two variants within itself (Castelle et al. 2016). Photographic examples and bathymetric expression of these four types are shown in Figure 2.4.

The two types of hydrodynamic rip currents are both highly transient, with inconsistent alongshore position within a given beach and short life spans. Hydrodynamic rip currents are those that form purely from hydrodynamic processes on morphologically planar beaches, which are uniformly sloped alongshore. They spawn when instabilities are generated by strong longshore currents, or when an incredibly weak or absent longshore current causes a “flash” rip (a short lived surf-zone eddy). In both cases, there is no associated channel in the bathymetry.

In contrast to transient hydrodynamic rip currents, the other types are formed by characteristic alongshore morphological variations. Bathymetric and boundary rip currents are also the results of hydrodynamic processes, however, in these cases, the morphology of the vertical variability in the surf zone and/or inner shelf drives the spatial variability of the hydrodynamics, causing rip currents in these categories to form in relatively persistent alongshore locations. The formation of boundary-controlled rip currents is predominantly controlled by rigid structures that interrupt alongshore flows. These can be natural or anthropogenic features; examples include rocky headlands, jetties, groins, and piers. Because permanent structural elements force the rip current circulation, this type of rip, when it forms, is consistently located adjacent to the structure. When the rip current forms along the side of the structure facing the incoming waves, the ‘downwave’ side, it is called a deflection rip because the structure is deflecting the longshore current flow. When the rip current forms in the lee of the structure, sheltered from incoming waves, it is called a shadow rip (Castelle et al. 2016).

In the case of bathymetric rip currents, location can vary with the development or collapse of nearshore sandbars, or the location can be permanently controlled by submarine canyons or reef structures. These rip currents can be subdivided into (i) channel rip currents and (ii) focused rip currents. Channel rip currents form in temporary or permanent channels in bathymetric substrate because wave breaking is weaker or absent in those locations (waves aren't shoaling because of the larger depth of the water column). Focused rip currents are similar, but the alongshore variability in breaking wave height that generates them is caused by wave refraction across offshore anomalies in the bathymetry, such as three-dimensional sandbars (Castelle et al. 2016).

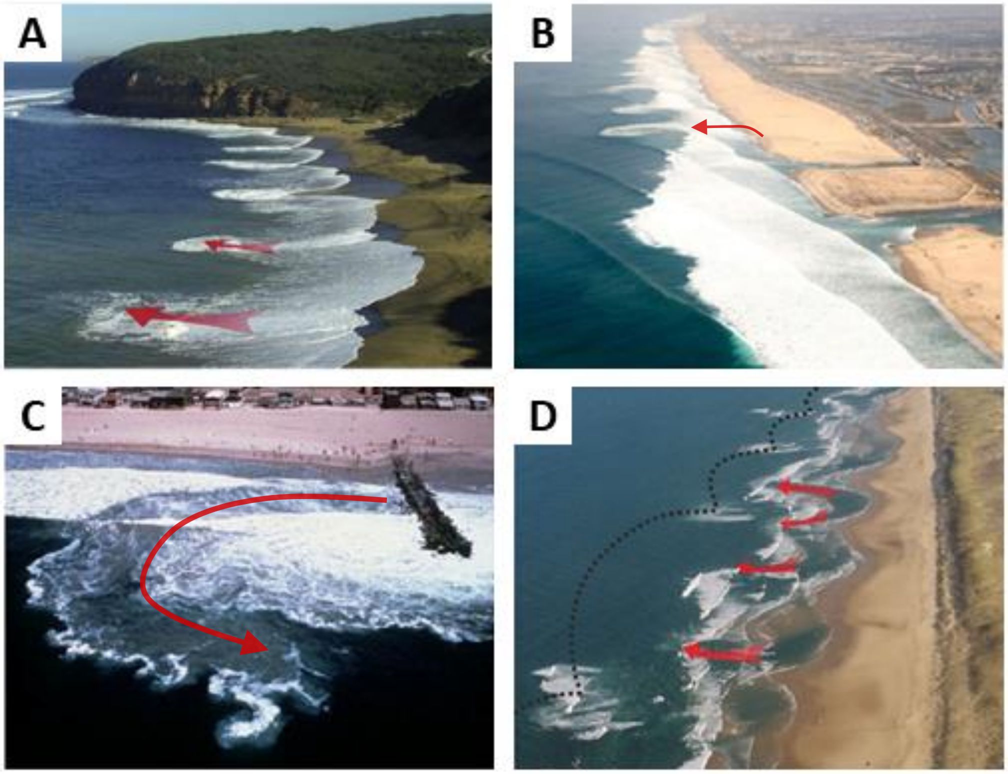

Figure 4 Photographic examples of the primary rip current types. From the top left, the types shown are: (A) swash or mini rip, (B) hydrodynamic rip, (C) boundary rip, and (D) bathymetric rip. All images are adapted from Castelle et al. 2016.

2.3 Rip currents and drowning

The vulnerability of beach users to drowning in a rip current depends on the combination of beach hydrodynamic and bathymetric conditions, personal and group behaviors, and rip current knowledge of the individual (Houser et al. 2010, 2011; Brander 2013). Lack of rip current knowledge was identified as being associated with rip current drownings by Morgan et al. (2009) in addition to gender, age, alcohol consumption, and overconfidence in swimming ability. In 2014 the World Health Organization (WHO) published their first global report on drowning[1], declaring it a major global health hazard because drowning "is among the 10 leading causes of death" for young people in every region of the world. A major factor in drowning deaths in all bodies of water is a "lack of barriers controlling exposure" and lack of "adequate, close supervision" for those at risk:

> "Once someone starts to drown, the outcome is often fatal. Unlike other injuries, survival is determined almost exclusively at the scene of the incident and depends on two highly variable factors: how quickly the person is removed from the water, and how swiftly proper resuscitation is performed. Prevention, therefore, is vital." (WHO 2014)

In the United States, records of cause of death are difficult to consolidate and analyze; previously it has been especially difficult to determine which drowning deaths are specifically

---

[1] Drowning is defined as "the process of experiencing respiratory impairment from submersion/immersion in liquid" (WHO 2014). Technically, a person can experience drowning and not die as a result; for that reason we refer throughout this chapter to both drowning and fatal drowning.

attributed to rip currents. As a result, peer-reviewed articles have published estimates for annual fatal drownings in rip currents in the US that range from 35 per year (Gensini and Ashely 2009) to more than 100 per year (Lushine 1991). However, the US Lifesaving Association (USLA) has increasingly maintained detailed records. Their most recent annual review reported that in 2015, there were 95,024 recuse performed by USLA lifeguards, of which 48,213 (51%) were rip-current related. Despite this high rescue record, 5 fatal rip-related drownings occurred on patrolled beaches – which is far less than the 31 confirmed rip-related deaths that occurred on un-patrolled beaches (USLA 2015). In Australia, the Surf Life Saving Association (SLSA) has kept diligent records for some time; since 2002 they have reported an average 22,000 rescues per year, of which 80% are rip-related. Despite this highly effective rescue rate, there are still an average 21 rip-related fatalities in Australia each year (Brighton et al. 2013). In Costa Rica, mortality reports across the country are well documented and consolidated. An average 53 people have drowned fatally in marine environments each year since 2001. The majority of these deaths (64%) were Costa Rican citizens; of the foreign fatalities, the largest group of tourists was from the US (43% of foreign drownings; Arozarena et al. 2015).

Because rip currents do not pull a person under the water (they pull you away from shore, but not down), drowning begins when a swimmer is unable to touch the bottom while keeping their head consistently above water. This can happen as a result of exhaustion, panic, hyperventilation, or any combination of the above while the person is experiencing the stressful conditions of the rip. The body’s response to stress includes a physiological, adrenaline reaction that causes, among other things: increased heart rate resulting in raised blood pressure; dilation of the bronchi causing rapid, shallow breathing; prioritizing blood flow towards muscles and organs; and decreased blood flow and reduced function in the parts of the brain that produce logical, rational thinking and evaluation (LeDoux 1996). This process is sometimes called the “fight or flight” response; it is particularly problematic for a person caught in waters where they cannot easily stand or otherwise keep their head above water. For these reasons, common rip current awareness campaigns emphasize “don’t panic” and “stay calm” messages. It is also imperative that swimmers avoid swimming directly back into the current. Recall that rip current speeds have been tracked with GPS-tracked as high as 2 m/s, and averaging 0.3-0.7 m/s, while Olympic swimmers have set records at 2 m/s; the current world record for the 100m freestyle swim is held by Cesar Cielo of Brazil, who swam it in 46.91 seconds, or an average pace of 2.13 m/s (FINA 2016). It is easy to understand, then, that an average person attempting to swim against such a current will make no progress, and quickly become exhausted.

2.4 Beach user knowledge of rip currents

Rip currents can be identified from the beach as: (a) dark gaps in breaking waves, as (b) brighter water if they are transporting lots of seafoam (white), or as (c) discolored or murky water because they are transporting lots of sediment (Figure 2.5). While rip currents are visible, it can be difficult for beach users to spot them and difficult to adequately train people. In 2007, several hundred beachgoers in Australia were intercepted on their way to the beach. They were asked a series of questions meant to assess their knowledge and behaviors relating to beach safety; additional questions recorded subjects’ non-identifying personal characteristics (e.g. age, gender, self-rated swimming ability, etc.). One set of questions asked subjects to draw an arrow on a photograph indicating where (if) they saw a rip. Results indicated that immediately after a rip current education campaign, 28% of respondents showed improved ability to identify rip currents in still images of rip currents; 6 months after the campaign 58% of those who followed-up (responded a second time) had maintained their improved knowledge (Hatfield et al. 2012). This suggests that safety campaigns have at least some measureable effect on subject's ability to see rip currents once trained.

Recent evidence suggests that while the majority of beach users are aware of rip currents and the hazard they pose, they are not able to identify a rip current (Caldwell et al. 2012; Brannstrom et al. 2014). Most beach users surveyed in Florida and Texas (>80%) incorrectly indicated that the photograph with the heaviest surf represented the most hazardous surf conditions and greatest potential for the development of rip currents, or failed to identify rip currents in photographs (Caldwell et al. 2012; Brannstrom et al. 2014). This is consistent with the results of Sherker et al. (2010) who argued that the majority of beach users are unable to identify the rip current and that "beachgoers clearly need to know what a rip current looks like in order to actively avoid swimming in it." The majority of participants surveyed at Pensacola Beach, Florida identified heavy surf areas as the location of rip currents, versus the relatively flat water of the current or the darker color water of the rip channel actually shown (Caldwell et al. 2012). Given sufficient information, it is possible for beach users to be able to identify a rip current with confidence (Hatfield et al. 2012). However, the ability to identify a rip current or to recognize posted warnings about the rip current danger is not a guarantee that a beach user will not drown, particularly for those who choose to swim in unsafe and unpatrolled sections of the beach (Drozdewski et al. 2012; Williamson et al. 2012).

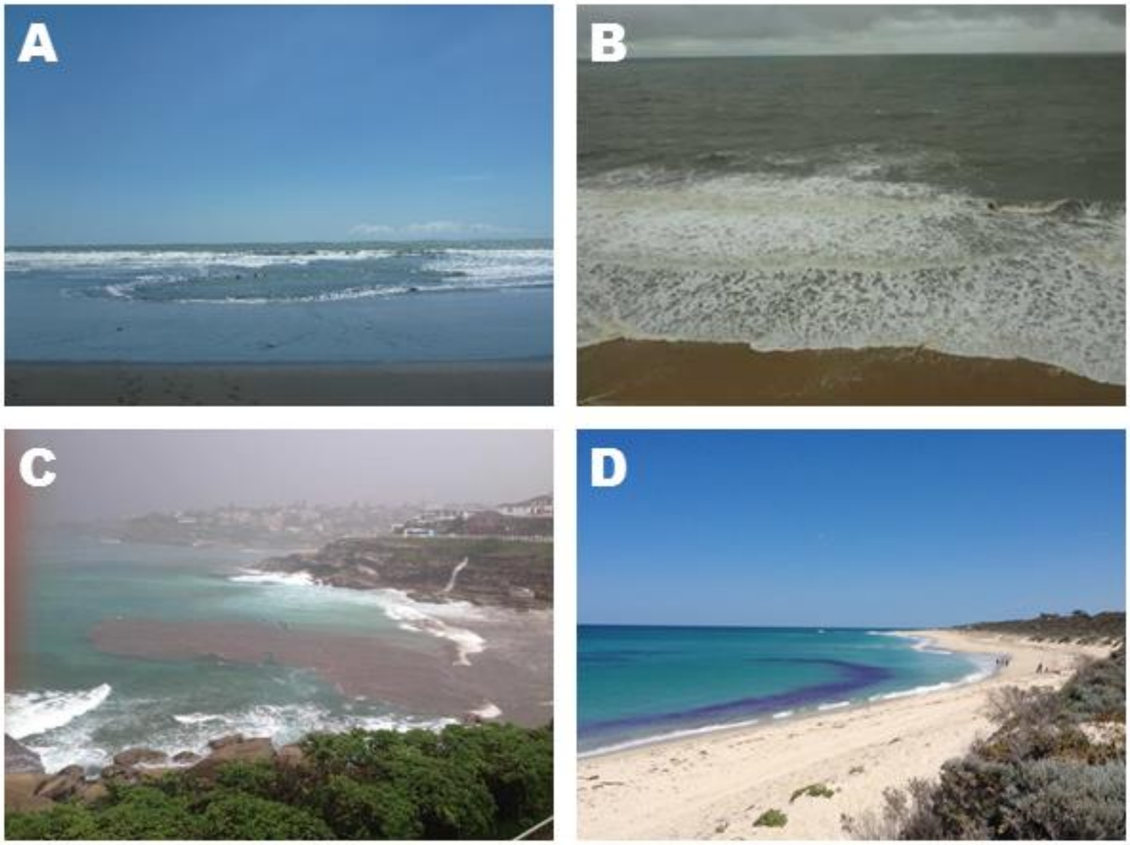

Figure 5 Rip currents can be identified from the beach as (a) dark gaps in breaking waves, as (b) brighter water if they are transporting lots of seafoam (white), or as (c) discolored or murky water because they are transporting lots of sediment. In image A, the breaking waves on either side of this rip current generate bright white sea foam, and the rip current is a dark slick lacking breaking wave (and therefore lacking the white foam). In image B, the rip current is carrying seafoam out to sea, and the concentration of white foam on the surface makes it appear brighter than the surrounding breaking waves. In image C, the rip current is carrying sediment out to sea, which gives it a “muddy” color. In image D, a rip current expert (Dr. Rob Brander, a.k.a. “Dr. Rip”) has dumped purple dye into this rip current as an educational exercise. Photo A credit S. Trimble; photos B, C, D credit of R. Brander via Science of the Surf.

A study conducted in Texas in 2012 expanded the Florida study (Caldwell et al. 2012) by conducting n=392 face-to-face interviews on three Texas beaches during the height of summer season (Brannstrom et al. 2014; 2015). This structured interview included a “spot the rip" in the photograph question similar to previous surveys, but expanded this analysis to ask subjects (a) to sort 5 images of the same location, with varied levels of waves sizes and rip current hazard, in order from least to most hazardous conditions, and (b) to indicate the most dangerous place to swim by selecting cells within a superimposed grid on the photos. The majority of subjects (87%) were unable to identify the rip current space as the two most dangerous location. An inability to visibly recognize the hazard may be related to beach habits and is positively correlated with a lack of knowledge regarding the physical causes of rip currents (Brannstrom et al. 2014). This is especially problematic alongside results showing that the same population was unsure of the proper escape routes, as the majority of respondents who failed to identify rip currents in photographs also said they would swim straight back to shore to escape (Brannstrom et al. 2014).

Results from Australia (Mathews et al. 2013) and Texas (Brannstrom et al. 2015) also sugggest that many beachgoers do not recognize posted warning signs and flags. Mathews et al. (2013) found that the majority of n=472 beachgoers did not heed posted warning signs, where less than half (45%) of subjects interviewed at four Australian beaches noticed any of the signs posted along their beach entry path. In Texas, 48% of n=392 respondents had not seen posted warnings signs, and those who did see them did not measurably modify their behavior as a result, saying only that they would "enter the water with caution" (Brannstrom et al. 2015). In addition, surveys of n=407 subjects in the United Kingdom (UK) used open-ended questions to determine beachgoers' general knowledge level and understanding of rip currents and the lifeguard patrol system there; in accordance with the other studies completed in English speaking countries (Australia & the US) the majority of subjects (65%) could not correctly explain what a rip current is or what it looks like; however in the UK most subjects

(77%) did understand that water hazards played a role in lifeguard’s decision to post red and yellow flags denoting safe swimming areas (Woodward et al. 2015).

2.5 Existing safety programs

Informing the public about the rip current hazard has become a national priority in a number of countries including the United States (e.g. Ashley and Black, 2008; Brannstrom et al. 2013), Australia (e.g. Sherker et al. 2008; Brighton et al. 2013), the United Kingdom (e.g. Woodward et al. 2013), India (Arun Kumar and Prasad 2010), and Costa Rica (Arozarena et al. 2015). As described by Carey and Rogers (2005) there are cooperative and coordinated efforts at many levels in the United States designed to improve public education about rip currents. For example, the National Weather Service (NWS) of the National Oceanographic and Atmospheric Administration (NOAA) issues surf zone forecasts for some areas that include a 3-tiered rip current outlook (low, medium, and high risk of rip currents forecast). In general, these forecast products are not disseminated in a consistent manner among offices and therefore are not communicated seamlessly (NOAA 2015). These rip current forecasts are used to varying degrees by local lifeguard associations who warn beach users of the rip current hazard through active intervention, signs and/or flags.

The International Life Saving Federation advises beach lifeguards to raise colored flags indicating whether the risk of dangerous surf and rip currents is low, moderate, or high by raising a green, yellow, or red flag (respectively). The general advice under each condition is that a green flag indicates safe swimming, yellow flags indicate that weak swimmers are discouraged from entering the water, and red flags are used to advise that all beachgoers are discouraged from entering the water (ILSF 2004). In the US, determination of the rip current hazard level is dependent on the daily surf zone forecasts provided by the National Weather

Service (NWS), which is based on studies by Lushine (1991a, b). These rip current outlooks are based on the wind and/or wave conditions forecast for that day and whether or not they are expected to support the development of rip currents. Meteorological factors have also shown to have an influence on rip current intensity as 90% of rip current drowning and rescues in two Florida counties took place when wind speeds were 12 m/s or greater, directed onshore and within 30° of normal (Lushine 1991a, b).

In Australia, red and yellow flags have been used to signal safe swimming areas since 1935 (National Museum of Australia 2015). From 2010-2012 the Surf Life Saving Association (SLSA) developed a strong advertising campaign reminding beachgoers to swim only between red and yellow flags; these flags are temporarily posted each day by the opening shift lifeguard and indicate a rip-free and surfboard-free area that is guaranteed to be patrolled heavily by the guards on duty. The UK also uses the red and yellow flag system and credits it with lowered fatality rates on their beaches (Woodward et al. 2013).

Perception of the rip current hazard depends in part on trust in experts and authorities, and trust in the protective measures they employ (Njome et al. 2010; Heitz et al. 2009; Terpstra 2009, 2011; Barnes 2002). Inaccuracies in the forecast or a discrepancy between the forecast and what is observed a specific beach at a specific time can erode confidence in the forecast (Siegrist and Cvetkovich 2000; Espluga et al. 2009), and has the potential for beach users to downplay the hazard on future visits (Hall and Slothower 2009; Scolobig et al. 2012; Green et al. 1991; Mileti and O'Brien 1993). A discrepancy with a rip current forecast may reflect the overly general nature of the forecast or the inability of beach users to identify a rip current and relate the forecast to an actual feature (see Caldwell et al. 2012; Brannstrom et al. 2014, 2015).

Many beaches in the United States and around the world post a rip current warning sign that informs beach users how to escape a rip current, and a simple illustration of a rip current from an aerial perspective (Figure 2.6). The sign was developed by the NOAA-USLA Rip Current Task Force, which was convened in 2003 to establish consistent rip current education efforts and improve data sharing about rip current rescue data; the primary product of the task force was a rip current brochure and sign template that could be duplicated and posted along boardwalks and beachfronts. The rip current warning sign developed by the NOAA-USLA Rip Current Task Force is part of the "Break the Grip of the Rip!®" education campaign, which was initiated in 2004 by the NWS, Sea Grant and the United States Lifesaving Association (USLA). The campaign aims to educate the public of the dangers associated with rip currents by providing information about rip currents, including why they are dangerous, how to identify them, what to do if caught in a rip current, and how to help someone else if they are caught in a rip current. This message has been disseminated through various means such as the NWS Rip Current Safety webpage, brochures, beach signs, videos, newspapers, articles, and television. Given the recent research into the effectiveness of the sign and the "Break the Grip of the Rip!" message, this campaign is currently under revision by a small task force formed by NOAA that includes the NWS, NOAA scientists, the USLA, and coastal geomorphologists from various universities in the United States, Canada, and Australia.

The NOAA beach warning sign was adopted by the State of Florida and warning signs are posted at all beach access points at Pensacola Beach Florida (Caldwell et al. 2010). In 2002, state legislation in Florida required a uniform beach safety program be established that require public beaches and coastal areas to display warning and beach safety flags. An amendment to this section in 2005, required beach warning flags to become standardized to the system that is used currently. Despite these efforts, there are still drownings at Pensacola Beach (NWS 2017b). Warning signs are required at all beaches in Florida and are posted at every beach access point along Pensacola Beach, regardless of if they are located where lifeguards are stationed. The rip current warning sign generalizes rip currents into a simplified form that they rarely resemble and as a result, it has been suggested that rip current warning methods be re-evaluated.

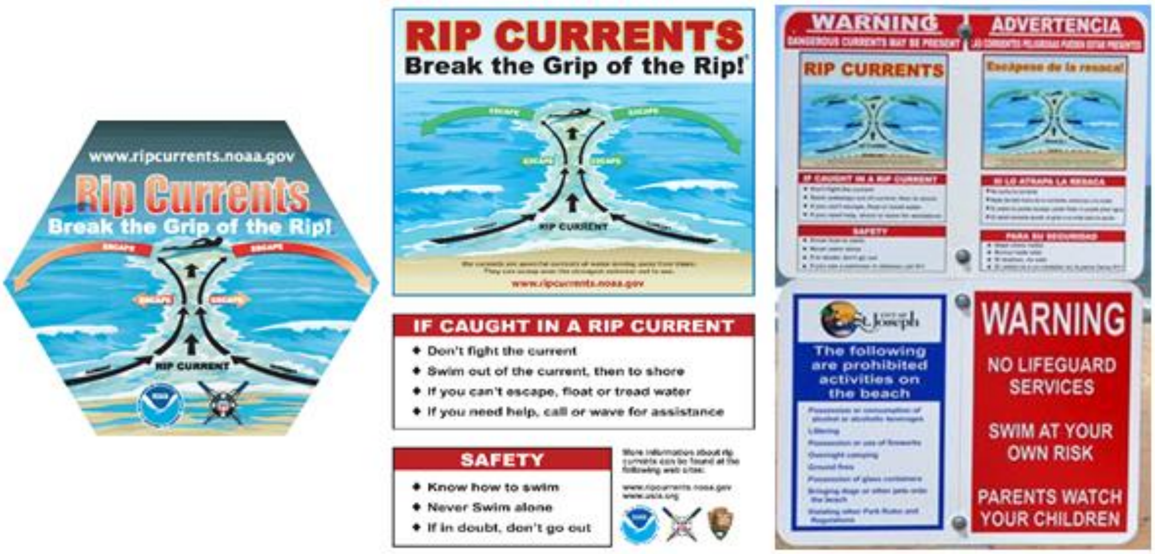

Figure 6 Various stages of the development of the standard NOAA rip current sign. Sign A was one of the earliest drafts of the sign originally designed by NOAA in 2004. Sign B is an updated version, posted widely in the US but currently undergoing more evaluation and adaptation. Sign C is an example of a sign adapted by a town in the US whose governing body added multiple languages and site-specific information (all images from NWS 2017c).

Until the last five years, escape strategies were developed and advertised based on scientists' understanding of physical rip current flow. For obvious ethical reasons, no study was able to track and observe unsuspecting rip current victims to assess typical victim behavior or successful escape routes. Because rip currents are focused flows of water perpendicular to shore, early messaging primarily broadcast a “swim parallel” message, based on the concept of swimmers being able to escape the flow away from shore by breaking out of the channelized flow. As an increasing number of studies tracked rip current circulations with GPS-tracked buoys and dyes, some data revealed that 80-90% of rip currents (on certain coasts) follow a recirculation pattern (MacMahan et al. 2010) that could bring floating individuals back to shore. These findings prompted some experts to argue that a “float and follow” escape strategy may be preferable since it does not rely on a victim’s swimming ability for effective escape.

To test the effectiveness of multiple escape strategies, a volunteer-based experiment in Australia used GPS to track the “time to safety” of volunteers who randomly selected an escape strategy before entering a rip current on a transverse bar and rip type beach (McCarroll et al. 2013, 2014, 2015). Results revealed that for this common rip current type, the optimal strategy was swimming parallel in the direction of alongshore flow. Recall that beach types which develop rip channels also have an alongshore current flowing parallel to the beach in a singular direction. Volunteers who had to swim parallel out of the rip current and into this current were effectively fighting two strong flows and had prolonged “time to safety.” Swimming parallel, then, is not universally effective. However, those volunteers who attempted to float to safety by “riding” the recirculating pattern of the currents were in for a long ride; in 10 minutes, only 44% (less than half) had reached a sandbar or other shallow feature where they could safely stand. In comparison, within the same 10 minute period, 80% of even the slower swimmers facing the alongshore current had reached safety. This suggests that slow and steady swimming is probably a preferable escape strategy (over floating; McCarroll et al. 2015). However, there was no singular strategy which was successful for all possible current speeds, location within the rip current from which escape was attempted, or swimming ability (speed), and small changes to these conditions (like tide, start location, or swim direction) had major impacts on outcomes (McCarroll et al. 2015).

Figure 7 International adaptations of the rip current sign designed by NOAA in 2004. Sign A is posted in Costa Rica (credit: Dr. Chris Houser at the University of Windsor), sign B is adapted to Chinese (NWS 2017c), and sign C was spotted by a colleague in Denmark (credit: Dr. Phil Wernette at the University of Windsor).

2.6 Recent research into human/rip current interactions

As noted, rip currents are a worldwide health issue (Sherker et al. 2008; Short and Hogan 1994) responsible for hundreds of deaths internationally each year; estimates range from 35 to 150 for the US (Gensini and Ashley 2009; Lushine 1991), and more than 22,000 rescues (Short and Hogan 1994) and ~21 deaths per year in Australia (Sherker et al. 2008; SLSA 2009; Brighton et al. 2013). Rip currents are well researched in the physical sciences but rescues, injuries, and deaths are still common because they result from a complex mixture of the physical forces we understand and "personal and group behaviors, and knowledge" that we still do not fully grasp (Brannstrom et al. 2014a, p.1124; Brander 2013). Efforts to bridge the gap between public knowledge and scientific understanding of rip currents (Sherker et al. 2010; Brannstrom et al. 2014a, 2014b) show that the scientific and public policy communities do not completely understand relationships amongst the multiple causes of rip current risk – specifically the overlap between physical forces that generate currents and social factors that prime beachgoers for vulnerability (Brander et al. 2013). For example, in a Texas-based survey of 392 beachgoers, only 13% of subjects correctly identified a photograph as showing the most hazardous conditions and precisely identified the rip current in that photograph (Brannstrom et al. 2014a).

Although the scientific community has a solid grasp on the physical forces causing rip currents, the general public is still vulnerable because we have not fully addressed the human element of this physical hazard (Brander 2013). Previous research conducted in Texas interviewed 392 adults on the beaches of Galveston, Corpus Christi, and Port Aransas (Brannstrom et al. 2014a, 2014b). The surveyed population demonstrated an overall lack of knowledge regarding the forces that cause rip currents, and an associated inability to see them in photographs (Brannstrom et al. 2014 a, 2014b). Similar studies in Australia (Caldwell et al. 2008; Sherker et al. 2010) and the US (Brannstrom et al. 2014a, 2014b) have evaluated beach intelligence, beach use habits, and demographics, but no previous study has included spatial analysis of answers and rip current proximity. For this reason, the research detailed in the dissertation is the first to connect a large number face to face interviews with beachgoers on a rip-prone beach and link results with demographic groups, beach-use groups, and observed beach-user behavior. No study of this kind has involved geo-location analysis relating subjects' answers to their proximity to a rip current.

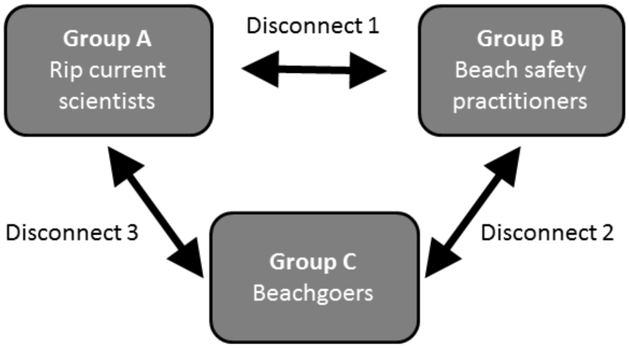

Figure 8 Present distribution of knowledge regarding rip currents, adapted from Brander and MacMahan (2011).

For this reason, the survey used in the dissertation is designed to intercept beachgoers on a rip-prone beach and gauge their knowledge in combination with proximity to a rip. The interviews examine beachgoers' knowledge regarding the forces that generate rip currents, rip current escape, rip current avoidance, and the interpretation of existing warning systems.

Survey results are then combined with a physical study of the rip currents identified from bathymetry at the study site (derived from satellite imagery), and evaluated for a relationship between answers and proximity to a rip current, thereby linking perception and behavior to the physical hazard.

Mounting evidence suggests that beach access management can inadvertently steer unsuspecting beach users towards rip-prone areas, increasing the chances of a drowning occurring on that beach (McKay et al. 2014), meaning that when developers do not consider beach and nearshore geomorphology in their designs for beach access management, they may force unsuspecting and unaware beach users towards the rip current hazard and increase the potential for drownings. Official access points create a sense of trust from beachgoers in experts and authorities, and trust in the protective measures they employ (Njome et al. 2010; Heitz et al. 2009; Terpstra 2009, 2011; Barnes 2002). Trust is a means to reduce uncertainty, and avoid making informed decisions to avoid and mitigate a hazard, which means that access points need to be safe (Siegrist and Cvetkovich 2000). Because beach users tend to select areas of the beach that are most convenient to the access point, beach activity can be concentrated in the most dangerous areas as observed in the examples from Pensacola Beach, Jaco Beach and Bondi Beach. Since most beach users are unable to identify a rip current (see Caldwell et al. 2012; Brannstrom et al. 2014, 2015), those who assume access points are safe are going to calibrate their observations and experience, or interpretations of other access points. The public's beliefs change very slowly and are persistent despite evidence to the contrary (Nesbitt and Ross 1980), which means that the inconsistencies noted in the present study can persist despite experiences and observations that suggest that the accessed part of the beach is not safe.

The safety of beach goers could be greatly increased at each beach with relatively simple measures. At Pensacola Beach, where beach access points over low dunes are inadvertently leading visitors to swim in rip-prone areas, those in charge would need to reconstruct beach access to line up with the offshore ridges and larger waves, in morphologies less prone to rip current development. At Playa Jaco, where larger streets and access points are located near the river mouth that generates rip-causing sandbar deposits, improved signage should be placed at the beach entrances close to the regularly forming rip currents. Lifeguards already patrol this area, and the beach access is not through any man made features (rather, the entire beach is open to parallel road sides with unrestricted access). Instead, they would benefit highly from introducing the red and yellow flag system employed in Australia and the UK, which would focus swimming towards the lifeguard stand and away from rip currents. Lastly, at Bondi Beach, moving the bus stops to the safer, more dissipative end of the beach would keep tourists away from "Backpacker's Express" and other rip current activity concentrated north of the beach's center. It might also help to post signs specifically at the southern end, where rip currents are more likely, that include phrases like "surfers only;" these would be in addition to the signs posted at every entrance that already warn of rip currents. These examples are site-specific, but similar combinations of beach morphology and access structure could occur at many global beaches.

Although surveys of hundreds of beachgoers have shown that in some locations nearly half of the population has at least some understanding of rip current development and proper escape strategies (Caldwell et al. 2012, Drozdewski et al. 2012, Brannstrom et al. 2014, Woodward et al. 2015), this does not mean that only half of the population is vulnerable to the rip current hazard as it could be the result of confirmation bias in these studies. Additional research shows that experience and/or understanding of a hazard do not guarantee that beachgoers will take the appropriate actions to prepare for the hazard or avoid the hazard altogether (Sietgrest and Gutscher 2006; Karanci et al. 2005; Hall and Slothower 2009; Johannesdottir and Gisladottir 2010). As noted by Haynes et al. (2008), "it is now understood that there is not necessarily a direct link between awareness, perceived risk, and desired (by risk managers) preparations or behavioral responses" (see also Miceli et al. 2008). As noted by several of the respondents, if everyone else at the beach is getting into the water and not heeding the rip current warning (out of ignorance or purposeful neglect) there is a chance that the beach user will feel compelled to enter the water despite understanding the risk. As noted by one of our respondents: "I never noticed and thing unusual and people, in general, don't seem to adjust their behavior," suggesting that decisions are made based on what other beach users are doing rather than rip current forecasts (Lapinski et al. 2014). The tendency to follow the behavior of others may be enhanced when someone goes together as part of a group and enters the water because everyone is willfully ignoring the risk or is ignorant to the severity of the risk (see Mollen et al. 2012). Aronzarena et al. (2015) provide specific high profile examples from Costa Rica where students or young males from San Jose enter the water because everyone else is entering the water because of "group think." The negative consequences (of not getting in the water and of not behaving as part of the group) may outweigh a person's perception of the risk posed by a rip current hazard.

Beaches prone to the development of rip currents can benefit from a number of infrastructure and access improvements in order to prevent rip current fatalities by curating the social norm to overcome "group think." One approach would be to redirect beach users to relatively safe areas on the beach, similar to the 'swim between the flags' campaign promoted by Surf Lifesaving Australia (see Sherker et al. 2010). The red and yellow flag campaign implemented in Australia is credited with reducing rip-related drownings. However, beach users may still choose to swim outside the flags or in unpatrolled sections of the beach, thus putting themselves at risk. A general flag on the beach to warn beach users of the rip current hazard, such as those implemented by lifeguards on US coasts, may lead to differing experiences on the same day (see Kaiser and Witzki 2004; Brilly and Polic 2005), and therefore a different interpretation of the forecast accuracy in the future and downplay of the risk. Mileti and O'Brien (1993) describe the reasoning as “If in the past the event did not hit me negatively, I will escape also negative consequences of future events.” At the same time, beach users will not be able to conceptualize events that have never occurred or to see future trip currents to the beach as anything more than a mirror of past visits or experiences (Kates 1962; Tversky and Kahneman 1973). Alternatively, as proposed by Short and Hogan (1994), lifeguards could be stationed in high-risk zones to provide quicker response times to swimmers in danger.

At Pensacola Beach, where semi-permanent rip current channels develop as the innermost bar migrates landward through the late spring and summer, beach access points can be built or moved so they align with relatively safe spaces between rip current hot spots. Similar infrastructure changes would be effective at Bondi Beach, where the bus stops could be shifted to the dissipative end of the beach. When nearshore morphology causes rip currents to form reliably in a certain part of the beach, access can be built that encourages beachgoers to predominantly use a safer part of the beach. At Galveston, the presence of structurally-controlled rip currents at regularly spaced intervals and directly seaward of the primary access points has required that Galveston place lifeguard stands at each access point along the seawall with flags and warning signs.

In the UK and Australia red and yellow flags, posted by trained lifeguards to mark safe swimming areas, are recognized by a significant portion of those intercepted on the beach during studies (Woodward et al. 2015; Drozdewski et al. 2012; Brannstrom et al.2014). In the countries reviewed here, the surf lifesavers and/or lifeguards rescue thousands of people per year from rip currents. There are also individual beaches with records indicating the effect of lifeguards on the health and safety of the community. For example, Playa Cocles, was the deadliest beach on the Caribbean coast of Costa Rica, with more than 20 fatal drownings on record, peaking with 5 in 8 days in 2004 (Arozarena et al. 2015). Following this deadly week in 2004, the Playa Cocles community quickly formed a grassroots-funded lifeguard program and they have had zero fatal drownings since (Arozarena et al. 2015). In contrast, the Playa Tamarindo beach community on the Pacific Coast also formed a community funded lifeguard program to lower its fatality rates in 2004, and while the lifeguard program was in place, no fatal drownings occurred. However, the program closed in 2007 due to a lack of funding, and since there have been 3 fatal drownings (Arozarena et al. 2015). These cases are not limited to Costa Rica. Similarly, in the United States, there are a number of communities which experienced drastic changes in fatality rates with the creation or dissolution of lifeguard programs. Nassau beach in Florida eliminated their lifeguard program in 1989 to reduce city expenses; less than a year rough surf resulted in 20 bystander rescues and 5 deaths on Memorial Day weekend – a popular beach day for much of the US. The city quickly reestablished the lifeguard patrol and there were no more fatalities (Branche and Stewart 2001). Ocean Beach, near San Francisco, California, also removed lifeguards from their beaches to resolve budget concerns in the early 1990s; rescues and drownings continued to occur, peaking with 7 fatal drownings in the summer of 1998. The lifeguard post was reestablished and fatal drownings ceased (Branche and Stewart 2001). At Ocean Beach, near San Diego, California, there is a long tradition of lifeguard patrols since the early 20th century; nearly 15 million people visit this beach every year, and lifeguards pull an average of 7,000 people from the surf annually; the average fatal drowning rate is less than one person per year (Branche and Stewart 2001).

The Center for Disease Control (CLC) is a United State government institution that conducts scientific research into health threats. In their 2001 report on the effectiveness of lifeguards, the CDC stated: "There is no doubt that trained, professional lifeguards have had a positive effect on drowning prevention in the United States" (Branche and Stewart 2001). This summary was backed by significant and varied data, including: only 0.025% of drowning deaths in the US occurred on USLA guarded water bodies (Branche and Stewart 2001); the vast majority of drownings occur on unguarded beaches (Mael et al. 1999); and that the statistical likelihood of fatally drowning on a beach patrolled by USLA guards is less than one in 18 million (USLA 2001). In Australia and the UK, where the red and yellow flags indicate rip-free, safe swimming zones for beachgoers, rescues still occur and flags still must be placed each day by a patrolling lifesaver. For these and many other reasons, recent reports by the Center for Disease Control (a US federal health organization) and the SLSA in Australia, in conjunction with the US Lifeguard Association (USLA), are increasingly advertising that the best survival message for swimming on rip current-prone beaches is to always swim near a lifeguard.

As long as construction of beach access ignores rip current formation, planners and policy makers are setting themselves up for fatalities on their beach, which is bad for business. Signs are only somewhat effective, and highly trained surf lifesavers are the best source of public safety. Beach managers and other governing bodies must consider how infrastructure, signage, and paid patrols affect beachgoer safety. As long as the public remains largely unaware of how to identify, avoid, and escape rip currents, beach infrastructure and signage can exacerbate the rip current hazard risk.

2.7 Conclusions

Coastal geomorphologists have an increasingly clear picture of how rip current circulations form and contribute to surf zone morphologies. To further understanding, spatially dense measurements of surf zone bathymetry at decreasing temporal scales are needed. This surface has been historically difficult to capture. This dissertation presents one method for computing surfzone bathymetry on a rip-prone beach using a multispectral satellite which near daily image capture. Additional sections reveal an algorithm which might use such surfaces to automate detection of bathymetric rip current locations, helping to mitigate high drowning rates by aiding in forecast and hazard identification. Because lifeguard presence is proven an effective rip current mitigation technique without technological barriers, one dissertation section also details a model which has successfully reduced fatal drownings in one community for 13 years. In addition, and National Science Foundation funded research project highlights the role of beach access and infrastructure controls beach goers exposure to the rip current hazard. The dissertation, as a whole, showcases a suite of methods and results which can be applied by coastal geomorphologists and policy makers to increase public safety and reduce the risk of the international rip current hazard.

3. MAPPING NEARSHORE BATHYMETRY AND RIP CHANNELS OF INTERMEDIATE BEACHES WITH WORLDVIEW3 MULTISPECTRAL DATA

3.1 Abstract

Rip currents are concentrated flows of water that form in the surf zone of intermediate beaches in response to three-dimensional bar morphology and alongshore variation in wave breaking. These currents can flow up to (and greater than) 2 ms^{-1} and pose a hazard to swimmers, who can be caught unexpectedly and carried swiftly into deep water. At eye level, these currents appear as a dark gap through breaking waves; this contrast becomes easier to spot from higher vantages. In satellite imagery, the dark gap is even more apparent and time-lapse imagery from high viewpoint sensors is a proven rip-tracking methodology. The clearer water and lack of wave breaking within the rip current can also provide visibility of bottom type in shallow, optically clear water such as found at the study site (Bondi Beach, Sydney, Australia). This paper demonstrates the capability of the Digital Globe WorldView3 multispectral satellite to identify rip channels and model bathymetry in the surf zone of an intermediate beach. This satellite has a 1 day pass-over rate with <2 m ground pixel resolution in 8 bands, including ‘yellow’ (585-625 nm) and ‘coastal blue’ (400-450 nm). The classification of pixels using the spectral information of these and other bands in the imagery serves as a proxy for classes of depth, and calibration with field data results in a bathymetric surface model with <2m horizontal resolution and < 1 m vertical accuracy. This resolution and accuracy are adequate for identifying rip channels in bathymetry where rip currents will form under the right wave conditions. In the future, these methods can be used to map the surf zone of intermediate beaches as frequently as the 1.1 day flyover rate of the satellite; such frequent

bathymetric mapping would provide further insight into the geomorphological transition of intermediate beaches between states and aid in mapping and predicting the rip current hazard.

3.2 Introduction

Dangerous rip currents can form on most beaches with breaking waves. Rip currents are concentrated flows of water that form in the surf zone of intermediate beaches in response to three-dimensional bar morphology and alongshore variation in wave breaking. They can vary in location, strength, and appearance, making it difficult to predict exactly where and when a specific current will form. Research also shows most people do not know to see and/or escape rip currents (Caldwell et al. 2012; Brannstrom et al. 2014). As a result, rip currents are considered a global health issue because they are the greatest hazard to beachgoers on the beaches where and when they form: rip currents cause hundreds of deaths and tens of thousands of rescues worldwide each year (Sherker et al. 2008; Short and Hogan 1994). Australia records an average of ~17,600 people rescued from rip currents each year (Short and Hogan 1994) in addition to an annual average 21 fatalities that are attributed to rip currents (Sherker et al. 2008; SLSA 2009; Brighton et al. 2013). Rip current fatality records in the United States rip currents have been responsible for an annual average 59 fatalities since 2009 (NWS 2017b).

One way to reduce the annual number of drownings and rescues is to reduce swimmers' exposure to rip currents through increased awareness and promotion of safe beach use practices, including keeping people out of the water when and where physical conditions are primed for rip current development. Presently, some US weather stations broadcast a rip current forecast that attempts to increase public awareness, but this prediction is for large regions of beach (sometimes as large as 160 km or more of coast) and uses only wind and wave data to predict the level of risk rip currents may pose along a given coastal region (NWS 2017a). Such predictions and forecasts would be more accurate if they incorporated bathymetry because this would allow localized identification of specific rip channel locations. A site-specific prediction of the dangerous bathymetric rip channels (and the currents that can form in them) would localize lifeguard efforts and "keep out of the water" warnings, thereby lowering the hazard posed by these naturally forming features. However, at present, there is no easily accessible method for mapping bathymetry at the spatial and temporal resolution that would be required by forecasting models.

There are several types of rip current described in more detail below; the greatest hazard to swimmers is posed by rip currents that form with strong speed and persistent flow on beaches with large numbers of visitors, in part because preventing swimmers form entering these can be logistically difficult. Keeping the public out of rip currents that form in permanent locations only requires posting and enforcing "no swimming" zones adjacent to the structure forcing the rip current (e.g. Figure 3.1). In contrast, preventing entry into rip currents that form with variable location alongshore is more complicated because these rip currents form only when the winds, waves, and channels in the bathymetry are all present, and channels can be transient in time and space. Although some beaches form these rip currents in semi-regular locations, driven by inshore bathymetry such as submarine canyons (Shepard et al. 1941) or ridge and swale geologic framework (Houser et al. 2011), others that form are highly mobile (Castelle et al. 2016). Posting and enforcing "no swimming" zones for such rip currents is, therefore, more difficult for these rip currents than for the other types, which exacerbates the risk they pose to beachgoers. It is the primary objective of the research presented here to offer a satellite-based method for identifying the channels in nearshore bathymetry which are necessary for this most dangerous type of rip currents. Future application of these methods can be used to both (a) map and model channel formation through time, to address current gaps in coastal geomorphology regarding these transitions, and (b) aid in the long-term goal of providing site-specific identification of individual rip currents so that the public can be kept out of these dangerous features.

Figure 9 Picture of a “no swimming” zone enforced adjacent to groins at Galveston Beach, Texas, USA because of the rip current that is often forced against the groin when large enough waves are present.

3.2.1 Rip currents and rip channel morphology

Rip currents are naturally occurring circulation patterns that form in the surf zone of intermediate beaches as the result of feedback amongst waves, substrate, and bathymetry (Castelle et al. 2016). When alongshore variations in coastal morphology and incident wave angles interact they create variation in wave height and wave breaking alongshore, this in turn creates adjacent areas of high and low pressure, whereby water preferentially flows seaward through the weakest section of wave breaking (Haller et al., 2002; Castelle et al. 2016). The areas with higher waves and more intense breaking, are areas of high ‘set-up’ and are interspersed with adjacent areas of lower wave ‘set-up,’ where waves are lower and breaking is less intense (Castelle et al. 2016), which is often a lowered path through the bathymetry.

Rip currents can be generally described in four simplified categories: swash rips, hydrodynamic rips, boundary rips, and bathymetric rips (Castelle et al. 2016). Swash rips, sometimes called mini-rips (Russel and McIntire 1965), rarely extend past the swash zone into hazardously deep waters (Masselink and Pattiaratchi 1998; Dalrymple et al. 2011; Castelle et al. 2016). Hydrodynamic rips are dangerous because they form on relatively planar beaches with smooth bathymetry and they have inconsistent alongshore position within a given beach, however, these rip currents also have short life spans, making them difficult to predict (Castelle et al. 2016). In contrast, the third type (boundary rips) have long life spans, but persistent alongshore locations. Boundary rips form against rigid structures like rocky headlands, jetties, groins, or piers that interrupt the alongshore current. These permanent elements force a rip current circulation directly adjacent to the structure, making these rip currents highly predictable (Castelle et al. 2016).

The final type, bathymetric rips, are those which form on intermediate beaches, those between the end-member beach states of dissipative and reflective. In the present literature, coastal geomorphology typically ascribes beaches to one of six beach states, according to their processes and signature forms: dissipative, reflective, and four distinct intermediate stages between these two end-member states (Wright and Short 1984). The hydrodynamic processes and mechanisms of transport in each state are dependent on feedback between energy and form. Unlike the planar dissipative (gently sloped) and reflective (steep) beach states, the four intermediate states are characterized by their alongshore variations in form and energy gradient due to a complex bar morphology that develops as the bar migrates landward. As a result, rip channels in the morphology are an identifying form for the intermediate beach states and can therefore provide valuable information on beach evolution and classification (Wright and Short 1984). This study focuses on identifying rip channels, which form along intermediate beaches with breaking waves and three-dimensional bathymetric morphology. Of the four types of rip current, bathymetric rips are arguably the most dangerous.

Bathymetric rips pose the greatest hazard to swimmers (Brander and Scott 2016) because they can vary in location and can form in favorable swimming conditions. Rip channels can develop in breaks in sandbars as they move toward (accrete) or move away from (erode) the beach face; these processes form accretional rips and erosional rips, respectively (Short 1985). The accretion process associated with accretion rips is a slow progression through beach states, while erosion rips are associated with a beach's rapid jump to a more dissipative state under high energy conditions (Wright and Short 1984). Both rip current circulations can cause a safety hazard for beachgoers.

Bathymetric rips forming during accretion are perhaps more dangerous because they are associated with a beach's smaller wave conditions during a recovery period following a storm or other large wave action, when beachgoers may find conditions ideal for swimming (Short 1985). Because wave energy is decreasing at this time, these are the rip current conditions during which the water may look the calmest and therefore safe. The dissipating wave energy moves the sand bar back toward the beach face, and the returning water flow favors channels forming in breaks in the bar. Accretion rips are associated with crescentic bars, rhythmic bar and beach, and transverse bar and rip states (Wright and Short 1984). These rip currents can vary in width, up to 10s of meters across, and can last up to several days or even weeks if favorable conditions persist (Wright and Short 1984; Short 1985).

In most rip-current studies, the morphology of rip channels is described qualitatively, if it is described at all (Brander and Cowell 2003). The exception is Brander and Cowell (2003) who provide a detailed morphometric definition: rip channel width is variable because channel cross-section shape can vary widely, channel length is typically 1 – 2 times the width of the surf zone (with exceptions), and channel depth is the vertical distance from mean water level to the thalweg (Brander 1999; Brander and Cowell 2003). In general, rip channels have a relief ≥ 1 m from surrounding morphology and a width of at least 5 m (see Section 3 on Every Direction Variogram Analysis). Velocities are faster in narrower channels with constrained cross-sectional area, and/or greater relief (Brander 1999).

3.2.2 Bathymetric mapping

Frequent bathymetric mapping in the nearshore is of critical interest to coastal geomorphologists but historically, mapping the bathymetric surface of intermediate beaches has been logistically complicated. The knowledge gap in coastal geomorphology regarding transitions amongst morphometries in the surf zone of intermediate beaches is due in part to these logistical difficulties in mapping this bathymetric surface. Current barriers to daily bathymetric model development are: difficulty or cost of frequent deployment (low temporal resolution); low spatial resolution; and/or high cost associated with instruments capable of resolving or overcoming these issues. However, should these difficulties in mapping the nearshore be resolved, creation and deployment of adequate rip channel models could be greatly improved and used to lower rip current related beach-goer injury and death.

3.1.2.1 Laser-level topographic survey

A common bathymetric mapping method in coastal geomorphology publications is measuring transects with a laser level or other surveying instrument and interpolating a grid surface between them (Wright and Short 1984; Gorman et al. 1998; van Lacker et al. 2004). "[S]tudies of coastal processes and have traditionally been achieved by [these] standard surveying practices. However, despite the widespread use of various profiling techniques, surveying seaward of the shoreline remains problematic due to inherent inaccuracies and errors involved in obtaining precise measurements in a highly energetic environment characterized by breaking waves and strong currents" (Brander and Cowell 2013, pg 1). Difficulties inherent in these methods are problematic for surveying the surf zone of intermediate beaches because they require someone maintain a balanced stadia rod amidst breaking surf and it is dangerous to attempt to capture the depths within rip channels. Other methods for reading depth, such as side-scan sonar, can capture high-resolution bathymetry but can only be collected by a person driving a small craft; this limits the frequency and depth by which data can be collected (Brander and Cowell 2013; Austin et al. 2014).

3.1.2.2 Radar

Since the late 1990s, it has been possible to back-calculate the underwater surface in the surf zone from radar, and this technology is increasingly available (Bell 1999). By mounting an x-band radar (wavelength, ~3cm) instrument at a height (say, 10 m) above the water on a nearby structure, or atop a vehicle and driving along the coast (McNinch 2007; Shaw et al. 2016), it is possible to capture the water surface in high resolution through time; it is also necessary to have an offshore instrument tracking the incoming wave speed and height. Because the radar captures how waves on the water's surface transform while crossing the surf zone, it is possible to back-calculate the generalized underwater surface causing these transformations; this produces accurate bathymetric models of sandbar location (horizontal positional accuracy of the sandbar ±10 m) but these instruments do not technically "see" below the surface, and do not provide depths. Also, they and are expensive (McNinch 2007; Shaw et al. 2016).

3.1.2.3 Argus camera systems

In the last decade, several publications have demonstrated the ability of Argus cameras and imagery to determine bar location from time-averaged visible band imagery. By using a fixed camera location and programmed regular image capture, ten minute time exposures reveal an averaged nearshore wave field, seen as a smooth band of white in darker water. The imagery can also be used to create a 'variance image,' where values indicate the variance of the light intensity signal during the same ten minute time exposure, thus identifying pixels changing more or less frequently in time (and differentiating from pixels which are bright in the time exposure, but are unchanging in time; Lippman and Holman 1989; Van Omhoog Enckevort and Ruessink 2001). This Argus method has been shown as an excellent proxy for the underlying, submerged sand bar location (Lippman and Holman 1989 and Van Omhoog Enckevort and Ruessink 2001), but again does not reveal water column depth within rip channels or elsewhere and thus is not bathymetric model. Cost of installing and maintaining one of these systems starts at $200,000 (US).

3.1.2.4 LiDAR

LiDAR instruments, short for ‘light detection and ranging, have also been around for several decades. More recently processing has become increasingly accurate and precise, making it possible to penetrate a shallow water column and “read” the bottom surface in addition to the water surface. LiDAR maps bathymetry by sending a laser pulse out and evaluating the changes to the returned wavelength; changes to the waveform of the laser light can be used to back-calculate the distance from the instrument to the surface that returned the beam. An instrument can send out a dense array of pulses to generate a 3D model of a surface with high spatial accuracy (± 15 cm; Irish et al. 2016). Advances in data processing and the use of green laser pulses that can pass through shallow water have made these measurements more accurate in coastal zones. Costs are down to ~$1,000-2,000 per square mile of data, but could become more affordable as drone-mounted instruments become more economical (with decreasing UAS costs); at present, data are typically collected via manned aircraft.

3.1.2.5 Satellite derived bathymetry

Satellites can also be used to interpret bathymetry if adequate field data are acquired, because the depth of transmittance for different wavelengths within the electromagnetic spectrum have site-specific relationships between light attenuation and bottom type, provided that suspended material in the water column is at a minimum. Satellite technology is rapidly improving, with smaller pixel sizes and an increasing number of bands available to the public from commercial satellite companies. At present, the most refined product available to the public is the DigitalGlobe WorldView3 satellite, which can photograph most locations at ~ 1 day revisit rate, with 1.24 m pixels in the multispectral bands and 31 cm panchromatic pixels, and 12 spectral bands. It is possible to use this (and similar) data to map shallow water bathymetry by calculating how much light (especially in the “yellow” and “coastal blue” bands) has been reflected back to the satellite by the underwater topography. Unfortunately, because this requires a clear water column, it is most accurate in clearer, tropical waters and less accurate on turbulent and sediment-laden coasts.

Suspended sediments can attenuate calculated depth of the water column because they scatter and absorb light, clouding the relationship between transmittance of light wavelengths and distance into the water (Bachri et al. 2013). The calculation of water depth from light intensity uses laws of refraction because light refracts as it travels through a column of water, and different wavelengths of light are refracted to varying degrees (Stuffle 1996; Bachri et al. 2013). The intensity of light at a given wavelength (Id) that remains after attenuation through the water column is a function of the depth of the water column (d), the attenuation k (unique to each wavelength), and the intensity of the incident radiance (IO). This relationship can be modeled as a linearized relationship with the equation:

$$\log_e(I_d) = \log_e(I_O) - 2dk \tag{1}$$

This attenuation is weakest in the blue-green portion of the visible spectrum (other bands attenuate completely within a few centimeters). Because wavelengths near blue and green penetrate optically clear waters, minute differences in attenuation can be used to calculate shallow water bathymetry from spectral data (Benny and Dawson 1985; Jupp 1989). Previous studies have created accurate models using only blue and green bands of the spectrum, however, increased accuracy and precision have been made possible by recent advances in satellites technology which capture of additional information within the electromagnetic spectrum (Lee et al. 2011; Deidda and Sanna 2012; Miecznik and Grabowska 2012).

When implementing any satellite method, some assumptions must be made. It is necessary to presume that water quality (or the attenuation coefficient, *k*, for a given band) is constant across a single image. Variance in *k* is often acknowledged as realistically non-uniform, but also logistically impossible to account for, because high spatial resolution of differences in suspension would require dense field data of sediment suspension collected at the precise moment of image acquisition. Constant *k* must, therefore, be assumed. Field experiments have determined transport within rip channels occurs primarily near the bed, with "up to 50% of the sediments transported in the bottom 10% of flow" (Brander 1999).

It is also common to assume that the reflective properties of bottom type are consistent, but can also be accounted for if spatially dense maps of bottom type are available (Benny and Dawson 1983, Bachri et al. 2013). Bottom type is well correlated with bathymetric mapping algorithms and band math ratios (Lee et al. 2011). Theoretically, the attenuation of light over a single bottom type is a linear decay, where the slope is a function of the attenuation coefficients in two bands. The resulting deduction is that for a given of bottom type (e.g. sand), the shallowest pixels have the brightest values and the deepest pixels the lowest/darkest values (Bachri et al. 2013). Therefore, once the relationship between *k* in one band and *k* in another is known, the brightness of pixels can be interpreted to depth (Lee et al. 2011). Bathymetric DSMs with < 1 m accuracy were developed by this method by Jupp (1989) using the coasts of Queensland, Australia, "depth of penetration" (DOP) zones, and the Landsat TM satellite. Maximum deep-water radiance threshold values were calculated and 6 DOP zones were determined; the limited spectral data captured by the 7 bands of Landsat TM limits the ability to calculate more DOP zones from this data. Similarly, Benny and Dawson (1983) create spectral classes and mapped them to depth; in this method, class boundaries are treated as contour lines between DOP zones, because uniform spectral characteristics are interpreted as uniform depth characteristics.

For any method of calculating water depth from a remotely sensed image, values represent depth beneath the tide at the time of image capture. To offset this, a perfect methodology includes field data of depth collected throughout the tidal cycle; these field values represent the datum height (typically, the Lowest Astronomical Tide or LAT) plus the tidal height at the time measured. These site-specific tidal effects can then be used to remove tidal height from values derived from the imagery, using field averages for the tidal stage present when the image was captured.

Previous research has shown that the blue, green, yellow, and coastal blue bands provide the most accurate water depth information. These last two bands are unique to the WorldView satellites. Previous studies have demonstrated methods for deriving accurate depths at other tropical beaches (Loomis 2009; Lee et al. 2011), but no previous study has specifically examined these data in the surf zone or at a rip-prone beach. The purpose of this study is to demonstrate the accuracy of WorldView multispectral derived bathymetric DSMs in a surf zone that contains rip channels. This method of deriving bathymetry from multispectral satellite data has the highest accuracy in clear tropical waters such as those found on some portions of Australian coast (Loomis 2009; Deidda and Sanna 2012; Miecznik and Grabowksa 2012) but has not previously been applied to mapping rip channels or rip current hazards in the surf zone.

It may be possible to create daily bathymetric models by deriving depth from WorldView2 and WorldView3 satellite data. These instruments capture multispectral imagery with < 2 m resolution and a daily revisit rate (see table 3.1). The yellow and coastal blue bands of WV2 imagery have been used to calculate highly accurate (vertical accuracy +/- 0.20 m) bathymetric DSMs at depths from 0 to 20 m in optically clear, calm waters (Lee et al. 2011; Deidda and Sanna 2012; Miecznik and Grabowksa 2012). The best maps (highest accuracies) are produced when methods are calibrated to a priori field data of the bottom substrate and water column content.

The WorldView2 (WV2) satellite was launched in September 2009 and captures imagery approximately every 1.1 days (Digital Globe 2013). WorldView3 was launched in August 2014 and captures imagery every 4.5 days (or less, in some locations; Digital Globe 2016). These images capture 8 multispectral bands, with a root mean squared error (RMSE) for ground position < 1 m. The yellow and coastal blue bands have been used to develop bathymetric maps at depths up to 20 m deep with high spatial accuracy (Loomis 2009; Deidda and Sanna 2012; Miecznik and Grabowksa 2012). These features make data from the WorldView satellites the highest spatial and spectral resolution data publicly available, and the ~ 1 day revisit period means that it has a high temporal resolution as well (Digital Globe 2013).

Table 2 Specification of the WorldView satellites (Digital Globe 2013, 2014).

Feature	WorldView-2		WorldView-3	
Panchromatic resolution		0.46 m		0.31 m
Multispectral resolution		1.85 m		1.24 m
Average revisit rate		1.1 days		4.5 days
Bands	Panchromatic	450-800 nm	All of these WV2 bands, plus:	
	Coastal	400-450 nm	8 SWIR bands	1195-2365 nm
	Blue	450-510 nm	12 CAVIS bands	405-2245 nm
	Green	510-580 nm		
	Yellow	585-625 nm		
	Red	630-690 nm		
	Red edge	705-745 nm		
	Near-IR1	770-895 nm		
	Near-IR2	860-1040 nm		

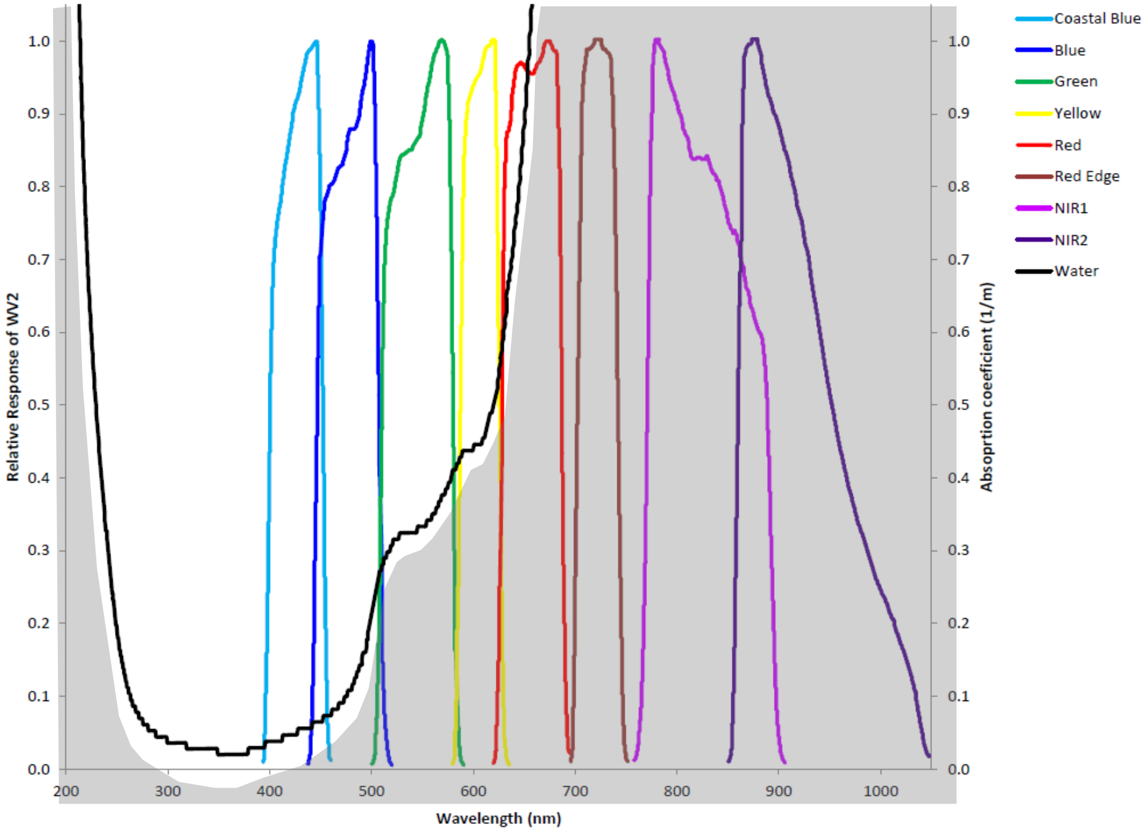

Figure 10 The spectral signature (absorption) of water and the spectral response function of WV2. Note that WV2 captures the yellow and coastal blue bands, 2 additional windows of the electromagnetic spectrum unique to this satellite and within the ideal, maximum transmittance of light.

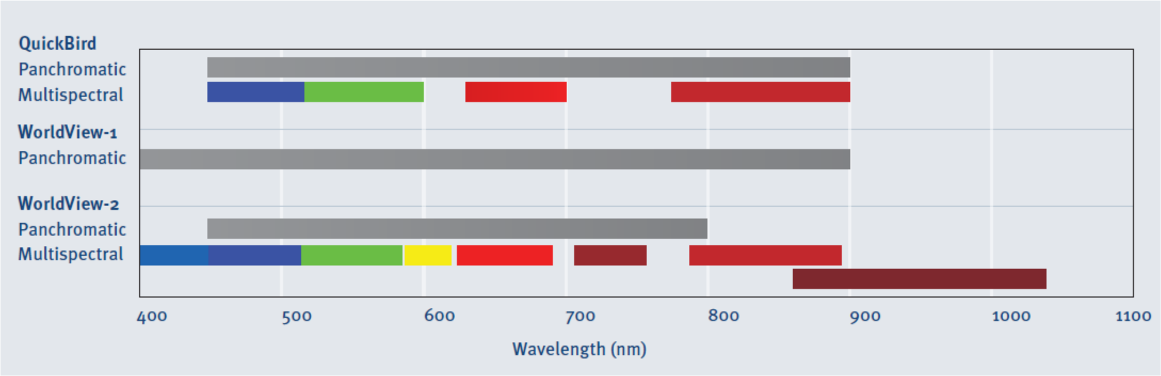

Figure 11 WorldView2 multispectral bands in comparison to a comparable satellite (from Digital Globe 2013).

3.3 Study site

Bondi Beach is located on the easternmost coast of Sydney, Australia (see Figure 3.4) at the front of Sydney’s most densely populated suburb (Bondi’s density was 10,188 residents per km² in 2011; Australian Bureau of Statistics 2012). The Australian coast along this part of New South Wales consists of prominent sandstone and shale headlands with embayed beaches between them (Short and Wright 1981; Short and Hogan 1990). Bondi is one such embayed beach (Short and Masselink 1999) because it is bounded on either end by 40 m high rocky headlands (McCarroll et al. 2016). Embayed beaches typically have rip currents immediately adjacent to both headlands, with 2 to 4 rip channels along the shore between them (Castelle and Coco 2014).

The orientation of the prevailing incoming waves combines with the headlands to create regular rip currents and large surf at the southern end of the beach. The protection offered by the southern headland creates an alongshore wave height gradient (Short and Masselink 1999), which creates multiple beach states along the shoreface (Wright and Short, 1984), “from more reflective at the protected end to more dissipative at the wave exposed end” (Short 1985, Short

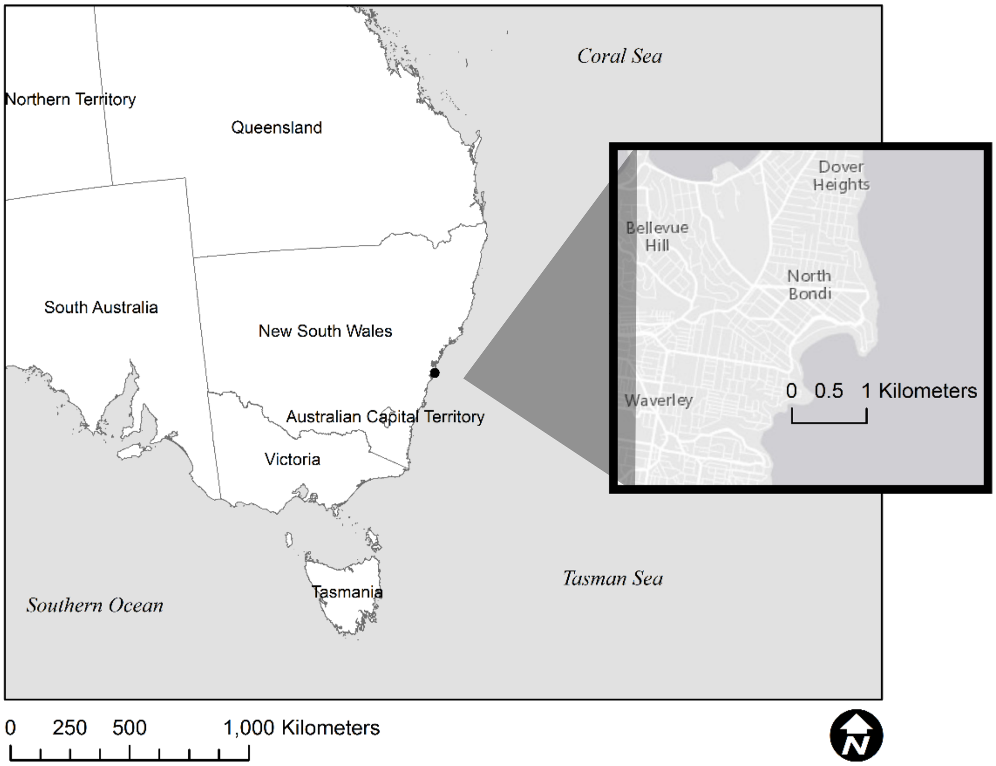

Figure 12 Location of the Australia study site, Bondi Beach.

and Brander 1999; quote from McCarroll et al. 2016, pg. 1). The intermediate states that form along the beach are characterized by rip channels that foster rip currents under the right wave conditions. Bondi transitions between intermediate states throughout the year (Wright and Short 1984) and is most commonly in the transverse bar and rip or rhythmic bar and beach state (Short and Hogan 1990). There are typically 3 to 4 rip currents spaced about 180 m apart along the 850 m beach (Short and Hogan 1990); the southernmost of these rip currents is a boundary rip, forced against the rocky headland to the south with various bathymetric rips forming, under the right conditions, in rip channels created by nearshore processes. The southern boundary rip current is so persistent it has earned the name “Backpacker’s Express,” because unfamiliar beachgoers are let off public transit at the beach access point on this southern end of the beach and do not typically walk to the north end of the beach where the surf is more gentle; they instead swim right into this strong rip current (TenPlay 2013; Brander 2009).

Bondi Beach is an iconic Sydney attraction, internationally famous as a great swimming and surfing spot, and one of Australia's most popular beaches (Destination New South Wales 2014). It was added to the Australia National Heritage List in 2008 (Australian Government: Department of the Environment 2008) and draws crowds to its restaurants, nightlife, pristine waters, and surfing throughout the day and all seasons (Short and Hogan 1990). Estimates in a 1990 report cited an annual summer beach population of more than 390,000 cumulative visitations to Bondi Beach (in 1985-1987), with an annual number of 213 rescues (prior to 1986) for an average 0.54 rescues per thousand visitations (Short and Hogan 1990). The beach has only grown in popularity and visitor density. More recent reports by the tourism board estimate an annual average 104,350 unique individuals to Bondi Beach each year and an estimated cumulative summer beach population of several million (Destination New South Wales 2014).

Bondi is also the birthplace of the world's oldest surf lifesaving club formed in 1906 (Short and Hogan 1990; Brawley et al. 2007). Today's lifeguards keep a lookout from towers and post yellow and red flags to define safe swimming areas; in the Australian warning system visitors are advised to swim between red and yellow flags (Surf Life Saving Australia 2012). The lifeguards along Bondi are kept busy, making an average 2,500 people per year, and about 85% of these rescues are tourists and other non-locals (TenPlay 2013). Despite the active professional lifeguard service, there are still occasional drowning deaths at Bondi. The most

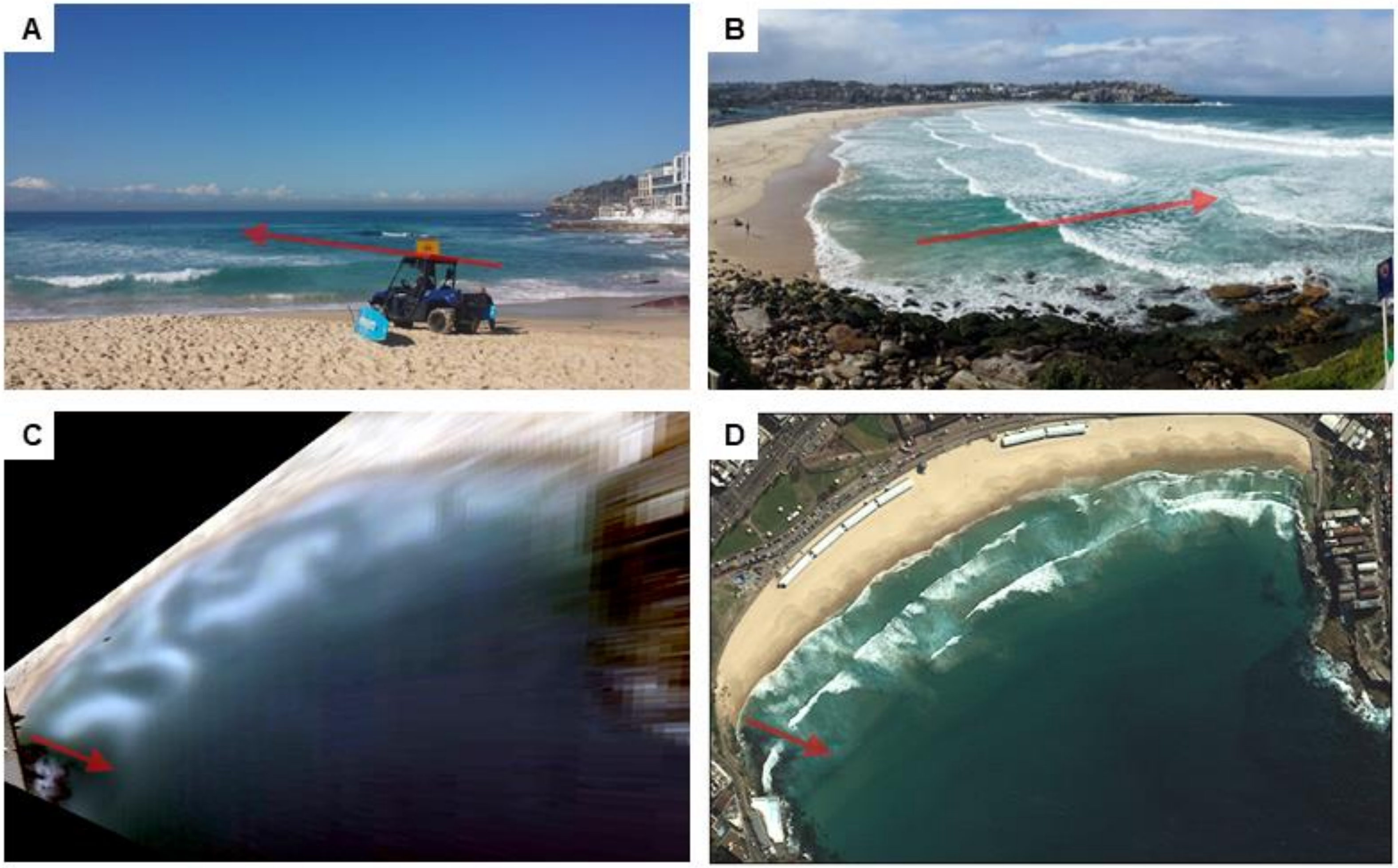

Figure 13 Images of rip currents at Bondi, from different vantages. "Backpacker's Express" is marked by a transparent red arrow in each: (A) a photo from eye level taken by the author in July 2015; (B) a photo taken from atop the southern rocky headland by the author in July 2015; (C) Argus camera time lapse from 1 August 2015 shows several rip currents, including "Backpacker's Express;" (D) Bondi Beach in an RGB composite of WorldView3 imagery from 6 August 2015.

recent rip-related fatality was in November 2013 (Surf Life Saving Australia 2012; Black 2013).

At eye level, rip currents appear as dark gaps through breaking waves (Figure 3.5). This contrast becomes easier to spot from higher vantages. In satellite imagery, the dark gaps in the surf created by rip currents are even more apparent, and time-lapse imagery from overhead cameras is a proven rip-tracking methodology (e.g. Van Ommhoog Enckevort and Ruessink 2001; Figure 3.5). The clearer water within the rip current can also provide visibility of bottom type in shallow, optically clear water. Bottom type is well correlated with bathymetric mapping algorithms and band math ratios, and these algorithms work best in spaces with consistent bottom type (Lee et al. 2011, Bachri et al. 2013). Bottom type at Bondi is consistently sandy with some reef near the headlands. The sand is primarily medium grained quartz (McCarroll et al. 2016).

3.4 Methods

To test whether WorldView imagery is a viable data source for mapping the bathymetric surface of a ripped intermediate beach, six objectives were completed: (1) field data were collected at Bondi Beach in July and August of 2015, (2) the best image captured by the satellites during the field study was acquired, (3) this image was processed from digital numbers (DNs) into surface radiance, (4) classifications were performed with the processed values, (5) spectral classes were mapped to depth using field data, and (6) RMSEz was evaluated with field data withheld from the calibration process. Each step is described in detail below.

3.4.1 Field data collection

Measurements of depth were collected on site on 31/07/2015, 01/08/2015, and 07/08/2015. The satellite image is from 06/08/2015. Wave conditions tracked by on offshore buoy at 1 hour intervals were also acquired from the Manly Hydraulics Laboratory. Typical conditions at Bondi Beach in the southern hemisphere winter include tides in the 0 – 2 m range (McCarroll et al. 2016), moderately high waves primarily out of the SE (Short and Trenaman 1992), a modal breaking wave height (Hb) of 1.6 m (Short and Trenaman 1992) and peak period (Tp) of 10 s (McCarroll et al. 2016). During these months the New South Wales coastline intermittently experiences winter storms and their large waves, with offshore significant wave heights (Hs) of ~0.43 m (Short and Trenaman 1992; McCarroll et al. 2016).

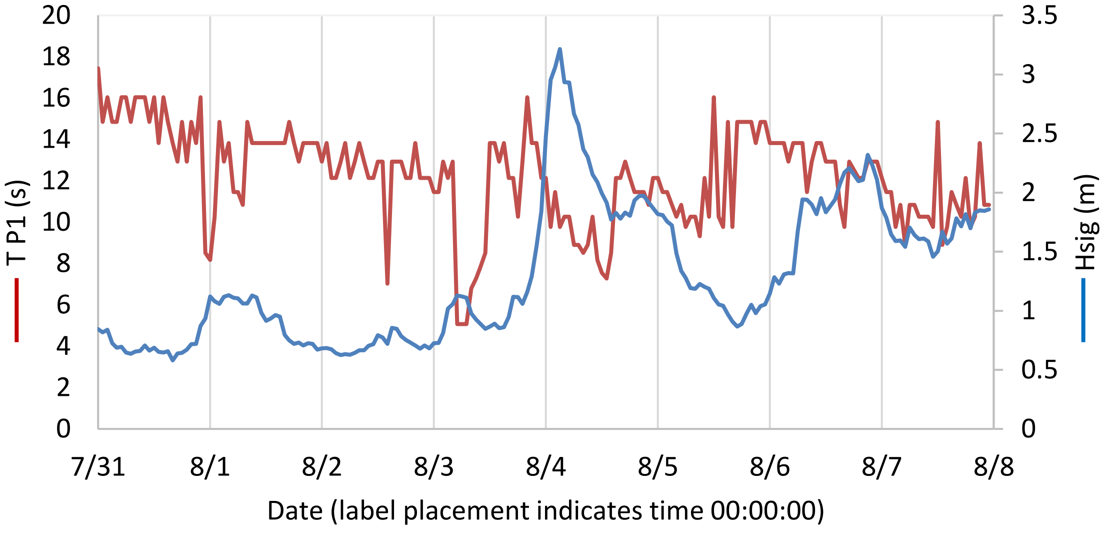

Figure 14 Wave data collected from the nearest buoy, maintained and processed by the NSW Public Works Manly Hydraulics Laboratory. Date labels and guidelines indicate midnight (00:00) to begin that date. The left axis/red line shows wave period (*T*) in seconds; the right axis/blue line shows significant wave height (H_{sig}) in meters.

Figure 3.6 shows the wave period (T) and significant wave height (Hsig) recorded for all dates of field data depth collection (31/07-7/08/2015). During this time, the mean significant wave height (Hsig) was 1.29 m and mean period (T) was 12.22 s (peak T was 17.44 s). The maximum Hsig measured during these dates was 3.22m (measured at 15:00 on 04/08/2015). All waves during the study came primarily from the SSE (156° from North; Figure 3.7).

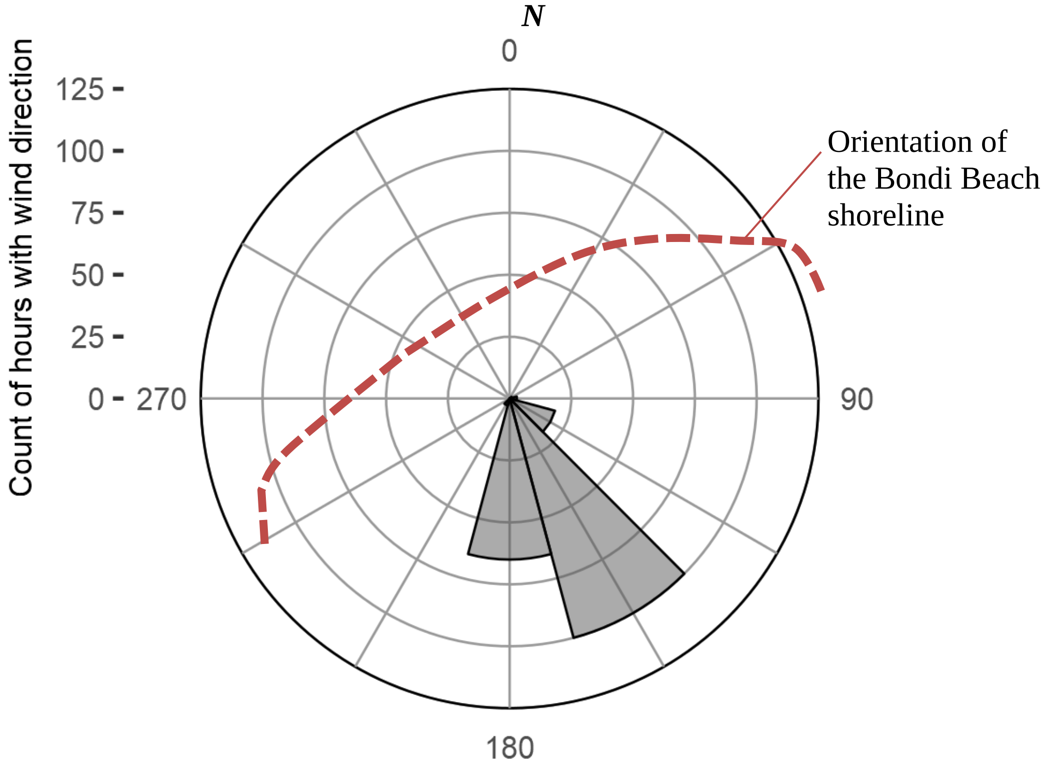

Figure 15 Wind rose from the week (168 hours total) of field data collection. The predominant direction was out of the SSE or about ~155-160°.

On the morning of 07/08/2015, an RTK GPS Unit was used to capture the elevations of the beach from the seawall to the water level, which was at extreme low tide (0.29 m at

06:00). On 31/07/2015 a laser level survey was conducted to capture within water depths, from the high water line to a maximum 150 m offshore from the high water line. The depths captured were those the authors could reach by swimming or walking along sandbars, then standing while holding the stadia rod and prism level for capture. For deeper measurements, captured on 01/08/2015, the author used a paddleboard to navigate out to depths reaching 4.9 m.

3.4.2 WorldView data

The image used was captured by the Digital Globe WorldView3 satellite at 10:02:42 local time on 6 August 2015. The digital numbers (DNs) assigned to pixels in the WorldView product as it is delivered to users have been radiometrically corrected by Digital Globe prior to delivery; they represent the "spectral radiance entering the telescope aperture" (Digital Globe 2013). These DNs are unique to WorldView imagery. These must be converted to spectral radiance before analysis, using equations and constants provided with the data by Digital Globe. After conversion, the shoreline was digitized so that all non-water pixels could be masked out of further analysis. The remaining values were mapped to depth using a combination of methods adapted from publications written prior to the launch of the WorldView satellites, but whose principle use of spectral information for calculation of water column depth is transferable to this higher resolution data (Benny and Dawson 1988; Lee et al. 2011).

3.4.3 DEM development

To map the processed radiance values to depth (in m), radiance values were classified using an unsupervised classification and the information in the WV3 "coastal blue," blue, green, and yellow bands to achieve the maximum number of classes; in this image, the result was 6 classes of pixels. Following Jupp (1989), each class represents a “depth of penetration” zone, or DOP. Within these classes, light of a given wavelength has been transmitted through similar depths; because the bottom type is uniform (and we assume transport within the water column is also uniform, and at a minimum) classes of similar spectral information are equivalent to classes of similar depth. Boundaries of the classes generated were then treated as contour lines and assigned depth values with statistical analysis of field data measurements of depth (Benny and Dawson 1985; Bachri et al. 2013).

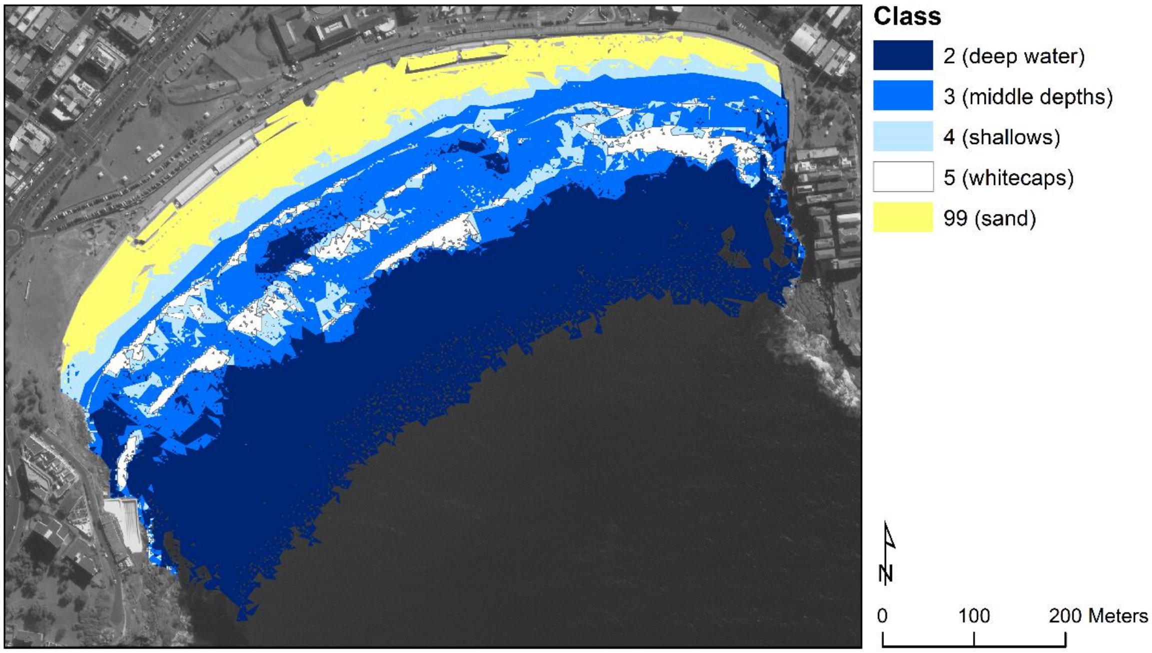

Figure 16 An unsupervised classification was run on masked data (run on only those pixels known as water) using the WorldView image from 06/08/2015. The resulting 5 classes are shown here superimposed on a grayscale version of the image. The classes have been colorized and named in the legend for visual interpretation.

To determine contour line values, previous studies have used frequency histograms of field measured depths within each DOP plotted together, and the intersection of histograms determines the value of the contour line separating them. However, in this experiment there are widely varied densities of field measurements within each spectral class; as an example, the RTK sampled thousands of points within the tidal range, but the paddleboard method only led to a few dozen measurements in the deepest waters. As a result, frequency histograms do not have clear intersections. Instead, to show separation of elevations measured within DOPs, Figure 3.9 shows box plots demonstrating the spread of values between classes. Note that the median of each class falls outside the first and third quantile of all other classes, except for where the median of class 3 falls just inside the interquartile range of class 4. Class 3, the middle depths of water, also has the largest number of outlier values. When creating the DEM, the value of a class boundary, or the contour line between classes, was calculated as a linear transition between class means.

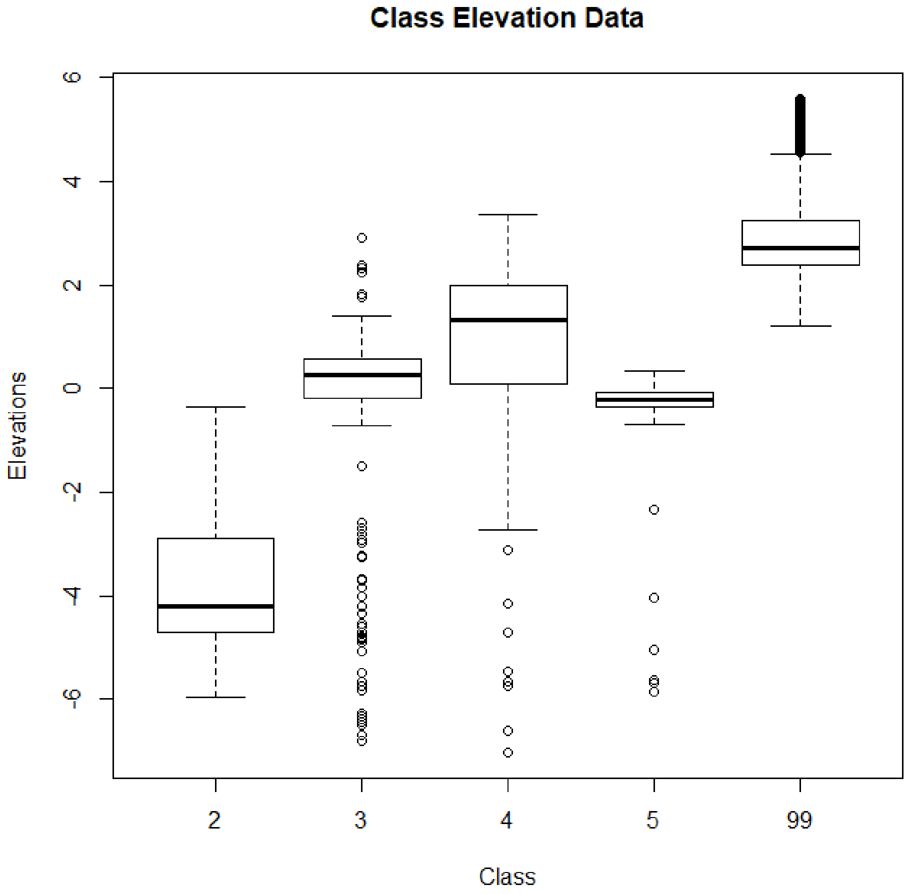

Figure 17 Box plot of the field-measured elevation values within the five spectral classes output by the ISO. In the plot, class numbers (across the x-axis) match those shown on the map in Figure 3.8 and the y axis elevation values (in meters) are field measured ground truth elevations. For a given spectral lass, the median elevation value is represented by a thick black bar. The surrounding box represents the first and third quartile. Any dots outside this range are outliers because they are more than 1.5*IQR (where IQR is the interquartile range) from the median.

3.5 Discussion of Results

Adequate field data were collected for the development of digital surface model of the surfzone for one date of imagery captured within the window of field data collection.

3.5.1 Calculating the depth of the water column under whitewater

To fill gaps in the DSMs caused by breaking wave white foam that obscures water depth, the height of the bar was calculated from incoming wave height data from a nearby wave buoy on that date. In calculating the depth to the bar in the image used (captured at 00:02:42 Zulu, or 10:02:42 in local time), only the wave heights and period recorded at that moment are used. At 10:00 local time, the wave period (T) was 13.82 s, the significant wave height (Hsig) was 1.818 m, and the wind was coming from the SSE, or 166° from North (unpublished data, NSW Public Works, Manly Hydraulics Laboratory). If the incident wave height is known, the depth of the water column at the location of the break can be estimated by the shallow water equation:

$$\frac{H_b}{h} = 0.78 \tag{2}$$

This identifies the moment when water particle velocity at the crest is equal to the waves celerity, which occurs when the ratio between the wave height (H_b) and the water depth (h) is approximately 0.78; this ratio varies slightly by beach, but in general a wave will start to shoal at 0.1, start to break at 0.3, and break at 0.78 (Davidson-Arnott 2010). Rearranging the equation to solve for the water depth at the point of breaking at Bondi Beach at 10:00 on 6 August 2015:

$$h = \frac{H_b}{0.78} = \frac{1.818\,m}{0.78} = 2.33\,m \tag{3}$$

Within the DEM developed, 2.33 m is the average depth within each class of the white, breaking wave water (Figure 3.8) used to estimate values of the bounding contour lines.

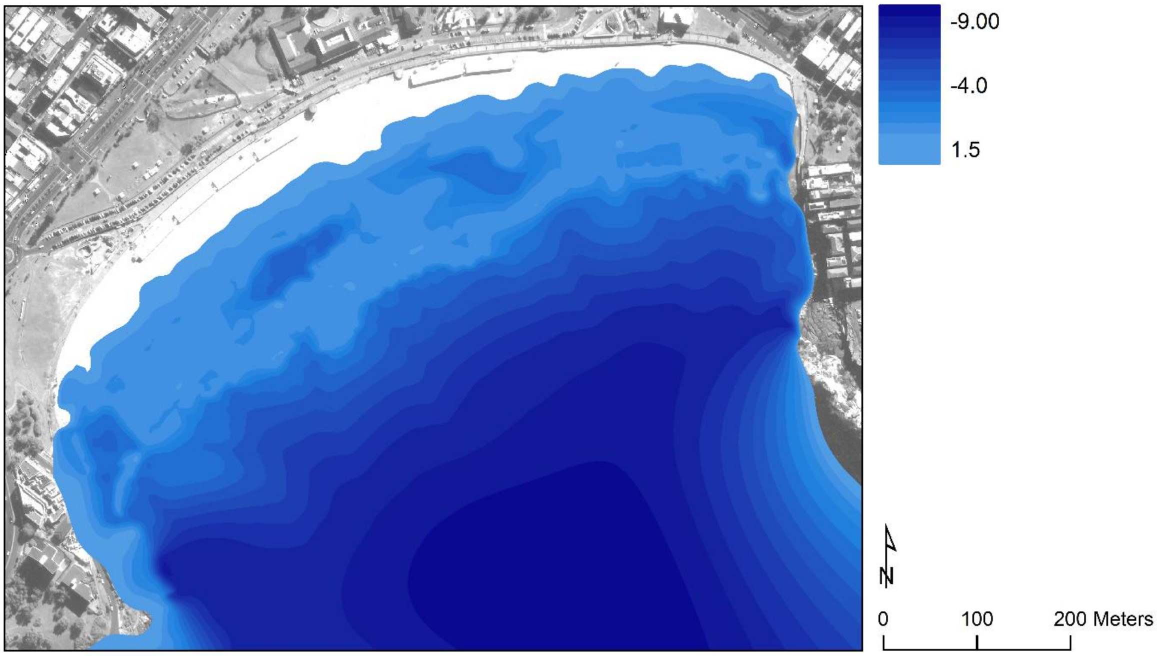

Figure 18 Final DEM, representing the bathymetry of Bondi Beach at 10:02 am on 06/08/2015.

3.5.2 Accuracy assessment

Root mean squared error (RMSEz) is a common evaluation of DSM accuracy. For this DSM, RMSEz was calculated with randomly selected values withheld from calibration stage. The formula for RMSEz is:

$$RMSEz = \sqrt{\frac{\sum(Predicted - Actual)^2}{n}}$$

and the result for this model was 0.91 m. Therefore, results show that the subaqueous elevation may be derived from WorldView data at Bondi Beach with RMSEz ≤ 1 m accuracy, which is less than the vertical definition required to identify rip channels (which have vertical displacement ≥ 1 m from the surrounding terrain; Brander and Cowell 2013).

3.5.3 Channel capture

Figure 3.11 shows the elevation of an alongshore transect at 60 m out from the zero elevation contour, the ‘shoreline.’ This shore-parallel line is shown in red on the map in Figure 3.11, and the right side of the figure shows the vertical profile at this location. Paths of light pink highlight where rip channels are visually identified in the imagery and might be expected to occur in the DEM. In all cases, dark gaps through breaking waves in the imagery are channels in the DEM as seen in the vertical profile extracted.

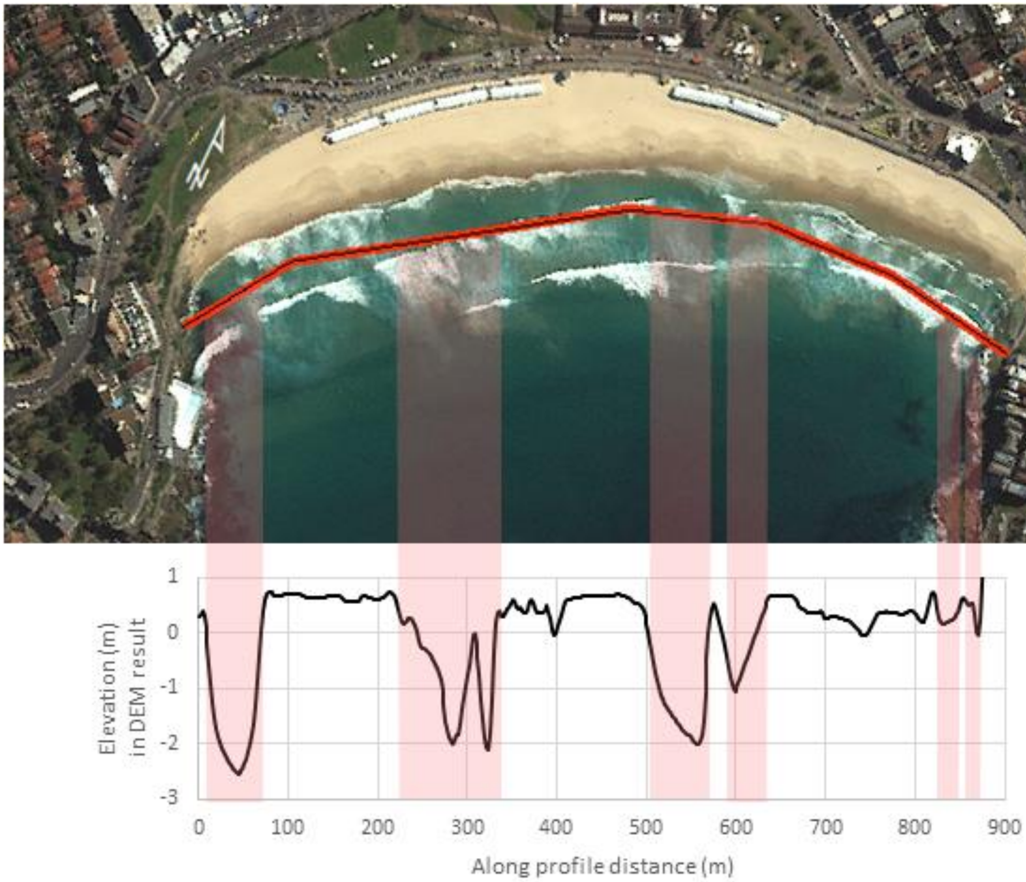

Figure 19 At top, the red line superimposed on the satellite image was used to extract a vertical profile from the DEM (shown in plot below). In the image, dark gaps through the waves are suspected rip currents. As highlighted by pink in the figure, these gaps in surf are co-located with channels in the DEM developed from the multiband version of the satellite data.

3.6 Conclusion

Quick, easy, accurate, and highly localized identification of rip currents would allow authorities to better protect beachgoers. The National Weather Service publishes some regional risk forecasts, but these only account for wave height and direction, so they only provide a general guide. With technological advances, it may soon be possible to include bathymetric measurements in these predictions, allowing predictions to be made for individual beaches rather than regions.

In this paper, methods are demonstrated which calculate bathymetric models of an active surf zone up to 20m deep with < 1 m vertical accuracy, which is adequate for identification of rip channels (which are vertically displaced from the surrounding landscape at ~ 1m). Although previous methods have used WorldView satellites to map depth, none has yet tested accuracy in a surf zone. The application presented here could potentially lead to daily accretion rip channel mapping and location prediction. This could be used to track a single beach through time and map the three dimensional transformation of a beach through Wright and Short's states. The present knowledge gap in the Wright and Short (1984) system of beach states lies in understanding how the 3-dimensional bar morphology develops as the bar moves landward at a large scale. At the time Wright and Short (1984) completed their study, 2-dimensional profile transects and qualitative observation of alongshore changes were the limits of possible data collection because spatially or temporally dense 3-dimensional observations were not possible in the 1980s. The authors recognized this in their concluding paragraphs, by stating that "predictability is certain to be improved progressively through continued observation, data collection, and analyses" and that "[e]xtension of the predictive models [to a global scale] will require more intensive use of remote sensing data" (1984, pg. 116). Instruments, technology, and computation power have since experienced rapid advancement and this study seeks to fulfill Wright and Short’s call for remotely sensed, global confirmation of their beach state evolution predictions while focusing on the modern need for improved rip channel observation, modeling, and prediction.

4. DEGREE OF ANISOTROPY AS AN AUTOMATED INDICATOR OF RIP CHANNELS IN HIGH RESOLUTION BATHYMETRIC MODELS.

4.1 Abstract

A rip current is a concentrated seaward current that forms in the surf zone of a beach. It is the result of alongshore variations in wave breaking. Rip currents can carry swimmers swiftly into deep water, and they are responsible for hundreds of fatal drownings and thousands of recues worldwide each year. These currents form regularly alongside hard structures like piers and jetties, and can also form along sandy coasts when there is a three dimensional bathymetric morphology. This latter rip current type tends to be variable in strength and location, making them more dangerous and more difficult to identify, thereby complicating surf safety efforts. The 'rip channel' in which these currents form has a characteristic morphology within bathymetry where the primary axis of self-similarity is oriented shore-normal. Here, it is demonstrated that degree of anisotropy can automatically identify such rip channels in bathymetric digital surface models (DSMs) with ≤ 2 m horizontal resolution. The characteristic signature of rip channels here identified distinguishes between sandbars, rip channels, and other beach features. As technological advances increase accessibility and accuracy of topobathy mapping methods in the surf zone, frequent nearshore bathymetric DSMs could be more easily captured and processed, then analyzed with this method. This would result in localized, automated, and frequent detection of rip channels. Such technology could ultimately reduce rip-related fatalities worldwide: (a) in present mitigation, by identifying the present location of rip channels; (b) in forecasting, by tracking channels as they evolve through multiple DSMs; and (c) in rip current education by improving local lifeguard

knowledge of the rip current hazard. The degree of anisotropy parameter can also be adapted to automate detection of other geomorphological features of interest.

4.2 Introduction

Rip currents are concentrated flows of water that form in the surf zone of a beach and flow seaward from the beach through breaking waves. They form on beaches as a result of feedback amongst winds, waves, substrate, and antecedent bathymetry, which combine to create alongshore variability in breaking wave height (Bowen 1969). When rip currents form where people swim they can carry unprepared swimmers (of all abilities) swiftly into deep water against their will (Drozdzewski et al. 2012, 2015). When this leads to panic and/or exhaustion, injury and fatal drowning can occur (Brander et al. 2011). Worldwide, rip currents are responsible for hundreds of fatal drownings and tens of thousands of rescues each year (e.g. Klein et al. 2003; Hartmann 2006; Gensini and Ashley 2009; Brewster 2010; Brighton et al. 2013; Scott et al. 2011b; Arun Kumar and Prasad 2014; Arozarena et al. 2015; Barlas and Beji, 2015; NWS 2017b). Calculating exact numbers of fatalities is barred by logistical difficulties in obtaining accurate incident reports, however: records in Costa Rica show ~ 51 fatalities per year (Arozarena et al. 2015); the United States averages 59 to 100 annual fatalities (NWS 2017b; Lushine 1990), and Australia has an average 21 fatalities, in addition to an estimated 17,600 people rescued from rip currents each year by surf lifesavers (SLSA 2009).

Drownings result from a complex mix of individual and group behaviors that lead people to unknowingly enter rip currents (Brander 2013). Interviews conducted on the beaches of Costa Rica (Arozarena et al, in review), Australia (Sherker et al. 2010), the United Kingdom (Woodward et al. 2015), and the United States (Caldwell et al. 2013; Brannstrom et al. 2014) revealed that the beach-going public is mostly unaware of how to visually identify rip currents and largely unaware of proper escape strategies. A recent nationwide survey conducted online in the United States revealed that the "Break the Grip of the Rip!" campaign has successfully educated some of the public because the majority of the n=1622 surveyed were able to correctly describe rip current escape strategies (Houser et al. 2017). However, there was a marked difference between frequent and infrequent beachgoers, where infrequent beach goers were more likely to identify the smooth water of a rip current as the safest swimming location in a photograph (Houser et al. 2017). The majority of research into beachgoer behavior shows that vulnerable populations persist despite warning, forecast, and safety programs.

Most drownings could be prevented by restricting unsafe swimming areas. Restrictions can be posted warning signs or fencing around the perimeters of unsafe pools and waterways (Branch and Stewart 2001; Trimble et al. in review). Where swimming could safely occur, the Center for Disease Control (CDC) reports that two important drowning prevention strategies are providing lifeguards at public locations that swimmers are known to frequent and campaigning to encouraging the use of these protected areas (Branch and Stewart 2001). Lifeguard presence is the strongest mitigation against drowning injury and fatality; between 1988 and 1997 the United States Lifesaving Association (USLA) recorded less than 100 fatal drownings at lifeguarded sites, and more than 75% of those drownings that did occur happened outside of patrol hours (USLA, 2000).

The Center for Disease Control (CDC) also reports that in addition to lifeguards, a second effective strategy is site-specific "keep out of the water" signs (Branch and Stewart 2001). The most effective combination of these two mitigation efforts, then, would be posting lifeguards and site-specific (daily mobile) "keep out of the water" signs where and when rip currents occur. However, if the goal is to mobile, daily signs placed by a knowledgeable person in front of a specific rip current when it forms, placement can be complicated because rip currents can vary in appearance, are harder to spot from eye level (the higher the vantage, the easier to see), and do not necessarily form in the exact same location each day. Placement by an individual can, therefore, be subjective and may not be the best strategy for a local government which might be held liable if injuries or drownings do occur. If, however, placement was objectively data-driven (rather than subjective) this would be a highly effective and reliable rip-fatality prevention strategy.

Figure 20 Images from Playa Cocles, a rip-prone beach near Puerto Viejo, Limón, Costa Rica show (at left) a bilingual sign explaining the meaning of the red, yellow, and green flags and (at right) the lifeguard standing next to a red flag he posted in front of a rip current. The bilingual sign is adjacent to the flag.

4.2.1 Rip current morphology

The formation of rip current circulations in the surf zone is an inherently complex process that can be generated by an array of conditions, outlined in Table 4.1 and described in detail in a recent review paper (Castelle et al. 2016). In general, rip current circulations develop when incident waves and coastal morphology interact to create variation in wave height and breaking alongshore (Haller et al., 2002; Castelle et al. 2016). Variations manifest as areas of higher wave 'set-up' (higher waves, more intense breaking) and lower 'set-up' (lower waves, less intense breaking) along the beach (Castelle et al. 2016). Set-up is increased with water column height and increased volume brought to the beach by breaking wave activity. It is largest landward of the bar, where breaking is most intense, and set-down (return flow towards the sea) is at a maximum just landward of low spots or gaps in the bar. This imbalance leads to an offshore flow in the area of low waves. The offshore flow further limits wave height and breaking, as well as reinforcing or even deepening the channel in the bathymetry, thereby leading to a stronger gradient and rip. The onshore flow that develops over the bar leads to the landward gradation of the bar and a further strengthening of the channel until the bar welds to the beach. Maximum rip current speeds are generally observed during a falling tide, when breaking is most intense, velocities are increased as channels become narrower with constrained cross-sectional area, and/or relief is greater (Aagard et al., 1997; Brander, 1999; Austin et al., 2010, 2014; McCarroll et al., 2014b; Scott et al., 2014).

Table 3 Conditions which can form rip currents – all of which can vary, depending on the angle of wave approach (Castelle et al. 2016). The center column lists the most common expression of the conditions which create rip currents; at right are listed the less common, but possible, expressions of rip morphology.

	Characteristic expression	**Exceptional expression**
Beach morphology	Alongshore, three-dimensional variability	Can be planar
Channel morphology	Distinctly deep channels, which can form along hard structures or along unrestricted, sandy coasts	Can be indistinct, as in the case of "flash" rips
Life-span	Persistent in occurrence and location	Can be transient, short-lived, as with "flash" rips
Speed	Maintains a mean flow	Can be unsteady
Length	Confined within the surf zone	Can extend well beyond the breakers, as with "mega" rips

At present, no singular rip current classification system is in widespread use, though several attempts to create one have been published (Short 1985, 2007; Dalrymple et al. 2011; Leatherman 2013). This publication will employ terminology as defined by the most recent and most comprehensive classification, described by Castelle et al. (2016). Rip currents can be described by four general categories. One rip current type is so small it may be called a mini-rip (e.g. Russell and McIntire 1965) or a swash rip (Dalrymple et al. 2011); these form in the center of small cusps (10 m wide curved slopes) on steep beaches and do not persist far enough past the swash zone to pose much of a hazard to beach goers (Masselink and Pattiaratchi 1998; Castelle et al. 2016). The remaining three categories are: purely hydrodynamic rips, which lack morphologic controls; bathymetric rips, which exist because of surf zone and/or inner shelf morphology; and boundary rips, which exist largely due to rigid boundary structures. The purely hydrodynamic rips that form on planar beaches are highly transient with short life spans, making them less hazardous than other rip current types. For these reasons, neither hydrodynamic or mini/swash rips are examined as part of this study.

In contrast to those two transient rip types, bathymetric and boundary rips are formed by characteristic alongshore morphologies. Bathymetric and boundary rips are created in part by vertical variability in the surf zone and/or inner shelf, causing rip currents in these categories to form in relatively persistent alongshore locations. The formation of boundary-controlled rips is predominantly controlled by rigid structures that interrupt alongshore flows. These can be natural or anthropogenic features; examples include rocky headlands, jetties, groins, and piers. Because permanent structural elements force the rip current circulation, this type of rip, when it forms, is consistently located adjacent to the structure (Castelle et al. 2016). This makes identifying and forecasting these rip currents easier than identifying and forecasting bathymetric rips. With bathymetric rips, location can vary with the development or collapse of nearshore sandbars, or the location can be partly controlled by submarine canyons or reef structures (Castelle et al. 2016). Because they can form at many variable locations alongshore, it is most difficult to keep swimmers out of bathymetric rips and they are the focus of the automated detection methods presented here.

This study focuses on identifying the signature of rip channel morphology to allow for objective and rapid identification. We define rip channels as topographic low spots in the nearshore resulting from feedback amongst waves, substrate, and antecedent bathymetry. In most previous rip current studies, rip channel morphology is either described in qualitative terms or the provided morphological description is incomplete (sometimes missing entirely). The exception is Brander and Cowell (2003), who describe a morphometric definition in detail; their definition is the one applied here. Rip channel depth is defined as "the vertical distance

Table 4 Values describing rip channel morphology as reported in peer reviewed literature. The type is described according to the four groups from Castelle et al. (2016) described above.

Paper	Width (m)	Length (m)	Depth (m)	Oreintation from shore (°)	Velocity (ms^{-1})	Type*
Brander et al. 2001	6–10	---	---	---	0.4-1.0	Bathymetric
MacMahan et al. 2010	50	135–180	Slope: 1/30	"Cross-shore"	0.4-0.65	Bathymetric
Gallop et al. 2011	---	55–120	---	90±40	---	Channel/boundary
Bruneau et al. 2014	14–20	~100	1–6	~90	0.5-0.6	Bathymetric
Castelle and Coco 2014	<50	200	2	~70	---	Channel/boundary
McCarroll et al. 2014	30–50	50–75	1–6	~90	---	Bathymetric
Pitman et al. 2016	30+	100+	---	90	---	Bathymetric
Scott et al. 2016	5–10	50–70	1–2.5	90	---	Boundary

from a given datum, such as mean water level, to the thalweg of the rip channel" (Brander and Cowell 2003). Length is typically 1 – 2 times the width of the surf zone (Brander 1999) but there can be exceptions. Rip channels have a typical relief ≥ 1 m from surrounding morphology and a width of at least 5 m (see table 4.2), though rip channel width is difficult to define because channel cross-section shape can vary widely (Brander and Cowell 2003).

4.2.2 Degree of anisotropy as indicator of rip channels

Degree of anisotropy is a parameter indicating the direction of minimum variance across a surface. For example, a glacial valley has a high degree of anisotropy in its elevation values because the tall bounds and low valley bottom both trend in a single direction. Rip channels also have a high degree of anisotropy in their elevation and are distinct from their surroundings because the steeply sloped sides are perpendicular to the shore parallel trend of the surrounding landscape. Previous efforts to geomorphometrically characterize rip channels took advantage of this signature characteristic, despite not using degree of anisotropy specifically, by linearly de-trending digital surface models (hereafter, DSMs), thus removing sloping nature of the bathymetry surrounding rip currents and isolating channel characteristics (Brander and Cowell 2003).

To identify these features' directional trends in bathymetric DSMs, original software was written that calculates the degree of anisotropy. The original software written for this analysis reveals orientation and severity of directional dependence in a surface and has previously been used to identify faults in mountainous environments (Bishop et al. in review). This parameter calculation integrates scale dependence and orientation to characterize the landscape in order to quantify the degree of anisotropy in surface models. It is employed here to identify locations and scales of anisotropic forms in the surf zone. Because rip channels are elongated features, lower than their surroundings, and oriented at an oblique angle to the shoreline, they have anisotropic values unique from sandbars and other surrounding bathymetry, thereby allowing for automated detection. Specifically, the nearshore bathymetry of sandy beaches is analyzed here with original software written to identify anisotropic spaces, seeking shore-normal forms of the right scale and with a high degree of anisotropy; these are rip channels which may form rip currents under the right incident wave angle, height, and period. The result is anisotropy as an indicator of rip channel presence in bathymetric DSMs.

The software outputs used in this analysis included 3 values: the length analyzed at the user-defined sampling frequency (range here: 1 – 100 m), the degree of anisotropy as a ratio value (from the variance of elevation values), and the orientation of the direction of minimum variance. The orientation value can be used to interpret directional dependence of relief; when calculated using elevation values as input, this metric shows the dependence of surface features at a range of scales. The resulting surface of anisotropic values creates a method for discovering directionally-dependent surfaces, identifiers, and interpretations of the landscape. By analyzing the directionality of self-similarity in the landscape at a nested, increasing window size, the primary research question sought to determine if rip channels exhibited an identifying signature unique from sandbars and other surrounding morphology.

4.3 Methods

4.3.1 Data

A bathymetric DSM was generated from Digital Globe WorldView3 multispectral data for Bondi Beach near Sydney, Australia (Trimble et al. in review). The resulting DSM consists of 2 m pixels covering a 0.30 km^2 area depicting the beach in early August 2015. Because of the Nyquist Frequency, it was determined that a pixel size of 2 m would ensure detection of rip channels at least 4 m wide and larger; 4 m was determined as the smallest object size based on the literature review summarized in Table 4.2 where reported rip channels have widths of 5 m and greater.

4.3.2 Sampling

To test the concept (degree of anisotropy as an indicator of rip channels), the bathymetric model was selectively sampled. Locations were chosen during field observations of the conditions on the date represented in the bathymetric model and they were selected by the authors to reflect three landforms: isotropic spaces (e.g. the gently sloping beach face), anisotropic and shore-parallel forms (e.g. sandbars), and shore-normal anisotropic forms (e.g. locations of observed rip currents). Of the 14 locations chosen, there 5, 3, and 5 locations in each category, respectively, with 1 location in an amorphous space, not known to fall in any of the three aforementioned categories but within the surf zone, a gap in the sandbars that did not have a current on the date of imagery.

4.3.3 Omni-directional variogram analysis

Degree of anisotropy was calculated as variance of elevations surrounding a central point at multiple distances and in multiple directions. The program calculates variance in elevation at user-defined intervals in directions (e.g. every 10°) and distances (e.g. 5 m steps) surrounding a central point (i,j); see Figure 4.2. For this analysis, variance was calculated at distances from 4 to 100 m at every 8°. The software can be implemented to varying distances and degrees, but for the rip-detection purposes of this paper, the object of interest (rip channels) is of primary interest when located within surf zone where swimmers are typically located (refer back to table 4.1).

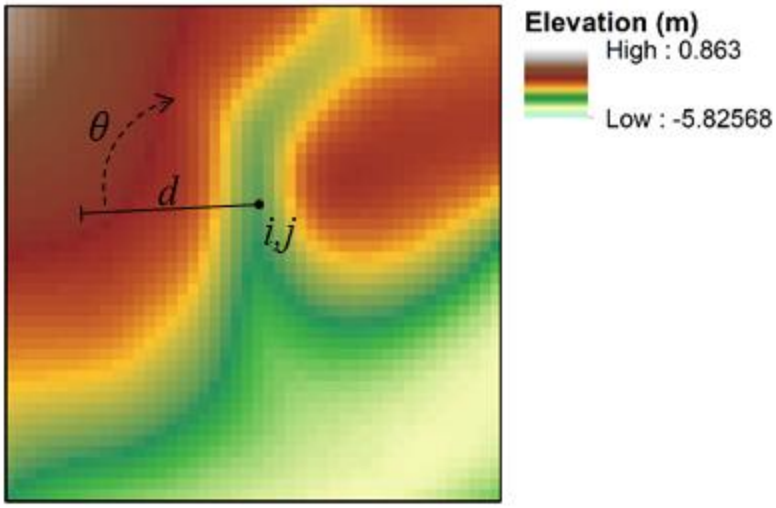

Figure 21 For every point of analysis (i,j), variance is calculated from all values across distance d in each direction (where direction is defined as 360°/θ, and θ is user-specified).

The program has many outputs. In this analysis, two are of primary importance. One output of the program is the direction of dependence at each distance analyzed, where the cardinal direction value was given is the primary axis across the central point for which the standard deviation of elevation values at that distance is at a minimum for all θ examined at that distance d. A second output is the degree of anisotropy as a single value, calculated as the ratio between two variance values: (a) the variance in elevation along the axis of minimum variance at that scale and (b) the maximum variance in elevation measured in any direction at the same point and scale (not necessarily perpendicular to the minimum). The ratio of these is a single value that reveals the degree of anisotropy for that particular scale, or distance, of analysis.

4.3.4 Cluster analysis to reveal signature rip channel values

It is possible to use the output values to draw a series of ellipses that serve as a visualization of the degree of anisotropy present in the surface. Ellipses are drawn for each scale of analysis over a sampled location, where the long axis is the length (in m) of scale analyzed (4 – 100 m), the short axis is degree of anisotropy (variance in minimum direction / variance in maximum direction) drawn as a distance in meters, and the orientation of the long axis is in the direction of minimum variance in elevations, when all elevations are sampled within the radius of the scale analyzed.. Smaller, inner ellipses indicate directional trends at smaller scales, while larger, outer ellipses indicate trends at larger scales. In the example in Figure 4.3, the elongated depression in the landscape dominates at the smaller scales, then again at the largest.

Figure 4.4 shows the nested ellipses from 4 – 100 m developed from selectively sampled training sites (in the categories sandbar, rip channel, and isotropic space) at Bondi Beach. These bathymetric data were collected by the authors, and presence of rips was corroborated by observation at the time of bathymetric data collection on-site with field measurements of depth, in ARGUS-style time lapse imagery, and in satellite imagery.

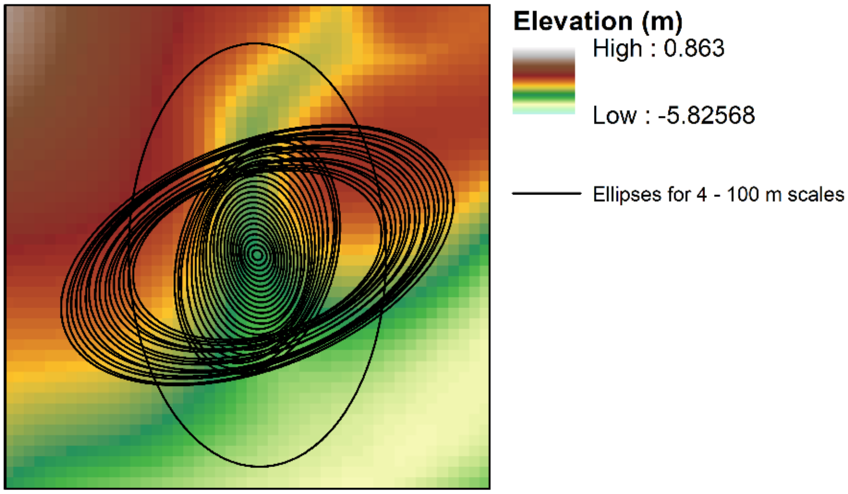

Figure 22 Ellipses drawn from result for a location within a rip channel.

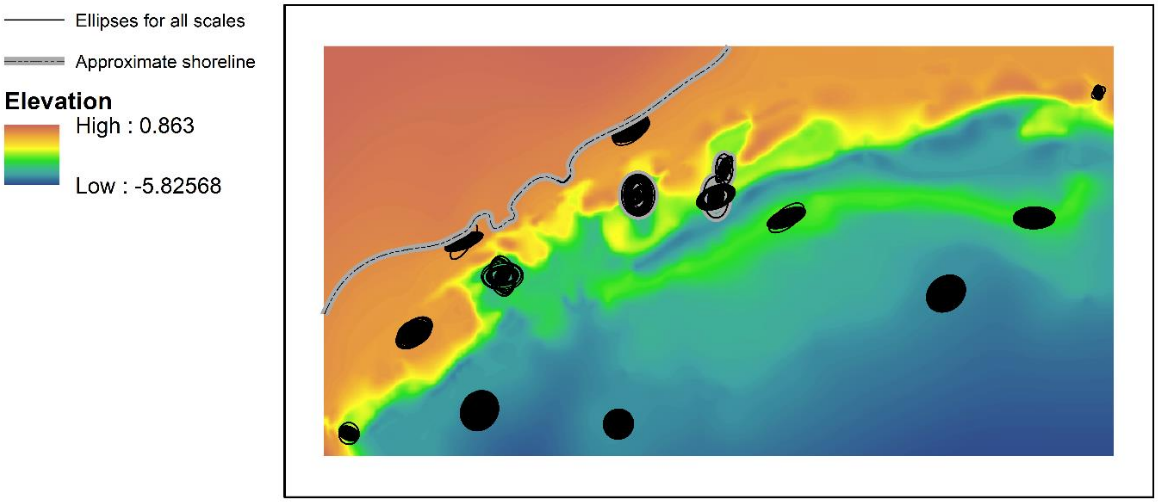

Figure 23 Ellipses drawn from program output for all sampled locations at Bondi Beach, Australia.

4.3.5 K-means cluster analysis

To objectively determine whether rip channels sampled possessed unique characteristics from other sampled sites, a k-means cluster analysis was performed on the outputs. This method was used because it does not require assumptions about the data, such as normally distributed values; it also requires the statistician to define the number of clusters. To explore the data for the ideal number of clusters, a sum of squared error (SSE) scree plot was produced using (i) orientation from shore normal of the axis of directional dependence and (ii) the degree of anisotropy (Figure 4.5). The point of inflection in the SEE plot indicates 5 clusters in the data. K-means clustering algorithm was then run on the standardized data to determine (regardless of geographic position within the DSM) which locations (and at which scales) fell into each cluster; 5 clusters appears to explain 86.5% of the data variance (within cluster sum of squares by cluster yields (between_SS / total_SS = 86.5 %). A map was then generated to show geographic location of the cluster results (see results, Figure 4.7).

4.4 Results

When k-means was run on standardized data with 5 cluster centers, the plot in figure 5 was produced. In this plot, the 5 clusters are colorized and separated by thresholds indicated on the figure. Table 4.3 below shows cluster statistics. The most anisotropic cluster (#3 at 0.82) is also nearly shore parallel at only 15.4°. These samples are sandbars, which are highly anisotropic and shore parallel. Clusters 1 and 5 are also very nearly shore parallel, at 14.8° and only 5.1°, respectively. Cluster 5 is also fairly anisotropic (at 0.51) and when colorized, appears to identify sandbars as cluster 3 does. However, cluster 1 is the least anisotropic (at 0.36) and has the most samples (n=205). These spaces have little directional trend.

Cluster 2 and 4 are both anisotropic (at 0.58 and 0.45) and rotated away from shore. Cluster 2 is nearly shore perpendicular (98.2°) and cluster 4 locations are also turned away (at 59°). These two clusters could be rip channels, and when colorized in the ellipses (Figure 4.7) appear in the sampled rip locations.

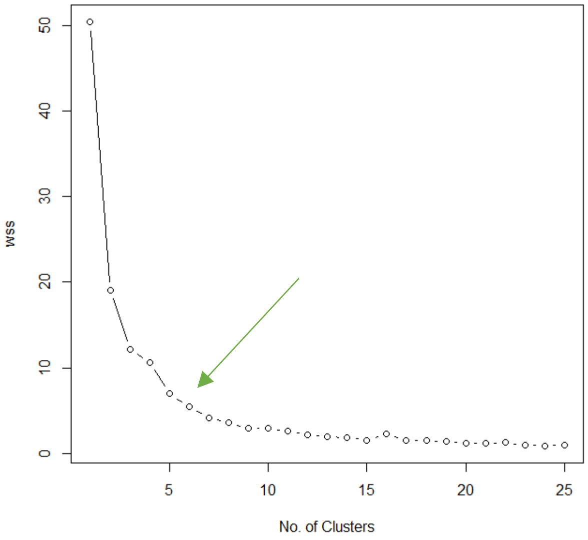

Figure 24 SCREE plot of Bondi test sites. “Elbow” at 5 indicates an ideal number of clusters within the data.

Table 5 Cluster statistics.

Cluster	Size (*n*)	WSS	Degree of anisotropy	Rotation from shore parallel
1	205	1.9459484	0.36	14.8
2	53	0.5937047	0.58	98.2
3	38	1.1908930	0.82	15.4
4	75	1.7663382	0.45	59.0
5	123	1.3058917	0.51	5.1

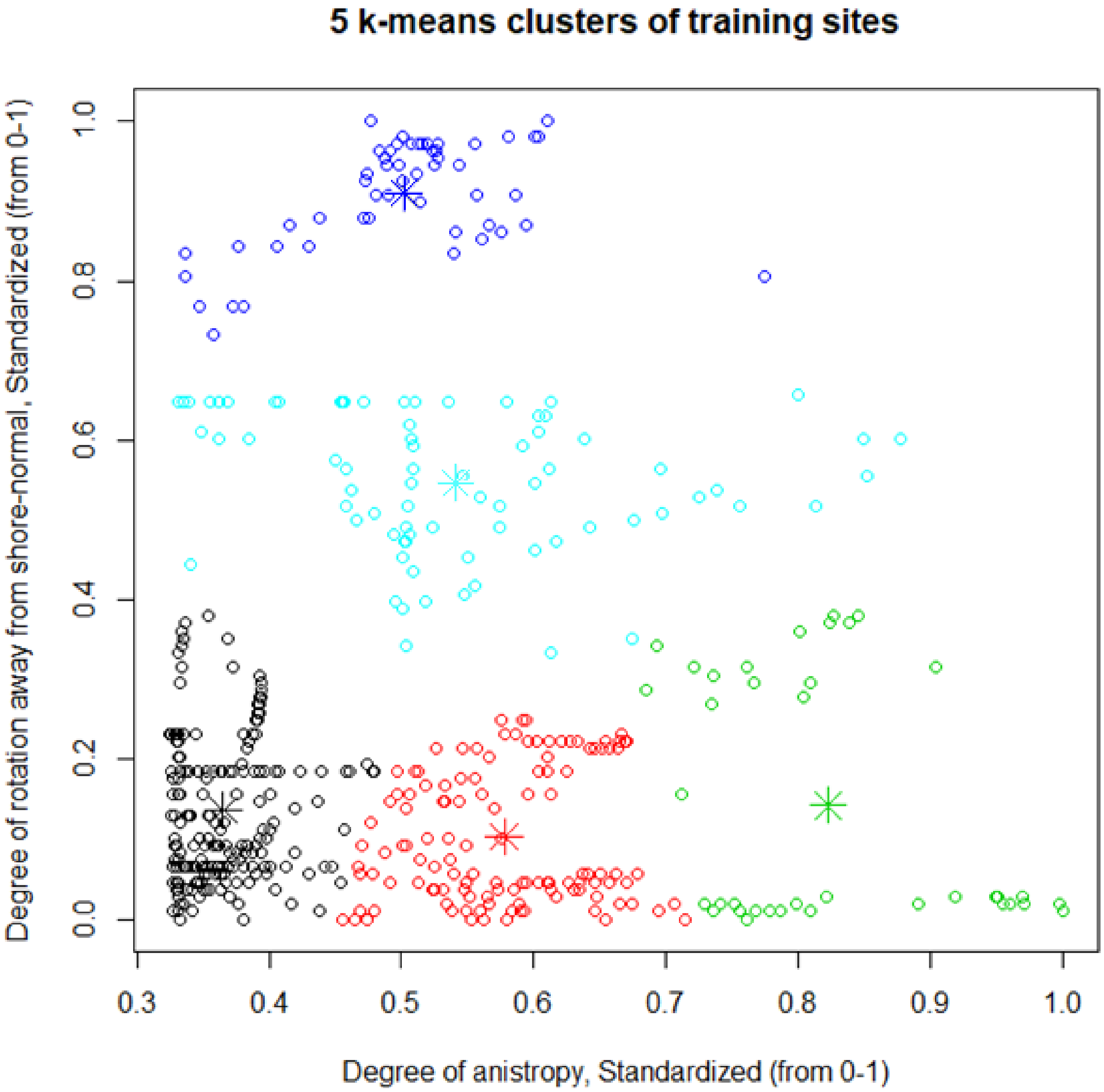

Figure 25 K-means cluster result with 5 clusters. Clustering algorithm input was 2 (standardized) outputs of analysis from every sampled location at every scale (4 – 100 m): the orientation of the minimum variance away from shore normal (y axis) and the degree of anisotropy (x-axis).

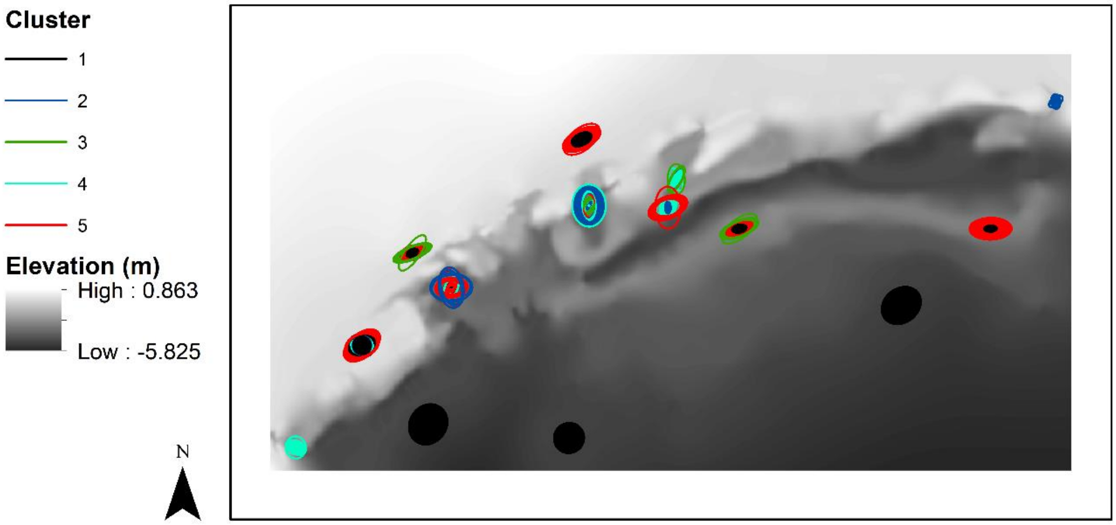

Figure 26 Ellipses at each sampled location and scale colorized to match k-means 5 cluster grouping (colors match with Figure 5).

When a map is drawn with the ellipses and they are color-coded according to the cluster analysis results, geographic distribution indicates patterns in cluster location and scale (Figure 4.6). Examples of the cluster categories at certain exemplar sample sites are shown in Figure 4.7. In this figure, an example location's vertical profile (sampled across the long axis black line) is shown to the right of the nested ellipses

4.5 Discussion and conclusions

Results for sampled locations at Bondi Beach indicate two clusters over locations and scales that meet the defining characteristics of rip channels as determined by literature analysis (table 4.1). When (i) the ratio of variance/scale of analysis and (ii) orientation are plotted as Cartesian coordinates *x* and *y*, respectively, the plot shown in Figure 4.6 is produced. The signature relationship between the orientation of minimum variance and the degree of

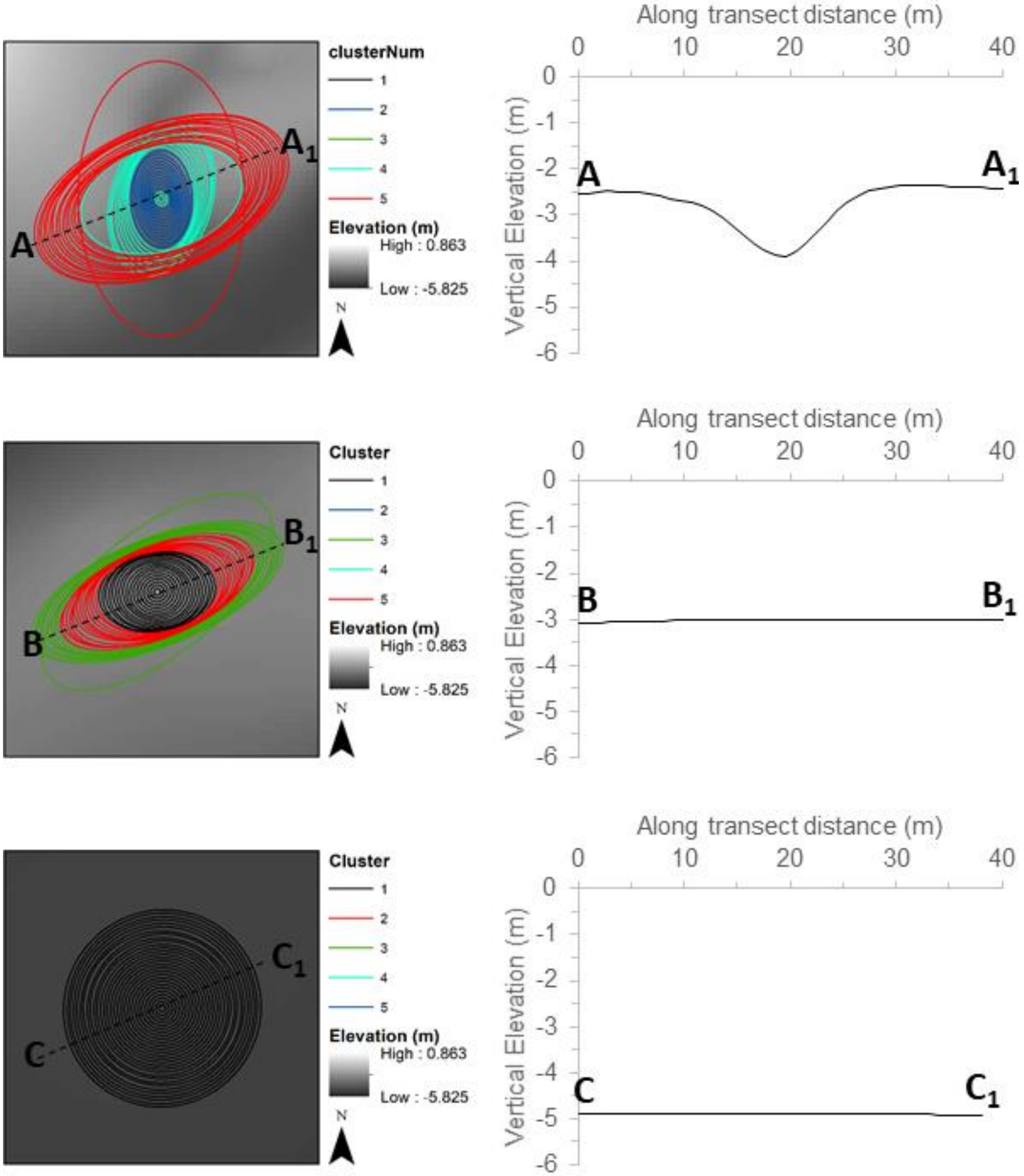

Figure 27 Example locations from within the dataset. Ellipses represent output from 4 – 100 m; rotation indicates directional trend at that scale. Narrower ellipses indicate stronger anisotropy. At the top (A) is a probable rip channel. At the center (B) is a sandbar. Bottom example (C) is an offshore location. The coordinating plots at right show elevation change across the black line, which is shore-parallel and sampled across the center of analysis at each location.

anisotropy that identifies probable rip channel landforms, as indicated by cluster analyses, suggests that spaces oriented shore-perpendicular (more than 45°) are rip channels. As in previous publications studying nearshore bathymetry (i.e. Brander and Cowell 2013), the authors acknowledge the restrictions of this approach because it can only be applied to detailed DSMs of nearshore topography which, for reasons previously discussed, are difficult to obtain. "It is also true that different sampling schemes affect the results of the method, but the same is true for any statistically derived estimate on any subject" (Brander and Cowell 2013).

This means that the identification process can be automated: with improvements in our ability to map bathymetry in the surf zone, this method could be used to automate the detection of alongshore locations of rip channels. This would allow lifeguards or other authorities to place daily "no swimming" signs and barriers alongshore. It would also aid significantly in developing models that *predict* rip current location and strength, and one day make it possible to provide the public with a "rip current forecast" that accounts for highly local bathymetry.

It may soon be possible to produce automated rip current location maps. This is because drone and remote sensing technology are rapidly improving our ability to map the surface below breaking waves in the surf zone. Degree of anisotropy, when considered alongside orientation of minimum variance, determines the signature relationship between probable rip channels and the surrounding landscape. To move from maps of previous conditions in to prediction of future rip current locations and strength, it may be possible to apply degree of anisotropy to indicate progressive movement and development of rip channels in bathymetric data. Regardless of the DSM data source, this software program's output could be used to automate detection of rip channel location, length, and narrowness. These features are key in identifying the severity or strength of the channel developed and could be used to interpret the movement and development of strong rip currents on popular beaches.

5. FACTORS CONTRIBUTING TO THE CLUSTERING OF SWIMMERS ON A BEACH WITH QUASI-REGULAR RIP CURRENTS*

5.1 Abstract

Rip currents are strong, narrow seaward-flowing currents that can carry swimmers swiftly into deep waters. In Australia, rip currents are responsible for 80% of all rescues by surf lifesavers (about ~17,600) and ~21 fatal drownings in Australia every year. Recent studies suggest that many physical and social factors can contribute to rip current related rescues and fatalities, but the behavior of beachgoers in and around this hazard remains poorly understood. While previous research has investigated beachgoer understanding and the demographics of drowning victims, this study is the first to relate self-reported knowledge and observed behavior of beachgoers to the location of rip currents at the beach. In an effort to improve existing rip current education strategies and reduce rip current drownings, the aim of this study is to determine whether proximity to a rip current is related to beachgoers' self-reported and observed behavior, with focus on their chosen swim location and awareness of the hazard at a rip-prone beach. Respondents (n=49) were interviewed at Bondi Beach, an internationally popular swimming and surfing destination near Sydney, Australia that also regularly develops strong rip currents. Rip channel presence was measured utilizing georectified time exposure imagery obtained by a remote video camera. Interview subjects were recruited once they were observed swimming, and questions gauged their awareness and understanding of the rip current

---

*Part of this section is reprinted with permission from Beach Management Tools, edited by Camilo M. Botero, Omar D. Cervantes and Charles W. Finkl, 2017, Coastal Education and Research Foundation, Inc. Fletcher, NC, USA. Copyright 2017 by Springer.

hazard. Surveys were geotagged and analyzed in relation to the locations of rip current hazards as identified in the exposure imagery. Results suggest that most people cannot visually identify rip currents, but that the ability to identify a rip current is not related to swimming near a rip current. These results are contrary to studies arguing that the visual break in waves created by a rip current may attract those who cannot see them. However, results here show that respondents who self-reported as poor ocean swimmers were more likely to sit near rip currents, were more likely to sit in the center of the beach, and were less likely to notice posted signs and warnings. Results suggest that these vulnerable populations are not drawn to the rip currents by their appearance, but are steered towards dangerous parts of the beach by infrastructure. Controls on within-beach location include nearby public transportation, parking, hotels, and other infrastructure which inadvertently lead them towards the most dangerous parts of this beach.

5.2 Introduction

Rip currents are strong, concentrated offshore directed currents originating in the surf zones on many beaches around the world. Where they exist, rip currents represent the greatest hazard to bathers and are considered a global health issue (Sherker et al. 2008; Short and Hogan 1994) because they are responsible for hundreds of deaths and tens of thousands of rescues worldwide each year. In Australia, surflifesavers perform an annual average 22,000 rescues, of which 80% are believed to be associated with rip currents (Short and Hogan 1994). Despite widespread lifeguard programs, there is still an average of 21 deaths per year in Australia (Sherker et al. 2008; SLSA 2009; Brighton et al. 2013). Rip current fatality data is also tracked in Costa Rica and the United States, which have recorded an annual average 51 (Arozarena et al. 2015) and 59 (NWS 2017) fatalities per year, respectively

Being a strong swimmer is not a guarantee of surviving a rip current because they can flow at speeds ranging from 1 ms-1 to more than 3 ms-1 (MacMahan et al. 2006; MacMahan et al. 2010; Houser et al. 2013). For perspective, Michael Phelps' world record in the 100m butterfly swim is 49.82 seconds, a rate of 2 ms-1 (FINA 2017), which means that regardless of swimming ability, even the strongest of swimmers can be at risk. Regardless of swimming ability, beach goers could avoid or escape rip currents by knowing how to identify them, escape them if caught, and/or by swimming in lifeguarded areas (Brander et al. 2011). If we can effectively reduce exposure to rip currents by increasing awareness and safe beach use practices, drownings and rescues can be reduced.

5.2.1 Previous interview studies

Although scientific understanding of the hydrodynamics that cause rip currents is well developed (Castelle et al. 2016), rescues, injuries, and deaths are still common, due in part to a poor understanding of beach user behavior and knowledge in relation to the rip current hazard (Brannstrom et al. 2014; Brander 2013). It is known that drownings result from a combination of personal and group behaviors (Brander 2013; Brannstrom et al. 2014), and that the severity of the rip current hazard is influenced by "various demographic, social, behavioral, knowledge based, and emotional factors" (quote from Castelle et al. 2016 pg. 1; Sherker et al. 2010; Hatfield et al. 2012; Williamson et al. 2012; Caldwell et al. 2013; Woodward et al. 2013, 2015; Brannstrom et al. 2014).

Coastal scientists and beach safety practitioners are aware of the hazards that rip currents pose to beachgoers, but the general public has demonstrated a general lack of awareness regarding rip current processes and their potential dangers, and the majority are unable to visually identify the hazard (Brander and MacMahan 2011, Caldwell et al. 2013; Sherker et al. 2010; Brannstrom et al. 2014a, 2014b). These trends have been revealed by a series of studies conducted by different researchers, but each emulated and built on the previously published findings.

An interview-based study in Australia was one of the first to recruit subjects on-site at the beach and test their rip-current related knowledge (Sherker et al. 2010). In the survey instrument, subjects were shown photographs of beaches from eye level and asked where they would swim; some images contained rips, some contained flags indicating safe swimming areas (per the Australian system), and some images contained both. In flagged images, the majority of subjects chose to swim between the flags, but when they were not present the majority indicated they would swim in the rip current. Given that 93% of subjects indicated they could identify a rip current, this stud identified an overconfidence in the surveyed population, and only 1 in 3 subjects who said they could identify a rip were able to do so (Sherker et al. 2010).

Next, a study based in Florida, USA, recruited subjects on a beach and asked them to circle the rip current in photographs taken at a very high and oblique angle from a hotel balcony. Subjects' style of identifying their chosen space in the photograph was widely varied, but many subjects indicated that the greatest rip current was present where large waves were breaking, rather than indicating the flat dark waters of the rip current between the waves (Caldwell et al. 2013). To build on the findings of both studies, research conducted on the beaches of Texas, USA showed subjects 5 photographs taken from eye-level (following Sherker et al. 2010) and asked them to first indicate the image with the most dangerous swimming conditions, the to identify dangerous spaces to swim by choosing cells within a grid superimposed on the photo. This method was aimed at deciphering whether subjects would choose a strong rip current as the most dangerous swimming condition; the survey instrument provided wide freedom of choice while standardizing comparisons amongst subjects' answers. In these results, only 13% of 392 beachgoers correctly identified the photograph showing the most hazardous conditions *and* precisely identified the rip current in that photograph. The inability to see rip currents in photographs was associated with an overall lack of knowledge regarding the forces that cause rip currents (Brannstrom et al. 2014).

In each study, there are barriers to reliability in the data. In the Australian research (Sherker et al. 2010) the questions were not specifically designed to identify subjects' ability to visually identify rips, and only one image was used to this end. In the Florida study (Caldwell et al. 2013), the images used were taken from a high viewing angle. In the Texas study (Brannstrom et al. 2014) subjects were asked to identify "dangerous" spaces, not rip currents by name. In each study, there were methodological reasons behind the instrument design; however results are routinely interpreted as subjects' demonstrated inability to notice dangerous rip currents, in person, when deciding where to swim on any given beach. In every case, subjects were being asked to identify rips in static images of surf while standing on the beach in front of the active surfzone. In addition, subjects may have been primed by previous questions; e.g. in Sherker et al. (2010) early questions included multiple images showing flags marking safe (rip-free) swimming conditions. There is also reason to believe that confirmation bias may play a role in data trends seen in these studies (Menard et al. *in review*).

While these previous studies have gauged the self-reported knowledge and awareness of beach users, no previous study has included spatial analyses of responses relative to rip current proximity. For this reason, the survey used in the present study was designed to target beachgoers on a rip-prone beach and gauge their knowledge of rip current avoidance and escape in combination with their proximity to a rip current (Appendix 1). This study is the first to geolocate and spatially analyze answers. It is also the first to include analysis incorporating quantified locations of rip current hazards. Location is recorded at the study site during the time of the interview with an ARGUS camera system. This was accomplished by first conducting and analyzing surveys, combining survey results with maps of rip currents created from camera footage taken of the study site, and using geostatistical analysis to evaluate relationships linking perception and behavior to the physical hazard presence.

This study tested two primary hypotheses regarding beach users' rip-current vulnerability, with many supplemental hypotheses also investigated. These hypotheses are based on conclusions of previous survey-based research (Caldwell et al. 2013; Sherker et al. 2010; Brannstrom et al. 2014a, 2014b). Hypothesis 1 proposes that the majority of beachgoers cannot visually identify a rip, but hypothesis 2 qualifies that despite this inability to visually identify rip currents, beachgoers' behavior (evaluated as their proximity to a rip current) will have no relationship to their inability to visually identify rip currents. Put more simply: previous studies have shown that beach-going populations generally lack knowledge of rip current appearance and are poor at identifying them in photographs, but we suspect that this inability does not translate to subjects' observed within-beach location. Posed as a question: do people who can't see rip currents choose to swim closer to a present rip current? If more vulnerable swimmers are swimming closer to rip currents, there would seem to be an apparent link between swimming near a rip current and being unable to see them. However, if there is no association between visual identification ability and chosen swimming location within a rip-prone beach, that would suggest that factors other than visual rip current presence are determining beachgoers' chosen water entry point.

5.3 Study site

Bondi Beach is located on the eastern coast of Sydney, Australia (see Figure 5.1) in Sydney's most densely populated suburb (Bondi's density was 10,188 people per square kilometer in 2011; Australian Bureau of Statistics 2012). It is the most popular beach in Australia (McLachlan et al. 2013) and is an Australia National Heritage site (Australian Government: Department of the Environment 2008) that draws large crowds with restaurants, nightlife, pristine water, and year-round surfing (Short and Hogan 1990). The tourism board estimates an annual average 2,223,400 unique visitors to the Bondi neighborhood each year, with approximately 104,350 of these people specifically going down onto the beach (Destination New South Wales 2014).

The southern end of the Bondi Beach is exposed to incoming waves and the shoreline is curved into the lee of the headland which shelters it. The beach gradually straightens across its 850 m length until meeting the northern headland (Short and Trenaman 1992). The headland structure creates an alongshore wave height gradient (Short and Masselink 1999), which in turn results in transition through multiple beach states along the shoreface (Wright and Short 1984). In general, the beach exposed southern end of the beach is more reflective, with a high-energy intermediate modal state, and the protected north end is more dissipative, modally in a low-tide-terrace beach state (Wright and Short 1984; Short 1985, 1999, 2007; McCarroll et al.

2016), but the beach does transition amongst beach states as storms and other wave events pass. The intermediate states that form along the beach are characterized by rip channels that foster rip currents under the right wave conditions. Embayed beaches typically have rip currents immediately adjacent to both headlands, with 2 to 4 rip channels along the shore between them (Castelle and Coco 2012). Due to the Bondi's orientation toward modal incoming waves, surf at the southern exposed end of the beach is large and rip currents are common (Figure 5.2). The rip current against the headland is so persistent, it is colloquially called the "Backpacker's Express," because travelers staying in a nearby hostel or riding the bus to the beach are likely to enter at this end and swim directly into this rip, rather than walking a kilometer to the north end of the beach where the surf is more gentle (Brander 2009; TenPlay 2013). As described by one Surf Lifesaving spokesman in an interview with The Guardian:

> "You could conceivably hop off a plane, go to your backpackers' hostel, hop on the bus and be swimming at Bondi within four hours and there is this terrible rip you wouldn't even know about." (Sean O'Connell, in an article for *The Guardian*; McMahon 2007).

In total, there are typically 3 to 4 rip currents at Bondi on any given day, of varying strengths, occurring about 180 m apart along the shoreface (Short and Hogan 1990) but weaker at the sheltered northern end of the beach, where the surf is smaller.

Bondi Beach is home to the Bondi Surf Bathers' Life Saving Club, purportedly the world's first surf lifesaving club, which was founded in 1906 (Short and Hogan 1990; Brawley et al. 2007). An additional lifesaving club also helps patrol the northern end of the beach on weekends and busy summer days. Lifeguards at Bondi patrol on four wheel drive vehicles, keep eyes in their watchtower, and post the red and yellow flags used nationally to designate safe swimming areas (Surf Life Saving Australia 2012). Bondi lifeguards make an estimated 2,500 rescues annually, and about 85% of these rescues are tourists and other non-locals (TenPlay 2013). One report estimates that the Bondi lifeguards rescue about one in 2,000 people who visit the beach, or specifically 0.54 rescues per thousand (Short and Hogan 1990). Despite the strong lifeguard presence, there is still an occasional fatal drowning; the most recent rip-related fatality was in November 2013 (Black 2013).

There are several sign types posted around Bondi Beach, and some examples are shown in Figure 5.3. The mobile red and yellow flags are posted at the beach each day by Surf Lifesaving Australia (SLSA) as part of the "Swim between the flags" campaign that began in 1935 (Johnson 2007); they post these flags anew each day to indicate a "supervised area of the beach and that a lifesaving service is operating" (SLSA 2017). Each day of active surveys, these flags were posted at the northern end of Bondi. A different sign type (Figure5. 3, center) is posted daily by the Bondi Beach Lifeguards at any rip currents they spot when guards arrive for the first shift of the day. Throughout this study, these signs moved daily, dependent on wave size and rip current presence as judged by the lifeguards from their watchtower. Other signs, like that on the far right of Figure 5.3, are permanently posted at the tops of stairs and ramps leading from the seawall down on to the beach.

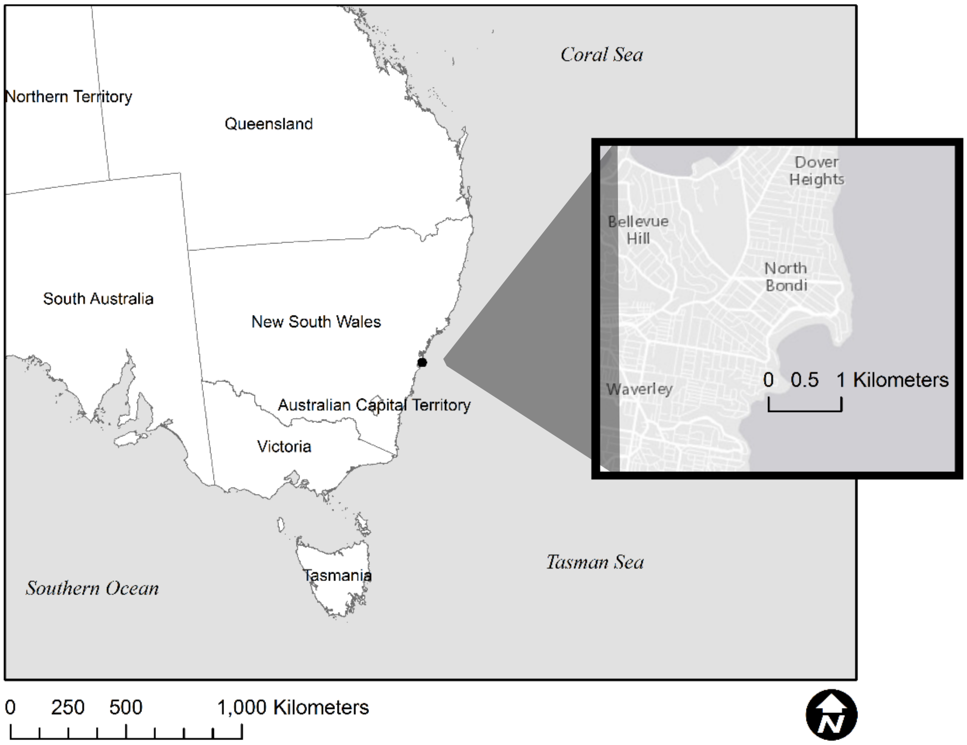

Figure 28 A map showing the location of Bondi Beach, Sydney, within the continent of Australia.

Figure 29 The “Backpacker’s Express” rip current is the dark slick from the beach to the last breaker outlined by the red arrow.

Figure 30 Examples of signage types at Bondi Beach. At left, a sign posted at each ramp from the seawall down to the beach, and three times across the 200m wide stairwell in the center of the seawall. In the center, a sign posted by the lifeguards each morning at the center of each rip current they can visually identify from their tower. At far right, the red and yellow flags used to denote a surf-board free safe swimming zone. These flags were placed in the same general space at the northern end of the beach on each day of the study.

5.4 Methods

The survey design was voluntary, anonymous, and approved by the relevant human subjects protection program (IRB2015-0382D). The survey instrument was adapted from previous, similar studies published in peer-reviewed journals (Brannstrom et al. 2014a, 2014b; Williamson et al. 2012); the entire survey is in Appendix A. The instrument contained a maximum 39 questions; in some cases, questions were interdependent (i.e. an answer of “no” to question 1 means there is no need to answer question 2). Most questions were multiple choice, though some were free-answer. The survey was designed with 4 distinct sections (see Table 5.1) and to take approximately 15 minutes to complete.

Table 6 Survey instrument question categories.

Part	**Focus of questions**
I	Observance of warnings and signs at the site
II	Identification of rip currents in photographs
III	Beach use habits
IV	Respondent data, such as swimming ability, age, education, or gender

The survey was administered by a single enumerator (ST) who visited Bondi Beach between 1 July 2015 and 1 August 2015 during peak usage hours (10:00 – 15:00) and weather conditions conducive to swimming and/or surfing. The enumerator wore a continuously running GPS unit and approached any person observed as having entered the water and appearing 18 years of age or older. The beginning and end times of the survey were recorded on the hardcopy document at the scene of the interview. This allowed the enumerator to retroactively geotag the interview location using the timed GPS track.

The demographics section was placed last in the instrument (Part IV) so that subjects might have developed a rapport with the enumerator and feel comfortable giving up this non-identifying information. This section began with four different questions regarding swimming ability. Subjects were asked to qualitatively and quantitatively evaluate their ability to swim in both a pool and open ocean environment; all were multiple choice questions. Respondents were asked to rate their swimming ability as "unable, weak, competent, or highly competent" in each environment. They were also asked to choose the maximum distance they could swim without stopping, in a pool and in the ocean. These questions helped determine whether subjects were consistently rating their swimming abilities.

In another series of questions (Part II), subjects were shown 3 photographs of beaches with visible rip currents and asked to identify (in each) the space that was the most dangerous spot for swimming (multiple choice; see Figure 5.4 on the previous page). Each photo contained a rip current, and the images were taken at Australian beaches from varying heights and angles. In each image, there were five possible answers: two areas of breaking waves, a rip current (in shallow water, a close but not perfect answer), a rip current (in deeper water – the correct answer), and an option "E" for nowhere, indicating there are only safe swimming locations in the image and none is more dangerous than the others. To score answers, a subject was given 5 points for each correct answer (choosing the deep water in the rip), 2 points for choosing the shallow water at the beginning of the rip current (close, but not entirely correct), and no points for indicating breaking waves or choosing answer "E." A complete breakdown of subjects' possible scores is shown in Table 5.2. After the photograph identification, subjects were asked several questions to evaluate their rip current knowledge, such as "Have you heard of rip currents?" and "What do you think a rip current looks like?"

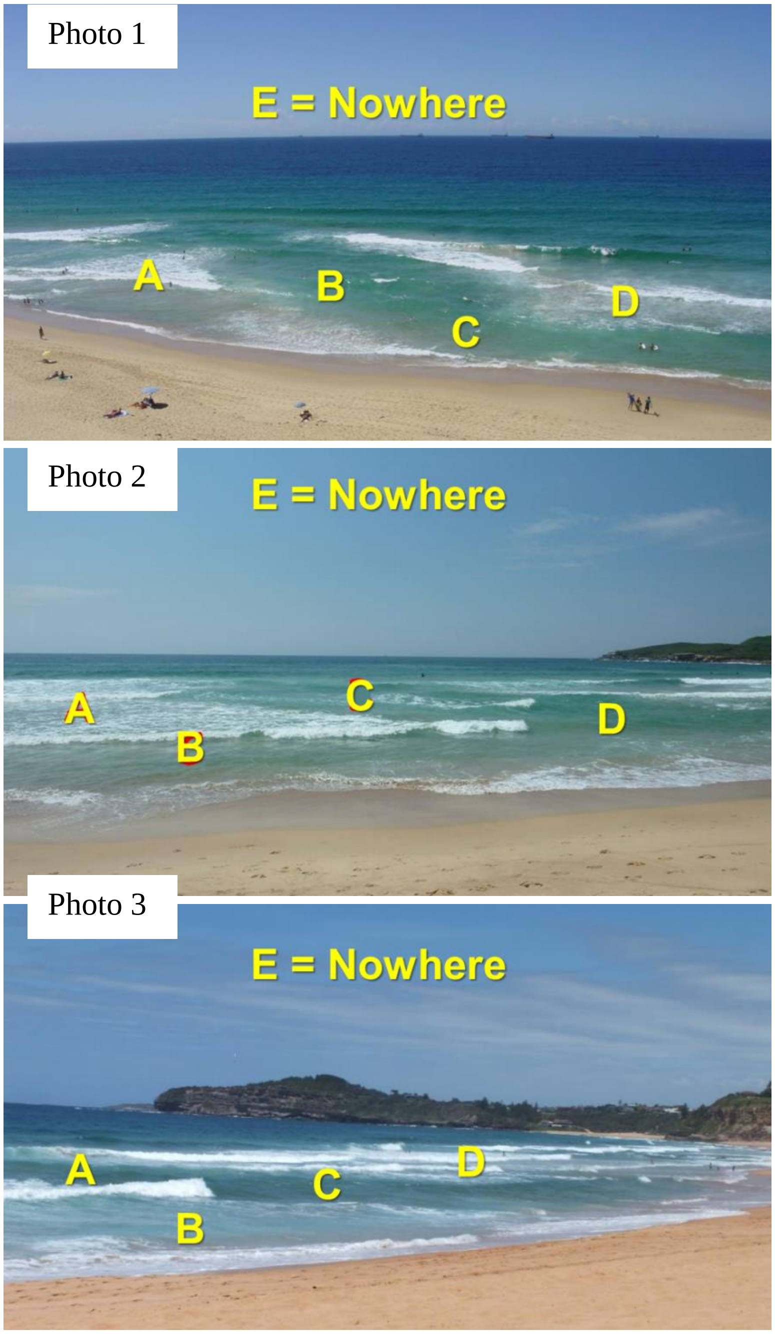

Figure 31 Images used in the photo identification questions. In these images, the viewing angle became increasingly lower/closer to eye level. In Photo 1, the angle is high and so the rip current is more visible as the dark water running away from shore, from letter C through letter B and onward. In this photo, the correct answer to the question "Where is the most dangerous place to swim?" is B (5 points). Choosing C would earn a participant 2 points, and choosing A, D, or E would earn 0 points. In photos 2 and 3, the more correct answers were C and A, respectively.

A 1 megapixel video camera mounted at 55m (above sea-level) atop a building on the southwest of the beach captures still images (at 1 Hz) from 9 am to 5 pm each day; when these images are time-averaged and rectified they produce the images shown in Figure 4.5 (for more on methods, see McCarroll et al. 2016 and Silva et al. 2009). Because rip currents are concentrated flows of water moving out to sea through the surf, they dampen breaking wave activity. This causes rip currents to stand out in time-lapse imagery in contrast to whiter pixels caused by waves breaking throughout the day as consistently dark shore-normal features. The images captured during hours that interviews were collected (i.e. sometimes only 10 am – 2 pm, other times 9 am – 6 pm) were coalesced into daily maps for each day of successful interviews. These images were georeferenced with MATLAB and rip currents were digitized from these images in a Geographic Information System (hereafter GIS; see Figure 5.6). The GIS was then used to automatically calculate the shortest distance between each geotagged interview and the nearest rip current on the date of that interview.

Table 7 Scoring method for photograph questions.

Grade	Score	# Right,	Close,	Incorrect	Description
A	15	All 3	0	0	All 3 correct
	12	2	1	0	2 rips and 1 shallow rip space
B	10	2	0	1	2 rips and 1 wrong answer
	9	1	2	0	1 rip and the shallow rip entry in the other 2
C	7	1	1	1	1 deep rip space, 1 shallow, and 1 incorrect space
	6	0	3	0	The shallow water location in all 3
D	5	1	0	2	1 correct, but with 2 wrong answers in the others
	4	0	2	1	2 shallow water rip entries, 1 wrong answer
F	2	0	1	2	1 shallow rip feeder and 2 incorrect answers
	0	0	0	All 3	All 3 incorrect

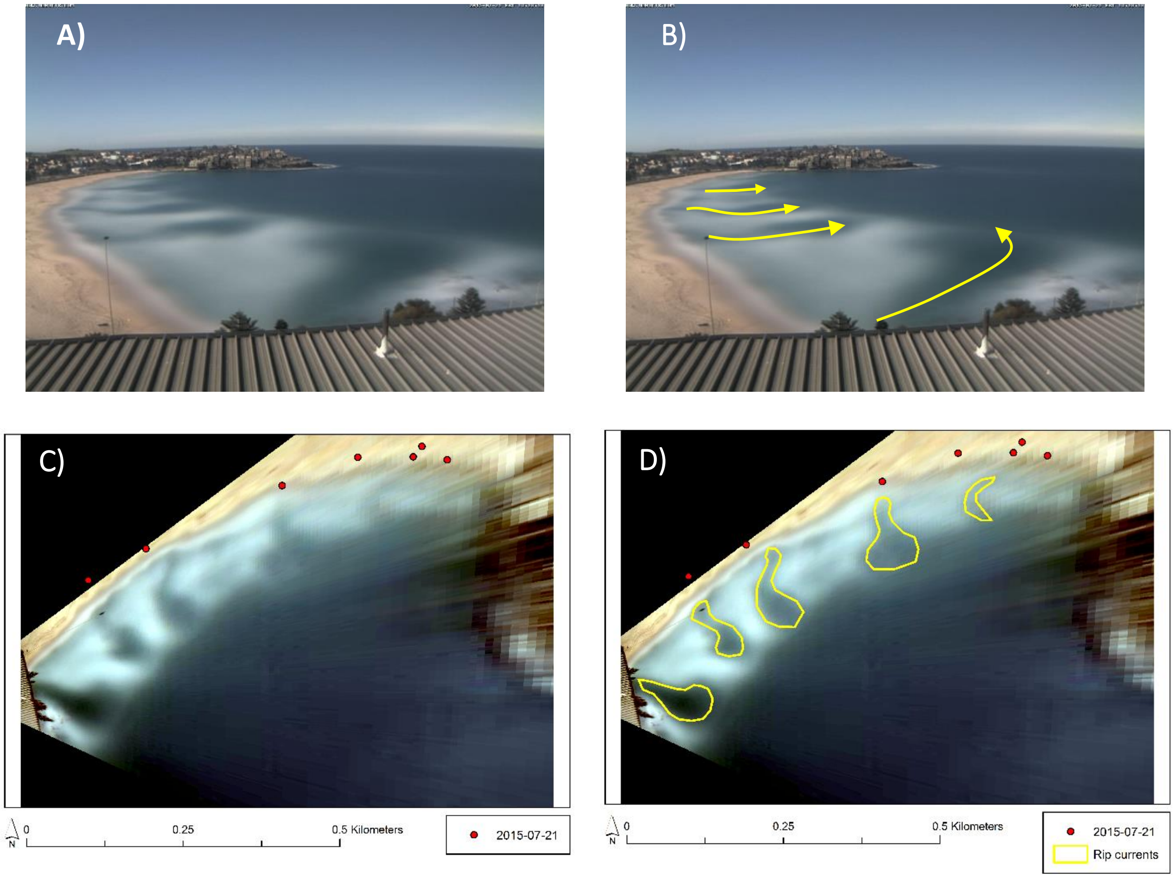

Figure 32 (A) An example of a single day's image from the study site (21/07/2015 from 11:00 – 15:30). (B) The same image, with rip currents highlighted by yellow arrows. (C) The same Argus image has been georectified. This map includes locations of that day's subjects as red dots. (D) The georectified image with rip currents marked by yellow polygons.

5.4.1 Statistical analyses

Chi-square testing ($\chi2$) was the primary test for statistically significant relationships amongst subjects' traits. When cross tabulation counts between traits did not meet the assumptions of a true chi-square test (e.g.: when more than 20% of cells had an expected count less than 5), the likelihood ratio significance was used to determine significance. Results indicate whether a relationship exists, but not the direction of influence; the direction of influence must be interpreted by the analyst.

Multiple geostatistical analyses were also performed using the geotagged surveys. Before performing any spatial autocorrelation tests, two outliers were identified and removed from the spatial analysis. These two surveys were more than 3 standard deviations (of distance) from their nearest neighbor. The remaining points were then analyzed with an Incremental Spatial Autocorrelation test (Moran's I) or to determine whether any of the qualities recorded in the 39 question survey had a non-random distribution within the beach. If a variable was determined to be non-random (at the 95% confidence level) then a Hot Spot (Getis-Ord Gi*) test was performed, using a fixed distance band; the fixed distance band value was the maximum peak distance determined by the Moran's I test. The hot spot analysis then revealed whether attributes with non-random distribution displayed clustering of high values (hot spot) or low values (cold spot) at the 95% confidence level.

5.5 Results

During the 10 days of active recruitment, when the weather was conducive for people to be on the beach, 65 subjects were approached and 49 completed the survey (acceptance rate = 75.4%). Precise beach population counts are not available for the dates of the study; however, using Australian Bureau of Statistics numbers (reviewed in section 2.1) there are an estimated 104,350 unique visitors to Bondi Beach each year. This averages out to ~286 persons each day, but does not account for highly seasonal variance in attendance; winter numbers are low. In addition, this is not the number of beachgoers who enter the water. The swimming winter population on days of the study was likely much lower than this 286 person average; regardless, if 286 possible subjects were present each of the 10 days of active recruitment, the enumerator would have approached 2.3% of the total population and successfully interviewed 1.7%.

5.5.1 Sample demographics

Of the complete subject pool, most were male (n=28, 57.1%), n=19 subjects (38.8%) were female, and some subjects preferred not to record an answer (n=2, 4.1%). The majority of subjects (n=22, 44.9%) were in their 20s but all age groups were represented (see Table 5.3). At least one subject from each education bracket was represented, though the majority (n=19, 44.9%) had completed a 4-year college degree. Country of permanent address was relevant to the hypotheses, and subjects came from a wide geographic spread: 59.2% (n=29) were from Australia, and those were mostly from the state of New South Wales, where Bondi is located (n=25 or 51.0% of all subjects). Only 8.1% (n=4) of those surveyed were Australians from other states. Non-Australian subjects were from the United States of America (n=5, 10.2%), Germany (n=3, 6.1%), and an additional 9 countries, which were each represented by n=2 subjects or fewer.

This population is a demographically representative sample of the beach going population at Bondi, as shown by its similarity to reports published by the Australian Bureau of Statistics (hereafter, ABS). The ABS estimates that young people (15-29 years) account for most (53%) of the international visitors who stay in Bondi, and the second largest age group that visits is 30-44 years olds (26%; Destination New South Wales 2014). These numbers are matched here, where the majority of subjects (44.9%) were younger than 30, and the second largest group (30.6%) were between 30 and 40 years of age.

ABS also estimates that Bondi visitors are equally likely to be Australian or international, and this subject pool was split evenly between Australians (59.2%) and internationals (40.8%). The ABS reports that Australian visitors to Bondi Beach are more likely to be from other states (40%) than from within NSW (60%; Destination New South

Wales 2014). Although this study's Australian subjects were primarily from within NSW, this is due to the large number of subjects from within 10 miles of Bondi Beach (n=15, 30.6%) who would not have been considered "visitors" by the ABS data collection. Lastly, the ABS reports that international visitors are most likely to come from the UK, China, New Zealand, and the USA (Destination New South Wales 2014); in this study international visitors were most likely to come from the USA or Germany, followed by the UK, New Zealand, and Italy.

A lack of Chinese and other international subjects in the pool can be attributed to language barriers that prevented recruitment and possibly the winter months when the study took place. These similarities validate the application of results presented to the further development of Bondi Beach which might affect the entire beach going population.

In a pool environment, most subjects (n=19, 55.2%) described themselves as "highly competent," and capable of swimming more than 500 m without stopping. In the open ocean, most subjects (n=24, 54.2%) described themselves as "competent" and capable of swimming 100 m without stopping. In both categories, subjects who evaluated themselves as "competent" were most likely to answer that they could also swim at least 100 m without stopping (in a pool: $\chi2= 22.691$, 8df, $p=0.004$; in an ocean: $\chi2= 52.154$, 10df, $p=0.000$). However, there is variety in how subjects evaluate competence (Table 5.4). One subject rated themselves as a "competent" pool swimmer but incapable of swimming 25 m without stopping, while another "competent" pool swimmer said they could swim more than 500 m before they need to stop. Likewise, although most subjects who rated themselves as "highly competent" ocean swimmers said they could swim 500 m or more, n=2 subjects who described themselves as "highly competent" could only swim 100 m in open water without rest.

Table 8 Summary of sample demographics.

Question	**Options**	***n***	**(%)**
Gender	Male	28	57.1
	Female	19	38.8
	Prefer not to answer	2	4.1
Age	17 or younger	2	4.1
	18 -20	7	14.3
	21-29	22	44.9
	30-39	8	16.3
	40-49	7	14.3
	50-59	2	4.1
	60 or older	1	2.0
Education	Less than high school degree	1	2.0
	High school degree or equivalent	5	10.2
	Some college but no degree	7	14.3
	Associate degree	5	10.2
	Bachelor degree	19	38.8
	Graduate degree	12	24.5
Country	Australia	29	59.2
	United States	5	10.2
	Germany	3	6.1
	Italy	2	4.1
	New Zealand	2	4.1
	United Kingdom	2	4.1
	Canada, Hungary, Ireland, Japan, Netherlands, Singapore	1 each	2.0

Table 9 Comparison of subjects' quantitative and qualitative self-evaluation of swimming ability (values indicate the number of subjects n who gave a particular answer).

Pool ability	**< 25 m**	**25 m**	**50 m**	**100 m**	**500 m**	**> 500 m**
Unable	0	0	0	0	0	0
Weak	0	0	1	0	0	0
Competent	1	0	4	9	4	1
Highly competent	0	0	1	6	6	16

Open water ability	**< 25 m**	**25 m**	**50 m**	**100 m**	**500 m**	**> 500 m**
Unable	3	0	0	0	0	0
Weak	5	3	2	0	0	0
Competent	0	2	6	13	1	2
Highly competent	0	0	0	2	1	9

When asked how frequently they go to a beach, subjects were evenly divided between frequent visitors (at least once a week or more, n=27, 55.1%) and infrequent (once a month or less, n=22 or 44.9%). Frequent beachgoers were primarily visiting Bondi Beach, going there at least once a month (n=19); only n=2 subjects who go to a beach at least once per week were not frequenting Bondi. The other half of subjects either go to Bondi "rarely" (n=14, 28.6%) or this was their first ever visit (20.4%); infrequent Bondi visitors were primarily beachgoers who visit beach once a month or less (χ2=18.588, 1df, p=0.000). There was no correlation between beach visitation frequency and any of the self-reported swimming skill levels or distances (in either the pool or ocean).

Most subjects interviewed indicated that they had noticed some signage or warnings when arriving on the beach that day (n=31, 63.3%), although one third had not noticed any of these (n=18, 36.7%). Chi-square (χ2) analysis was also used to determine if any particular characteristic made a person more likely to notice flags and signs. Being a frequent beach visitor, whether at Bondi or any other beach, had no relation to noticing signs and flags. Likewise, there was no relationship between observance and being: from Australian (χ2=0.993, 1df, p=0.319), from within New South Wales (χ2=2.294, 1df, p=0.130), or living within a 10 mile (16 km) radius of Bondi (χ2=0.943, 1df, p=0.332).

Of those who did acknowledge seeing some form of signage or warning, less than half altered their behavior as result (did alter n=13, did not alter n=18). Reasons given for not altering their behavior were most often related to a familiarity with the beach or the signs themselves, such as: "I already know what they mean/say;" "I swim all the time and it doesn't look too dangerous today;" or "I'm a strong swimmer." Although subjects were recruited only after someone in their party was observed in the water, n=3 subjects said they had not heeded the signs they saw because “I wasn't planning to swim.” Another group (n=3) hadn’t let the sign dictate their behavior because of what they observed others doing: “We went where the surfers already were;” “My cousins [those I’m with] don't care;” and “I just followed my friend.” One subject admitted that “We started for the flags but they were too far away.” Their sentiment was echoed by two other respondents, who had altered their behavior and moved to swim between the flags that day but admitted that “…when I'm short on time I don't [swim near a flag].”

Not all subjects sitting between (or within 10 m) the flags indicated that they had noticed them, but of the n=14 people sitting here, n=8 indicated that the flags were their reason for choosing to sit in that location. Of the n=35 people sitting and swimming away from the flags, the majority (n=21) indicated that they had noticed some form of signs on their arrival at Bondi that day; of these n=35 sitting away from the flags, n=8 had seen them. There were also n=5 subjects sitting away from the flags who answered “We looked for them [the flags] but we didn't see them!” or something similar. For example, one subject suggested that they didn’t see the flags because they “came from the south end” which suggests that they knew the flags were typically located at the other end of the 850 m beach. Another subject, who was from Ohio (United States) said they saw the “Red and yellow flags [but] I'm not sure what they mean.”

All subjects were asked why or how they had chosen that location within Bondi Beach for their activities. Answers were coded into groups that emerged during analysis; an answer could be given multiple codes (see Table 5.5). The most common answer was choosing to sit near the flags (n=12), followed by three answers with the same number of respondents (n=9): staying close to where they entered the beach, staying close to something else (like parking), or intentionally heading towards the waves, usually for surfing. Some subjects determined their location based on the presence of other people (n=12). For n=4 respondents, this meant being drawn towards other beachgoers, as with the subject who said “There were a bunch of girls here,” but for most (n=8) it meant choosing to stay away from others: “[We] were originally down south but moved here [because there were] fewer people.”

When asked to identify the most dangerous swimming location at Bondi Beach, n=11 specifically mentioned the rip currents and another n=5 mentioned the word currents but not “rip” currents specifcally. The majority (n=33) credited present dangers at the beach to rocks or surfers. Of the n=49 interviewed, 53.1% (n=26) did indicate that the southern end of the beach was more dangerous, though most of these people did not directly say that this idea was related to the stronger rip currents which form regularly at that end: of these n=26 only n=8 mentioned rip currents, and another n=3 said something about currents without using the word rip.

Later in the survey, subjects were asked to identify the most dangerous swimming location within three photographs (not taken at Bondi Beach), where the correct answer for each would be the deep water within a visible rip current. Only n=3 (6.1%) of those interviewed were able to choose correctly in all three photos. However, an additional n=12 subjects chose correctly in two photographs, while choosing the shallower rip current feeder as an answer in another. When considered together, these two groups of subjects make up about one third of all those interviewed (n=15, 30.6%). The bottom third of subjects (n=18, 36.8%) were unable to correctly identify the rip currents. Those in the middle (groups B and C in Table 5.6) inconsistently identified rip currents in the images they were shown (n=16, 32.3%). In the rest of the analysis presented here, these are referred to as subjects’ “rip current picture scores.”

Table 10 Reasons given for choosing a particular location within Bondi that day.

Determinant	***n***	**%**	**Examples**
The flags	12	24.5	To swim between flags.
Close to entry	9	18.4	Close to where we walked on to the beach. Flags were too far. Got tired of walking.
Close to something else	9	18.4	It's near where we parked. It's near where we had lunch.
Surfing/waves	9	18.4	This spot was recommended by other surfers for the waves.
Other people (away)	8	16.3	My sister & I wanted to sit away from the crowd. It's away from the surfers.
Other people (towards)	4	8.2	There were a bunch of hot girls here. […] Other people were swimming, including kids.
“Other”	5	10.2	It's pretty central. We're about in the middle of the beach, yeah?

Table 11 Scoring of photo questions.

“Grade”	**Points**	**Identified:**	***n***	**%**
A	12– 15	All 3 correct 2 rips and 1 shallow rip space	15	30.6
B	9 – 11	2 rips and 1 wrong answer 1 rip and the shallow rip entry in the other 2 photographs	10	20.4
C	6 – 8	1 deep rip location, 1 shallow, and 1 incorrect space The shallow water location in all 3	6	12.3
D	3 – 5	1 rip correctly chosen but with 2 wrong answers in the others 2 shallow water rip entries, 1 wrong answer	10	20.4
F	0 – 2	1 shallow rip feeder and 2 incorrect answers All 3 incorrect	8	16.4

Chi-square analysis revealed that rip current picture scores were correlated with just 3 characteristics tracked by the survey (at the 95% confidence level). Subjects who described rip currents, in one form or another, were more likely to score well on the photographs ($\chi 2$=37.134, 28df, >20% of cells have count <5 so likelihood ratio=0.043). Those who scored well were also more likely to know that rip currents are a visible hazard ($\chi 2$=10.984, 4df, 60% cells have expected count <5 so likelihood ratio is used, p=0.009). Every subject who got an “A” rip current picture score (n=15) also answer question 15 correctly, saying that yes, rip currents are a visible hazard. There was no relationship between being a frequent beach visitor, in general, and a higher rip current picture score, but those subjects who visited Bondi Beach at least once per week were more likely to do well on the photographs ($\chi2$=10.026, 5df, 66.7% of cells have expected count <5, and likelihood ratio p=0.023).

5.5.2 Spatial statistics of subjects’ answers and traits

The map in Figure 5.7 shows the geotagged locations of surveys, where colors represent the date an interview was conducted. The cluster of subjects at the north end of the beach is due to regular placement there of the red and yellow flags described earlier; the flags encourage swimmers to enter the water at this location. Of the 39 questions in the survey, 8 showed statistically significant clustering as determined by Moran’s I and Moran’s I (see Table 5.7). Only 3 were clustered with a 95% confidence level. These 8 questions were then investigated with Hot Spot analysis to determine which values were clustering (and where), and 6 variables had cold spots (clustering centers for low values). These 6 variables are shown in Figure 5.8.

For the non-identifying personal information collected, such as age and gender, there were was no significant spatial clustering (at the 95% confidence level). However, subjects’ beach visitation habits and swimming ability did show some clustering. Questions 18 and 19 asked (respectively) how frequently visitors went to Bondi beach (Q18) or to beaches in general (Q19). Both questions had non-random spatial distributions as determined by Moran’s I, but only the “all beaches” question was significant at the 95% confidence level. However, when these data were run through hot spot analysis there were no hot or cold spots at the 90%

or 95% confidence level. Of the six variables which had non-random distribution, four were the four swimming ability questions. As determined by Moran's I, this clustering was present at varying distances and levels of confidence (see Table 5.7). Of these, only ocean swimming distance was clustered at a 95% confidence level. Question 1, asking whether subjects had noticed any signage when arriving at the beach, was one of the three variables (of all 39) clustered at a 95% confidence level. Lastly, question 13 (Have you [ever] heard of rip currents?) was also clustered – but with only 90% confidence.

Hot spot analysis was performed for all 8 variables which Moran's I determined were clustered (see Figure 5.8). Beach visitation, questions 18 and 19, were not clustered with 95% confidence and did not have cluster centers for either high (frequent visitors) or low (infrequent visitors) values. Whether a subject said they had noticed signage upon arrival was significantly clustered (p=0.043677) and had a cold spot, or cluster of low vales, right in the center of the beach (confidence = 90%): people who said that No, they had not seen signage, were more likely to sit and swim within this part of the beach. Those who had never before heard the term rip currents (Question 13) were more likely to be sitting at the northern end of the beach, near the flags (95% confidence).

People who self-reported that they were weaker swimmers in a pool environment were clustered slightly north of center (95% confidence) but this did not translate to their self-reported swimming distances. Self-reported swimming ability in the ocean had a cluster of low values (poor ability) in the exact center of the beach, where there was also a cluster of people who did not notice signage. Those who also said they could not swim far in an ocean environment were clustered in the center of the beach with 99% confidence.

A primary hypothesis for this study was determining whether a significant relationship existed between within-beach location and an ability to correctly spot rip currents in photographs. Moran's I clustering analysis and hot-spot analysis of "rip current picture scores" did not reveal any spatial trends in answers. In addition, when subjects' rip current picture scores were analyzed in relation to their distance from a rip current (as calculated by chi-square methods described in section 3), there was no relationship between subjects' scores and whether they swam closer (or further) from a rip current (χ2=0.183, 3df, p=0.980).

All 39 questions were examined for a relationship to "rip current distance," or the shortest Euclidean distance from a subject's interview location and a rip current present in the time lapse imagery from the day of their interview. Of all possible traits, the only trait with a significant relationship to rip current distance was a person's self-rated swimming ability. Pool ability was insignificant, however, subjects who rated themselves as weak swimmers in open water, such as the ocean, were more likely to sit less than 50m from a rip current (χ2=12.5543, 8df, p=0.014). However, this relationship did not hold when estimated maximum ocean swimming distance was analyzed. All other variables were insignificant when analyzed alongside nearness to a rip current, including whether a subject had seen signage upon entering the beach, did well visually identifying rip currents in photographs, frequently visited Bondi, or hailed from local areas had no relationship to their distance from a rip current.

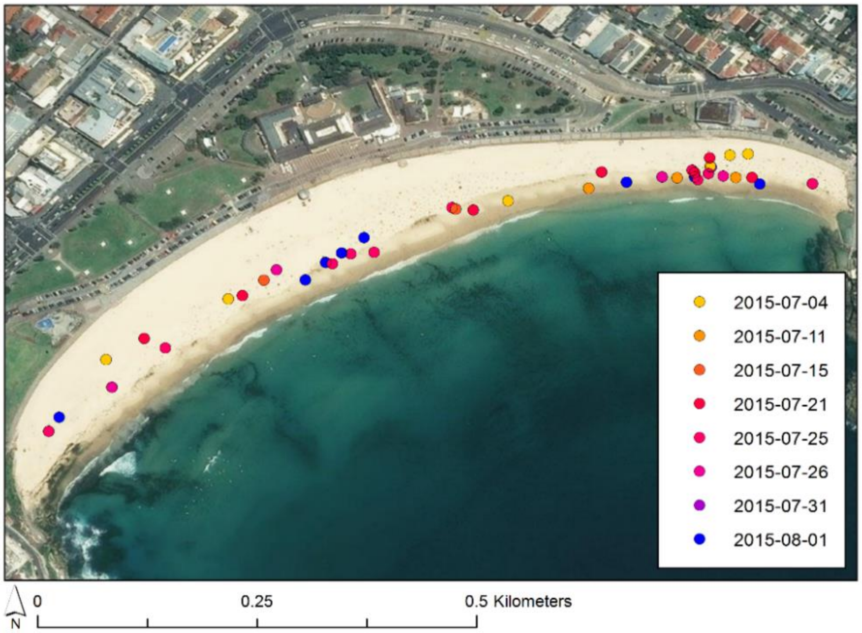

Figure 33 Map of all interview locations conducted during the study, colored by date conducted.

Table 12 Moran's I output for the only variables with non-random distributions

	Question	Values	Distance (m)	Moran's Index	Z-score	p-value
1	Did you see any of signs, flags, or other warnings when you arrived today?	Yes = 1 No = 0	98.09	0.111645	2.017181	**0.043677**
13	Have you heard of rip currents?	Yes = 1 No = 0	54.03	0.002444	1.881943	0.684141
18	How frequently do you come to this beach?	Everyday = 5 > 3/wk =4 1–2/wk = 3 1–2/mo = 2 Rarely = 1 1st ever = 0	76.06	0.127769	1.828914	0.067413
19	How many times per year do you visit any beach?		76.06	0.147657	2.086373	**0.036945**
27	How would you rate your ability to swim in a pool?	Highly comp = 3 Competent = 2 Weak = 1 Unable = 0	87.07	0.120274	1.931914	0.053370
28	How far can you swim without stopping in a pool?	>500m = 6 500m = 5 100m = 4 50m = 3 25m = 2 <25m = 1 I can't swim = 0	120.12	0.069601	1.677365	0.093471
29	How would you rate your ability to swim in open water, such as the ocean?	Highly comp = 3 Competent = 2 Weak = 1 Unable = 0	43.01	0.191083	1.945131	0.051759
30	How far can you swim without stopping in open water, such as the ocean?	>500m = 6 500m = 5 100m = 4 50m = 3 25m = 2 <25m = 1 I can't swim = 0	43.01	0.281187	2.693306	**0.007075**

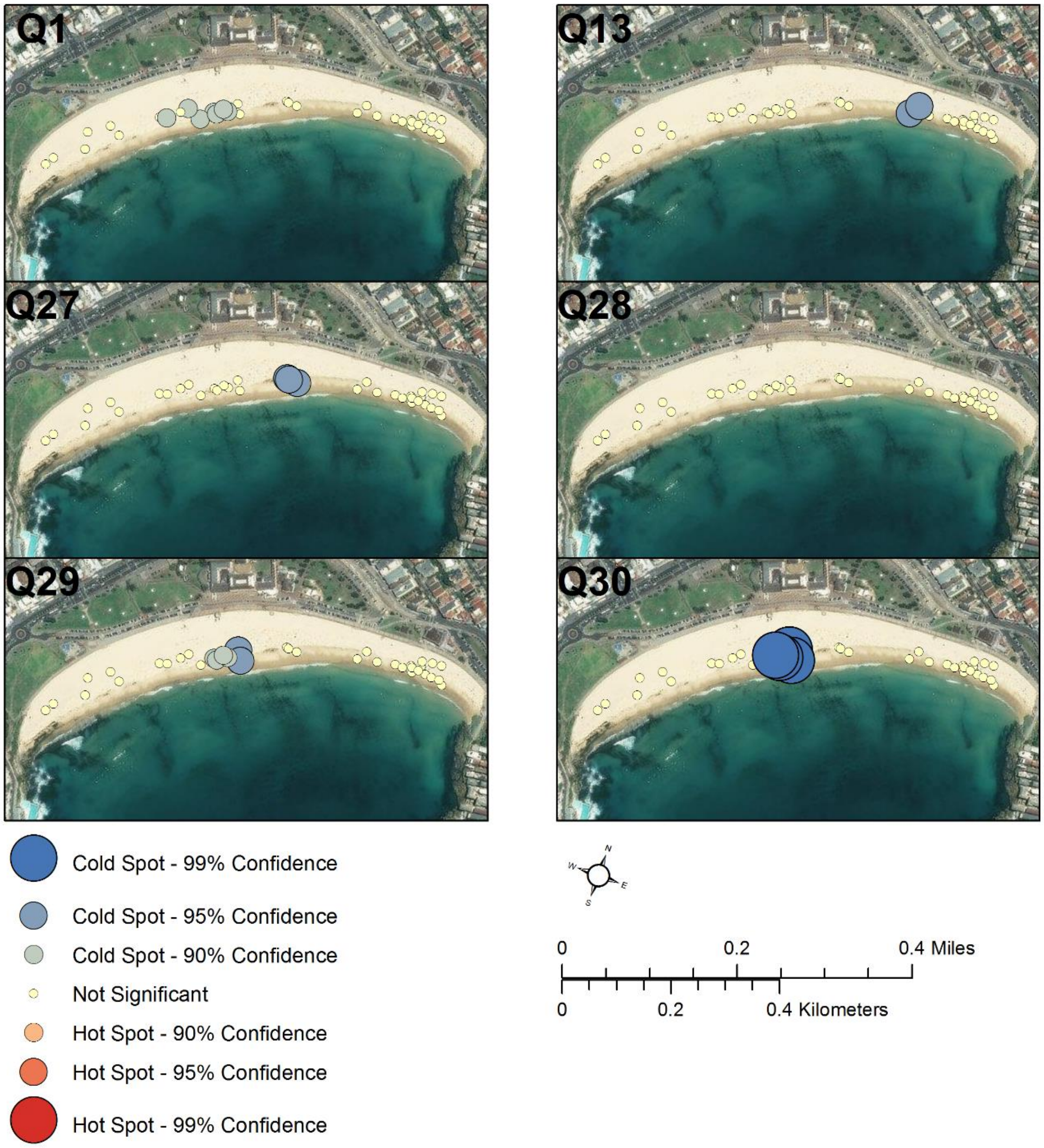

Figure 34 Hot analysis of the6 of variables identified by Moran's I. In Q1, people who did not notice signage tend to sit slightly south of the beach center, with 90% confidence. In Q13, people who had never heard the term rip currents are sitting near the flags at the northern end of the beach (95% confidence). In Q27, subjects who rate themselves as weak pool swimmers are sitting slightly north of center (95% confidence) but there is no center when they evaluate themselves quantitatively in response to Q28: maximum pool swimming distance. When asked about their ocean swimming ability, weak swimmers (Q29) who also estimate they can't swim far in open water (Q30) are sitting in the center (99% confidence).

5.6 Discussion

The two primary hypotheses of this study were (1) that most subjects would be unable to consistently identify rip currents in photographs and (2) that inability to visually identify rip currents would not translate to these swimmers (those who do worse at spotting rip currents) choosing to swim closer to rip currents. In addressing the first hypothesis: only n=15, or less than one third of subjects (30.6%), were consistently able to spot all three rip currents in photographs, reinforcing findings from previous studies conducted in other parts of Australia and the rest of the world: this study is in agreement with previous research findings, that the majority of swimmers cannot consistently see rip currents (Caldwell et al. 2014; Brannstrom et al. 2014).

In addition to this confirmation of previous studies' findings, new trends were observed amongst those who did well in the visual identification portion of the survey. Previous studies have not determined specific qualities associated with better identification abilities; here, chi-square analysis revealed that better scores in identification questions were correlated with three qualities: (1) visiting Bondi Beach at least once per week ($\chi2=10.026$, $p=0.023$); (2) knowing that rip currents were a common danger at Bondi Beach ($\chi2=37.134$, $p=0.043$); and (3) knowing that rip currents are a visible hazard ($\chi2=10.984$, $p=0.009$). However, as shown during spatial autocorrelation and hot spot analysis, none of these groups of subjects congregated in any particular part of the beach. This reinforces the conclusion that the distribution of people within the beach area is not influenced by an ability to see rip currents, familiarity with rip currents as a hazard, or even familiarity with Bondi itself.

Interestingly, there was a concentration of less knowledgeable subjects (those who had not heard the term rip currents) at the northern end of the beach near the flags. This part of the beach was a not a cluster center for any other groups. This suggests that these subjects are self-aware of their lack of beach hazard knowledge: they may not know what a rip current is, but they are aware that they are safer from "something" by choosing to swim between the flags. When the subjects interviewed in this area were asked why they had chosen their within-beach location, "the flags" was the most common answer (n=8). The second most common reason (n=5) was that the location was close to something else. Examples include: it's "near north [the] end where I'm staying, between the flags, [and] less crowded;" and because of the "(A) flags, (B) parked at north end, (C) son feels safer here." The only other trend in answers from these 14 people was that the location was away from others, whether that was "away from the surfers" (n=2) or simply other people (n=2) who crowd the rest of the beach: "My sister and I wanted to sit away from the crowd." None of the answers from these n=14 subjects mentions rip currents. Subjects at this safer end of the beach were choosing that location for reasons controlled by the infrastructure, whether temporary (the flags), permanent (parking), or secondarily influenced (crowds are funneled onto other parts of the beach by other permanent infrastructure). This corroborates findings by other researchers at other beaches, such as Playa Jaco, Costa Rica (Trimble et al. 2017) and Pensacola Beach, Florida, USA (Houser et al. 2015), where beach populations are observed clustering near parking lots and beach entrance mechanisms.

In testing the second hypothesis, there was no relationship between a subjects' distance to the nearest rip current and their ability to visually identify rip currents in photographs. It has previously been speculated that swimmers self-rating as weak might be drawn to the visual gap in breaking waves presented by a rip current. When breaking waves are present elsewhere, it was believed that people who thought poorly of their swimming ability would choose to swim where the waves were lessened, and/or where the water might appear smoother. However, results presented here show this is not the case because an inability to visually identify rip currents was unrelated to choosing a within-beach swimming location that is closer to a rip current.

Although poor swimmers were not statistically related to poorer scores on visual rip currents identification, they did sit closer to rip currents than others. Also, maximum ocean swimming distance, pool swimming ability, and maximum pool swimming distance were not correlated with nearness to a rip current (like ocean swimming ability was), but these qualities were correlated with ocean swimming ability (see Table 5.8). This suggests that people who judge themselves to be weaker swimmers in open ocean water are in general not strong swimmers, and that these weaker swimmers are more likely to sit near rip currents – for reasons other than their inability to visually identify rip currents, because there was no significant relationship between scores on the rip current photograph questions and sitting/swimming nearer to a rip. This suggests that some other factor, not the appearance of the water or the appearance of the rip currents themselves, is driving vulnerable swimmers to sit in certain rip-prone parts of the beach.

Table 13 All variables significantly related to self-reported ocean swimming ability (question #29), when analyzed with Chi-square ($\chi2$) analysis at the 95% confidence level.

#	Variable	$\chi2$	df	p-value
	Distance to a rip	12.5543	8	0.014
27	Ability to swim in a pool	14.886	6	0.021
28	Maximum swimmable distance in an pool environment	29.641	12	0.003
30	Maximum swimmable distance in an ocean environment	53.288	10	0.000

As shown by hot spot analysis, those who self-rated as weak ocean swimmers were more likely to sit near the exact center of the beach. This location was also a cluster center (hot spot) for subjects who did not notice signage and who self-reported that they were weaker swimmers in a pool environment. Two subjects interviewed in the center of the beach, when asked to evaluate their ocean swimming ability, gave effectively the same answer: “I don’t swim in the ocean.” In those two cases, the subjects had arrived at Bondi, walked onto the beach in the middle via the primary staircase, and not walked far within the beach. Although both of these people said they did not like to swim in the ocean, subjects in this study were only recruited once someone in their group had been observed entering or leaving the water. “Group think” has been shown by previous studies to influence the vulnerability of swimmers on rip-prone beaches; subjects exhibit a tendency to follow the behavior of others. This effect may contribute to some swimmers’ willingness to enter the water, if their group is willfully ignoring a risk or is ignorant to the severity of a risk (see Mollen et al., 2012). Specific instances of this effect are have been documented in Costa Rica, in high profile incidents where weak swimmers entered the water on Costa Rican beaches ‘because everyone else’ was, and perished (Aronzarena et al. 2015). With rip currents, the “group think” effect may specifically be that for the would-be victim, the negative consequences of behaving against the group (by not swimming with them) may appear to outweigh the person’s perception of any risks in the surf.

The geomorphological factors generating regularly located rip currents at Bondi Beach (namely, the combination of the embayed shape and modal incident wave angle) create rip currents with increasing frequency and strength along the southern half of the beach. This is echoed by the regular placement of the red and yellow flags at the northern end of the beach during this study. Unfortunately, development of Bondi Beach has also concentrated on this

Figure 35 Landmarks digitized from a collection of tourism maps, collected from popular websites. Bus stops, hotels, hostels, parking, restaurants, and shopping are all concentrated from the center south. Icebergs Club and the Bondi to Coogee beach walk are both located at the southern tip of the beach. Backpacker's express is highlighted by red "B.E." oval (also the southern end of the beach).

side of the 1 km stretch of sand (Figure 5.9). Hotels, restaurant, and shopping are most common along the southern end, from Bondi Road to Hall Street, which runs to the southern end and center of Bondi, respectively. In addition, the bus routes that non-locals would use to get to Bondi (numbers 380, 381, 382, or 333) all let riders off at stops at the southern tip and center of the beach. In addition, two large attractors to tourists, the Icebergs club and the Bondi to Coogee beach walk path, are both located at the southern end of the beach. Bondi is not the only beach where development may be leading crowds to concentrate closer to common rip current locations. Mounting evidence suggests that beach access construction can inadvertently steer unsuspecting beach users towards rip-prone areas of a beach, thereby increasing likelihood of drownings (McKay et al. 2014; Trimble et al. 2017). Warning signs are posted at each of the ramps and stairways down on to the sand at Bondi (refer back to Figure 5.3), and previous work has demonstrated that beachgoers can develop the ability and confidence to visually identify a rip current from public safety campaigns (Hatfield et al. 2012). However, most research (Drozdzewski et al. 2012; Williamson et al. 2012) is corroborated by these results in suggesting that an ability to identify a rip current or to recognize posted warnings will not fully prevent beachgoers from choosing to swim in unsafe and unpatrolled sections of the beach.

At Pensacola Beach, Florida, USA, rip currents develop regularly along the beach between transverse ridges on the inner shelf (Houser 2009; Houser et al. 2011). These ridges also create a pattern of alternating complex and less developed dunes (Houser et al. 2011). As a result, low dunes are coincident with regular rip currents, and rip-current related rescues and fatal drowning incidents are clustered along the beach (Barrett and Houser 2012; Houser et al. 2015). In part to limit dune disturbance, well-intentioned policy makers then preferentially built beach access in the areas with smaller dunes. Unfortunately, because the same nearshore processes that create low dunes also foster rip current circulations, these beach access structures lead beach-goers to preferentially enter the most rip-prone sections of the beach. Analysis of locations of small dunes and beach access points at Pensacola Beach and revealed that parking lots tend to be located immediately landward of rip current hotspots, meaning that beach users have a strong potential of entering a rip channel and needing rescue or fatally drowning (Houser et al. 2011; Barrett and Houser 2012; Houser et al. 2015).

In Costa Rica, Playa Jaco (Jaco Beach) is an embayed 2 km beach fronts a valley drained by three small rivers and bounded by two rocky headlands. The central stream discharges into the surf zone, depositing a sediment terrace that generates alongshore variation in wave breaking and sets up a central a rip current, with others sometimes spawning off along the beach to the north. Because it is the center of the valley and close to the main highway, the main public access point is also located here. Similar to Pensacola Beach, beach access points at Jaco inadvertently focus beach users towards rip-prone parts of the beach. Despite signage and lifeguard patrols, Jaco records more drownings than all other beaches in Costa Rica combined (Arozarena et al. 2015; Trimble et al. 2017).

At Galveston Beach, in Texas, USA, rescue incidents have been clustered along the seawall portion of the beach, where groins generate rip currents under a wide range of surf conditions (personal communication, Galveston Park Board). Despite the fact that the beach access points are found directly landward of the structurally-controlled rip currents, the strong lifeguard presence here makes 50,000 to 60,000 each year, and drownings are more likely to occur outside the guarded seawall beach. Here, the risk to the public created by the seawalls and beach infrastructure has been partially mitigated by the deployment of lifeguard posts adjacent to each rip-generating groin (Trimble et al. 2017).

The results of the study present here suggest that from a managerial standpoint, decision makers should focus on building access that steers people away from persistent rip currents and posting lifeguards more heavily where rip currents regularly occur. This is because the beach going public does not tend to notice signage and alter their behavior as a result, they generally do not have the ability or knowledge to visually identify rip currents, and they do not consider rip current presence when choosing their within beach location (with the exception of knowledge surfers, who are not considered vulnerable).

5.7 Conclusions

Because only one third (30.6%) of all subjects were able to consistently identify rip currents in photographs, we confirm that the majority of beachgoers cannot visually identify rip currents. However, there was not a statistically significant relationship between subjects who scored poorly on photographs and sitting near a rip current. The GPS-located interviews revealed that an individual’s ability to identify a rip current by sight does not relate to their chosen swimming location within a rip-prone beach. The only significant characteristic shared by those who were more likely to sit close to a present rip current was a self-identified poor swimming ability in open ocean water. These beachgoers are not necessarily attracted to the break in waves provided by an outgoing current, but other factors are influencing their decision to enjoy the beach and enter the water closer to regular rip current locations.

Vulnerable beach-goers, like those who are not strong ocean swimmers or who do not heed posted warnings, may be more likely to choose their within-beach location based on the nearness of other features, such as parking or bus stops. This is also true of people who are not frequent visitors to a particular beach. Because rip currents can form in preferential locations as a result of nearshore geomorphology, it is important to build intelligent beach access that accounts for this geomorphology. If this is not done, it is possible to inadvertently focus vulnerable populations towards regularly forming rip currents. In multiple international locations, the same physical landscape that makes beach development easier in a given location is also generating regular rip currents.

Although signs may be placed at these entrances, multiple studies have shown that less than half of a beach population will see, interpret, and apply the warning information in the signage. To more fully protect the beach-going public and mitigate rip current related injuries and fatal drownings, it is necessary to consider local geomorphology controlling rip current location and construct beach access that steers swimmers towards safe waters where the currents are less likely (or unable) to form.

6. MAINTAINING A DONATION-FUNDED LIFEGUARD PROGRAM

6.1 Abstract

Rip currents are concentrated, seaward-directed flows of water that form amongst breaking waves on beach worldwide. These naturally occurring phenomena can be dangerous and even deadly when they carry weak or unknowledgeable swimmers into deeper waters. Estimated rip-current fatality rates are about 21, 51, and 59 people per year in Australia, Costa Rica, and the United States, respectively. The US Center for Disease Control and the World Health Organization have both published reports detailing the severity of frequent drownings worldwide, and the critical role of lifeguards in preventing fatalities. In this study, interviews were conducted in a small beach community in a middle-income country where rip currents were a cause of frequent fatal drownings prior to 2004. In response, the community formed a donation-dependent lifeguard patrol and successfully ended rip-related drownings at the patrolled beach. Results highlight subjects' perception of the lifeguard program's benefit to the community (both direct and indirect), its financial stability, and potential for growth. In this case, the community mobilization of resources has resulted in a drastically improved fatality record. However, in other, similar cases, programs were forced to shut down because of financial stress, which this program is currently experiencing. Results of interview analysis suggest that the local community was united in starting and sustaining the program, but changes must be undertaken for the program to continue. This grassroots, donation-dependent format may serve as a model for similar communities in that it allows the immediate creation of a lifeguard program, and up to a decade of sustained patrol of a dangerous beach. For continued program survival, additional growth and finances may be necessary.

6.2 Introduction

Rip currents are concentrated, seaward-directed flows of water that form amongst breaking waves on beaches worldwide (Shepard et al. 1941). They are naturally occurring phenomena that result from alongshore variations in wave breaking, and can be dangerous (even deadly) when weak or unknowledgeable swimmers become caught in them and carried swiftly to deeper waters (Brander et al. 2011). Exact numbers of death and injury caused by rip currents are logistically difficult to collect, in part because “drowning prevention, much like other areas of injury prevention, is a young and emerging field” (Branche and Stewart 2001). Recent efforts to consolidate national records have been made by the United States, Costa Rica, and Australia. The national Surf Life Savers program reports nearly 22,000 annual rescues at Australian beaches, of which approximately 80% are related to rip currents; there are still an annual average 21 fatalities (SLSA 2009). Rip current fatality estimates for the US have ranged from 35 per annum (Gensini and Ashley 2009) to nearly 100 (Lushine 1990), but records published since 2009 suggest there are an annual average 59 fatal drownings from rip currents in US waters (NWS 2017b). In Costa Rica, national records of natural disaster related deaths have been kept for several years, and there are ~51 fatal drownings attributed to rip currents each year (Arozarena et al. 2015).

The World Health Organization (WHO) lists drowning (in general, not just that caused by rip currents) as the third leading unintentional-injury cause of death (WHO 2014). Drownings have significant health economic impacts where they occur, and lifeguards are a critical component of a drowning prevention system (Branche and Stewart 2001). In the top 10 strategies for reducing drowning events of all types worldwide, the WHO lists providing safe swimming areas (such as lifeguard patrolled beaches) and increased research into community reaction to drowning (WHO 2014). We present here a case study of a single community where a donation-dependent lifeguard program was successfully formed following a spike in fatalities at the local beach and has since prevented fatal drownings in the area's notorious rip currents for 13 years. Many aspects of this model may serve as an example to other communities which might wish to adapt a similar system; there are, however, some struggles this successful program faces.

6.2.1 Global and local impacts of fatal drowning

Drowning is "the process of experiencing respiratory impairment from submersion/immersion in liquid" (van Beeck et al. 2005) and many health organizations differentiate between 'drowning' and 'fatal drowning,' as this process does not have to result in death (WHO 2014; USLA 1999). Drowning is within the top 10 causes of death in every region of the world for people under 25, but 91% of all drowning deaths occur in middle or low income countries (WHO 2014). Once someone has begun to drown, the outcome is often fatal because unlike with other injuries, surviving drowning is "determined almost exclusively at the scene of the incident" and "depends on two highly variable factors: how quickly the person is removed from the water, and how swiftly proper resuscitation is performed" (WHO 2014). In essence, the only way to ensure both actions occur is to swim under the supervision of a trained lifeguard.

Specific details and data regarding all types of drowning, including rip-current related fatalities, is logistically difficult to collect (especially in many low- and middle income countries) which hinders efforts by decision makers at all policy levels in planning, implementing, and monitoring drowning prevention measures (WHO 2014). "In addition, the way deaths are classified means the full extent of the world's drowning problem is underrepresented… [d]ata on non-fatal drownings, which could reveal something about the burden of serious injury and lifelong disability, are not routinely collected" (WHO 2014). There is a need for "much more national and international attention focused on drowning, given the limited data available on its true scale and the heavy toll it takes on families, communities, and economies" (WHO 2014).

6.2.2 Economic effects of fatal drowning

Many lifeguard programs are begun only after a large drowning event. "[W]hen many people drown at once […] entire villages and communities are shattered" (WHO 2014). The economic cost of such events is also high, "and while difficult to quantify globally, national-level estimates for Australia, Canada and the United States of America (USA) range from US$ 85 million to US$ 4.1 billion per year" (WHO 2014). "Community and local government officials facing decisions about whether to begin, retain, or discontinue lifeguarding services typically want to know whether lifeguards are truly effective in preventing drowning and other aquatic mishaps, and whether the value of providing lifeguard protection outweighs the costs," as cost is typically the primary criterion in this decision (Branche and Stewart 2001, pg. 1). "Evidence suggests that lifeguard services benefit public safety by saving lives, lowering drowning rates, and preventing injuries in aquatic recreational environments" (Branche and Stewart 2001, pg 5). Lifeguards also provide more indirect economic and social benefits to the community by preventing the much greater costs and losses incurred by fatalities. These include direct costs, such as medical care, but also the more indirect loss of the victims' economic productivity (Hassell 1996) and the cost of emotional and social trauma which burden to victims' family and friends (Branche and Stewart 2001).

The cost of a single catastrophic injury or death can be measured economically in both categories. In the United States the economic value of a life lost to unintentional injury death (as happens with rip current fatal drowning) was estimated at $790,000 in 1997 (National Safety Council, 1997). Adjusting for inflation, that number would be closer to $1.2 million today (BLS 2017). This would put the economic burden of the ~59 annual rip-current related drownings in the United States at almost $72 million per year in this decade. It is also possible to estimate the economic and social costs prevented by establishing a successful lifeguard program. Assuming that just 1% of all 88,601 rescues performed by lifeguards in the US in 2016 (USLA 2017) had resulted instead (in the absence of a lifeguard) in a fatal drowning, the economic cost avoided by successful lifeguard action was > $1 billion. These estimates only account for fatalities, but injury prevention is also an economic and social capital savings incurred by lifeguard success.

"While these estimates help demonstrate the range of costs of drownings and water related injuries and the benefits of prevention on a national scale, the numbers may be so large that they do not assist decision makers working with a single, community facility" (Branche and Stewart 2001, page 12). Various economic models have been created to guide communities and decision makers in estimating their own benefits and costs. One such model converts values with ratios; by this estimate, not having lifeguards in a community of 10,000 would cost citizens a minimum $300,000 per year but up to $6.8 million (Mael, Seck, and Russell 1999; BLS 2017). In comparison, salary and benefits (typically 50% of costs) for a single, full-time, year-round lifeguard in the San Diego beach patrol (one of the most well-paid in the country) started at $58,000 in 2015 (Flaccus 2015). Not all beaches need year-round patrols, and seasonal or part-time guards with no benefits cost a community even less. These economic values make a quantitative case for instituting lifeguard programs to prevent injury and deaths as they offer significant savings as a whole (Branche and Stewart 2001).

6.2.3 Lifeguard effectiveness

Lifeguard patrols are still a new societal mechanism, relatively speaking. The surf lifesavers club at Bondi Beach in Australia claims to be the world's first; it was established in 1906 (Short and Hogan 1990; Brawley et al. 2007). In the US, the popularity of surf bathing as a recreational activity rose steadily throughout the 1800s and by the early 1900s, so many people were swimming at the beach that the annual average fatal drowning rate was as high as 9,000 people each year (American Red Cross, 1995), in part because so little was understood about swimming safety and drowning prevention. Records by the USLA show that in 2016, only 25 people drowned on guarded beaches, with another 154 fatal drownings occurring on unguarded beaches or outside patrol hours (USLA 2017) and U.S. lifeguards rescue an addition estimated 100,000 persons each year (Branche and Stewart 2001). "Most drownings are preventable through a variety of strategies, one of which is to provide lifeguards in public areas where people are known to swim and to encourage people to swim in those protected areas" (Branche and Stewart 2001, pg. 1). It is for these reasons that the WHO lists providing safe swimming areas, such as lifeguarded waters, as #2 in its list of 10 drowning prevention strategies (WHO 2014).

The USLA estimates that the chance of drowning on a beach guarded by USLA trained guards is less than one in 18 million (USLA 1999). Increased presence and training of USLA guards on US beaches coincides with a drop in the rescue-to-drowning ratio from ~ 1 every 2,004 rescues in the 1960s to only ~ 1 in every 4,832 rescues in the 1990s (Branche and Stewart 2001). In the decade from 1988-1997, there were fewer than 100 fatal drownings in all waters (not just beaches) guarded by USLA lifeguards, and most of these (>75%) occurred outside of patrol hours (USLA 2000). Unfortunately, an annual trend is that most drownings occur outside of areas that are patrolled (Mael, Seck, & Russell, 1999) and in 2001 about 65% of US beaches were still unguarded (Brewster & Richardson, 2001). In addition to rescue statistics, it is important to note that "for every rescue, an effective lifeguard makes scores of preventive actions, such as warning an individual away from a dangerous area," thereby preventing an even greater number of dangerous events (Branche and Stewart 2001).

6.2.4 Previous case studies

Perhaps some of the most compelling evidence advocating for lifeguard presence comes in the form of multiple case studies in communities where rescues and fatalities occurred in dramatically different numbers following the establishment or removal of a lifeguard program (Branche and Stewart 2001). Nassau County, Florida, eliminated their lifeguard program as a cost saving measure in 1989. The following Memorial Day weekend, surf conditions generated strong rip currents all along the beach, causing 5 fatalities and 20 near-victims who survived as a result of bystander rescue. The lifeguard program was immediately reestablished and fatalities ceased (Branche and Stewart 2001). Similarly, at Keawaula Beach in Hawaii, 2 fatalities and 40 near-victims were rescued by bystanders before a lifeguard post was created in 1992 and no deaths have been recorded since (Branche and Stewart 2001). Ocean Beach, located in California near San Francisco, experienced slow removal of existing lifeguard programs throughout the 1990s and drowning events began to increase. Following a peak 7 deaths in a matter of months in 1998, the program was reestablished and fatalities ceased (Branche and Stewart 2001). This is not a phenomenon unique to the United States; the community of Tamarindo in Costa Rica also closed their community funded lifeguard program (due to lack of funds; La Nación, October 1, 2007) and although no drownings were reported in the 3 years the program was running, there were 3 drownings the first two years it was shut down (Arozarena et al. 2015).

6.2.5 Community funded organizations

There is a body of literature in sociological research which investigates how grass-roots organizations form, behave, and sustain themselves – including a body of work specifically focused on these groups when they are related to community health in middle and low income countries. The lifeguard organization investigated here falls into these categories because it was incepted by local members of the community, is maintained by the same, and is an integrated part of the community. Sociologists have used the term ‘mobilization theory’ to describe the formation of community groups in response to external threats on local resources when both social cohesion and shared meaning in the community are high (Watanabe et al. 2015). In this case, the external threat is a natural hazard, whose formation cannot be controlled and which threatens the resource of income from tourism. For such organizations to succeed (sustain themselves), the community must sustain a high level of engagement with the organization. This is developed through collaborative effort amongst people who are “affiliated by geographic proximity, special interests, or similar situations,” and inspired to improve or maintain their well-being (Watanabe et al. 2015).

The formation of grassroots organizations, like this lifeguard program, are often sparked by a community-wide acknowledgement of some source of discontent. However, when a program is successful it relieves this discontent over time and sustainment of the program must be motivated by other motives. In sociological theory surrounding community mobilization, the "community engagement continuum" has five levels of community ownership and leadership which can be described as continuum (CDC 2011):

- 'Outreach' is the lowest form of communication and is only one-way, usually top-down
- Once the community is invited to provide feedback to leadership, a group has reached two-way communication, or 'consultation'
- At the level of 'cooperation,' there is a partnership between the community and leadership
- 'Collaboration' occurs when communication flows freely through organization levels, and all aspects of the program include a partnerships
- The highest level of community engagement is 'shared leadership,' where "the community shapes communication, makes decisions and takes initiatives" (CDC 2011)

No matter the level, empowerment is an important element in sustaining programs. For this reason, sustained community engagement of any type is necessary to the organization's survival, as engagement cannot happen without empowerment but also produces empowerment (Treno and Holder 1997; Watanabe et al. 2015). "Community engagement [must] mature into empowerment" to sustain interventions into the health of the community (Watanabe et al. 2015).

"In the community engagement continuum, health empowerment develops incrementally over time as people gain their knowledge and skills, form coalitions, and develop collaborative networks (social capital) to make decisions and take action for change" (Watanabe et al. 2015). In a case study of successful grassroots organizations aimed at resolving health related issues in the community, maximized face-to-face communication was a key element (CDC 2011; Watanabe et al. 2015). In these cases, barriers to engagement, which include health literacy issues, financial difficulties, and underdevelopment of infrastructure required to deliver the health service, had been minimized "through active collaboration and mutual assistance" between the organization and external beneficiaries, such as state-related funding agencies (Watanabe et al. 2015). Grass-roots organizations often face funding challenges, as there is nothing inherit in their formative process that "automatically ensures program success" (Treno and Holder 1997). As such organizations grow, external support and funding can become necessary for sustaining the program because the source of discontent which sparked its formation does not remain constant over time (Walsh 1981).

6.2.6 Study site

The anonymous community where this study takes place is in a middle-income country with high reliance on tourism focusing on the natural environment, including nearby beaches. At the study site, strong surf and an idyllic beach environment attract a growing number of international tourists but also generate strong rip currents. Drownings have occurred there before but in the wake of a particularly deadly holiday week in 2004, when a peak number of 5 people drowned in 8 days, the community created a donation-dependent lifeguard program. In the 13 years since, there has been only one fatality during patrol hours, when a person had a heart attack while at the beach (not due to the surf or rip currents; personal communication with the program director, 2015).

The country does not yet have a nationwide lifeguard program like the USLA in the US or the SLSA in Australia, though the American Red Cross has published to social media that they are working with the national government there to create one. Until that program is running nationally, the study site remains one of only two guarded beaches in the country. The other beach is patrolled by state funded guards at one of the most popular beaches in that region. In the community studied here, the beach is patrolled by a single lifeguard who bikes in several miles every day from a nearby town. He patrols from 9 am to 5 pm every day, excepting the occasional day where he asks for time off and/or recruits a similarly capable friend to cover for him (personal communication with the guard, 19 July 2016).

The community has a localized economic geography, with many small businesses employing fewer than 10 people; it appears the grocery store may be the largest employer in the community (unconfirmed, based on observations by the author). The same is true of the tourism sector in the community, and there are not currently any chains or franchises present. Many other beach communities in the country have a higher degree of stratification among tourist-oriented firms, with some family-owned businesses but also large corporate entities (and everything in between). In the community studied here, many subjects knew each other. Although this is in part because they were recruited based on their status as donors to the lifeguard program (and may have known each other through the program) not all subjects were the owner of the business where they worked. Despite being employed at lower levels in the firm, they were still (at times) familiar with owners of other small businesses in the community.

This localized economic geography, specifically the lack of franchises and large firms, may have an effect on the program's origination and development.

6.3 Methods

A semi-structured interview was designed and approved by the relevant human subjects review program (IRB2012-0379D). On three visits to the study site, in January, March, and July 2016, the primary author recruited subjects by door-to-door solicitation during business hours with low traffic. Recruitment was determined by the lifeguard program's website, where the interviewer obtained a list of all donors in July 2014 and July 2016. Donating business or individuals were listed on the website in categories denoting whether they were one-time, multiple occasion, or frequent (large) donors to the program. Exact dollar amounts of individual donations were not advertised, although the categories were assigned ranges. Aside from their names, no other contact or personally identifying information was listed. This impeded contacting individual donors specifically. However, because nearly all of the donating businesses were located in the nearby town (distance from lifeguard tower to downtown was < 1 km) and they were marked with signage advertising the same name listed on the lifeguard website, it was possible to identify and locate most of the donating businesses. Of those listed on the website as donors from July 2014 until July 2016, 42 were businesses in the nearby town which it was possible to locate; 21 of these were approached during the three trips.

By nature of the approved recruitment process, recruits could be either employees or owners of donating businesses. The lifeguard, one of his occasional relief workers, and the program founder were also interviewed. To comply with the human subjects review board, the interviews were kept anonymous. Throughout the remainder of the study, to preserve anonymity, subjects are referred to by randomly assigned, non-gendered names common in the author's native country. Subjects were given an information sheet that provided project details, contact information for the author, and which asked for consent to record the interview. If consent was granted, the researcher conducted the interview, alternatively in English or the local language. Answers were recorded with audio and notes written in view of the subject. The audio was transcribed later. The semi-structured survey design is provided in Appendix B.

During analysis, responses were coded according to themes which emerged from the text, however in some cases results clearly reflect the semi-structured nature of the survey instrument. For example, respondents sometimes repeat words from the question within their answer (e.g. including the word 'benefit' in answer to the question "Do you feel that your business directly benefits from the lifeguard program?").

6.4 Results

To preserve anonymity, subjects are referred to by non-gendered English names randomly assigned by the authors. Of the 21 contacts made, 12 people completed an interview (contact rate: 50%; response rate after contact: ~57%). These included the program founder, the lifeguard, and a man who works as the lifeguard's occasional relief. The other 9 subjects either work at business listed as donors on the website for at least 2 years (from July 2014 – July 2016). Five of those interviewed did not know Cory ran the program; for one Pat it became apparent during the interview that they did know the program founder "Cory" and socialized with them regularly, but until the end of interview Pat "didn't know [Cory] was even part of it." This splits the subject pool into three primary groups: 3 people involved in the program (the founder Cory and two lifeguards), 4 subjects who knew Cory, and 5 who were removed enough from the program they didn’t know who was in charge (Table 6.1).

Respondents worked at a variety of business types and sizes and all reported being regular (usually monthly) donors. Five subjects owned the business where they worked and were therefore also in charge of the decision to donate to the program. Others estimated how frequently their boss donated to the program. Subjects were associated with the community for a wide variety of years; while Lynn had lived there their entire life Colby had lived in the country less than a year.

Table 14 Generalized and anonymous demographics of subjects.

"Name"	Originally from	Lived locally	Familiar with program founder?	Business type	Business role
Cory	English speaking country A	22 years	Is founder	Hotel	Owner
Sam	Nearby town	Entire life	Yes; is primary lifeguard	Lifeguard	Employee
Taylor	This town	Entire life	Possibly; occasional LG assist	Unknown	Unknown
Blair	This country	5 years	Yes	Tour operator	Employee
Kris	Spanish speaking country B	22 years	Yes	Hotel	Owner
Pat	English speaking country A	5 years	Yes, but did not know as founder	Hostel/bar	Owner
Tracy	English speaking country C	11 years	Yes	Spa & School	Employee
Alex	English speaking country A	7 or 8 years	No	Scuba shop	Employee
Jody	Spanish speaking country D	11-12 years	No	Coffee shop	Employee
Lynn	This town	Entire life	No	Tour operator	Employee
Robin	This country	3 years	No	Salon/spa	Owner
Colby	Spanish speaking country E	< 1 year	No	Bar/restaurant	Owner

6.4.1 Benefits

Each respondent was associated in some way with a business dependent on the local tourism. Aside from the two lifeguards, no two respondents work for the same business. When asked how their individual income was associated with the beach itself, subjects gave a wide range of answers ranging from Jody, who works at an organic coffee and snack shop directly across from the beach and sees a direct benefit from beach traffic, to Alex, who does not think the beach has much to do with success at the scuba shop. Pat perhaps gave the clearest explanation, when they said their hostel/restaurant/bar benefits “more indirectly, just because that is the […] surf beach, so it gets surfers into the town. They come here to go there, mainly.”

When asked to discuss the various benefits of the lifeguard program to their business, respondents gave a mix of answers. Tracy was grateful because they said the lifeguards “take care of our clients” where Pat was direct with “people are still alive to spend money” because of the lifeguards. Alex, of the scuba shop, saw no direct connection to his business but thought there was a positive effect on the town economy as a result of the lifeguard program because there are fewer reported deaths:

> “Having the lifeguard tower there, and protecting the tourists, it creates tourism because they don’t have that embassy saying it’s dangerous – because the embassy will not differentiate between a death of a drowning or a mugging. If 5 people die here, 5 people are dead. It still becomes a dangerous place to come […] A death in this town isn’t good for anyone. Drowning, murder, or anything in between.”

The U.S. Embassy in this country does not post city-specific reports of crimes but does maintain a website which includes “Embassy Messages” and a link to the 2017 Overseas Security Advisory Council (OSAC) Crime Report for the region. This page (last updated on March 2, 2015) includes the message:

> “U.S. Embassy [in the Capital] has received reports of a particularly high number of violent assaults and robberies in the [study site] region (from [northernmost town] through [central town] to [the study site]), often involving invasions of rental homes and eco lodges.”

The idea that embassies might warn citizens away from town if deaths of any kind are reported was a constant among respondents, even though this message took some effort to find, it does not report the number of crimes, and it does not mention fatalities. Cory, whose hotel is located across the street from the guarded beach, reiterated Alex’s attitude and how the lifeguards might fit into it:

> “People drowning doesn’t have a significant effect on visitation. People getting assaulted has a significant effect […] However, I think [that] on the other hand, having a lifeguard program here is […] an added value.”

He then went on, however, to add that the internet is a larger source of information that it was before the lifeguard program started in 2004: “Now, I’ll take that back. If you had an epidemic of drownings […] if 5 people drowned in 8 days, again, then [that] would have an economic effect."

By the respondents' line of thinking, the lifeguards may not necessarily attract more business, but their effect is felt through keeping safety records within embassy's limits. Respondents were consistent in sharing this impression that at least some of such an indirect benefit affects their business. As Lynn described the relationship, their tour operator business does not necessarily get more traffic because they are near the only lifeguarded beach in the region, nor would they lose business if the lifeguards went away, instead "we have benefit, in a way, but not direct."

Cory was quick to point out that the benefits from the lifeguard program to the community can be hard to measure because:

> "[A fatal drowning is] a terrible event for anybody that's on the beach, it's a terrible event for the host hotel, not to mention the family… it has a negative psychological effect […] so speaking of it in purely economic terms is not complete."

Adding that prior to the lifeguard post, there were a few drownings each year: "every family has lost someone" and "not just the tourists [benefit]." This was supported by one of the respondents; one of Tracy's coworkers had lost her husband to a rip current before the lifeguards were established: "[He was] a local man […] he went in to the water and she watched him being taken out…"

Respondents all shared the view that the entire community, not just the tourists, was safer and healthier because of the lifeguard patrol. This was most often defended in a report of how there were many drownings before the lifeguard post was established, and few to none after, yet surrounding (unguarded) beaches continue to have fatalities. Kris said that before the lifeguards "había mucha muerte allá" (there were many deaths there) but no deaths after; this was echoed by Lynn who said that back then "people didn't have information."

Taylor pointed out that people continue to die on other nearby beaches because they remain unguarded. Pat described a recent event at the closest unguarded beach to town: "My mother in law was in town for Christmas and they're sitting out there on the beach and she watched somebody down over there because there are no lifeguards." Although Pat had only lived locally for about 5 years, first started visiting almost 15 years ago before there was a lifeguard program and confirmed that there was a difference in safety because of the guards: "I surf, I go down [to that beach] probably 3 or 4 times a week […] I haven't seen anybody drown while [the guards are] out there and I've seen them save multiple people […] every month or so I've watched [the lifeguards] save somebody." Jody thinks there are probably "daily" rescues, Blair estimates they make 4 or 5 saves per week, and Cory, who runs the program, reports that since the program's inception there have been an estimated "more than 500 critical rescues" that were "life or death" situations. Tracy, who has lived in the town for over a decade, had a good deal to say about the positive effect the program has on the entire community:

> "Most people are attracted to [this beach] because it's one of the best surfing beaches in the area […] but it's not a great beach for swimming. I don't swim [there]. There's too many rip tides. The currents are too strong. It's a very volatile section of the water inasmuch as you do not know how quick that can change […] so to have a lifeguard

> program there is invaluable […] There's more drownings [there] than at any other beach […] in this area."

Since the program began in 2004, both Sam and Cory confirm there has been one drowning during patrol hours; in Sam's words, he was a healthy, big, strong man – which is proof anyone can drown. As Cory described the incident, a man had a heart attack or similar health complication in shallow waters and he could not be revived; the family of the victim did not relate the incident to the lifeguard program.

6.4.2 Finances

When asked whether it was financially difficult to give to the program, all respondents answered that donating was easy (whether the owner of the business or simply an employee). Although some subjects rated the effort as '2, somewhat easy' (on a scale of 1-5) most rated the effort as '1, not difficult' and Alex said the donation was "no, not at all" difficult to make, though he is not the person who makes the decision. This finding is consistent with other answers, given that: respondents had such positive things to say about the program, no one reported having ever heard negative commentary in the community about the program, and recruitment was determined by a record of donations to the program. Tracy said specifically donations are "not huge" and that the spa gives about US$10 per month, which is much less than a single treatment there.

Program founder, Cory, stresses that financial instability threatens the lifeguard post. The irregular and occasionally insufficient funds result in lifeguards without perfectly regular salary, benefits, or paid time off – all aspects which Cory wants to see included in the program.

Sam (the lifeguard) says that a lack of health insurance is their primary concern. Financial instability has been the root cause of many other lifeguard programs closing (as outlined in section 6.1.4) and Cory fears this fate for his own program.

Lynn, who has lived in town their entire life, suspected that the majority of businesses in town do not donate, and although Cory also says "way less" than half of all businesses in town are able to donate to the program, they justified these numbers by saying a significant portion of the "solid" (stable, constant, and larger) businesses do donate. The seasonal nature of the tourism economy was also credited by Tracy and Robin as the primary reason more in the community do not contribute. For many businesses it is perhaps difficult to give monthly donations because they cannot survive the "off" season, says Tracy: "we donate monthly but I think other businesses are less consistent which is maybe what the problem has been historically with trying to keep the program going […] Businesses come and go here very quickly." Robin seconds this by adding that some businesses close completely in the 'low season' and that multiple organizations ask for monthly donations, which may be why only some businesses choose to donate to the lifeguards. Pat also mentioned that "There's a lot of things that ask for donations [every month] so we have to make a budget." Pat says they regularly donate to the lifeguard program every year, "but for others we have to budget" to be able to donate.

Cory says "there's not much more [the program] can do" to solicit more donors or larger donations from small businesses: "We need one large private donor" or government help, which the only other persistent lifeguard program in the country receives (it is located in a different region). Sam, the lifeguard, says they have filed the necessary paperwork with their state government to start this municipal-assisted funding source. Blair, who says they know

Cory well, made only one suggestion for changes to the program, which was that Cory may have maxed out their personal network and greater outreach into the community could result in more donors:

> "The image in the community have to be more exposure. Everybody link the thing with [Cory] and it should be not like that. It should be like, the program itself [put forward]. So many people don't even know about it because, it's normal, if I direct a program like that, I gonna try to - the closer people to me or my friends try to help me out, right? Of course, if there's people that normally don't really like me that much or *I don't even know them* that much, there's going to be less [involvement from them]."

Blair added that many people don't even know how to find out for themselves how the program is funded. That Cory is well known within the community is supported in part by Pat's remark that Cory is "a part of a lot of different programs here" and in that half of the respondents knew the founder personally, although Pat did not know Cory ran the program until the end of the interview. In addition, when asked who might run it, Alex said "if I had to guess it would be [Cory], [who] has started all the [regional] surfing competitions, and I think the surf competitions go with the lifeguard tower and promoting safe surfing and surfing in general here. […They've] got [their] hands in everything so I guess [they'd] be the one."

Part of Cory's role in the organization is soliciting donations, but it is the lifeguard Sam who makes monthly rounds for the donations, who said that is their least favorite part of the job. During the interview, Sam took a crumpled print out of an excel spreadsheet on which notes detailing donations each month were marked in the columns. Sam said that during rounds at the beginning of each month, each business decides what to give and that not everyone gives every month; the result is that sometimes Sam works without pay. This sense of duty is supported by statements from Tracy, who said that primarily the post is just Sam every day, who is “dedicated to what [they’ve] been doing. I’ve seen [Sam] go out there and I’ve known for a fact [they’re] not being paid. But this is 7 or 8 years ago when people were just not pitching in the money and [Sam] still went and worked.” However, when asked what they needed most to improve the program, Sam mentioned that increased funds would mostly alleviate the irregularity in salary and harped on their desire for health insurance benefits. They did not mention increased or improved equipment, or increased number of coworkers. It would appear that Sam is content to watch the beach every day as they currently do.

6.4.3 Changes and growth

When asked whether they had ever heard anything negative about the program, not one respondent said yes. When prompted for suggestions regarding changes or improvements that could be made, the response from all was to further grow and build the program. In some cases, this meant adding to the existing system in place at the beach, like Alex who wanted to see the tower “directly connected to any sort of emergency service.” Tracy wanted Sam to have additional help, imagining a “little team of people, a regular team not just [Sam …] It would be nice to see other local young men, surfers and the like, being trained.” Tracy also suggested this team could patrol not just the beach currently watched, but the other one or two beaches near town as well. This opinion was echoed by other respondents, like Taylor who also reiterated that drownings continue to occur on the other beaches near town because this is the only guarded beach in the region. In general, all respondents suggested at some level that the beaches all over the country are dangerous and more guards are needed throughout. Cory said that the original idea was to expand the program throughout the region, but that funding has yet to reach the level that would be needed for such growth.

Both Alex and Cory implied that increased training would be beneficial, “Not saying that they’re not trained well, but you can always improve” (quote from Alex). Some funds do currently go towards funding, as Cory mentioned that several of those who work as guards had been to a week-long training event with a national water safety organization 6 months prior to the interview, but Cory also suggested that continued training is good.

In lieu of a full-fledged lifeguard program, Cory suggested that nearby communities with even fewer funds might at least emulate the signs and flags posted by these guards at their beach. Although Cory said that “Signs are, in and of themselves, insufficient. If a beach thinks putting up signs is going to have a significant effect, from experience: it doesn’t,” but went on to add that when a community can’t raise money for a trained lifeguard, having “at the very least [to have] 1 person who puts flags, signs, has a whistle, and is schooled in recognizing currents. There is still great value in that, even if they can’t swim” because adding that one person with a whistle, in their opinion, makes a significant difference. Tracy echoed that signs alone are not sufficient, saying “Many tourists, I have noticed, pay no attention whatsoever and continue to go into the water and continue to swim out far, oblivious to the red flags.” These anecdotal accounts are supported by research, where scientists have found that the majority of beachgoers do not heed signage alone (e.g. Matthews et al., 2014, Brannstrom et al. 2015).

6.5 Discussion

The United States Center for Disease Control (CDC) and the World Health Organization (WHO) both advocate for lifeguards as a priority for countries seeking to lower their rates of fatal drowning, which is a leading cause of accidental death in every region of the world, especially for young people (WHO 2014). The WHO says that this international public health hazard “can be prevented through targeted prevention strategies [like…] public awareness, appropriate policies and legislation, and research that refines what is seen as best practice and that identifies new drowning prevention measures” (WHO 2014). In this study, research is conducted to outline one community’s successful creation of a successful program.

This middle/lower income country’s surf town has adopted a system with a lifeguard tower, and on-site flags placed by that experienced guard directly in front of each rip current. This adheres to the WHO’s directive that certain strategies “have worked in high-income countries and some low and middle-income countries – scaling up these approaches will bring further gains” (WHO 2014). It may also be possible to adapt this system to work in a different region of this country, or in another country altogether. When deciding whether to fund lifeguards as part of a drowning prevention strategy, “policy makers should consider public attitudes about lifeguards and legal issues related to using lifeguards” (Branche and Stewart 2001, pg. vii). To that end, anonymous interviews like those conducted here might aid a community in determining whether lifeguards will be given a positive reception. In this community, the monthly donations are seen as an easy sacrifice for the increased community health and economy.

Prior to 2004, the town examined here was the deadliest in this region of this country. Following a deadly week in 2004, members of the community banded together and formed a donation-dependent lifeguard program. Since the lifeguard post was established, there have not been any fatal drownings associated with the surf or rip currents. All those interviewed, who are associated with businesses which donate to keep the program running, had positive opinions about the lifeguards' positive effect on the health of the community, the increased safety, and the combined (if indirect) positive effect on the economy. However, the diligent head lifeguard has at times prioritized this duty to the community to the point that they worked without pay. The lifeguards are also still in an unstable position because there is not enough funding for the program to provide them with critical needs, such as health insurance. The majority of those interviewed would like to see the program grow to include more training and more guards, possibly expanding to nearby beaches. Until the program can find additional and/or larger sources of funds, however, its lifespan will remain tenuous. In many other cases of similar programs, lack of funds leads to closure.

Adaptable strategies that have worked here include several listed by the WHO, such as (a) posting signage and designating hazard waters, (b) timely rescue and resuscitation by trained individuals, (c) and increased supervision of swimming areas (WHO 2013). Another reason this community's program has worked to date is their integration of drowning prevention in to the local setting: "Understanding the way communities live around water is critical to developing and implementing effective drowning prevention programmes and policies … This is particularly important in low- and middle income settings" (WHO 2014). Although the WHO goes on to claim that "establishing programmes to instill these skills in low- and middle-income countries requires a certain set of conditions, including generally high education levels, a culture of good Samaritanism and legal protection for those attempting rescue and resuscitation" (WHO 2014) the legal protection and possibly education level are not guaranteed in the community examined by this study. What is apparent in this community is the ‘culture of good samaritansim’ as the program runs entirely on donations. However, as the WHO warns that “lack of these conditions poses a significant obstacle to the establishment and effective function of such programmes in low- and middle-income countries,” it is possible that having only one of the three qualities present in full may be contributing to the program’s present instability (WHO 2014).

6.6 Conclusion

A small community, once plagued by frequent rip-current related fatal drownings which peaked with 5 deaths in 8 days in 2004. As the local economy depends on tourism associated with the beach, one local expatriot hotel owner began a donation-dependent lifeguard program which is still running 13 years later. There has been one fatal drowning in that time, which appears to be related to the victim’s personal health and not the environment. The program is evidently successful, and the 12 subjects interviewed all had positive views regarding the program’s role and effect on local community health and economy, extending beyond that of the tourists to the locals as well. Because it depends on small monthly donations from local businesses, the program has experienced financial instability, and the senior lifeguard has, at times, worked without pay. While this model has persisted more strongly than pother community-run programs in this country (and others), and locals would like to see it grow and spread though the region and the country, it cannot do so without an increase in fund amount and consistency.

7. CONCLUSIONS

Rip currents are naturally occurring phenomena on beaches all over the world. Previous research shows rip drownings are caused by a combination of personal and group behaviors with the physical environment. A beach may be prone to forming strong rip currents, but without swimmers in the vicinity such currents are not necessarily hazardous. On the contrary, a much more hazardous condition can exist when rip currents form on heavily populated beaches with vulnerable swimmers, even if that rip current is relatively weak by comparison. The co-incidence of a rip and swimmers, the 'hazard,' does not result purely from geomorphology, but from gaps in knowledge amongst scientists, beachgoers, and policy makers, and these knowledge gaps then persist because of communication barriers. The primary knowledge gap in coastal geomorphology exists because theory isn't fully resolved regarding the transformation of nearshore bars (and the subsequent development of rip currents) as beaches shift between Wright and Short's (1984) beach types, though significant development of knowledge in this field is growing.

In this dissertation, different knowledge gaps were addressed by each section. Section 2, the literature review, presented the knowledge gaps by offering a comprehensive summary of the present body of research into both the human and physical elements of the rip current hazard. Sections 3 and 4 presented new technological methods for increasing geomorphological knowledge that can also be applied to mitigate the rip current hazard. Sections 5 and 6 provided options for closing communication gaps between scientists and the vulnerable public. Together, these sections investigated the international rip current health hazard as a geographic problem, with a significant human component in addition to physical, geomorphological, and empirical elements. The full dissertation can perhaps best be summarized in an idealized mitigation plan. Below, results of the dissertation as a whole are outlined as stages of a theoretical mitigation plan.

7.1 Stage 1: Lifeguards

Establishing and funding a lifeguard post is an immediate and cost-effective mitigation technique that local authorities can use to lower risk of rip current related injury and death. As described in the literature review, the USLA estimates that the chance of drowning on a beach guarded by USLA trained guards is less than one in 18 million (USLA 1999). Another convincing statistic in support of establishing lifeguard programs is the ratio of the small direct costs incurred per lifeguard *to* the large indirect costs avoided by the community (such as medical costs induced by an incident or economic loss following a death; Branche and Stewart 2001) Interviews at the study site for Section 6 show that members of this community agreed. Donors to the lifeguard program were in agreement that it benefited the local community heavily, not only the visiting tourists or the handful of hotel owners adjacent to the dangerous beach. This donation-dependent model for funding a lifeguard post has been successful in this community for over a decade, however, the section introduction also described the collapse of other similarly-structured programs. Because lifeguards are such a successful mitigation strategy and lower cost than the remaining tactics proposed here, a donation funded program can serve as an immediately applicable *first* step towards long-term rip current mitigation for a community.

7.2 Stage 2: Intelligent beach access

In accordance with the establishment of a regular lifeguard patrol, another mitigation step policy managers can employ is the construction of beach access and related development that accounts for geomorphologically controlled, regularly located rips. By conducting a geomorphological analysis of their beach, developers could build accommodating beach access that depressed development in rip-prone areas of the beach and encouraged swimming in spaces less likely to develop rip currents. Results of Section 4 revealed why and how people select a swimming location within a rip-prone beach and can be applied to improving beach access design and warning sign placement. At this study site (Bondi Beach near Sydney, Australia) attractions like hotels and shopping were primarily located at the southern end of the beach, as were the public transit bus stops. Unfortunately, the beach's embayed shape and regular incoming waves create a regular rip current at the same southern end of the beach, with other rips sometimes spawning off towards the center of the beach. As a result, the physical hazard is co-located with the controls on the distribution of people within the beach. At this and other beaches, construction of access, public transit, and development of attractions could be focused away from regularly occurring rip currents to reduce exposure of the public and mitigate the hazard. A recently published textbook section by the Ph.D. candidate further details how this beach *and others*, with different rip morphologies but the same result, could all benefit from a redesign of access, as this is not a Bondi-specific problem (Trimble and Houser 2017).

7.3 Stage 3: Tracking rip locations over time

An inability to map surf zone bathymetry is one hindrance to the mitigation of rip currents because, without it, coastal geomorphological theory lacks complete knowledge of transformative processes in the surf zone – including the role of rip channels and currents in transitions between Wright and Short's (1984) beach states. Section 3 presented a novel method for mapping bathymetry on intermediate beaches using high spatial, spectral, and temporal resolution imagery from the WV3 commercial satellite operated by Digital Globe. The satellite has a daily flyover rate and images that are free to the US federal government, with costs starting at ~\$600 per 25 km^2 of imagery for other clients. As with many similar technologies, the cost and availability of this imagery (and similar products) are likely to become increasingly accessible.

Because the relationship between surface radiance in this imagery is related to depth, the satellite data was used to map rip channel locations in the surf zone and increased the number of available options for mapping rip current locations. By employing this technique to develop multiple models through time at a given beach, the methods detailed in Section 3 make it possible to observe the evolution of rip channels through time. Combined with wave and wind data, future research could resolve understanding of the role played by rip channels and rip current formation in the transformation of beaches through Wright and Short's beach states. Moving forward, these methods could be used to improve the identification of dangerous swimming locations and the mapping of beach state transition mechanisms. Such application will improve our understanding of rip current behavior and thereby mitigate the hazard.

7.4 Stage 4: Automating rip location detection

Whether developed from WorldView imagery or another emerging technology, high temporal and spatial resolution models of bathymetry in the surf zone may be processed with the every-direction variogram analysis presented in Section 4 to automatically detect rip channels. As demonstrated in this section, variance of relief (as a proxy for the degree of anisotropy) identifies the characteristic signature of topographic rip channels and distinguishes them from other bathymetric features. As mapping the surf zone becomes more affordable and feasible, software that computes the metric presented in Section 4 can be used to automate the detection of rip channels along the coast, which will aid in keeping swimmers out of dangerous waters. In the future, it could be possible to capture bathymetry on a frequent time scale with unmanned aerial systems (UAS) and evaluate such models with the degree of anisotropy metric, empirically locating unsafe swimming locations on a frequent time scale. On a beach with a regular lifeguard patrol, this method and information could be used to deploy site-specific “stay out of the water” flags and warning signs, providing an immediate response to the formation of rips and thereby mitigating the risk posed by these currents.

7.5 Summary

The primary objective of this dissertation was to provide a series of tools which beach managers and scientists can use to improve public safety and reduce rip-current related fatal drownings. Each section addressed one aspect of the public health hazard posed by some rip currents; combined, these findings represent applications of geographic thinking, including modern remote sensing and GIS technologies, to the closing of knowledge gaps. As a complete document, the dissertation can be used to mitigate the physical, human, and societal causes of rip-current related injury and death, thereby resulting in fewer rip current fatalities worldwide.

REFERENCES

American Red Cross. 1995. Lifeguarding Today, St. Louis, Missouri: Mosby Lifeline.

Arun Kumar, S., and Prasad, K. 2014. “Rip current-related fatalities in India: a new predictive risk scale for forecasting rip currents.” *Natural Hazards.* 70:313–335.

Arozarena, I., Houser, C., Gutierrez-Echeverria, A., and Brannstrom, C. 2015. “The rip current hazard in Costa Rica.” *Natural Hazards*. 77(2): 753-768.

Australian Bureau of Statistics. 2012. “3218.0 - Regional Population Growth, Australia, 2010-11 Quality Declaration.” Published online at 11:30 AM (Canberra Time) 30/03/2012 http://www.abs.gov.au/ausstats/abs@.nsf/Products/3218.0~2010-11~Main+Features~New+South+Wales

Australian Government: Department of the Environment. 2008. “National Heritage Places: New South Wales: Bondi Beach.” 25 January 2008. http://www.environment.gov.au/heritage/places/national/bondi

Bachri, S., Banda Selamat, M., Siregar, V., and Wouthuyzen, S. 2013. “The Comparison of Bathymetric Estimation from Three High Resolution Satellite Imagery.” Seminar on hydrography, Batam Island, Indonesia, 27-29 August 2013.

Barlas, B., and Beji, S. 2015. “Rip current fatalities on the Black Sea beaches of Istanbul and effects of cultural aspects in shaping the incidents.” *Natural Hazards.* 2:811–821.

Barrett, G. and Houser, C. 2012. “Identifying hotspots of rip current activity using wavelet analysis at Pensacola Beach, Florida.” *Physical Geography*, 33(1):32-49.

Bell, P.S. 1999. “Shallow water bathymetry derived from an analysis of X-band marine radar images of waves.” Coastal Engineering, 37(3):513-527.

Black, S. 2013, 5 November. “Search for missing Japanese swimmer off Bondi Beach continues as survival hopes fade” The Daily Telegraph.

Branche CM, Stewart S. (Editors). 2001. Lifeguard Effectiveness: A Report of the Working Group. Atlanta: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control. 36 pp.

Brander, R. 1999. “Field observations on the morphodynamic evolution of a low-energy rip current system.” Marine Geology. 157:199-217

Brander, R., Cowell, P., and Short, A. 2001. “Morphometric Approaches to Describing Rip Current Behaviour.” *Journal of Coastal Research*. SI34:128-137

Brander, R.W. and Cowell, P.J. 2003. “A trend- surface technique for discrimination of surf- zone morphology: Rip current channels.” Earth Surface Processes and Landforms. 28(8): 905-918.

Brander, R. “June 2009: The Backpackers Express, Bondi Beach, Australia” Science of the Surf: Rip of the Month.

Brander, R., Bradstreet, A., Sherker, S., and McMahan J. 2011. “The behavioural responses of swimmers caught in rip currents: new perspectives on mitigating the global rip current hazard. International Journal of Aquatic Research and Education. 5: 476-486.

Brander, R.W. and MacMahan, J.H. 2011. Future challenges for rip current research and outreach. Rip Currents, Beach Safety, Physical Oceanography and Wave Modeling, edited by: Leatherman, S. and Fletemeyer, J., CRC Press, Boca Raton, FL, pp.1-29.

Brander, R. 2013. “Thinking space: can a synthesis of geography save lives in the surf?” *Australian Geographer*. 44:123–127.

Brander, R.W. 2015. “Rip currents.” In: Treatise in Hazards and Disasters. Edited by Ellis, J., and Sherman, D. Elsevier, pp. 335–380.

Brander, R., and Scott, T. 2016. “Science of the rip current hazard.” In: The Science of Beach Lifeguarding: Principles and Practice.” Edited by Tipton, M., Wooler, A., Reilly, T. CRC Press, pp. 67–86.

Brannstrom, C., Trimble, S., Santos, A., Brown, H.L., and Houser, C. 2014. “Perception of the rip current hazard on Galveston Island and North Padre Island, Texas, USA.” Natural Hazards. 72(2):1123-1138.

Brannstrom, C., Trimble, S., Santos, A., and Lee, H., and Houser, C. 2014. “Beach user ability to identify a rip current and hazardous surf conditions.” Natural Hazards. 72:1123-1138.

Brawley, Sean & Bondi Surf Bathers' Life Saving Club. 2007. The Bondi lifesaver: a history of an Australian icon. ABC Books, Sydney, Australia.

Brewster, B. 2010. “Rip current misunderstandings.” *Natural Hazards*. 55:161–162.

Brighton, B., Sherker, S., Brander, R., Thompson, M., and Bradstreet, A. 2013. “Rip current related drowning deaths and rescues in Australia 2004–2011.” *Natural Hazards and Earth Systems Science*. 13:1069–1075.

Bruneau, N., Bertin, X., Castelle, B. and Bonneton, P. 2014. “Tide-induced flow signature in rip currents on a meso-macrotidal beach.” *Ocean Modelling*. 74: 53-59.

Bowen, A. 1969. “Rip currents: Theoretical investigations.” *Journal of Geophysical Research*. 74:5467–5478.

Bureau of Labor and Statistics. 2017. “Databases, Tables & Calculators by Subject: CPI Inflation Calculator.” https://www.bls.gov/data/inflation_calculator.htm

Caldwell, N., Houser, C., Meyer-Arendt, K. 2013. “Ability of beach users to identify rip currents at Pensacola Beach, Florida.” *Natural Hazards*. 68:1041–1056.

Castelle, B. and Coco, G. 2012. “The morphodynamics of rip channels on embayed beaches.” Continental Shelf Research, 43:10-23.

Castelle, B. and Coco, G. 2014. “Surf zone flushing on embayed beaches.” *Geosphysical Research Letters.* 40:2206–2210.

Castelle, B., Scott, T., Brander, R. and McCarroll, R. 2016. “Rip current types, circulation and hazard.” *Earth-Science Reviews,* 163:1-21.

Center for Disease Control (CDC) Agency for Toxic Substance and Disease Registry (ATSDR) Committee on Community Engagement (2011) Principles of Community engagement, 2nd edition. National Institute of Health Publication No. 11-7782. http://www.atsdr.cdc.gov/communityengagement/pdf/PCE_Report_508_FINAL.pdf

Craig, W., Brant, I., Hite, M. P., & Davis, W. M. (1925) The "Undertow.” Science, 62:30-33.

Dalrymple, R., MacMahan, J., Reniers, A., and Nelko, V. 2011. “Rip currents.” *Annual Review of Fluid Mechanics*. 43:551–581.

Deidda M. and G. Sanna 2012. “Pre-processing of high resolution satellite images for sea bottom classification”. Italian Journal of Remote Sensing. 44(1):83-95

Digital Globe. 2013. “WorldView-2 8-band Applications Whitepaper: The Benefits of the 8 Spectral Bands of WorldView-2.” https://www.digitalglobe.com/resources/white-papers

Digital Globe. June 3, 2013. “Data sheet: WorldView2: WorldView-2 spacecraft information and specifications.” https://www.digitalglobe.com/resources/satellite-information

Digital Globe. October 17, 2014. “Data sheet: WorldView3: WorldView-3 spacecraft information and specifications.” https://www.digitalglobe.com/resources/satellite-information

Destination New South Wales. 2014. “Bondi Visitor Profile” published in “International Visitors Survey (YE June 2009 to YE June 2014)” and “National Visitors Survey (YE June 2009 to YE June 2014)” by Tourism Research Australia

Drozdzewski, D., Shaw, W., Dominey-Howes, D., Brander, R., Walton, T., Gero, A., Sherker, S., Goff, J. and Edwick, B. 2012. “Surveying rip current survivors: preliminary insights into the experiences of being caught in rip currents.” *Natural Hazards and Earth System Sciences*. 12(4):1201.

Drozdzewski, D., Roberts, A., Dominey-Howes, D. and Brander, R. 2015. “The experiences of weak and non-swimmers caught in rip currents at Australian beaches.” *Australian Geographer*. 46(1):15-32.

Fédération Internationale de Natation (FINA). 2017. FINA World Records (as of March 20, 2017).

Flaccus, G. 2011. “Life’s a beach and pay is high for SoCal lifeguards.” The Seattle Times, originally published 20 May 2011 at 5:03pm.

http://www.seattletimes.com/life/lifestyle/lifes-a-beach-and-pay-is-high-for-socal-lifeguards/

Gallop, S., Bryan, K., Coco, G., and Stephens, S. 2011. “Storm-driven changes in rip channel patterns on an embayed beach.” *Geomorphology*. 127:179–188.

Gensini, V., and Ashley, W. 2009. “An examination of rip current fatalities in the United States.” *Natural Hazards*. 54:159–175.

Haller, M., Dalrymple, R., and Svendsen, I. 2002. "Experimental study of nearshore dynamics on a barred beach with rip channels." Journal of Geophysical Research. C6:107.

Hartmann, D. 2006. "Drowning and beach-safety management (BSM) along the Mediterranean beaches of Israel - a long-term perspective." Journal of Coastal Research. 22:1505–1514.

Hassell, C.A. (1996). Pediatric Drowning Prevention Awareness Program. Masters thesis. Lynn University, Palm Beach, Florida.

Hatfield, J., Williamson, A., Sherker, S., Brander, R. and Hayen, A. 2012. "Development and evaluation of an intervention to reduce rip current related beach drowning." Accident Analysis & Prevention, 46:45-51.

Houser, C., 2009. "Geomorphological controls on road damage during Hurricanes Ivan and Dennis." Journal of Coastal Research, 25(3):558-568.

Houser, C., Barrett, G. and Labude, D. 2011. "Alongshore variation in the rip current hazard at Pensacola Beach, Florida." Natural Hazards, 57(2): 501-523.

Houser, C., Arnott, R., Ulzhöfer, S. and Barrett, G. 2013. "Nearshore circulation over transverse bar and rip morphology with oblique wave forcing." Earth surface processes and landforms. 38(11):1269-1279.

Houser, C., Murphy, T. and Labude, D. 2015. "Alongshore correspondence of beach users and rip channels at Pensacola Beach, Florida." Natural Hazards, 78(3):2175-2183.

Houser, C., Trimble, S., Brander, R., Brewster, B. C., Dusek, G., Jones, D., and Kuhn, J. 2017. "Public perceptions of a rip current hazard education program: 'Break the Grip of the Rip!'" Natural Hazards Earth System Science. 17:1003-1024.

Irish, J.L, McClung, J.K., and Lillycrop, W.J. 2016. "Airborne Lidar Bathymetry: The SHOALS System." US Army Engineer District - Mobile. Mobile, United States. #AD1003887

Johnson, B. (2007, February 3) Aussie dream ends in tragedy. The Daily Telegraph. Retrieved from http://www.dailytelegraph.com.au/news/nsw/

Jones, W.C. (1925). The Undertow Myth. Science, 61:444

Jupp, D. L. B. 1989. "Background and extension to depth of penetration (DOP) mapping in shallow coastal waters," in Proceedings of the Conferense of Remote Sensing Applications: Projects Using microBRIAN Image Processing Systems. pp. 77–94.

Klein, A., da, F., Santana, G., Diehl, F., and Menezes, J. 2003. "Analysis of hazards associated with sea bathing: results of five years work in oceanic beaches of Santa Catarina State, Southern Brazil." *Journal of Coastal Research*. SI 35:107–116.

Kuester, M. 2016/02/22. "Radiometric Use of WorldView-3 Imagery." Technical Note, *Digital Globe.* https://dg-cms-uploads-production.s3.amazonaws.com/uploads/ document/file/ 207/Radiometric_Use_of_WorldView-3_v2.pdf

Lascody, LL. 1998 "East central Florida rip current program." National Weather Digest. 22(2):25-30

Leatherman, S. 2013. "Rip currents." In: Coastal Hazards. Edited by Finkl, C. Coastal Research Library 6. Springer, pp. 811–831.

Lee, K., Kim, A., Olsen, R. and Kruse, F. 2011. "Using WorldView-2 to determine bottom-type and bathymetry." In the proceedings of *SPIE Defense, Security, and Sensing*, session SPIE 8030, Ocean Sensing and Monitoring III, pp. 80300D (May 04, 2011). International Society for Optics and Photonics.

Lippmann, T. and Holman, R. 1989. “Quantification of sand bar morphology: A video technique based on wave dissipation.” *Journal of Geophysical Research*. 94(C1):995-1011

Loomis, M. J. 2009. “Depth derivation from the WorldView-2 satellite using hyperspectral imagery.” Master’s thesis; Naval Postgraduate School; Monterey, California. pp. 69

Lushine, J.B., 1991. “Rip currents: Human impact and forcastability.” Coastal Zone 91 (Long Beach), American Society of Civil Engineers, pp. 3558-3569

MacMahan, J.H., Thornton, E.B., and Reniers, A.J.H.M. 2006. “Rip current review.” Coastal Engineering. 53:191–208.

MacMahan, J., Brown, J., Brown, J., Thornton, E., Reniers, A., Stanton, T., Henriquez, M., Gallagher, E., Morrison, J., Austin, M., Scott, T., and Senechal, N. 2010. “Mean lagrangian flow behavior on an open coast rip-channeled beach: a new perspective.” *Marine Geology*. 268:1–15.

Masselink, G., and Pattiaratchi, C. 1998. “Morphological evolution of beach cusps and associated swash circulation patterns.” *Marine Geology*. 146:93–113.

Matthews, B., Andronaco, R., and Adams, A. 2014. “Warning signs at beaches: Do they work?” *Safety Science*. 62:312-318.

McCarroll, R., Brander, R., Turner, I., Power, H., and Mortlock, T. 2014. “Lagrangian observations of circulation on an embayed beach with headland rip currents.” *Marine Geology*. 355:173–188

McCarroll, R., Brander, R., Turner, I. and Van Leeuwen, B. 2016. “Shoreface storm morphodynamics and mega-rip evolution at an embayed beach: Bondi Beach, NSW, Australia.” Continental Shelf Research. 116:74-88.

McKay, C., Brander, R.W. and Goff, J. 2014. “Putting tourists in harms way–Coastal tourist parks and hazardous unpatrolled surf beaches in New South Wales, Australia.” Tourism Management, 45:71-84.

McLachlan, A., Defeo, O., Jaramillo, E. and Short, A.D. 2013. “Sandy beach conservation and recreation: guidelines for optimising management strategies for multi-purpose use.” Ocean & Coastal Management, 71:256-268.

McNinch, J. 2007. “Bar and Swash Imaginging Radar (BASIR): A Mobile X-band Radar Designed for Mapping Nearshore Sand Bars and Swash-defined Shorelines Over Large Distances.” *Journal of Coastal Research.* 23(1):59-74

McMahon, B. (2007, February 5) Australia's 'hidden dangers' take deadly toll on tourists. The Guardian. Retrieved from https://www.theguardian.com/world/

Ménard, D., Houser, C., Brander, R., Trimble, S., and Scaman, A. “The psychology of beach users: Importance of confirmation bias, action and intention to improve beach safety.” (for submission to Accident Analysis and Prevention).

Miecznik, G. and D. Grabowksa (2012). “WorldView-2 bathymetric capabilities.” In *Algorithms and techonologies for multispectral, hyperspectral, and ultrapsectral imagery XVIII.* Edited by S.S. Shen and P.E. Lewis. pp. 10

National Safety Council (1997). Accident Facts, 1997 edition. Itasca, Illinois: National Safety Council.

National Weather Service. 2017a. “Surf Forecasts.” http://ripcurrents.noaa.gov/forecasts.shtml (last accessed 17 October 2017).

National Weather Service (NWS). 2017b. “U.S. Surf Zone Fatalities.” http://www.ripcurrents.noaa.gov/fatalities.shtml (last accessed 20 April 2017).

National Weather Service (NWS). 2017c. “Signs, Videos, Resources.” http://ripcurrents.noaa.gov/signs_brochures.shtml (last accessed 17 October 2017)

Omhoog Enckevort, I.M.J. Van and Ruessink, B.G. 2001. “Effect of hydrodynamics and bathymetry on video estimates of nearshore sandbar position.” *Journal of Geophysical Research*. 106(C8): 16969-16980

Pitman, S., Gallop, S., Haigh, I., Mahmoodi, S., Masselink, G. and Ranasinghe, R. 2016. “Synthetic imagery for the automated detection of rip currents.” *Journal of Coastal Research.* 75(1): 912-916.

Roy, S., Koons, P., Osti, B., Upton, P., and Tucker, G. 2016. “Multi-scale characterization of topographic anisotropy.” Computers & Geosciences 90: 102-116.

Russell, R., and McIntire, W. 1965. “Beach cusps.” Geological Society of America Bulletin. 76:307–320.

Scott, T., Russell, P., Masselink, G., Austin, M., Wills, S., and Wooler, A. 2011b. “Rip current hazards on large-tidal beaches in the United Kingdom.” In: Rip Currents: Beach Safety, Physical Oceanography and Wave Modeling. Eds: Leatherman, S., Fletemeyer, J. CRC Press, pp. 225–242.

Scott, T., Austin, M., Masselink, G. and Russell, P. 2016. “Dynamics of rip currents associated with groynes—field measurements, modelling and implications for beach safety.” *Coastal Engineering*. 107:53-69.

Shaw, J., Ayoub, F., Jones, C., Lamb, M., Holt, B., Wagner, R., and Mohrig, D. 2016. “Airborne radar imaging of subaqueous channel evolution in Wax Lake Delta, Louisiana, USA.” *Geophysical Research Letters*. 43(10):5035-5042.

Shepard, F. P., Emery, K. O., & La Fond, E. C. (1941). Rip currents: a process of geological importance. The Journal of Geology, 49(4), 337-369.

Sherker, S., Brander, R., Finch, C. and Hatfield, J. 2008. “Why Australia needs an effective national campaign to reduce coastal drowning.” Journal of science and medicine in sport, 11(2):81-83.

Sherker, S., Williamson, A., Hatfield, J., Brander, R., and Hayen, A. 2010. “Beachgoers’ beliefs and behaviours in relation to beach flags and rip currents.” *Accident Analysis and Prevention.* 42:1785–1804

Short, A.D. and Wright, L.D. 1981. “Beach systems of the Sydney region.” The Australian Geographer. 15(1):8-16.

Short, A.D. 1985. “Rip current type, spacing and persistence, Narrabeen Beach, Australia.” *Marine Geology*. 65:47–71.

Short, A.D. and C.L. Hogan. 1990. “Chapter 17: Sydney’s southern surfing beaches: characteristics and hazards,” in Recreational Uses of Coastal Areas. The GeoJournal Library Volume 12, pp 199-210

Short, A. and Trenaman, N.L. 1992. “Wave climate of the Sydney region, an energetic and highly variable ocean wave regime.” Australi)an Journal of Marine Freshwater Research. 43: 148–173.

Short, A. D. and Hogan, C. L. 1994. “Rip currents and beach hazards: their impact on public safety and implications for coastal management.” Journal of Costal Research. SI12:197-209

Short, A. 1999. Handbook of Beach and Shoreface Morphodynamics. Wiley, Chichester, Australia.

Short, A., and Brander, R. 1999. “Regional variations in rip density.” Journal of Coastal Research. 15:813–822.

Short, A.D and Masselink, G. 1999. “Embayed and structurally controlled beaches.” In: A.D. Short (ed) Handbook of beach and shoreface morphodynamics, John Wild and Sons Ltd., New York.

Short, A.D. 2007. “Australian rip systems - friend or foe?” Journal of Coastal Research. 50:7–11.

Short, A.D. 2007. Beaches of the New South Wales Coast: A Guide to Their Nature, Characteristics, Surf and Safety. (second edition), Sydney University Press, Sydney.

Short, A.D. 2010. “Role of geological inheritance in Australian beach morphodynamics.” Coastal Engineering. 57: 92-97

Silva, A.N., Taborda, R., Catalão, J. and Freire, P. 2009. “DTM extraction using video-monitoring techniques: application to a fetch limited beach.” Journal of Coastal Research, 1(SI56):203-207.

Stuffle, L. D. 1996. “Bathymetry from Hyperspectral Imagry.” Master’s thesis; Naval Postgraduate School; Monterey, California. pp. 87

Surf Life Saving Australia. 2009. National Coastal Safety Report.

Surf Life Saving Australia. 2012. “Stay safe this summer: always swim between the red and yellow flags.” Published 22 October 2012, visited 02 May 2015. https://sls.com.au/content/stay-safe-summer-always-swim-between-red-and-yellow-flags

Surf Life Saving Australia (SLSA). 2017. “Flags and Signs.” https://beachsafe.org.au/surf-safety/flags-and-signs

TenPlay. “Bondi Rescue: About Bondi Beach.” Published: 05 September 2013, visited 02 May 2015. http://tenplay.com.au/channel-ten/bondi-rescue/articles/about-bondi-beach

Thornton, E., Sallenger, A., and MacMahan, J. 2007. “Rip currents, cuspate shorelines and eroding dunes.” *Marine Geology*. 240:151–167.

Treno, A. and Holder, H. 1997. “Community mobilization, organizing, and media advocacy: A discussion of methodological issues.” *Evaluation Review*. 21(2):166-190.

Trimble, S., and Houser, C. “Seawalls and signage: how beach access management affects rip current safety” in Beach Management Tools. Edited by Camilo M. Botero, Omar D. Cervantes and Charles W. Finkl. Coastal Education and Research Foundation, Inc. Fletcher, NC 28732, USA

Trimble, S., Houser, C., and Brander, R. (*in prep*) “Factors contributing to the clustering of swimmers on a beach with quasi-regular rip currents.”

Turner, I., Whyte, D., Ruessink, B., and Ranasinghe, R. 2007. “Observations of rip spacing, persistence and mobility at a long, straight coastline.” *Marine Geology*. 236:209–221.

United States Lifesaving Association. 1999. National Lifesaving Statistics. Available at www.usla.org/PublicInfo/stats.shtml

United States Lifeguard Association. 2017. “American Lifeguard Rescue and Drowning Statistics for Beaches.” Last visited July 11, 2017. http://www.usla.org/?page=STATISTICS

van Beeck, E. F., Branche, C. M., Szpilman, D., Modell, J. H., & Bierens, J. J. 2005. A new definition of drowning: towards documentation and prevention of a global public health problem. Bulletin of the World Health Organization, 83, 853-856.

Walsh, E. 1981. “Resource mobilization and citizen protest in communities around Three Mile Island.” *Social Problems*. 29(1):1-21.

Watanabe, N., Kaneko, A., Yamar, S., Taleo, G., Tanihata, T., Lum, J., Larson, P., and Shearer, N. 2015. “A prescription for sustaining community engagement in malaria elimination on Aneityum Island, Vanuatu: an application of Health Empowerment Theory.” *Malaria journal*. 14(1):291.

Williamson, A., Hatfield, J., Sherker, S., Brander, R., & Hayen, A. (2012). “A comparison of attitudes and knowledge of beach safety in Australia for beachgoers, rural residents and international tourists.” Australian and New Zealand Journal of Public Health, 36(4):385-391.

Woodward, E., Beaumont, E., Russell, P., and MacLeod, R. 2015. “Public Understanding and Knowledge of Rip Currents and Beach Safety in the UK.” *International Journal of Aquatic Research and Education*. 9:49-69

World Health Organization. 2014. Global report on drowning: preventing a leading killer. 76pp.

Wright, L.D. and Short, A.D. 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Marine Geology, 56(1-4):93-118.

APPENDIX A

THE SURVEY INSTRUMENT (FORMATTING REMOVED)

Part I) Warnings and Signs

1. Did you see any of signs, flags, or other warnings when you arrived today? `[ Y ] [ N ]`
2. If yes, what were they? (Examples: flags, sign, etc.) [Free answer]
3. Did the signs/flags/warnings cause you to change your behavior? `[ Y ] [ N ]`
4. If yes, how? [Free answer]
5. If you had seen a warning or safety information sign posted when you entered the beach today, would it have changed your behavior? `[ Y ] [ N ]`
6. If yes, how? [Free answer]
7. Where on this beach do you think is the most dangerous place to swim (is any part more hazardous than others)? [Free answer]

Part II) Rip knowledge

8. Which place in photo A do you think is the most dangerous? `[ A B C D E ]`
9. Which place in photo B do you think is the most dangerous? `[ A B C D E ]`
10. Which place in photo C do you think is the most dangerous? `[ A B C D E ]`
11. Have you heard of dangerous undertow? `[ Y ] [ N ]`
12. Have you heard of rip tides? `[ Y ] [ N ]`
13. Have you heard of rip currents? `[ Y ] [ N ]`
14. Do you think any of these are the same thing?
    a. Yes, they are all names for the same thing.
    b. Yes, undertow and rip tides are the same (but not rip currents)
    c. Yes, undertow and rip currents are the same (but not rip tides)
    d. Yes, rip tides and rip currents are the same (but not undertow)
    e. No, none of these are names referring to the same thing.
15. Do you think a person standing on the beach can spot or see rip currents? `[ Y ] [ N ]`
16. What do you think a rip current looks like?
    a. They are invisible.
    b. I don't know
    c. [Free answer]
17. If you were caught in a rip current, what would you do?
    a. don't know
    b. try to swim out of it parallel
    c. float until it took me to shallow water
    d. swim straight back to the beach
    e. signal for help

f. a combination of some of the above

Part III) Beach Use

11. How frequently do you come to **this** beach?
    a. Everyday
    b. 3 or more times per week
    c. 1 – 2 times per week
    d. 1 – 2 times per month
    e. Rarely
    f. This is my first time at this beach
12. How many times per year do you visit **any** beach?
    a. Everyday
    b. 3 or more times per week
    c. 1 – 2 times per week
    d. 1 – 2 times per month
    e. Rarely
    f. This is my first time at any beach
13. Why did you choose this beach today?
    a. Safe
    b. Close to where I'm staying/living
    c. Ease of access
    d. Beauty
    e. Surf/waves
    f. Reputation/tourist attraction
    g. Other (please specify)
14. Why did you choose to sit/swim at this location on this beach?
15. In general, when you go to the beach, what water activities do you participate in?
    a. None/Don't go in the water
    b. Stand/wade in shallows
    c. Swim in deeper waters (waist deep or more)
    d. Boogie boarding
    e. Surfing
    f. Other (please specify)
16. Have you ever had difficulty in the water? `[ Y ]  [ N ]`
17. If you have, which of the following best describes your experience?
    a. I was caught in a rip current
    b. I had trouble because of large/rough waves
    c. I got tired/got a cramp
    d. I was stung/bit by marine life
    e. Other (please specify)
18. Still regarding your past experience, how did you recover from it?
    a. I rescued myself
    b. I was rescued by a bystander/friend/family
    c. I was rescued by a lifeguard
    d. Other (please specify)

19. Did you require medical attention after this experience? `[ Y ] [ N ]`

Part IV) Respondent Data

20. How would you rate your ability to swim in a pool?
    a. Unable to swim
    b. Weak swimmer
    c. Competent swimmer
    d. Highly competent swimmer
21. How far can you swim without stopping in a pool?
    a. I can’t swim
    b. Less than 25 m
    c. 25 m
    d. 50 m
    e. 100 m
    f. 500 m
    g. More than 500 m
22. How would you rate your ability to swim in open water, such as the ocean?
    a. Unable to swim
    b. Weak swimmer
    c. Competent swimmer
    d. Highly competent swimmer
23. How far can you swim without stopping in open water, such as the ocean?
    a. I can’t swim
    b. Less than 25 m
    c. 25 m
    d. 50 m
    e. 100 m
    f. 500 m
    g. More than 500 m
24. What is your gender? `[ M ] [ F ] [ Prefer not to answer ]`
25. Which group below includes your age?
    a. 17 or younger
    b. 18 -20
    c. 21-29
    d. 30-39
    e. 40-49
    f. 50-59
    g. 60 or older
    h. Prefer not to answer
26. What is your highest level of completed education?
    a. Less than high school degree
    b. High school degree or equivalent
    c. Some college but no degree (e.g. Graduate Diploma)
    d. Associate degree (e.g. Graduate Diploma)
    e. Bachelor degree (e.g. Undergraduate Degree)

    f. Graduate degree (e.g. Master or PhD)
    g. Other(please specify)

27. In what country do you currently live?
28. In what state/province do you currently live?
29. What is your zipcode/postal code?

APPENDIX B

THE SURVEY INSTRUMENT

When necessary to preserve anonymity, specific names or other identifying details have been redacted [and marked with brackets and gray highlight] or entirely blocked out: [redacted]

Interview Framework: [redacted] Lifeguard Program

Interviews will begin after reading, signing, and discussing the Informed Consent Form. **The final question on the consent form asks: What will I be asked to do in this study?** The interview will begin as a follow up to that question.

Respondent Code:________

A. Respondent Background

Obtain credentials of respondent:

- How long have they lived in the [town] area [years or months]?
- How long have they lived in [country] [years or months]?
  - Where did you live before that/where are you from (if not [this country])?
- How often do they go to [the lifeguarded beach]?
  - Who is with them on these trips? [friends, family, small children, elderly, small group, large…]
- Do they go to other beaches?
  - Where are these other beaches?
  - What about those locations is different from [the guarded beach]?
  - How often do you go to these other beaches?
- How do they make their living in [this town]? [Restaurant, shop, hotel, etc…]
  - How long in current position [years or months]?
  - Are they the owner of the establishment where they work?

B. Lifeguards

Lifeguard post today:

Does your business directly benefit from the [redacted] beach attraction?

Likert → 1 2 3 4 5 Explain rationale

1 Not much at all
2 Somewhat
3 Neutral
4 Moderate
5 Very much

Has your business ever financially supported the LG program?

How regularly? (per month, per year)
Is making donations difficult?
Likert → 1 2 3 4 5 Explain rationale
1 Not difficult at all
2 Somewhat easy
3 Neither difficult nor easy
4 Somewhat difficult
5 Very difficult

Do you feel that your business directly benefits from the LG program?
Likert → 1 2 3 4 5 Explain rationale
1 Not much at all
2 Somewhat
3 Neutral
4 Moderate
5 Very much

Do you think [this town] economically benefits from the LGs at [beach]?
Likert → 1 2 3 4 5 Explain rationale
1 Disagree strongly
2 Disagree
3 Neutral
4 Agree
5 Agree strongly

"[the town] has safer/healthier lives because of the LGs at [the beach]"
Likert → 1 2 3 4 5 Explain rationale
6 Disagree strongly
7 Disagree
8 Neutral
9 Agree
10 Agree strongly

Lifeguard post in the beginning:

Who are/were the key figures involved in developing the lifeguard post at [the beach]?

What is/was your role in developing the lifeguard post at [the beach]? [Allow for respondent to discuss this answer in his/her own terms]

What is/was your role in maintaining the lifeguard post at [the beach]? [Allow for respondent to discuss this answer in his/her own terms]

Lifeguard post outcomes:

How many drowning deaths do you think (know) there were before the lifeguard post was established?

How many drowning deaths do you think (know) have occurred since the lifeguard post was established?

How many rescues do you think (know) have occurred since the lifeguard post was established?

Have there been any complaints about the lifeguard post?

What was the nature of the complaints?

Were these problems before the establishment of the post, or only after?

Do you think the LG system needs any changes? [Allow for respondent to discuss this answer in his/her own terms]

Do you think other [country name] beaches need lifeguards?

Why or why not?

C. Conclusion

Do you have economic interests in the lifeguard post? [remind respondents that all questions are voluntary and they may opt out of any question]

Did most business owners in this community voluntarily give funds to the organization?

Are there particular individuals within the organization with whom you routinely communicate?

Would you recommend us contacting them?