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Ocean and Coastal Management 238 (2023) 106584

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Relationships between the tide and fatal drowning at surf beaches in New South Wales, Australia: Implications for coastal safety management and practice

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A R T I C L E I N F O

Keywords:
Ocean tides
Beach safety
Lifeguard management
Rip currents

A B S T R A C T

Beaches are popular, recreational destinations, but can be hazardous environments where drowning fatalities and other types of injuries can occur. Ocean lifeguards and beach safety managers make operational safety decisions based on ocean conditions, including various elements of the tide. This study addresses assumptions about the tide that are common in beach safety management; assessing the scientific basis that informs these decisions by evaluating the relationship between elements of the tide and fatal drowning on microtidal surf beaches in New South Wales (NSW), Australia. Lower tidal water levels and time periods closer to low tide were associated with increased likelihood of fatal drowning at surf beaches, while tidal phase (rising vs falling), tide range, and the rate of change of falling or rising water levels were not. These results have implications for ocean safety management and those responsible for educating the public about beach safety issues. Broad statements or anecdotal opinions that are not location or beach-specific should avoid describing times with falling water levels (an outgoing tide) as being inherently more dangerous.

1. Introduction

Many beaches around the world are popular recreational destinations, but they can also be hazardous environments. Both person-based and environmental factors contribute to potential bather/swimmer risk on beaches in a synergistic fashion (Morgan et al., 2008; Brander, 2018) and drowning is a major concern for any coastal community (Koon et al., 2021a). In Australia, a country renowned for surf beaches, beach culture and beach tourism, just over half (51%) of the 141 coastal drownings deaths between July 2021 and June 2022 occurred on beaches (SLSA, 2022). Person-based risk factors on surf beaches include swimming ability (McCool et al., 2008), choice of swim location (Sherker et al., 2010), knowledge of surf hazards (Williamson et al., 2012), beach activities (Willcox-Pidgeon et al., 2017) and the presence/absence of lifeguards (Gilchrist and Branche, 2016). Physical environmental hazards include variable surf zone morphology and water depths, large breaking and surging waves, dangerous shore breaks, strong uprush/-backwash on beach faces, and in particular, rip currents. Rip currents are strong, narrow offshore flows through the surf zone that are fundamentally driven by temporal and spatial variability in breaking waves and are considered to be the main hazard to ocean swimmers and bathers on beaches where they occur (Castelle et al., 2016). This is the case in Australia where 85% of rip current-related deaths occurring at a beach and an average of 26 people fatally drown in rip currents annually (SLSA, 2021).

One physical parameter that is often overlooked as a potential contributing factor to drowning on ocean beaches is the tide. In its simplest form, the tide refers to the vertical rise and fall of water forced by the gravitational interaction between the sun, moon, and earth (Hicks, 2006). While the rise and fall of the tide across ocean beaches and surf zones is gradual and does not present a direct hazard, the tide may pose a risk to bathers and swimmers indirectly in several ways.

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https://doi.org/10.1016/j.ocecoaman.2023.106584
Received 28 October 2022; Received in revised form 16 March 2023; Accepted 17 March 2023

First, increased water depths around high tide may pose a hazard to non-swimmers and young children who may find themselves inadvertently out of depth. Second, as water depth changes with the tide, the type of wave breaking at the shoreline and across sand bars can change. For example, at high tide, waves will break at the upper part of the beach profile, which is often steeper and can lead to impact-related surf zone injuries associated with more pronounced wave shore-breaks (Puleo et al., 2016; Castelle et al., 2019). Third, tidally induced changes in water level also alter wave-breaking intensity across the surf zone and therefore influence the development of surf-zone currents, such as rip currents (Bruneau et al., 2011; Austin et al., 2014). Finally, while tidally induced currents are minimal along open-ocean beaches, they can be significant in the vicinity of tidal inlets, coastal engineering structures such as seawalls, groynes, and jetties; and beach nourishment locations (Radermacheret al., 2018). On rugged coastlines characterised by large tidal ranges, straits and offshore islands, offshore-driven tidal currents can also interact with the incident wave field to create larger breaking wave heights during the rising tide (Lewis et al., 2019). However, on beaches characterised by rip currents, it is the role that the tide has in influencing rip current flow behaviour through changes in wave breaker patterns that is arguably the most important factor in relation to swimmer and bather safety.

On most microtidal beaches characterised by intermediate beach states with sand bar and rip channel morphology according to the Australian Beach State Model (Wright and Short, 1984), the presence of alongshore non-uniform surf zone topography enhances alongshore variability of wave breaking patterns, which is a key mechanism driving rip current flow (Castelle et al., 2016). As the intensity and alongshore variability of wave breaking across this non-uniform topography increases at lower water levels, numerous field measurements have documented maximum rip current flow velocity occurring around low tide (Aaagard et al., 1997; Brander, 1999; Brander and Short, 2001; MacMahan et al., 2006; Scott et al., 2014; Moulton et al., 2017). However, most of these studies occurred on micro-tidal beaches with tide ranges less than 2 m where the location of the surf zone is relatively consistent over a tidal cycle (Masselink and Short, 1993). On meso- and macro-tidal beaches, with tide ranges of 2–4 m and >4 m respectively, rip current flow is short-lived. On such beaches where the alongshore variable bar/rip morphology can even emerge at spring low tide, rip flow can be maximised between low at mid to mean high tide water depths depending on surf zone bathymetry patterns, the location of rip current channels, and height of incident waves (Bruneau et al., 2011; Austin et al., 2013, 2014; Scott et al., 2014). Regardless, it is well established that tides can modulate rip current flow and, by association, the potential hazard of rip currents to swimmers.

A number of studies have related tidal phase (e.g. rising/falling) with the rip current hazard. Lushine (1991) noted that 75% of rip current-related drowning deaths in south-east Florida occurred in a 6-h period from 2 h before low tide (falling tide) to 4 h after (rising tide). Dusek et al. (2011) found that most rescues conducted by lifeguards at Kill Devil Hills, North Carolina between 2001 and 2009 were made during the approximate lowest one-third of water levels. As a result of this finding, Dusek and Seim (2013) incorporated tides into a probabilistic rip current forecast model based on a relationship between tidal elevation and rip current rescues.

In a review of 519 rip current drowning deaths across the United States between 1994 and 2012, Paxton and Collins (2014) reported that the tide was either falling, or low, at every drowning location except one. Arun Kumar and Prasad (2014) reported that more rip current drowning deaths in India occurred in the time period 1 h before, to 3 h after, low tide, suggesting that mid-low tide may have stronger rip current flow. They also found a relationship with tide range, as most drowning deaths occurred two days before and on the third day after larger spring tide ranges.

At beaches in the UK, Scott et al. (2014) found that rip current incidents involving lifeguard action occurred disproportionally around low water levels. Li (2016) also identified rip current development and risk to swimmers on Chinese beaches as being more prevalent at low tide. Silva-Cavalcanti et al. (2018) found that drowning in Recife, Brazil occurred more frequently at low tide, particularly 1 h before falling or rising tides, but no significant correlation was found between drowning and tidal phase. In a study of both fatal and non-fatal drowning incidents on beaches in southwest France, Castelle et al. (2020) found that drowning events occurred disproportionally around mean low tide level. In a follow-up study, de Korte et al. (2021) used Bayesian networks and found that rapid changes in tidal elevation during days with large tidal ranges resulted in slightly more drowning incidents with no statistically significant difference between rising and falling tide.

Ocean lifeguards and beach managers rely on various elements of the tidal cycle for operational and public safety planning (SLSA 2020a), and it is unknown what, if any, scientific basis informs these decisions. For example, a popular and long-held belief amongst lifeguards and surfers is that rip currents flow faster during falling tides, and therefore these periods are inherently more dangerous (Schwab, 2017; Koon et al., 2018). Despite lack of scientific evidence, lifesaving manuals and training programs in Australia teach new recruits that falling water levels lead to faster flowing rip currents, and rising water levels mean generally slower flow speeds (SLSA 2020b). Similarly, a systematic analysis of content shown in the popular reality television show 'Bondi Rescue', which depicts daily activities of lifeguards at Bondi Beach, Australia's busiest beach, found that lifeguard discussions of rip currents were frequently coupled with language associated with conditions worsening with the falling tide (Warton and Brander, 2017). However, field measurements of rip current flow on microtidal beaches have predominantly shown symmetrical velocity distributions around low-high-low tide cycles, that is, measured rip current velocity does not differ between rising or falling phases of the tide (MacMahan et al., 2006; Brander and Short 2001; Brander and Scott, 2016). Similar symmetry has also been documented on macro-tidal beaches (Scott et al., 2009; Austin et al., 2010, 2013) although Bruneau et al. (2014) found that rip velocities on a beach in south-west France were stronger on a falling tide due to the presence of tidal currents induced by the higher tide range.

The axiom that the falling tide results in more dangerous conditions for swimmers continues to influence lifeguard decision-making and other beach safety prevention efforts in relation to swimmer safety. To this end, the primary aim of this study was to evaluate if statistical relationships exist between fatal surf beach drowning and various stages of the (micro) tidal cycle in New South Wales (NSW), Australia.

The motivation for this work was to investigate assumptions about the tide's relationship to drowning risk that are commonly considered within ocean beach safety management. While these assumptions are usually rooted in ideas about the tide's influence on rip currents, as previously described, the research questions, methodological approach, and interpretations of statistical analysis are tailored towards practical implementation by ocean safety managers who consult daily tide predictions in planning and decision-making. Therefore, the analysis presented in the methods and results section of this study focus on elements of the tide, but are discussed in the broader context of rip current and beach safety management. The findings of this study have the potential to provide information useful to those responsible for beach management, lifesaving services and beach safety public education.

2. Methods

This retrospective cross-sectional analysis evaluated the relationship between elements of the tide and fatal drowning on surf beaches in New South Wales (NSW), Australia occurring between 1 July 2004 and 30th June 2019. Surf beach drowning deaths were defined based on a series of decision rules guided by Morgan et al. (2008) including: i) the location had to be an open ocean beach (i.e. not within bays, harbours, estuaries and other environments protected from ocean wave activity) that was confirmed by visual inspection of each site on Google Earth by authors WK and RB; and ii) at the time of death, the decedent was participating in beach-related recreational activities e.g. swimming/wading or snorkelling, as opposed to boating or personal water craft use, falls or jumps into water, land or rock-based fishing, non-aquatic transport, and SCUBA diving. It should be noted that by design, tidal factors are considered in isolation and do not account for variability in wave and other conditions in data analysis.

This study addresses four specific research questions (RQs).

RQ1. Is tidal phase associated with fatal drowning on surf beaches – are drowning deaths more likely to occur during a particular phase? Tidal phase (Fig. 1) here refers to the stages of the tidal cycle where water levels are rising (incoming/flood tide) or falling (outgoing/ebb tide).

RQ2. Is tidal water level associated with fatal drowning on surf beaches – are drowning deaths more common at lower or higher water levels? In this study, tidal water level refers to the elevation (m) of the ocean water surface at any given time relative to Australian High Datum (AHD).

RQ3. Is there a relationship between fatal surf beach drowning and time-based elements of the tidal cycle? Time is an essential element for planning and beach safety management. Knowing if time periods before or after low or high tide more likely to result in a drowning event would be helpful for lifeguard decision makers.

RQ4. Is fatal drowning associated with the range of the tide or the rate water levels change? Does tidal phase (rising vs falling water levels) influence any associations? Tidal range here refers to the vertical difference in meters between tidal water level predictions at successive high and low tide levels (Fig. 1), e.g., the distance between high and low tide, which varies between daily and lunar month tidal cycles. This question aims to address if periods of large tide ranges (e.g., during spring and king tides) result in rapid changes in water levels that may manifest as times of increased risk.

2.1. Physical setting

NSW was the chosen location of study for several reasons. First, it is Australia's most populous state with the greatest number of beach visitations and beach-related drowning deaths (SLSA 2022). Second, tides along the open ocean NSW coast are uniform, in contrast with the rest of Australia and many other parts of the world. The NSW coast experiences semi-diurnal tides and has a micro-tidal range (mean of 1.3 m; maximum of 2 m), which varies less than 0.2 m along the coast (Short, 2007). As noted by Short (2007), there is only a negligible difference, on the order of a few cm's and minutes, between the height and arrival time of the tide along the NSW coast between Tweed Heads (in the north) and Eden (in the south) – a straight line distance of approximately 1000 km. Given this uniformity, Short (2007) also notes that tide predictions for Sydney are often used to represent the entire NSW coast. The lack of variation in tidal height and times along the NSW coast is also evident in official tide charts from the NSW Department of Planning, Industry and Environment (NSW DPIE, 2021) and from the NSW Department of Transportation (NSW DoT; 2021), which recommends time adjustments from Sydney on the order of minutes for locations in the far north and south part of the state.

A final determining factor for focusing on NSW is that the entire coastline is characterised by a similar wave climate (Short and Trenaman, 1992) and relatively consistent morphological beach types. (Short, 2007). The NSW coast consists of 721 beaches of various morphologic types according to the beach state models of Wright and Short (1984), however most exhibit intermediate beach states characterised by various configurations of sand bars, troughs, and rip current channels, with the most common and extensive beach state being transverse bar and rip (Short, 2006, 2007). As such, most open ocean beaches in NSW are considered to be “surf beaches”.

2.2. Data sources, linkage and variables

This study used death data from the Surf Life Saving Australia (SLSA) Fatality Database and hindcast tidal predictions produced by the Manly Hydraulics Laboratory (MHL), a unit within the Water Division of the NSW Department of Planning and Environment. The SLSA Fatality Database, described in detail previously by Lawes et al. (2020, 2021), is curated from information from the National Coronial Information System (NCIS), a database maintained by the Victorian Department of Justice and Community Safety, and supplemented with additional details from media sources and lifeguard incident reports when available. Analysis in this study was restricted to SLSA records of fatal surf beach drowning events which occurred in New South Wales between 1 July 2004 and 30 June 2019 and, following Arozarena et al. (2015), included only cases where incident timestamps were available to which tidal data could be matched (n = 232).

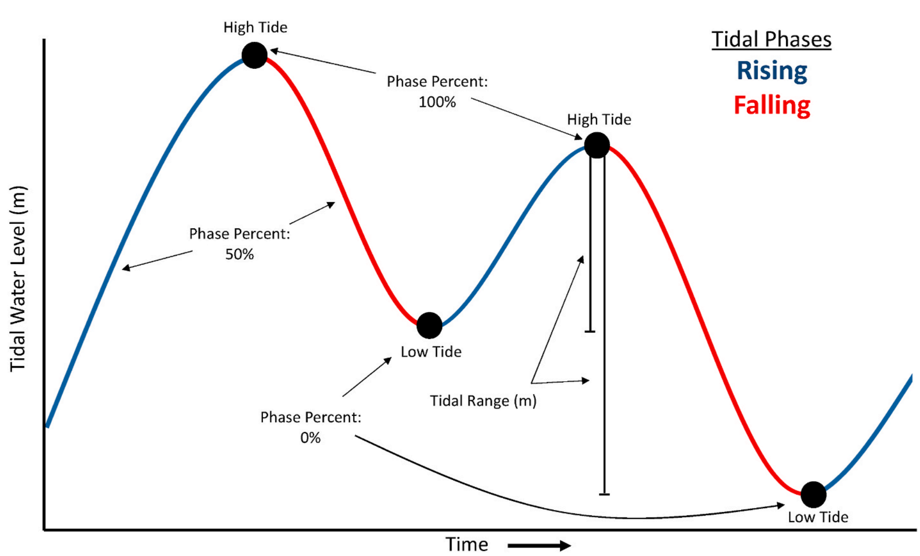

Fig. 1. Diagram showing terminology used in this study: tidal phases (rising vs falling); phase percent (0% = low tide, 100% = high tide, regardless of actual tidal water level in meters); tidal range (vertical difference in meters between sequential low and high tides).

MHL tidal data included 15-min hindcast tidal water level predictions in meters for the entire study period for Middle Head in Sydney Harbour, relative to the Australian Height Datum (AHD). Each fatal surf beach drowning in the SLSA dataset was linked to the MHL measurement closest in time, resulting in a timeseries of tidal water level predictions with a binary case variable designating each timestamp and tidal water level measurement as a case or non-case. From this timeseries, multiple additional tidal variables were calculated for analysis.

First, the rate of tidal water level change in meters per hour was calculated for each tidal water level prediction as the difference between each predicted tidal water level height and the immediately preceding predicted tidal water level height, multiplied by four as each prediction was 15 min apart. Tidal phase (rising vs falling water levels) was determined from the rate of tidal water rate of change variable: positive values indicated rising water levels, negative values indicated falling water levels. This tidal phase variable was verified using the VulnToolkit in R, which also extracts high and low tides from time series datasets (Hill and Anisfeld, 2021). While still present, the 15-min resolution reduces uncertainty in determining the phase (rising vs falling) of the tide for each case.

Tidal water level height predictions were converted to a standardized percent variable to assess if "lower" or "higher" sections of each tidal phase were associated with drowning rates. Each tidal water level height prediction was converted to a percent representing its location between the previous and next tidal turns, where 100% was high tide and 0% was low tide. That is, 50% indicates the halfway point between high and low tide in every tidal phase, but 50% represents different actual tidal water level height values from phase to phase. Range was calculated as the difference in meters between each low and high tide in order to evaluate if drowning deaths occurred during phases where the difference between high and low tide is larger or smaller, and subsequently tidal water levels are changing faster or slower.

2.3. Data analysis

Poisson regression was used to test for relationships between tidal variables of interest and fatal surf beach drowning. Multiple models were constructed to answer the research questions (Table 1). Each model included predictor variables specific to that research question, detailed below and in Table 1. Each model also included fixed effects adjustment terms to control for the confounding effects of variation in beach usage. Identified *a priori* and detailed in Table 2, adjustment terms were included for weekday vs weekend, hourly seasonality, and yearly seasonality.

Table 1
Multivariable models and descriptions.

Model	Description
Model 1	Phase: falling vs rising water levels
Model 2.1	Phase percent (standardised tidal water level variable)
Model 2.2	Phase percent (standardised tidal water level variable) with interaction term for phase (falling vs rising water levels)
Model 2.3	Water level height in meters (AHD)
Model 2.4	Water level height in meters (AHD) with interaction term for phase (falling vs rising water levels)
Model 3.1	Hours away from low tide
Model 3.2	Hours away from low tide with interaction term for phase (falling vs rising water levels)
Model 4.1	Tidal range (vertical distance in meters between sequential high and low tide)
Model 4.2	Tidal range (vertical distance in meters between sequential high and low tide) with interaction term for phase (falling vs rising water levels)
Model 4.3	Rate of tidal water level change in meters per hour
Model 4.4	Rate of tidal water level change in meters per hour with interaction term for phase (falling vs rising water levels)

Table 2
Confounding adjustment term descirptions

Fixed Effect Adjustment Term	Description
Weekend – Yes	Binary categorical variable indicating if the timestamp occurred during a weekend (Saturday or Sunday) or not; reference variable: Weekend – No.
cos(day)	This is the first of two seasonality terms adjusting for the effect of the day's position in the year. Following Stolwijk et al. (1999), this fixed effect term was calculated as: $cos\left(\frac{2\pi d}{365}\right)$ Where d represents the number of that day in the year.
sin(day)	This is the second of two seasonality terms adjusting for the effect of the day's position in the year. Following Stolwijk et al. (1999), this fixed effect term was calculated as: $sin\left(\frac{2\pi d}{365}\right)$ Where d represents the number of that day in the year.
cos(hour):	This is the first of two seasonality terms adjusting for the effect of the day's position in the year. Following Stolwijk et al. (1999), this fixed effect term was calculated as: $cos\left(\frac{2\pi h}{24}\right)$ Where h represents the number of that day in the year.
sin(hour)	This is the second of two seasonality terms adjusting for the effect of the day's position in the year. Following Stolwijk et al. (1999), this fixed effect term was calculated as: $sin\left(\frac{2\pi h}{24}\right)$ Where h represents the number of that day in the year.

Tidal phase (RQ1) was assessed via a binary variable with levels *rising* and *falling* (Model 1). Tidal water levels (RQ2) were tested in four different models evaluating two separate predictor variables. Model 2.1 tested a standardized continuous variable of values from 0 to 100 representing the percent of the current tidal phase where 0 = low tide and 100 = high tide; Model 2.2 tested the same phase percent variable with an added interaction term to assesses if the relationship between phase percent and fatal surf drowning was affected or altered in a non-additive manner depending on if water levels were falling vs rising, represented as *phase percent * phase*. Model 2.3 used the predicted tidal water level height in meters (AHD) as a predictor variable; Model 2.4 also used predicted tidal water level height in meters (AHD) as a predictor and added an interaction term for falling vs rising water levels as previously described, represented as *water level in meters * phase*.

Similarly, time of the tidal cycle (RQ3) was also assessed in two stages. First, using the number of minutes away from low tide as a continuous predictor, we evaluated if times closer to low tide were associated with increased or decreased drowning rates irrespective of if that time was before or after low tide (Model 3.1). Second, an interaction term was added for falling vs rising water levels (*minutes from low tide * phase*) to evaluate if the likelihood of fatal drowning on surf beaches increased or decreased as time approached and moved away from low tide (Model 3.2).

Tidal range (RQ4) was also assessed in four models using two different predictor variables with interaction terms. First, we evaluated tidal range, a continuous variable referring to the vertical difference between water level predictions at successive high and low tides, to assess if times with "larger" or "smaller" phase changes were associated with fatal drowning on surf beaches (Model 4.1); then we added an interaction term (*tidal range * phase*) to evaluate if the relationship changed depending on if water levels were rising or falling (Model 4.2). Next, we tested if "faster" or "slower" changes in rising or falling water level heights were associated with drowning by evaluating the absolute value of tidal water level change in meters per hour, with smaller values representing slower changes in water levels and higher values representing faster changes in water levels (Model 4.3); then, as before, we added an interaction term (*rate of change * phase*) to evaluate if the relationship changed depending based on rising or falling phase (Model 4.4).

Poisson regression calculates incident rate ratios (IRRs) with 95% confidence intervals and the statistical significance of individual terms in each model was tested using Wald tests. Descriptive analysis was conducted using R, regression analysis was conducted using the *glm* function in R, data visualisation was conducted using Tableau Desktop [Computer Software] and the *ggplot2* and *ggdensity* packages in R (Wickham, 2016; Otto and Kahle, 2022), Supplementary File 2 includes a description and relevant code for re-producing the figures in this manuscript.

3. Results

There were 616 drowning deaths in coastal locations in New South Wales between 1 July 2004 and 30th June 2019, of which 306 occurred at surf beaches. Of these, 15 cases did not involve beach recreational activities, 40 cases did not have reliable time and or date information, and a further 19 cases were deemed not to have occurred in a surf beach location, leaving 232 cases for analysis. Among the variables tested, lower tidal water level and times closer to low tide were statistically associated with increased likelihood of fatal drowning events. Tidal phase (rising vs falling water levels), times specifically before or after low tide, and size of a tidal phase's range were not statistically associated with surf beach drowning fatalities ($p > 0.05$). Results relating to each research question (RQ) from Section 1 are presented below, and full results from multivariable regression models are available in Supplementary File 1.

3.1. RQ1: tidal phase

In the study period, 48.3% (n = 112) of drowning deaths occurred during rising water levels, 47% (n = 109) occurred during times with falling water levels, 9 (3.9%) occurred during the 15-min high tide period, and 2 (0.9%) occurred during the 15-min low tide period. Fig. 2 shows each case along the cycle of falling and rising water levels according to its phase percent (standardised water level height), with darker shaded areas indicating areas of higher case density (See Supplementary File 2). The lack of any visually detectable pattern between rising and falling water levels in Fig. 2 was also confirmed by multivariable regression results: there was no statistical evidence that rising or falling water levels resulted in higher likelihood of drowning fatalities on surf beaches ($p = 0.23$). In short, drowning rates did not differ by phases in the tide.

3.2. RQ2: tidal water levels

Surf beach drowning fatalities occurred disproportionately at lower water levels. Fig. 3A shows the differences in proportion between cases (when drowning deaths occurred) and non-cases (when drowning death did not occur) at each predicted water level height, values greater than 0 indicate a higher proportion of cases occurred at that water level. Fig. 3B shows the actual proportion of cases (bars) compared to non-cases (line) occurring at each predicted water level.

In the standardized measure that converted water level height predictions to a proportion of each phase with the high tide turn being 100% and the low tide turn being 0%, cases occurred across a range of actual water level heights in meters. Fig. 4 shows the standardized phase percent of each drowning death case (y-axis) plotted against its actual water level height in meters (x-axis). Cases again occurred in higher proportions at lower phase percent values with 46.1% (n = 107) of cases occurring in water levels below 25% of their tidal phases (Fig. 2). However, there was a noted concentration of cases occurring near high tide as well: 17.2% (n = 40) occurred in water levels above 90% of their phase (Figs. 2 and 4). These higher phase percent cases (>90%) occurred at water heights ranging from 0.1 m to 0.97 m (Fig. 4).

Multivariable regression analysis showed a statistically significant association between fatal drowning events and lower tidal water levels using both the standardized percent variable and the actual water level prediction in meters, neither of which were affected by tidal phase. In the standardized water level percent model, high tide, with 100% water level, was associated on average with 0.6 times as many drowning fatalities as low tide, 0% water level (CI = 0.41–0.87; $p = 0.007$). That is,

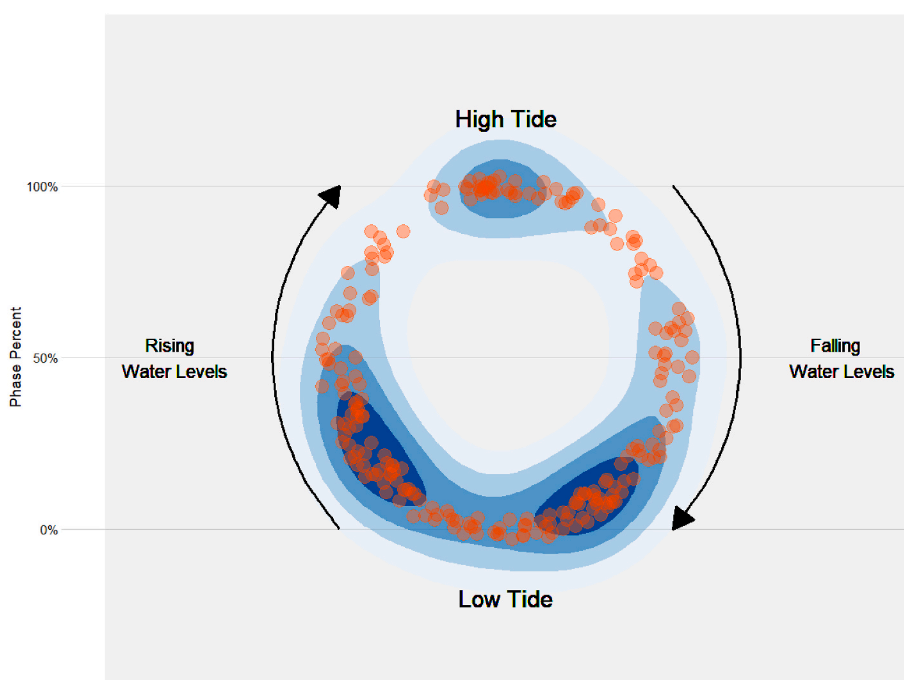

Fig. 2. Surf beach drowning deaths by phase (rising vs falling water levels) and tidal water level as a percent of each phase (0% = low tide, 100% = high tide) with areas of higher probability density indicated in darker blue, New South Wales, Australia, between 1 July 2004–30 June 2019 (Supplementary File 2).

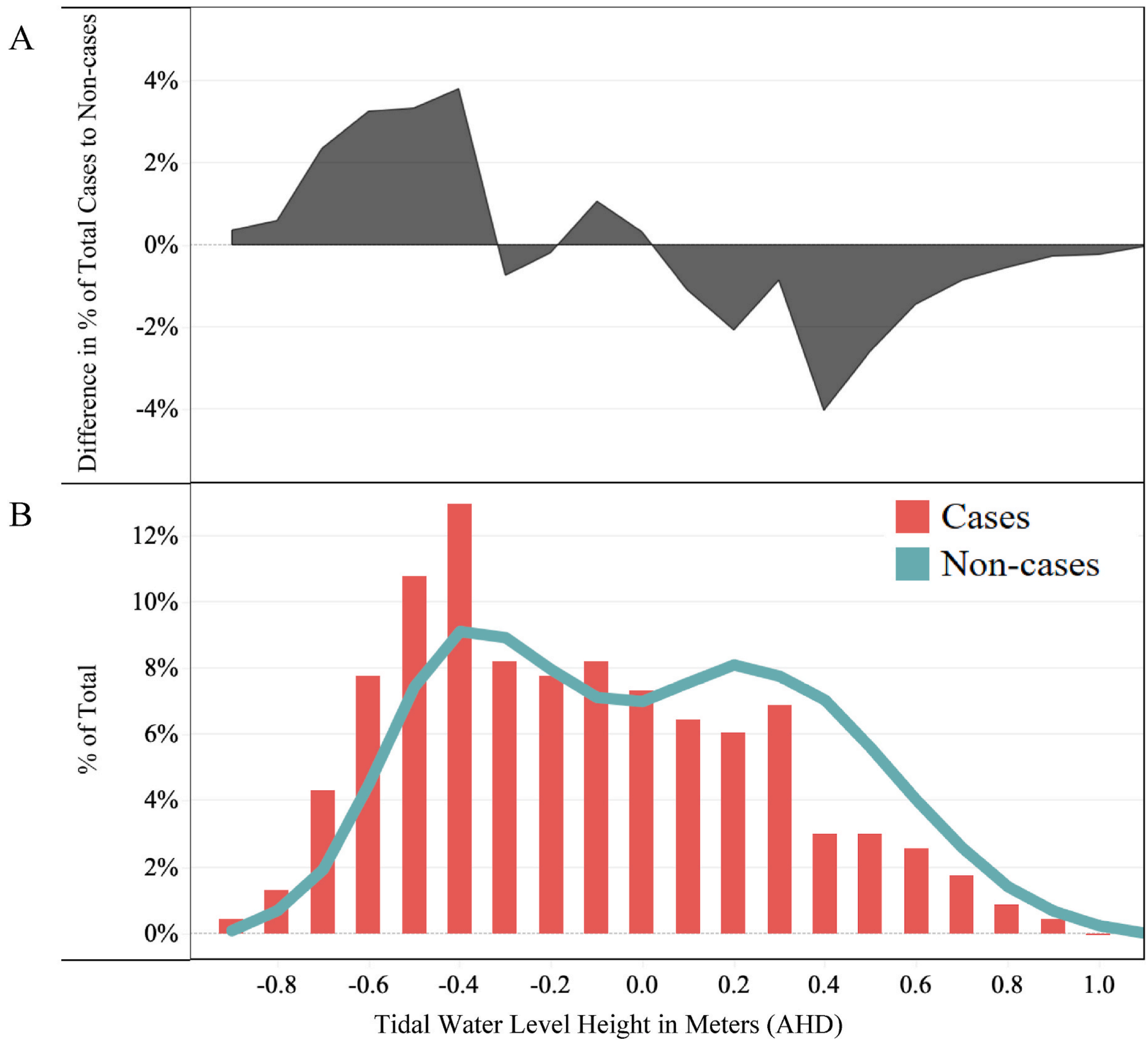

Fig. 3. Differences in distribution of surf beach drowning deaths (bars; n = 232) and tide predictions with no deaths (line; n = 596,054) by water level height in meters (AHD), New South Wales, Australia, between 1 July 2004–30 June 2019.

drowning deaths at surf beaches are 40.4% more likely to occur during times when tidal water levels are at low tide compared to high tide, regardless of actual water height in meters (CI:13.4%–59%). In the model based on tidal elevation in meters, each additional 1 m of tidal elevation was associated with a 44.7% decrease in the likelihood of fatal drowning events (95%CI: 0.39–0.78; p = 0.001). Rising versus falling water levels did not statistically influence the association between phase percent or water level in meters (Joint test of interaction coefficients: p = 0.219 [phase percent], p = 0.537 [water level in meters]).

3.3. RQ3: time of tidal cycle

In multivariable regression, there was statistical evidence of a trend where time periods closer to low tide, regardless of if they were before (falling) or after (rising), were associated with increased drowning incident rates (IRR for increasing hours away from low tide: 0.92; 95% CI: 0.85–0.98, p = 0.013). For each additional hour further away from low tide, drowning fatalities were 8% less likely to occur (2%–15%). A separate model included an interaction term for hours from low tide and tidal phase to evaluate if time periods approaching (falling water levels) or moving away (rising water levels) from low tide affected the trend. The joint test of coefficients for interaction between water level and phase of the tide was not statistically significant (p = 0.17), indicating that drowning rate trends did not differ between times before or following low tide.

3.4. RQ4: Tidal range and rate of water level change

Results from multivariable regression indicated that the size of the tidal range was not associated with surf beach drowning rates (p = 0.983) and there was no statistical evidence that rising or falling tidal water levels influenced that lack of a relationship (p = 0.416). Additionally, there was no pattern in surf beach drowning deaths and the rate at which tidal water levels rise or fall: Fig. 5A shows the differences in proportion of surf beach drowning deaths and tide predictions with no deaths by tidal water rate of change rate of change in meters per hour; Fig. 5B shows the distribution of surf beach drowning deaths (bars; n = 232) and non-cases (green line; n = 596,054) by tidal water level rare of change in meters per hour. Fig. 6 shows surf beach drowning cases (red points) by tidal water level rate of change in meters per hour (negative = falling, positive = rising) and tidal water level height in meters (AHD) overlaid on the probability density of non-case tide predictions (grey polynomials, see Supplementary File 2). As with the tidal range, the rate of change of falling or rising water levels was not associated with surf beach drowning deaths in multivariable regression (p = 0.25) and was not influenced by phase (p = 0.418). This means that there is no increase

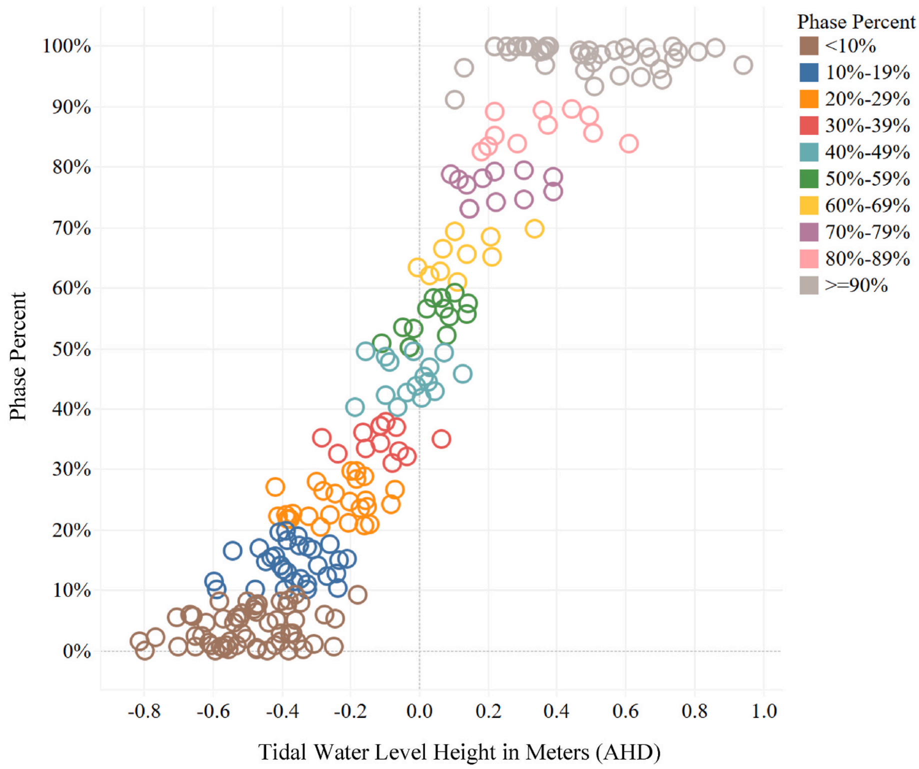

Fig. 4. Surf beach drowning deaths by phase percent (0% = low tide, 100% = high tide) and water level height in meters (AHD), New South Wales, Australia, between 1 July 2004–30 June 2019.

in drowning risk with a *"big drop in the tide"* or *"quickly rising water levels."*

4. Discussion

This study contributes new understanding to the relationship between characteristics of ocean tides and the occurrence of drowning deaths along the microtidal surf beaches in New South Wales, Australia. These data show that tidal phase, i.e., the "direction" of the tide (rising vs falling), did not play a role in distinguishing periods when surf beach fatal drowning deaths were more or less likely to occur. Similar observations were made along the meso-macrotidal beaches of southwest France (de Korte et al., 2021). Drowning deaths occurred in rising and falling phases and all water level heights, but there was evidence that lower water levels and times closer to low tide were statistically associated with fatal drowning in this location. As described in Section 1, rip currents are responsible for a large proportion of beach-related drowning fatalities in NSW and while this study did not focus solely on rip current drowning fatalities, these results align with the best scientific understanding of rip current flow behavior. Field measurements of rip current flow in a range of surf beach environments have shown that flow velocity is symmetrical in magnitude in relation to the tidal stage at which maximum velocities occur, typically around low tide on microtidal beaches (MacMahan et al., 2006; Brander and Scott, 2016; Brander and Short, 2001). In simple terms, rip current flow is driven by the action of breaking waves, often across three-dimensional surf zone morphology, and typically increases at lower water depths regardless of whether the tide is falling or rising as surf zone morphology does not vary significantly during a tidal cycle. Similarly, these results indicate that lower water levels, *regardless of tidal phase*, explain at least some variability in when drowning deaths are more likely to occur, contrary to existing beliefs (SLSA 2020a,b).

The finding that lower water levels were associated with increased drowning fatalities in NSW, Australia support results from beaches in other parts of the world. Drowning events were also more likely to occur around low tide in studies from France (Castelle et al., 2019, 2020), Brazil (Silva-Cavalcanti et al., 2018) and India (Arun Kumar and Prasad, 2014). However, drowning is a relatively rare event, making robust analysis difficult without multiple years of reliable data. Lifeguard rescues or visual observations of hazard level may be a useful outcome to further evaluate risk at surf beaches, although these data are usually only available from lifeguard reports which can be subject to validity and reliability issues (Williamson, 2006; Koon et al., 2021b; Dusek and Seim, 2013). Some studies have examined the relationship between lifeguard rescues and the tide: Dusek et al. (2011) and Scott et al. (2014) found increased rescue activity at lower water levels in North Carolina and the United Kingdom, respectively, and another study from a single beach in California found mixed and conflicting results along different sections of the beach (Koon et al., 2018). Further work with alternative outcome measurements (besides drowning deaths) like non-fatal drowning incidents (Castelle et al., 2019), and/or the use of webcams (Dusek et al., 2019), machine learning (de Silva et al., 2021), or optical flow (Mori et al., 2022) methods for rip current detection would be worthwhile.

Of note, while results here, and from previous studies, indicate that drowning events were more likely at lower water levels, several cases in this study occurred at water levels near high tide, in the top 90% of their phase (Fig. 2). These high tide cases occurred across a range of actual water levels (Fig. 4) and were not enough to deter the trend in multivariable statistical analysis, but they are worth addressing. While we can only speculate by providing plausible scenarios, to truly answer this question requires an assessment of the cause of each drowning death, information which is difficult to collect reliably, and consideration of the multiple other environmental, physical and human/social variables that induce risk.

One possible explanation is that as high tide is associated with deeper water, there is a greater likelihood that poor, or non-swimmers, may simply find themselves out of their depth, particularly on steep beaches,

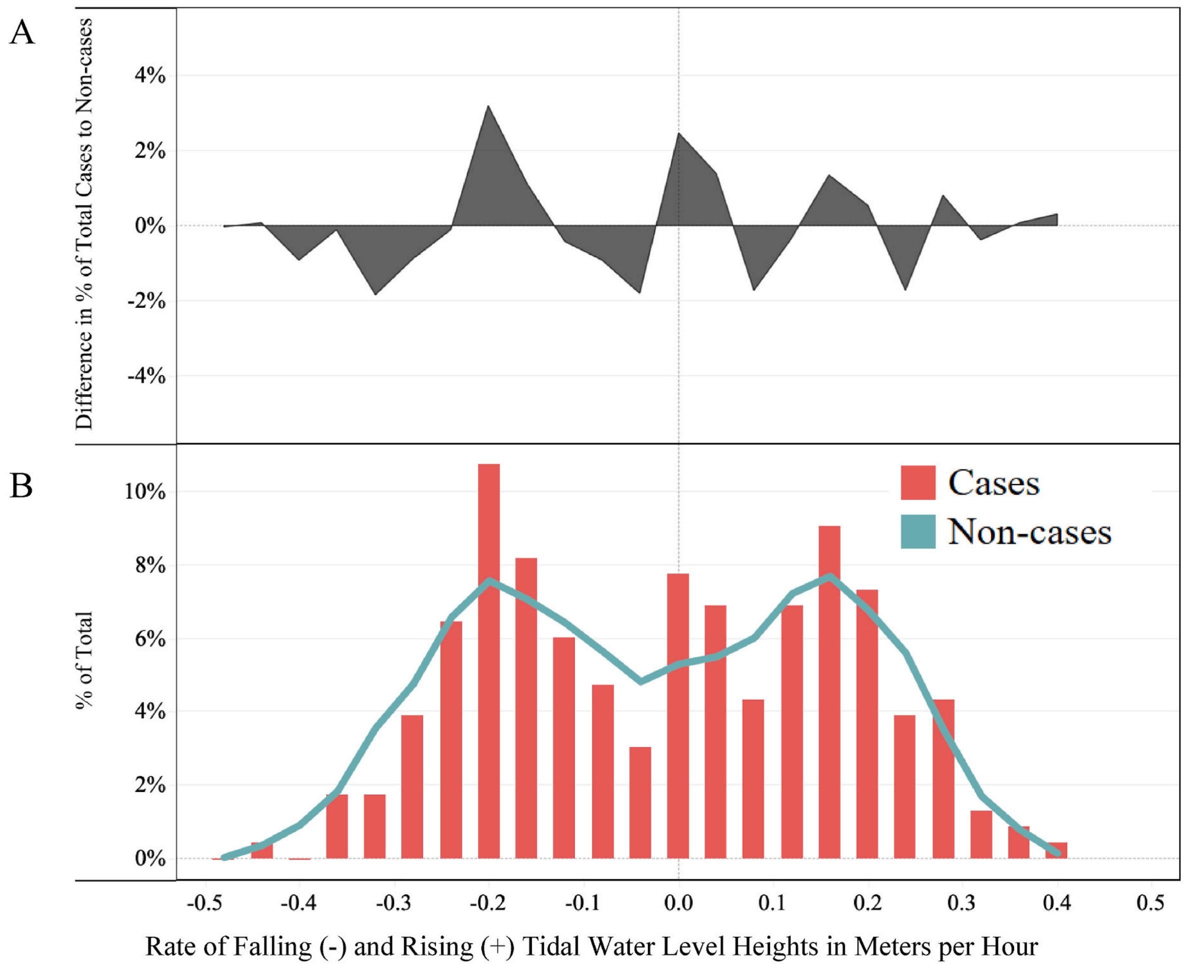

Fig. 5. Differences in proportion and distribution of surf beach drowning deaths (bars; n = 232) and tide predictions with no deaths (green line; n = 596,054) by tidal water level rate of change, New South Wales, Australia, between 1 July 2004–30 June 2019.

or those characterised by deeper troughs and channels. It is also possible that more people tend to enter the water at high tide as wave breaking across the surf zone is less intense. Conversely, high tide shifts the position of the shoreline to upper parts of the beach, which tend to be steeper and promote more powerful shore break conditions (Puleo et al., 2016; Castelle et al., 2018; Muller, 2018; Doelp et al., 2019). Bathers may attempt to pass through the shorebreak quickly and find themselves in deep water. It is also possible that these high tide cases occurred during large surf, which, if big enough, could cause active flash rip currents at mid and high tides (Castelle et al., 2016). In southwest France (Castelle et al., 2020), a disproportionate number of (fatal and non-fatal) drownings incidents were also observed during high tide levels. Information from the incident report forms indicated that a substantial amount of these incidents were caused by small-scale swash rips and/or shore-break waves (Castelle et al., 2019). Further study which somehow accounts for these human factors and incorporates other physical variables would greatly serve to advance understanding in this area.

The finding that times closer to low tide (RQ3) were more likely to result in drowning deaths is not surprising as it is essentially a reparameterization of the finding that lower water levels (RQ2) are associated with increased fatal drowning likelihood. Moreover, as previously stated, these results also align well with the latest rip current science. Although there is a statistically significant association between both lower water levels and times near low tide with fatal drowning, the point estimates of the relationships were small, limiting actual use in any safety-related decision-making or education capacity. Our results indicate that a drowning death is 8% (2%–15%) more likely for every hour closer to low tide, a difference of questionable importance in the grand scheme or safeguarding against fatal drowning. Again, this result highlights the importance of evaluating other physical parameters, such as wave height.

4.1. Implications for ocean safety management

There are several reasons why the findings of this study are important for coastal management and policy, specifically for those with safety-related responsibilities including lifeguard operations and beach safety education. First, training programs and manuals for lifeguards working at beaches with a microtidal tide range (<2 m) should not teach new recruits that phase of the tide, large tide ranges, or rate of water level change will influence the risk of drowning. There is no evidence to support lifeguard instruction suggesting that "falling tides" or "large dropping tides" result in higher rip current and drowning risk. Ocean lifeguard training on physical hazards of the beach and surf zone environment should be evidence-based and our findings should prompt lifeguard training program managers to review and consider updates to existing training content.

Second, these results should be considered in future ocean lifeguard operational guidelines, planning, and decision making, especially related to staffing and resource allocation. Findings from RQ2 (Section 3.2) indicate that lower tidal water levels are associated with greater risk to swimmers and bathers, regardless of if the tide was rising vs falling. This means that along with other factors such as beach attendance and

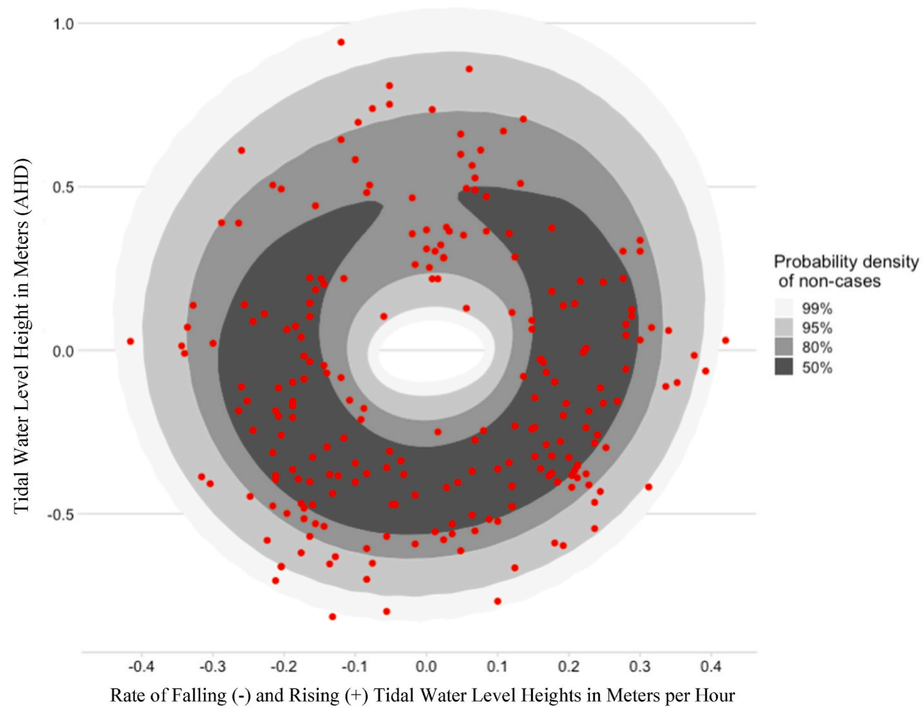

Fig. 6. Surf beach drowning deaths (points; n = 232) by tidal water level rate of change in meters per hour (negative = falling, positive = rising) and tidal water level height in meters (AHD) overlaid on the probability density of non-case tide predictions, New South Wales, Australia, between 1 July 2004–30 June 2019.

risk from physical hazards, decisions regarding lifeguard staffing levels and/or placement should consider when water levels are low, and not be based on whether the tide is rising or falling.

Finally, information about the influence of the tide on drowning risk should be carefully considered before inclusion in beach safety messages or public safety announcements intended for the public. For short communications, such as on social media, ocean beach safety managers may be better off promoting swimming at lifeguarded locations or other more general open water safety messages (Moran et al., 2011). Discussion on how the tide influences rip currents and drowning risk is more complex and may be more appropriate in longer beach safety educational talks or presentations (Brander et al., 2022; Koon et al., 2023).

Of note, this analysis occurred at a macro level and did not examine specific locations where times with falling water levels may actually alter risk or specific hazards, such as tidal currents near river mouths, harbor entrances, tidal lagoons or estuaries. While lifeguards should be trained to understand both general principles about physical hazards and drowning risk and specific features of the beaches they work at, it may be unrealistic to expect the same of the public. While evidence for effectiveness is limited (Koon et al., 2021a), beach safety signs are one way to educate the public in specific locations where tidal currents are an important hazard, or, where the tide can cut off access to the beach. Additionally, some of these beach safety management implications may not be applicable to meso-macrotidal beaches, where larger tidal gradients (both rising and falling) have been associated with a slight increase in probability of drowning incidents (d. e de Korte et al., 2021).

4.2. Limitations

This study had several important limitations. First, the analysis only assessed tidal factors with the occurrence of fatal drowning, which is a rare event. The study did not include non-fatal drowning or rescues, which are also indicators of dangerous situations and may be helpful in evaluating a more holistic parameterization of surf beach risk and relationships with different environmental variables (Scott et al., 2014; Dusek et al., 2011; Dusek and Seim, 2013; Castelle et al., 2019, 2020).

Second, fatalities, regardless of where they occurred in NSW, were linked to the water level prediction from the Sydney (Middle Harbour) tidal station that was closest in time to the incident. As described in Section 2.1, tidal predictions from Sydney are applicable to the entire NSW coast (Short, 2007). Some error may be present in the linkage by time, although minimal as the SLSA drowning fatality dataset is based on reliable coroner data with emergency response timestamps from several sources including police and lifesavers.

Third, there were 40 cases where NCIS death data provided an estimated time of death range, not a time stamp information from which we could link tidal information. It is possible that these missing data induced some element of selection bias, although it is unlikely that cases with missing incident times occurred systematically in relation to tidal factors.

This study intentionally examined the relationship between tides and fatal surf beach drowning along the microtidal New South Wales coast in isolation and did not consider other environmental variables, such as beach and surf zone morphology, waves and weather, or human factors such as ocean experience. To this point, it is worth highlighting that case inclusion was not restricted to only those deaths caused by rip currents as this information reported from the scene of a drowning event would be inconsistent and unreliable. Some of the included cases here may have been due to other non-rip current causes, however our fundamental study objectives were to explore the implications for beach safety management which is concerned with all bathers. Additionally, this study used hindcast tidal water level predictions, versus actual measurements, that do not account for non-tidal residual from other factors that might influence water level such as waves or weather (e.g., high/low pressure, storm surge, wind). People are less likely to be on the beach in strong winds or inclement weather (Castelle et al., 2019) and on days when people are swimming, water level differences due to weather, such pressure or wind, would be negligible if not zero.

Finally, it should also be emphasised that these findings are restricted to a microtidal environment and may not be applicable to surf beaches with larger tide ranges. On no beach is the risk of drowning determined by the tide alone. Further research is necessary to better understand how these other variables and factors, as well as the tide, contribute to the risk of drowning on surf beaches both individually and synergistically as needed.

5. Conclusions

The risk of drowning on surf beaches is complex and composed of several interacting factors, including the tide. This study provides important evidence that contributes to the understanding of risk on surf beaches by establishing that statistical associations exist between some tidal variables and the occurrence of fatal drowning along surf beaches in New South Wales, Australia. Fatal drowning was more likely to occur during times of lower water levels, and, importantly, that the likelihood of fatal surf beach drowning was not related to the phase of the tide – either falling or rising. While these findings do not prove that tidal variables caused the drowning fatalities, these results have implications for ocean and beach safety management and those charged with educating the public about beach safety issues. Broad statements or anecdotal opinions that are not specific to a particular place or beach should avoid describing times with falling water levels (an outgoing tide) as being inherently more dangerous.

Ethics

This study was conducted with ethics approval from the Victorian Department of Justice and Community Safety Human Research Ethics Committee (CF/21/15898).

Authorship contribution statement

WK and RB conceptualized the study and planned analysis. WK conducted formal analysis with input from GD and BC. WK and RB drafted the original manuscript, with input from GD, BC, and JL. All authors reviewed and approved the final manuscript.

Funding

This study was supported by the Lake Macquarie and Northern Beaches City Council Smart Beaches Project, an Australian Government Smart Cities and Suburbs Round 2 Project.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: William Koon, Robert Brander reports financial support was provided by Lake Macquarie City Council. Jasmin Lawes reports a relationship with Surf Life Saving Australia that includes: employment.

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors would like to thank Shane Daw, Luke Strasiotto, and Jessica Ledger from Surf Life Saving Australia, who made data from their Fatality Database available for this study; Tony Blunden from the Smart Beaches Australia Project and Brad Sutton from the Lake Macquarie City Council, who were involved in preliminary study conceptualisation; Eve Slavich from UNSW Stats Central who advised on statistical analysis for this study; and Sam Maddox from the Manly Hydraulics Laboratory who advised on tide predictions for the NSW coast.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106584.

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