A study on the Physical Characteristics of Currents and Wave Climate at Ramla Bay

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A dissertation presented to the Institute of Earth Systems of the University of Malta for the degree of Bachelor of Science (Hons) in Earth Systems

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Abstract

This baseline study investigates the nature of sea current circulation and wave climate of the wider Ramla Bay area, specifically the significant wave height and the wave direction, using numerical models. This study was undertaken because no existing studies or data on the physical hydrodynamics of the area are available. This information is unconditionally important for the input into management decisions. Through reviewed literature, it was expected that a cellular circulation arising from the formations of rip currents within the bay prevail. This was thought to be the case at Ramla because of the circular pattern of *Posidonia oceanica* seagrass beds in the centre of the bay. The results showed that rip currents were not prevalent during the studied period. The mapped sea currents were found to predominantly flow along the contours of the coastline around the embayment. It was, however, concluded that the occurrence of strong rip currents, should not be excluded as a possibility during the winter period when strong wave conditions occur. Data from the SWAN model for wave direction was found to approach the coast predominantly from the North East direction. Signifying possible accumulation of sediments on the west side of the embayed beach. Wave direction was also observed to have a positive relationship to the ensuing current direction but were found to be statistically insignificant. The significant wave height wave was also found to be significantly larger in the winter months compared to the summer months. Within the bay the temporal variation of SWH exhibited less fluctuation compared to deeper waters. The SWH was also found to be strongly associated with alterations in atmospheric pressure and showed that Ramla Bay is powerfully protected during storm events, by drastically attenuating the wave energy. This is an essential role when considering the dynamics of the beach morphology, as well as the dynamics of the backshore dunes.
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Chapter 1 Introduction

1.1 The dynamic nature of physical coastal oceanography

Wave climate and the hydrodynamics of sub-surface currents vary across time and space, particularly when migrating from deeper water to shallower waters. Such changes can be attributed to physical and biological factors, such as bathymetry, topography, geology and vegetation cover. The properties of wave fields and the generated longshore currents can cause the sand-bar in an embayed beach to migrate in the cross-shore and longshore direction over varying time-scales, ultimately altering the beach shape and sediment balance (Ojeda, Guillén, & Ribas, 2011). The direction of surface waves is governed by the wind direction. To an extent, the wave direction controls the direction of the current. However, this is subject to change due to a temporal response lag at different depths and the physical influence of the coastal topography and bathymetry (Röhrs et al., 2012). Currents are also generated within the nearshore zone due to wave breaking and the loss and transfer of wave energy (Tang, Lyu, & Shen, 2014). The formation of rip currents may be attributed to the complex changes in wave properties that occur to the wave field propagating within an embayment (Xie, 2012).

This dissertation examines and analyses the nature of sub-surface currents within a small embayment. The study focuses on Ramla Bay, which is situated on the North coast of Gozo. Observations made using satellite images of Ramla Bay reveal a circular pattern of Posidonia oceanica in the centre of the bay that extends some 400m from the beach (Figure 1.2). Posidonia oceanica rely on currents for dispersing fragments for colonization and supplying sediments suspended in shallow water to form a consolidated sandy substrata, usually in embayments where sediments tend to collect (Di Carlo, Badalamenti, Jensen, Koch, & Riggio, 2005). Understanding the sub-surface current circulation and wave climate of embayments, such as at Ramla Bay, may be useful to a set foundation towards future studies pertaining various fields, such as bather safety, sediment transport, biological interactions and pollutant diffusivity.
In operational oceanography, numerical models are used to simulate scenarios governed by mathematics and physics to produce outcomes that best represent what is happening in nature. Numerical models bring together data from other models to produce these outputs, which in turn aid in better understanding the seas and ocean from day-to-day situations to extreme events to long term changes. With this information, predictions can be made (Stewart, 2008). Numerical modelling was used to obtain data simulating the wave characteristics within the bay and the surrounding area, which would not be possible using in-situ techniques. In the analysis of results section, the acquired in-situ data in the field by drifters is compared to the SWAN coastal model. In particular, the Significant Wave Height (SWH) and Mean Wave Direction (MWD), are analysed. Understanding how wave climate changes spatially at the site and inter-annually has direct application to understanding the forces shaping beach morphodynamics. This is essential for coastal engineering and management.

1.2 The Study Area

The area of interest is confined to an open embayment, Ramla l-Hamra Bay, on the North coast of Gozo (Figure 1.1), located approximately at latitude 36.062671°N and longitude 14.283805°E. Ramla Bay is characterised by an embayed beach facing northwards. Embayed beaches develop along coasts of discordant orientations outlined by an alternating hill and valley topography (Castelle & Coco, 2012; McCarroll, Brander, Turner, Power, & Mortlock, 2014), where predominant wave climate is directed against the coast. The geological setting of the headland-bay is the product of the bands of faults that run perpendicular to the coast as part of the horst and graben system that is typical of the Maltese archipelago (Devoto et al., 2012; Micallef et al., 2013). Bays are located within the graben sector (the downthrown block, wedged between two ridges) where beaches may be formed where the mouth of the valley meets the sea. Protruding headlands correspond to the horst ridges that have been uplifted through tectonic faulting (Magri, 2006).
The study area boundary for current measurements is clearly defined to encompass Ramla Bay (Figure 1.1). However, the area covered by modelled data may exceed this boundary area, with more extensive coverage, encompassing the surrounding area. The surface bathymetry at Ramla is capricious with sandy sediments covering most of the central area of the bay, rock and boulder fields covering both sides of the bottom of the headlands and extensive, dense *Posidonia oceanica* beds dominating the areas beyond the mouth of the embayment (Figure 1.2). In conjunction with the knowledge of alongshore variation in bar morphology and bathymetry in general; conditions specific to Ramla Bay may result in complex hydrodynamics of the circulation within the nearshore due the presence of the submerged ruins of a historic defence sea wall (Figure 1.3). The wall runs the entire length of the bay but has undergone severe degradation from interfering beach users and boating activity (Figure 1.2).
Figure 1.2: Satellite Image of Ramla Bay with the easily noticeable circular pattern of *Posidonia Oceanica* seagrass beds and the presence of a crescentic alongshore sand bar, as well as the remnants of the seawall, marked within the red border (Source: Google Earth).

Figure 1.3: Plan of culturally historical features present at Ramla Bay (Source: Azzopardi, 2015).
A study by Farrugia, Fsadni, Yousif and Mallia (2005) reveals that annually, the Maltese Islands experience winds coming from the general North-West direction (Figure 1.4). As indicated in Figure 1.5, there exists a pattern in the season variation in wind speed around the Maltese Islands, whereby the summer months are characterised by relatively weaker winds than those during the winter months. Studies have observed rip currents to be more likely to occur and stronger under high energy wave conditions, particularly with high swells (Haller, 2002). Acknowledging this fact, drifters were deployed in as many different sea state conditions possible during the data collection time frame. Unfortunately, strong waves limited the access to Ramla Bay by boat, during the winter months.

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1.3 Research Problem and Motivation of the Study

Understanding the dynamics of currents in shallow embayments, such as Ramla, is essential in forecasting sediment budgets and biological processes (Jones & Monismith, 2008). Most of the previous studies that consider the same area have been concentrated towards beach morphology, sediment dynamics, coastal management, tourism, etc. and have excluded a direct focus on the physical hydrodynamic processes. Presently, there is no existing data for the dynamics of sea currents and wave climate specific to Ramla Bay. The research carried out in this project will serve as an addendum to the growing compilation of such data for the Maltese Islands. Its application could be effective in the role of management, particularly important to Ramla due to its status as a Natura2000 site (Figure 1.6).
1.4 Aims and Objectives of the Study

This study will attempt to answer several questions that can be categorised into the following fields:

1. Biophysical Field
   a. Do coastal currents, particularly with rip currents as the main mechanism, play a role in shaping the circular pattern of *Posidonia oceanica* beds observed in the centre of the bay during the summer period?

2. Hydrodynamic Field
   b. How do sub-surface currents behave throughout the Ramla Bay embayment?
   c. What is the nature of the wave climate of the embayment and how does it vary over the inter-annual period?
   d. What is the nature of the relationship between the incoming wave direction and current direction within the embayment?
   e. What is the relationship between the Significant Wave Height and the atmospheric pressure?

From the biophysical aspect the hypothesis would suggest that the circulation of currents adhere to a circular gyre pattern due to the nature of the geography of the bay and to the meteorological and hydrodynamic characteristics, whereby rip currents are likely to be the predominant driving force of this circulation system. If rip currents are present, they are expected to occur as headland rip currents i.e. on the sides of the headlands rather than in the centre of the bay.

For the field of hydrodynamics, it is hypothesized that the general pattern of current flow in absence of rip currents would exhibit an alongshore flow parallel to the coastline and contours. The shallow water processes which alter wave characteristics, whereby the wave heights increase and the velocity of the wave orbitals decreases. Therefore, it is hypothesized that weaker currents measured will be produced within nearshore zone of the bay, where there is lower energy due to increased dissipation of wave energy due to breaking, compared to currents in deeper portions of the bay.
The wave climate is expected to vary between the calmer summer period and the high energy winter period. The average direction of the incoming wave field is suspected to approach predominantly from the north-west direction and ultimately re-orientate within the bay to be parallel to the beach, due to the physical control of the embayment geography. The relationship between wave direction and sub-surface currents should be proportional for poorly stratified waters. However, because of complex dynamic processes, especially in the surf-zone, there may be some contradictions to this hypothesis.

It is also hypothesised that the significant wave height (SWH) would be greater during the winter months and have a larger range of variation between deeper and shallower water, than would be exhibited in the summer months. Furthermore, it is suspected that climate has a strong influence on the behaviour and nature of the SWH. Periods of low atmospheric pressure storm events would result in accentuating conditions of SWH relative to normal conditions.

The aim of this study is to develop an understanding of the hydrodynamic nature concerning the current circulation system and characteristic of the wave climate present within Ramla Bay, Gozo. The study on wave climate will cover a six month period between August 2015 and January 2016 (due to the availability of data) and between July 2015 and October 2015 for current flow measurements, due to time restraints. Tangentially, it is of additional interest to conduct a simple bathymetric survey of the bay as a baseline to review the extent of bathymetric control of mean flows.

The objective is to collect in-situ data on current flow within the defined boundaries of the study area at Ramla Bay using GPS tracked drifters to measure sub-surface currents 1m below sea level. The in-situ data is to be then compared with the modelled output from Rosario-SHYFEM coastal model for validation. Concurrently, modelled data for wave characteristic produced in the SWAN model will be statistically analysed to observe the time variance spatial evolution across the bay. Also, the wave direction will be statistically correlated to the direction of current flow obtained from drifter measurements to analyse the relationship between the two parameters. The scope is not to study the direct biological processes related to the Posidonia oceanica but the
physical means by which the biological components may be influenced by local currents. Furthermore, because of certain limitations and restrictions, the study could only be focused on a few selected physical parameters, namely, current direction and speed, wave direction, significant wave height and to a lesser extent depth and wind. All the raw data collected throughout the study will be compiled and be made available for future use in other studies.

1.5 Significance

Similar studies on currents, for validating numerical models using empirical data have been carried out elsewhere in the past, with particular interest on near-shore circulation and rip currents. However, in Malta, information on the nature of currents and the influence they exert on the changing environment, is lacking. Coastal currents, especially those circulating within embayments are coherent to studies pertaining to sediment transport, the dispersion of pollutants discharged into the marine environment (Spydell & Feddersen, 2012) and public safety.

Coastal surveyors interested in understanding the evolution the morphological alterations of the coast, require surveys on hydrodynamic nature and wave climate of an area and how these also change in time, due to natural or anthropogenic causes (Inukai, Kuroiwa, Matusbara, & Noda, 2001). More importantly, at the EU level of management of the marine environment comes the Marine Strategy Framework Directive (MFSD), accompanied by an extrinsic link to the NATURA 2000 network (Figure 1.6) and Habitats Directive. The remnant sand dune systems in the backshore of the embayed beach at Ramla has recently been observed by the Gaia Foundation, who is responsible for the management of the area, to migrate towards the sea (A. Micallef, personal communication, April 20, 2016). This suggests the interplay between aeolian and wave dynamics altering the beach state, whereby it is possible that more sediment is accreting to allow for dune migration. This is entirely speculative as no studies have been undertaken for the area. Nevertheless, this underlies the importance and relevance of this dissertation as a holistic source for other studies.
1.6 Review of Dissertation

In the second Chapter of the dissertation, the compilation of scientific literature studied on the subject, pertaining to the physical processes of current formation, wave characteristics and fluid dynamics, will be discussed. The methods and equipment in oceanographic studies are also discussed. Chapter three explains the materials used, as well as the methodology undertaken, from field work to data processing to analysis and the limitations encountered during the length of the study. The penultimate chapter discusses the results acquired and the discussion interpreting results. The interpretation makes the link to the hypotheses and literature reviewed and answers the research questions. The conclusion outlines the outcome of the project and the significance of the dissertation to answering the question.
Chapter 2 Literature Review

The Literature Review discusses the research conducted in previous studies. The literature analysed relates to the physical mechanism of the formation and relationship of waves and currents, particularly within the nearshore zone, where more complex hydrodynamic processes take place. Also discussed, are the operations of physical oceanographic research, directly conferring to the numerical models used in this dissertation.

2.1 Features of Embayments

Embayments are ubiquitous along banded regions of valleys and hills at the coast; innately identifiable by the curvature of embayed beaches and accompanying headlands (Castelle & Coco, 2013; Daly, 2013). The general and simplified profile of any beach will include the swash zone, the surf zone, the nearshore zone and offshore zone (Figure 2.1).

![Figure 2.1: The physical zonation of the coast (Source: Davidson Arnott, 2009).](image)

The nature of currents and waves changes as they propagate towards and the coast, whereby the influencing topography and the geology of the coast, are
major contributors in deciphering how waves and currents change. Therefore, it is required to understand not only the wind and wave climate of a study area but also, the geography of the coast where interactions take place (Conley et al., 2008).

![Diagram of zones describing waves processes over a sandy seabed](Source: Davidson Arnott, 2009).

Within the surf zone of sandy/shingle beaches, longshore sandbars form parallel to the shoreline (Figure 2.2). In some cases, crescentic sand bars form. Sand bars are usually rhythmic and vary seasonally in shape (van Enckevort, 2004). The hydrodynamic influence of the wave climate and subsequent currents, constantly alter the sand bar and ultimately the features of the sandy, unconsolidated bathymetric substratum (Price, Ruessink, & Castelle, 2014). The persistence and changes in hydrodynamic processes are far more variable within a shorter timeframe compared to morphological processes, which span longer time scales (Blondeaux, 2001). Storms have a greater capacity to drastically change a shingle bedform than the usual nearshore hydrodynamic processes. The morphological profile configuration is reset after major storms along the coast (Schwartz, 2012). The sand bars are essential for initiating the wave breaking process, by which the dynamics within the surf zone are characterized (Van de Lageweg, Bryan, Coco, & Ruessink, 2013). At Ramla Bay, the sandbar was found to disappear between fluctuating summer and winter conditions (Azzopardi, 2015). Masselink and Hughes (2003) clarify that
the migration of the sand bar infers that the depth of closure and the wave base also vary accordingly (see Section 2.4.1).

The swash zone refers to the ranging levels of the wave run-up and run-down along the sloping beach face (foreshore); this is partially where sediment is uplifted and where wave induced currents are formed (Bakhtyar, Barry, Li, Jeng, & Yeganeh-Bakhtiary, 2009). Consequently, the hydrodynamic characteristics of the narrow swash zone alter the morphological shape and profile of the foreshore seasonally (Larson, Kubota, & Erikson, 2004). These alterations are largely dependent on the frequency and magnitude of nearshore waves, the sedimentology of the beach and the general beach morphology (Vousdoukas, Velegrakis, Dimou, Zervakis, & Conley, 2009). Subsequent cross-shore currents deliver the suspended material seaward, where it may be circulated within the bay by alternative currents within the semi-closed cell of the embayment. This results in erosion of the beach (Baquerizo, Lozada, Mendoza, & Silva, 2010).

2.2 Geological Control

Geological features are capable of controlling the distribution of wave energy and therefore the characteristics of the wave spectrum and currents. In the case of embayments featuring headlands and decreasing depth of the seafloor, attenuation of the energy of waves propagating towards the coast occurs (McCarroll et al., 2014). Other than the configuration and shape of the coast, the surface roughness of the sea bottom will play a major role in the behaviour and velocity of bottom currents that explicably alter subsequent current flows above it (Signell, Beardsley, Graber, & Capotondi, 1990). Drag and surface roughness have greater effects on waves and current dynamics within the surf zone (i.e. within the wave base zone) rather than outside it. Bottom roughness is inheritably temporally variable due to modifications in
bedform morphology and succession of vegetation growth (Feddersen, Gallagher, Guza, & Elgar, 2003).

The generalised beach classification parameterisation techniques do not embody the circumstances undergone with embayed beaches due to the inherent control and influence that headlands have on nearshore current circulation (Loureiro, Ferreira, & Cooper, 2013). The topography of headland-bays coerces the flow of coastal longshore currents, as well as giving rise to small scale currents localised to an embayment that in some cases give rise to cellular circulation (Loureiro, Ferreira, & Cooper, 2012).

The *Posidonia oceanica* seagrass meadows, which are densely abundant beyond the mouth of the bay, influence wave climate and hydrodynamic characteristics within the bay by attenuating wave energy. The physiology of the seagrass meadows, with their flexible and sometimes short aboveground biomass reduces their capacity to attenuate wave energy, compared to other, more rigid biomass. However, seagrass meadows compensate by altering the erodibility of the seabed, making it more consolidated by sediment accretion (Christianen et al., 2013). Therefore, the morphology of the seabed is more susceptible to alteration by hydrodynamic processes where it is bare and unconsolidated. Borg, Rowden, Attrill, Schembri and Jones (2009) studied the *Posidonia oceanica* cover at Ramla Bay. They found that the seagrass coverage is progressively increasing, when contrasted to fragmentation, despite the high exposure. Evidently, the consolidation of the sandy substrata is likely to increase, thus the hydrodynamics of the area may be altered due to this, in the future. Also, they assert the need to understand the localised hydrodynamic characteristics and wave climate, so as to study the coverage and fragmentation of *Posidonia* meadows, as well as other benthic habitats.

**2.3 Wind**

Numerous forces are responsible for the movement of a body of water. The oceans are mainly set in motion by surface winds, predominantly by storms in open waters (Davidson-Arnott, 2009; Klemas, 2012). Wind applies a surface pressure, which in turn alters the surface elevation of the water, forming waves.
For sub-surface currents to be generated, there must be a downward transmission of momentum from the surface by means of Reynolds Stresses. Reynolds stress occurs, when the horizontal movement of water at the surface is out of phase with the surface elevation. Without this process the only method for momentum transfer down the water column is by turbulent diffusion (Nielsen, Callaghan, & Baldock, 2011). The veering of surface currents can be observed with changes in wind direction. However, there tends to be a lag in veering of sub-surface and deeper currents that are considered to be wind driven (Drago, 1980).

The wind stress above the sea surface, eventually results in the transfer of momentum in the form of surface current flow, which can be expressed to be linear, in essence of a uniform eddy viscosity (Chang, Chen, Tseng, Centurioni, & Chu, 2012). The height and energy transferred to surface sea waves is dependent on the wind velocity and duration for which the wind blows in the same direction (Camilleri, 2012). Concurrently, wind shears have the capability of dissipating wave energy and therefore current flow (Ardhuin & Jenkins, 2006). Although strong high energy waves in the Mediterranean may occur, lacks the vast expanses of ocean for a significantly large fetch to develop and so, is generally lower energy waves compared to coasts surrounding open ocean systems (Mottershead, Bray, Soar, & Farres, 2014).

2.4 Waves

Waves have considerable effects on the mean flow of water; affecting the pressure and shear drag (Sullivan, McWilliams, & Moeng, 2000). The interaction between the atmosphere and sea surface, induces a flux by the transfer of most of the wind energy and momentum to waves. Wave breaking results in dissipation of energy, thereby inducing further fluxes in momentum and turbulent kinetic energy from the wave to surface and sub-surface boundary layers (Hong & Eng, 2003; Paskyabi & Fer, 2014). Turbulent mixing is enhanced by the energy flux from wave breaking (Gemmrich & Farmer, 2004), whilst accelerated mean flow is the outcome of stress adhered by the momentum flux. In saturated sea states, energy and momentum flux that are
transferred to wave fields, are balanced by the dissipation of energy from white capping/wave breaking (Weber, Broström, & Saetra, 2006). If energy is not dissipated, than momentum and energy is advected by waves and stored across the wave field (Röhrs et al., 2012).

Haslett (2009) describes the relationship between the surface wind speeds and the resulting growth in wave height. Wave height is directly proportional to the square of wind velocity. Sometimes, it is best to obtain a single calculated measurement for wave height that is representative of the state of the sea at a point in time. To do this, oceanographers use the Significant Wave Height (SWH), $H_{1/3}$, which is the mean of the highest one third of all waves at that point in time (Brown et al., 1999; Camilleri, 2012). Altunkaynak, ASCE and Özger (2005) assessed the spatial variation of SWH and found that the climatic conditions have a powerful influence on the nature of the SWH. They also explain the importance of SWH in representing and determining the wave energy. A study on the physical characteristics of the wave climate was conducted in 2003 for the Maltese Islands. The SWH was the main parameter measured. However, the scale of the study, using numerical models, encompassed the entire Maltese Islands and so, the resolution was quite low. The closest point of model SWH to Ramla was 10km north east of the islands. The study found that the general 10% of the exceedances of SWH of the year was below 1.5m (Scott Wilson Kirkpatrick and Co. Ltd, 2003).

The wave height increases with the intensification and duration of onshore winds. Ultimately waves tend to break further outside the surf zone (Aagaard & Hughes, 2010). Determining the inter-annual variations in wave climate can be done by analysing a group of parameters, namely the significant wave height and the mean wave direction. This understanding can be used to describe the spatial distribution of wave energy (i.e. wave spectrum) at varying frequencies and subsequently, describe the wave systems of different sea states of a given area (Sanil Kumar & Anjali Nair, 2015).

### 2.4.1 Wave Orbitals
Particles at the surface, where waves are present, exhibit a circular orbital movement; with the highest velocities and forward movement along the crest and the lowest velocity and backwards movement at the trough (Figure 2.3). Waves of increasing amplitude, experience an accentuation of this effect. A net flow is produced, whereby the particles flow in the direction of the travelling wave (Lentz & Fewings, 2012; Monismith, Cowen, Nepf, Magnaudet, & Thais, 2007; Simpson & Sharples, 2012). This was coined the Lagrangian current, which is also referred to as the Stokes Drift. Surface drifters are designed to measure this drift. This orbital effect is transposed down the water column, with gradually shrinking orbitals succeeding further down. The bottom boundary layer, present above the seabed, transforms circular orbitals into elliptical orbits (Simpson & Sharples, 2012). Wave orbitals attenuate down the water column to a depth equal to half the wavelength – referred to as the wave base. When the wave base delineation is approached, waves begin to interact with the seabed. The wave base can be used to define the depth of closure, which marks the “boundary between the upper and lower shoreface…and can be used to infer a seaward limit to significant cross-shore sediment transport” (Masselink & Hughes, 2003, p. 196; Nicholls, Larson, Capobianco, & Birkemeier, 1998).

Figure 2.3: Transposed forward motion of water particles under the forces of propagating energy. Arrows show orbital motion is off put slightly in the direction of wave energy (Source: “Ocean in Motion: Waves and Tides,” n.d.).
2.4.2 Wave Shoaling

Waves propagating towards the coast, i.e. travelling from deep waters to increasingly shallow water, undergo shoaling (Benetazzo, Carniel, Sclavo, & Bergamasco, 2013; MacMahan et al., 2011; Newell, Mullarkey, & Clyne, 2005). Shoaling accounts for the changes of wave properties that eventually lead to breaking. These changes are characterised by decreasing wavelength, speed and wave period, which result in increasing wave height and therefore increased wave steepness (Davidson-Arnot, 2009). The development of shoals creates alterations in the wave breaking process (Idier, Falqués, Ruessink, & Garnier, 2011). The interaction of, incoming and outbound, long waves with shoaling short waves, results in a flux of energy depending on the phase (Van Dongeren, Svendsen, & Sancho, 1996). Near bottom velocities of wave orbitals vary greatly and rapidly when waves begin the shoaling process (Lentz & Fewings, 2012).

2.4.3 Wave Breaking

Wave breaking in the nearshore is the main mechanism for generating physical processes leading to the set-up and wave-induced currents, including longshore, rip and undertow currents (Smit, Zijlema, & Stelling, 2013). The scale of the many different types of motions resulting from breaking waves can range from large vertical motions to minor turbulence, as a means of releasing the waves energy (Lubin, Glockner, Kimmoun, & Branger, 2011).

Wave-current interactions have a mutual effect on one another, as waves contribute to the formation of currents, whilst concurrently currents have an effect on waves (Benetazzo et al., 2013). This relationship shows that currents exert the greatest influence when the direction of the current flow opposes that of the propagating waves. Along shore currents flowing within a shallow embayments will behave differently depending on the wind stress (Jordi, Basterretxea, & Wang, 2011), which may give rise to waves or no waves. The presence of surface waves propagating to shallower water, omitting the area
within the surf zone, will drastically reduce the magnitude of the underlying wind driven sub-surface currents due to frictional drag between the wave-current interaction (Signell et al., 1990).

2.4.4 Wave Refraction and Diffraction

When the incident wave front travelling from deep water to increasingly shallower water at an angle to headland-bay coasts, wave refraction occurs (Kusky, 2008). A physical property of water waves, dictates that wave speed and wavelength decreases as water depths decrease, whilst the wave height increases (Pickard & Pond, 1983). Conveyed by Snell’s Law, as one end of the wave interacts with a shallower depth first, forcing it to decrease in speed, the other end of the wave continues to travel at the initial speed. As a result, the wave diverts towards the normal of the beach marked between the deeper and shallower depths (Figure 2.4). When wave refraction occurs, wave fronts can be observed to approach shallower water at nearly parallel directions to the beach (Garrison, 2013; Godin, 2009).
Figure 2.4: Wave refraction occurrence as waves move into shallower water. Notice how refraction is not complete and waves still break with some angle, on the beach. (Reproduced from Unit 5: Tsunami Propagation, n.d.).

Figure 2.5: The process of wave refraction where incoming waves alter direction to align their propagation parallel to the beach (Source: Waugh, 2009).
The occurrence of wave orthogonals approaching the headland-bay perpendicularly, is not a good representation of the general wave climate. For most of the year, waves approach at an angle. When incident waves approach an embayment obliquely, the headland controls the direction of the incoming wave field. By the process of diffraction, coupled with refraction (Yasso, 1965), wave orthogonals bend around the headland (Davis Jr & Fitzgerald, 2004; Lutgens & Tarbuck, 2012) and because depth is continuously changing, wave crests closer to the headland are diverted around it, whilst the further waves continue moving in their initial direction (Figure 2.5), are subject to refraction. Diffraction results in variation of wave heights along the incident wave front (Svendsen, 2006). The outcome gives rise to a shadow zone (Figure 2.6); a sheltered area where waves are greatly attenuated (Holthuijsen, 2007; Woodroofe, 2002). It can also occur throughout the water column by means energy dissipation of bottom waters that interact frictionally when variations in seabed covers appear, such as seagrass beds on sandy bottom (Dalrymple, Hwang, & Kirby, 1984).

![Figure 2.6: Wave diffraction and refraction as wave orthogonals approach an embayment at an oblique angle, whereby the headland has significant control creating a shadow zone behind the headland. (Source: Woodroofe, 2001).]
This effectively creates spatial variability in the wave breaking process in the alongshore direction, such that the shadow experiences low energy waves, as opposed to the unaffected portion of the shore that receives higher energy waves. This in turn creates alongshore gradients in radiation stresses (Aagaard & Vinther, 2008), thus driving longshore currents within the surf zone.

Breaking waves are characterised by two portions, the bore and the roller region. The bore is the state of the wave after breaking, followed by the roller. The roller is the surging remnant after the wave has broken whilst approaching the shore. The vertical turbulence velocities, as well the kinetic energy, decreases with depth from the trough of the breaking waves. The horizontal velocities, however, are relatively uniform with depth (Lin & Liu, 1998). Approaching waves breaking, most commonly at an angle to the shore, exemplify wave energy dissipation, ensuing a highly turbid region. In this final stage of the incident waves transformation, momentum is transformed into currents (Peregrine, 1998).

2.5 Currents

As elaborated in previous sections, currents at and near the surface, are driven by the wind stress and by Stokes Drift resulting from waves. In deep waters, the surface current response to wind can be considered to be inertial. Therefore, there is a delayed lag response between wind and surface currents (Stewart, 2008). The lag explains why currents can be observed traveling in different directions to the overlying wind (Capodicasa, Foti, & Scandura, 1991; Mao & Heron, 2008). The scale at which wave-induced currents flow, generated in the nearshore, are considered to be unaffected by the planetary forces, such as the Coriolis force (Jenter & Madsen, 1989; Ozkan-Haller, 2014; Tang et al., 2014).

In deeper waters, physical layers within the water column can be delineated from one another by a shifting angle of current direction. This is known as the Ekman spiral (Garrison, 2013). The transference of stress through the water column is direct and so water movement follows the direction of the stress
applied (Lentz, 1995). Currents in the Maltese Islands are generally weak, as they are throughout most of the Mediterranean because of the negligible significance of tides (Basterretxea et al., 2004; Jordi et al., 2011). Drago (1980) shows that there is a consistency with the dominant large scale current flow around the Maltese islands in a SE direction and this consistency is disrupted in cases of large storm events. In shallow waters of Ramla Bay, strong winds and wind shear at the surface are the main driven of mean flow, with some negligible influence from tidal pressure gradients, whereby there is little stratification of currents with depth (Jones & Monismith, 2008).

2.5.1 Turbulence and Radiation Stress

Turbulence occurs due to instability by the breaking process of waves on the shore (Tang et al., 2014), with maximum turbulence occurring within the breaker zone and swash zone (Bakhtyar et al., 2009). Swirling vortex of fluid describes turbulence best and exists on different scales of length and time. Small morphological variations in the seabed are responsible for the development of small eddies, by which horizontal convection of eddies is driven by waves following the bore (Peregrine & Bokhove, 1999). As turbulent eddies lose mechanical energy, they decrease to smaller scales until the dissipated energy eventually is transformed into heat by molecular viscosity (Brown et al., 1999; Mohsin & Tajima, 2014; Svendsen, 2006). This gives rise to augmented diffusivity, which in turn drive fluxes in momentum and energy that is referred to as stress (Celik, 1999; Kraichnan, 1976). The eddy viscosity in association with this turbulence, accounts for the process leading to the production, advection and dissipation of turbulent flow in the surf zone (Inukai, Kuroiwa, Matusbara, & Noda, 2001; Mohsin & Tajima, 2014).

Variation in radiation stress within the nearshore is a requirement for generating currents, whether cross-shore or alongshore. This radiation stress is the product of the net momentum flux forced by the dissipation of breaking waves (Newell et al., 2005). The incident shoaling and breaking waves create a bi-directional variation in the mean sea level, referred to as the set-up and set-down. On open coasts, when incident waves approach the shore
perpendicularly, the radiation stress gradient is balanced by the set-up/set-down variation (Stive & Wind, 1982) and so no longshore currents are created (Yu & Slinn, 2003). This does not apply to headland embayments because of the array of alterations in wave dynamics discussed before. When there is differential breaking along the shore, then pressure and radiation stress gradients develop within the surf zone. This is responsible for the momentum transfer from waves to currents (Peregrine, 1998). Turbulent shear stress is the mechanism by which the differences between radiation stress gradient and pressure gradient (uniform with depth) are balanced, in turn driving currents (Ting & Kirby, 1994). There is a linear decrease in the turbulent stress down through the water column until reaching the bottom boundary layer (Cox & Kobayashi, 1996), thusly disrupting the no-slip characteristics of the bottom boundary layer surface (Garcez Faria, Lippmann, Stanton, & Thornton, 2000).

### 2.5.2 Longshore Currents

Longshore currents form within the nearshore zone. The mechanism driving longshore currents, is the variation in radiation stress and wave set-up/set-down along the shore, which are caused by variance in wave breaking along the surf zone (Idier et al., 2011). As discussed throughout this Chapter, differential wave dissipation concurs with (Johnson, 2004):

1. Topographic and bathymetric variations
2. Spatially varying approaching wave fields
3. Approaching high frequency surface waves with low frequency waves, such as edge waves. This is related to effects of shoaling as described in the previous section.
4. Wave-current interactions within the surf zone

This forms areas of high energy dissipation that produce a resultant mean flow towards the zone low energy dissipation (Smith, 1993), brought about by breaking waves of relatively smaller breaking wave heights. Longshore current generation occurs exclusively in the surf zone; with maximum speeds occurring in the middle of the surf zone (Davis Jr & Fitzgerald, 2004). These flows can
move beyond the nearshore zone and flow along the periphery of winding coast (i.e. around headlands). Thus, follow the contours of the coastline. The generated longshore currents, with speeds ranging from 0.3 – 1 ms\(^{-1}\), exhibit a proportional relationship with the angle that the propagating wave field makes with the shoreline and the orbital velocities of waves once within the breaker zone (Brown et al., 1999).

2.5.3 Undertow

Undertow currents commonly occur under high energy wave conditions and/or when there is the absence of a longshore bar. They result from the landward moving water by waves that pile up and elevate the set-up. Momentum balance is then achieved by means of seaward moving currents below the surface moving water, i.e. concentrated close to the seabed (Davis Jr & Fitzgerald, 2004; Scandura, 2011). Balance is maintained by returning water by landward moving waves above (Yu & Slinn, 2003). The set-up is responsible for vertical imbalances in momentum flux and pressure gradient – the foundation for driving undertow (Cox & Kobayashi, 1996). Ohlmann, Fewings, & Melton (2012), used drifters to study how current velocities moving shoreward change with decreasing depth. They found that under weak winds, drifters decelerated as they move onshore. This decrease in velocity is brought about by seaward moving undertow. Their study, however, was conducted on an open system coast, characterized by long beaches and wide surf zones.

2.5.4 Rip Currents

Rip currents are jets of narrow, relatively fast flowing currents towards the sea that occur throughout much of the world’s beaches (McCarroll et al., 2014; Winter, van Dongeren, de Schipper, & van Thiel de Vries, 2014). Rip currents are considered a danger to beach users, where numerous deaths are associated with drowning when caught up by these relatively strong currents (Castelle et al., 2014). The momentum flux generated by incoming breaking waves within the surf zone creating an imbalance between the inside and
outside of the surf zone. The conservation of mass requires there to be balance and this balance is brought about by the creation of currents that flow seaward (Johnson, 2004). Topographic and bathymetric variations, particularly with respect to variations in sand bar morphology can cause this variation in wave breaking (Miles, Guza, Elgar, Feddersen, & Ruessink, 2001). Where breaks in sand bars are present, wave breaking will not occur as much (locally) in that portion, as it would over the rest of the bar. The piling of water behind the bar will seek to maintain balance by flowing through the break, outwards to sea as a rip current through the funnelled past of least resistance (i.e. the break) (Murray & Reydellet, 2001).

Two types of rip currents can be associated with headland-bay embayments; topographic and mega rips (Macmahan et al., 2009). The intensity of the rip currents and longshore currents are inversely related, in respect to the factors governing intensity, which are wave height, wave direction and directional spread (Dusek & Seim, 2013). Storm events may lead to the formation of mega rips, which are intensified versions of topographically controlled rip currents that can cause severe beach erosion (Short, 2010).

Figure 2.7: The anatomy of a rip current (Source: Johnson, 2004).
A rip current consists of three integral parts (Figure 2.7). Rip currents develop by means of feeder current. Feeder current refer to alongshore currents generated within the surf zone as discussed before. Their existence disrupts the longshore moving flow of alongshore currents (Johnson, 2004). Obtaining data sets acquired in the field on rip current measurements is difficult because of the shallow depths in which they originate and their transient nature, making it hard to know where and when to take measurements (Haller, 2002). A fully comprehensive computation of the complex circulation dynamics of rip currents is plausible with numerical modelling, yet may require bathymetric and wave data, which may not always be obtainable (Leatherman & Fletemeyer, 2011).

2.5.5 Embayment classification

Masselink & Short (1999) recognised the profound difference in hydrodynamic circulation between an open and long beach coastal system with that of an embayment, characterized with headlands or rocky outcrops. They designed a formula to express this relationship. This design is mainly directed towards classifying the degree of embaymentisation with the presence of headland rip currents in relation to the incident wave field (Razak, Dastgheib, Surydai, & Roelvink, 2014).

As proposed by Castelle & Coco (2012), certain issues arise with the original design, as it disregards the fact that the wave energy dissipation will be less at the headlands compared to the attenuating effect the sea bottom has on wave energy as waves approach shallower depths (Garrison, 2013; Pickard & Pond, 1983). Therefore, for embayments receiving low to moderate energy waves characterised with prominent headlands, the scaling parameter could be deceptive.

Three types of embayment circulation may occur. Normal circulation typifies open beaches, having no headlands or barriers (Razak et al., 2014). The second type of circulation flow is described as cellular circulation. The occurrence of cellular circulation is signified by strong headland control, in which rip currents are formed at either side of the embayment or in less likely
instances, in the centre. This type of circulation typically results in the formation of a small gyre that circulates within the confines of the bay. This has consequential implications on the migration of the sand bar but also beach shape (Castelle & Coco, 2012; Daly, 2013; Razak et al., 2014). Normal type circulation can also be possible in embayments with headlands where the size, length and shape of the beach is large enough for currents and waves not to be powerfully affected by interfering topography. This may result in numerous rips occurring across the beach. This is referred to as transitional circulation, which may be assumed to be an intermediate of the prior two (Castelle & Coco, 2012).

The significance of the embayment characterisation and the hydrodynamic processes involved is important when applied to integrated coastal zone management, by the concept of sediment cells. Sediment cells can be described as “spatially discrete areas of the coast within which marine and terrestrial landforms are likely to be connected through processes of sediment exchange… commonly identified as self-contained where little or no sediment movement occurs across cell boundaries” (Stul, Gozzard, Eliot, & Eliot, 2015, p. 5). This coastal cell concept aims to understand the sediment budget of a closed system, in which studies on the dynamics of currents and wave climate within a cell need to be understood, not only spatially but over short to long term periods for future management of the coastal area (Montreuil & Bullard, 2012; Sedrati & Anthony, 2014).

2.6 Lagrangian Measurements

In operational oceanography, currents are measured by either Eularian or Lagrangian methods. The Eularian approach primarily involves measuring current vectors from a fixed point on the sea bottom, making it possible to determine currents distribution and magnitude through the water column (Sharples & Simpson, 2012). The Lagrangian method does the opposite. The Lagrangian method tracks the current vectors freely, untethered to the seabed by means of drifters that flow with the current on the sea surface or sub-surface (Emery & Thomson, 2004). A drifter deployed in proximity to rip currents should
theoretically follow a similar trajectory. This has been recorded to occur in the field by Schmidt, Woodward, Millikan and Guza (2003), when a drifter was deployed within the surf zone of a rip channelled bay. Lagrangian measurements from drifters are subject to the net movement of sub-surface water movement in the direction of the travelling wave field, which is caused by the underlying physics of wave orbitals (Capodicasa et al., 1991; Sharples & Simpson, 2012), known as the Stokes Drift.

2.6.1 Drifters

Drifters can be simple in design and cheap, equipped with a low cost GPS logger and be just as effective (MacMahan, Brown, & Thornton, 2009). The accuracy of the equipped GPS can vary significantly depending on whether it is differential or non-differential. Non-differential GPS trackers are more accurate than the former, however, they are much larger. The added bulk would, consequently, impair the drifter’s abilities, particularly when measuring within and outside the surf zone (Sabet & Barani, 2011). A description of the custom made drifter used in this project is provided in the Methodology Chapter.

2.6.2 Rosario-SHYFEM Model

The SHYFEM model (Shallow Water HYdrodynamic Finite Element Model) is a two-dimensional vertically integrated model, which solves shallow water hydrodynamic equations of coastal areas, in which time integration is resolved using a semi-implicit algorithm (Dinu, Bajo, Umsgiesser, & Stânică, 2011). The Rosario-SHYFEM model is a recently developed model specified to the Maltese Islands. Consequently, there is a lack of related literature. The SHYFEM model is governed by the shallow water equation (Equation 2.1).
Equation 2.1

\[
\begin{align*}
\frac{\partial U}{\partial t} + gH \frac{\partial \zeta}{\partial x} + RU + X &= 0 \\
\frac{\partial V}{\partial t} + gH \frac{\partial \zeta}{\partial y} + RV + Y &= 0 \\
\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} &= 0
\end{align*}
\]

Where, \( \zeta \) is the water level, \( g \) is the acceleration due to gravity; \( t \) is time; \( H \) is the depth of water. \( X \) and \( Y \) are substitutable components for other elements, such as wind stress or non-linear terms. The \( U \) and \( V \) components represent the transports in the horizontal dimension \((x,y)\), which can be extracted from the \( U \) and \( V \) velocities in the vertical dimension by means of integration (Desira, 2015; Umgiesser, Canu, Cucco, & Solidoro, 2004). Finite elements of the model refer to an unstructured numerical grids that are generated by an automatic mesh generator. The Rosario-SHYFEM model applies a triangular finite element grid that is defined by nodes (Figure 2.8). The grid becomes more refined closer to the coastline, resulting in a higher resolution to be obtained where the variation in hydrodynamics is more complex. The depth is specified for each element, with the velocities of the currents quantified at the centre and the water level prescribed at the nodes (Dinu et al., 2010; Umgiesser et al., 2004).

Figure 2.8: Rosario SHYFEM gridded mesh consisting of triangular elements and node, which become more refined closer to the coastline for a higher resolution (Source: Produced by PORG).
SHYFEM is also assembled by a number of models and equations which compute different physical processes and features. Namely, these are wind driven waves, wave-driven forces, wave-current interactions, sediment dynamics, shear and frictional stresses, cohesive and non-cohesive sediments, advection-diffusion equations, morphodynamics, amongst many more. Respectively, these models include a hydrodynamic model, spectral wave model, sediment transport model and bed model. When input into the hydrodynamic model, the radiation stress gradient of the wave induced forces produces results for the changes in wave set-up/down and correspondingly, currents (Ferrarin et al., 2008).

2.6.3 SWAN Model

The SWAN Model is a coastal phase averaged, Eularian based model that produces predictions of the development of energy within the wave spectrum of waves approaching the coast (Gorrell, Raubenheimer, Elgar, & Guza, 2011; Liau, Roland, Hsu, Ou, & Li, 2011). The third generation model, was developed to produce outcomes for the spectrum of wave conditions under the influence by indiscriminate wind, current and bathymetric conditions (Daly, 2013; Ris, Holthuijsen, & Booij, 1999). The general equation (Equation 2.2) run in the SWAN model is:

Equation 2.2

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_{\sigma} N + \frac{\partial}{\partial \theta} c_\theta N = S_{\sigma}
\]

Whereby \( t \) is time, \( x \) and \( y \) are the horizontal coordinates, \( \theta \) is the direction and \( \sigma \) is the intrinsic frequency. The action density is represented as a function of all these parameters by means of \( N(\sigma, \theta; x, y, t) \). Through development of numerical equations, it has been adapted for coastal shallow waters, so as to simulate wave processes, such as refraction and shoaling (Ris et al., 1999). Energy dissipation due to current and/or topographical interactions, as well as wave breaking and bottom friction are computed. In the initial development of the model, diffraction may have been omitted but is now possible to compute
by using a phase-decoupled refraction-diffraction approximation. Wave-current interactions may be modelled to produce a more realistic output but requires input of current information, generated from a current model (Choi & Yoon, 2011). The SWAN coastal model is run on data input from other models, such as SCMR and SKIRON, which models wind. Therefore, if there is a deficit of data from the component proxy models, then the data produced from SWAN will also have data gaps.

The SWAN model in Malta has already been validated by Drago, Azzopardi, Gauci, Tarasova and Bruschi (2012), using observational wave data collected by the moored instruments, such as the Datawell Waverider buoy. Ideally, highly accurate in-situ data is collected for all physical parameters (i.e. wave climate and currents) but the long term measuring is restricted to a localised area. Therefore, numerical models are often implemented to extrapolate data to provide a synoptic interpretation that spans a wider spatial and temporal range. The SWAN model has a spatial resolution of 0.001°, encompassing a domain marked by a boundary between 14.040-14.700°E in longitude and 35.665-36.206°N in latitude (Azzopardi, 2012). The outputs of the model can be generated in three hourly intervals, providing Significant Wave Height, Peak Wave Period (of the variance density spectrum) and Mean Wave Direction (Drago et al., 2012).
Chapter 3 Methodology

3.1 Materials Used

The field work for this project required the use of a main vessel to travel to the location, as well as a smaller and easily manoeuvrable vessel, in order to move around the bay with ease, to deploy and recover the drifters. A logbook was also kept to take record readings.

3.1.1 Bathymetric Depth Equipment

A bathymetric map was produced for a more comprehensive understanding of how the local topography and bathymetry may affect sea current flow. This required the use of GPS application (Satellite Check by DS Apps) and a pressure depth gauge (used by divers), which was tied to a weighted line. Unfortunately, because the pressure depth gauge was designed as an analogue measuring device, the readings were of a low accuracy of approximately +/- 1m. The accuracy was found to be far higher in deeper water than in shallower water. This was discovered when comparing the readings of the pressure gauge with the depth sounder on the vessel (for deeper water) and with a weighted measuring tape (in shallower water). The presence of the waves also caused variations in the readings. A measuring tape had to be used in shallower waters. The gauge consisted of two arms, both of which begin at the 0m mark. One arm moves across the gauge in response to changes in pressure. The other arm (orange) served as a marker that moved with the response arm but remained in place at the deepest reading, even when brought back to the surface (Figure 3.1).
Figure 3.1: Equipment used to measure bathymetric depths. (A) Line with weight attached at one end, (B) Diver’s analogue pressure depth gauge, (C) measuring tape with weighted end.
3.1.2 Drifters

The drifters used for this study have been custom designed for the application of measuring surface currents. A consequence of surface water drifters, is the inevitable influence of surface winds on the floating device. Therefore, the design attempt to minimize this frictional interference as much as possible (Poulain, Gerin, Mauri, & Pennel, 2009). The drifter possesses six components (Figure 3.2). The buoyancy weight, which kept the structure of the drifter in an upright position. The current vane is a wooden frame in the shape of a 3D cross, which resembles the CODE/Davis drogue design. Its function is to propel the drifter into movement by frictional drag from the surface area of the vane. The floatation device kept the drifter at the sea surface, while a water proof compartment was used to hold the GPS tracker. A flag was fixed so that the drifter would be easily tracked from the vessel, particularly for retrieval.

Figure 3.2: Diagram illustrating the components of the customised drifter and a photo of the drifter in the field whilst recording during a calm day (Source: Author).
1m long rope attached the current vane and the float/pole, as well as one connecting the vane to the weight. The weights were made from concrete, the current vane from wood, coated with protective paint and the float was made from a pool noodle. The container was placed as low as possible on the pole to reduce the friction forces from surface winds. Unfortunately, this compromise resulted in the occasional submergence of the container, which sometimes meant the GPS connection was lost and so, resulted in gaps in the data for some track recordings.

A miniHomer GPS, funded by the European Union, was used for the drifters. The miniHomer GPS Position Finder used had some beneficial features, ideal for the drifter design. Apart from being light-weight and compact in size, it was also accurate, with low power consumption. The mini homer was capable of taking a single instantaneous reading or be set to log coordinates continuously, with a pre-set time interval. Before the drifter was deployed, it was made sure that the GPS was in sync with the satellites above (NAVIN Corporation, 2013). The miniHomer is compatible with the Ntrip software, which imports geographical coordinates, displays the logged points on a map and export files in a number of formats. Ntrip was used to adjust the data recording setting of the miniHomer GPS so that recordings were taken every ten seconds.

3.2 Data Collection

3.2.1 Bathymetric depth Data

The pressure gauge was tied to the weighted end of the line and lowered to the seabed. A reading was marked on its analogue gauge, showing the deepest point it descended to. Simultaneously, a GPS position was taken using the smartphone app. The depth gauge was recovered and the reading marked, was recorded. Since a smaller vessel was used to take measurements, in cases when the wind was strong enough to cause the vessel to drift, a small anchor had to be dropped for every reading taken, in order to remain in place so that the GPS reading would correspond to the same position of the depth measurement.
The diminished accuracy in shallower water mentioned before, required the use of a measuring tape to be used in water, generally shallower than 5m. At the end of each session the coordinates and depth readings were input into an Excel spreadsheet and saved as a Comma Separated Value (CSV) file. A total of 340 data points were taken.

Bathymetric data encompassing the wider extent of the area across 286 points, was also obtained from the Physical Oceanography Research Group (PORG), within the Department of Geosciences of the Faculty of Science. To rasterise the soundings, Kriging interpolation was conducted on these two sets of data. The scope of this was to contrast and compare the products of two different methods of bathymetric surveys.

3.2.2 Drifter Data Collection

Two custom made drifters were supplied by the PORG. The drifters were deployed from the smaller vessel within the study area. Prior to deployment, the GPS logger was switched on and some time was allowed for the device to sync with the satellite in orbit overhead. Data recording was started from the main vessel and the time of activation was recorded. From the main vessel the drifters, with the GPS logger already within the waterproof containers, were taken out and deployed at a random position within the boundaries of the study area. The time of deployment and retrieval of each drifter for every track was recorded in a logbook. Whilst still recording, the drifter, was taken to a different part of the bay for a following deployment. The same procedure was repeated. During the deployment, the drifters were regularly monitored using a pair of binoculars.

It was found to be easier not to cease recording of the GPS between deployments because it would have increased the possibility for human error, possible water damage from removing the GPS from the container or losing the connection to satellites when switching the logger off and on. As a precautionary practice, the GPS logger was taken back on board the main vessel to download the tracks and view them in NTRIP, to ensure that
recordings were being logged. One drifter would have been deployed several times within a single day and data collection period spanned from between July till October of 2015 (Figure 3.3).

![Figure 3.3: Histogram of the number of tracks taken on the days of fieldwork.](image)

It was planned to record two hour tracks, or longer, if possible. However, this often could not be done due to numerous interruptions stopping the drifter. These interruptions were typically due to the presence of anchored boats, reduced visibility after sunset, as well as other circumstances mentioned in the Limitations section (Chapter 3). Using the digital wind anemometer on-board the main vessel a single reading of the local wind direction was recorded in the logbook that was representative of the general conditions of the day of the deployments. The wind direction and the starting points (of certain tracks) were colour coded for organising the final map products. (Table A-1 in Appendix A)

This method of keeping the GPS recording, whilst traveling with the drifter on board the small vessel and during track recording resulted in excess track data. Consequently, post data management was required to clean and remove the excess track data, whereby two different methods were used. One involved using Ntrip directly, where the entire track (track of current and of small vessel transportation combined) was split up, using the “Split Track” function. The
necessary tracks of the drifters were kept and saved as CSV file. The second method option, was to save the entire track as a CSV file and open it in Textpad. From the documented start and end times recorded in the logbook, the necessary data was kept and the excess removed. This process had to be done for every individual track that was recorded in a single session.

3.3 Data Processing

3.3.1 ARCGIS

With the complete set of cleaned data from tracks and bathymetric depth measurements in CSV format, ARCGIS was used to plot the output. The WGS_1984 Geographical Coordinate System was used for all map layers.

3.3.2 Bathymetric map

The latitude, longitude and depth, recorded in the logbook, were input into a Microsoft Excel spreadsheet. The spreadsheet was then saved as a CSV file. To compute a bathymetric map using ArcGIS, the latitude and longitude coordinates where placed in the x-axis and y-axis fields, respectively and depth (in m) in the z field. It was required that the coordinates be in decimal degrees format for ArcGIS to enable plotting each point. The CSV file was opened into ArcMaps and converted into a point shapefile.

To interpolate the shapefile and illustrate the depth contours, the Kriging Interpolation\(^1\) method was used because of its tested higher accuracy compared to other spatial interpolation methods (Jang, Park, & Choi, 2015; Shanshan, Meijian, Di, & Shaohui, 2015). The interpolated product could not account for the perimeter of the coastline. The map layer was modified by clipping the Kriging product using a polygon which outlines the boundaries of the study area and coastline. The polygon was traced along the coastline in

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\(^1\) The Kriging Interpolation method is a geostatistical spatial optimal estimator that utilizes a generalized linear regression (Ge & Cheng, 2014).
Google Earth and exported as a KML file. The KML file was converted into a layer file using the conversion tool function. With the polygon boundary layer on top of the Kriging output, the Image Analysis tool was used to clip out the area covered by the polygon from the Kriging output.

### 3.3.3 Drifter Data

The tracks were input into ArcGIS as CSV files and converted into shapefile files. Each track was illustrated by a series of points (i.e. those point taken every ten seconds). Each track was formatted to be represented as a line with an arrow bearing at the heading of travel. The drifter tracks were grouped into maps according to the day of recording and colour coded according to the direction of wind (Table A-1).

### 3.3.3.1 Calculations

Table 3.1 shows the structured model of the table used to process data and perform the calculations.

<table>
<thead>
<tr>
<th>Latitude (Radians)</th>
<th>Longitude (Radians)</th>
<th>Distance/second (m)</th>
<th>Bearing* 1-5</th>
<th>$V$ Component</th>
<th>$U$ Component</th>
<th>Pythagoras Equation</th>
</tr>
</thead>
</table>

*SPLIT INTO FIVE SEPARATE COLUMNS.

The raw data from the GPS was processed to obtain the distance between the series of recorded points, the bearing of travel between each set of points and the $V$ and $U$ component of the corresponding current. This enabled the quantification of the path, direction and velocity of travel for each drifter (i.e. the current). For every drifter track data file, the latitude and longitude (in decimal degrees) were inserted into an Excel spreadsheet. The angle in degrees was converted into radians, which was the required form to be used in subsequent equations.
The Haversine equation (Equation 3.1), which measures the shortest distance between two points on the curved surface of the Earth (Bullock, 2007; Drago et al., 2012), was used to calculate the distance between waypoints taken every ten seconds. The distance was divided by ten in another column to obtain the distance (in m) travelled in one second. Essentially, this spherical trigonometric formula is designed for a perfect sphere and computes the plane intersection of a sphere. Therefore, the Earth is assumed to have a perfect spherical shape, rather a geoid shape. Between two points with geographical coordinates (Figure 3.4), the change in latitude and longitude can be found. The derivation of the Haversine formula requires the radius of the Earth, which is about 6371km (Javale, Gadgil, Bhargave, Kharwandikar, & Nandedkar, 2014; Kifana, 2012).
Equation 3.1

\[ \Delta \text{lat} = \text{lat}_2 - \text{lat}_1 \]
\[ \Delta \text{lon} = \text{lon}_2 - \text{lon}_1 \]
\[ a = \sin^2\left(\frac{\Delta \text{lat}}{2}\right) + \cos(\text{lat}_1) \cdot \cos(\text{lat}_2) \cdot \sin^2\left(\frac{\Delta \text{lon}}{2}\right) \]
\[ c = 2 \cdot \text{atan2}(\sqrt{a}, \sqrt{1-a}) \]
\[ d = R \cdot c \]

Where, \( d \), is the distance between two points and \( R \), is the radius of the Earth. When input into Excel for computing, the formula has to be altered to be recognised in Excel (Equation 3.2).

Equation 3.2

\[ = \text{ACOS}(\sin(\text{LAT}_1) \cdot \sin(\text{LAT}_2) + \cos(\text{LAT}_1) \cdot \cos(\text{LAT}_2) \cdot \cos(LON2 - LON1)) \cdot 6371000 \]

The bearing along the straight path between two points on the Earth’s surface was calculated using the Forward Azimuth formula (Equation 3.3) so as to determine the direction of currents. The results were listed under the column ‘Bearing 1’. Equation 3.4 was input into Excel. There is no difference between Equation 3.3 and 3.4 in terms of result calculated. However, the Excel programme is designed so as to reverse the argument of the atan function. Equation 3.3 produces a final output in the range between -180° and 180°, which would have had to be adjusted to the appropriate compass range (0°-360°).

Equation 3.3

\[ \theta = \text{atan2}(\sin(\text{lon}_2 - \text{lon}_1) \cdot \cos(\text{lat}_2), \cos(\text{lat}_1) \cdot \sin(\text{lat}_2) - \sin(\text{lat}_1) \]
\[ \cdot \cos(\text{lat}_2) \cdot \cos(\text{lon}_2 - \text{lon}_1)) \]
\[ \theta = \text{ATAN2}(\cos(LAT1) \times \sin(LAT2) - \sin(LAT1) \times \cos(LAT2) \times \cos(LON2 - LON1), \sin(LON2 - LON1) \times \cos(LAT2)) \]

The calculated bearing was converted back to degrees, under column labelled as ‘Bearing 2’, for mathematical simplicity in further calculations. The positive values were copied to the ‘Bearing 3’ column and the negative values obtained were added by 360 (into column Bearing 3) to get a positive angle in a clockwise direction. The resulting list of positive bearings were filtered between the following ranges:

\[ 0 \geq \theta \geq 90, \]
\[ 90 > \theta \geq 180, \]
\[ 180 > \theta \geq 270 \]
\[ 270 > \theta \geq 360. \]

Figure 3.5: Diagram illustrating the quadrants with 0° representing North with the corresponding ranges of angles and the trigonometric element which determines how the \( V \) and \( U \) components would be calculated.
It was necessary to filter results before calculating $U$ and $V$ according to the quadrant in which the bearing lies. The sorted angles from column ‘Bearing 3’ were subtracted by 0, 90, 180 and 360, respective of the corresponding ranges above and put into column ‘Bearing 4’. This made it possible to find the angle between the Resultant and the axis. The results were then converted back to radians under the ‘Bearing 5’ column. Using the appropriate, trigonometric function, according to the region of the angle (Figure 3.5), the $V$ and $U$ components were calculated. The sign for both components is an indicator of the corresponding resultant region. In order to check that the solutions for the $V$ and $U$ components were calculated correctly, Pythagoras Theorem was applied to determine the length of the resultant component, which should have equated to the distance travelled per second, calculated before.

### 3.3.4 SWAN Data

The SWAN model is run and maintained by PORG. The model produces a forecast for three and a half days, supplying data with a resolution of 0.001° and a temporal frequency of three hours. For this study the PRG supplied monthly extracted data for Ramla Bay. Multi-columnar Point Files were produced, which contained all the relevant data for a single point. This data was input in ArcGIS. Each point contains the Latitude, Longitude and a time series of the Significant Wave Height (SWH) and Mean Wave Direction (MWD) (J. Azzopardi, 2012). The SWH and MWD, were represented in a grid boundary (Figure 3.6), comprising of 433 points.
3.4 Modelling Data

3.4.1 SWAN Model

The modelled data was produced for each point, extrapolated every three hours for the duration of each corresponding month between August 2015 and January 2016. For each month and for every grid point, the minimum, the maximum and the average values of each parameter were calculated. The geospatial analysis toolbox was used to interpolate the data using a natural neighbour interpolation method. An interpolated map was produced to illustrate the spatial distribution that represents the average conditions of the two parameters of every month. (Zhou, Huang, & Zhang, 2015). Again, the domain of the interpolated map extended onto land and so it had to be clipped, as was executed for the bathymetric map.

The averages of all six maps, for the average SWH was computed with the Raster Calculator function, which utilizes Python syntax to complete map
algebra expressions and produce a final raster product. The average had to be computed for each parameter individually by adding the spectrum of monthly average raster maps and dividing by six.

A map product was ultimately created, encompassing an area larger than the intended project boundaries. It was decided to provide a map on a larger scale because at the smaller scale of the bay area, the interpolated map of the modelled data would have had a low resolution for proper analysis. Additionally, it would be beneficial to foresee the external physical conditions that ultimately influence the conditions within the study area. The map may also prove advantageous for future studies of the surrounding area.

3.5 Statistical Analysis

The drifter tracks for currents were statistically analysed through a validation of the SWAN model. The drifter tracks were plotted in ArcGIS across the grid of the Wave Direction output from SWAN. Only a few tracks were taken, in which the points along the track, which coincided as close as possible to the SWAN grid points, spatially and temporally, were used. The selected drifter tracks had to be individually paired with the 3-hourly Wave Direction output from SWAN, so as to encompass the time the track was taken within the 3-hour time range from SWAN. The bearing values of the SWAN grid point of Wave Direction and the corresponding track points in closest proximity to one another were recorded in a table for each track. The tabulated data of wave direction and current direction (Table A-2) and a scatter plot was produced. The two variables were correlated using Pearson Correlation. The Root Mean Square Error (RMSE) was also determined to assess the level of association between the wave and current direction. The process of subsequent to verify the results is described in Chapter 4.

For current velocity, the $U$ and $V$ velocity components of a selected number of tracks, grouped according to the day of deployment, were plotted on separately into a time-series graph. So the individual tracks on the time-series could be identified and linked to the maps, colour coded marks on the selected tracks,
were added at the start of each of the selected track. The colour coded legend may be found on Table A-1 of Appendix A.

A time-series was drafted for the average SWH of the six months over the same point in the centre of the bay (Point 2). Additional time-series were conducted for each month across the five points along a transect of the grid from the SWAN model (Figure 3.6). The selected grid points ran seawards, perpendicular to the beach. More points concentrated within the bay were taken and gradually reduced further out from the beach. Point 1 corresponds to the point closest to the beach (i.e. shallowest) and every highlighted point up to the last (Point 5), represents the deeper water. Daily data for the average atmospheric pressure taken by a meteorological station in Rabat, Gozo, was acquired ("Underground Weather," 2016). The average atmospheric pressure time-series was superimposed to each time-series for analysis.

### 3.6 Limitations

Ramla Bay is a popular bathing area for people to retreat to during the summer, both on the coast and at sea. Unfortunately, the majority of deployments could have only been done during the weekend (due to the availability of the vessel), when the presence of people and recreational boats were highest. In cases when interruptions were suspected of occurring, the track would have had to be stopped and the drifter reset elsewhere. Similarly, a drifter deployment track would have been ceased when the drifter became entangled in the float line marking the boundary of the bather area, which was quite a common occurrence. If the drifter was not removed before colliding with the line, the line was otherwise raised to allow the drifter to pass and enter the surf zone that was situated shoreward of the float line. At this point, it would have to be stopped when the bottom weight of the drifter began caressing the sandy seabed.

The loss of a drifter on the 18th of July 2015, when it was deployed around the north-eastern area of the bay and possibly hit by a passing boat, hindered the capacity of data collection. Consequently, the amount of drifter tracks that
could have been recorded, was reduced, in addition to losing the stored GPS data already stored on the logger of the same day and the day before. The GPS tracker sometimes failed to take full records, resulting in significant data gaps for some track recordings. Unfortunately, a few track recordings had to be discarded. This error was assumed to be the cause of the temporary submergence of the GPS in rough conditions. A major limitation to the study was the restricted timeframe in which the area could have been properly studied. Ideally a more comprehensive study could have been undertaken, were the annual and seasonal trends would have been represented.

The low accuracy of the pressure gauge used to acquire depth readings for the bathymetric map entailed that the map product should serve as a reference for descriptive purposes and analysis. Also, because the embayment’s substratum is composed predominantly of sandy material, the seabed morphology is subject to major variations, both spatially and temporally, from when readings were taken. Therefore, the measurements taken represent the morphology and bathymetry of the bay at a fixed period (mid-August to mid-September). The Rosario-SHYFEM hydrodynamical model, which was to be used for a comparative analysis with the drifter tracks taken and to validate the model, was not successfully implemented on time and so could not be used for the analysis. This was a major limitation, as it was significant component of this dissertation. Accordingly, an alternative methodology was developed to statistically analysis the data acquired, as discussed above.
Chapter 4 Results and Discussion

In this Chapter, the results from the data collected in the field and produced and processed from models are presented. The study is also critically reviewed and the link between the results and the material discussed in the literature review, is made. Quintessentially, the research questions are answered in this Chapter and the discussion deciphers whether the hypotheses made, are correct or not. The bathymetric maps and drifter tracks were plotted separately for descriptive analysis. The same was done for maps produced for the average SWH and wave direction. The time series analytical method was used to graphically illustrate the variability of the SWH over time and space. A time-series was also plot for the $U$ and $V$ velocity components of selected current tracks. The difference between current velocities in relatively deeper waters outside the nearshore zone and those generated by wave breaking as longshore currents, are discussed. To measure the relationship between the wave and current direction for a selected number of drifter tracks, the Pearson correlation coefficient was determined and Root Mean Square Error was performed to check the level of association of the data with the line of best fit. All maps produced and referred to in this Chapter can be found in the Appendices.

4.1 Bathymetric Results

Two bathymetric maps of the study area were produced using data collected \textit{in-situ} (Figure 4.1) and by the Physical Oceanography Research Group (PORG) (Figure 4.2). Despite using a low accuracy measuring device for the \textit{in-situ} data, the map produced, still proved to have a more detailed, higher resolution than that of the PORG output. The PORG map does, however, encompass a wider extent of the area.

The \textit{in-situ} depth measurement map (Figure 4.1) shows two notable features of the bathymetry that are not illustrated in the PORG map. The west-side of the bay appears to have a more gradual slope and broader extent of the
shallow depth. On the east side of the bay, the gradient tends to be steeper, with a narrower extent of sub-marine rock fields. From observations made in the field at the time of data collection, this can be attributed to the extensive rock field below sea-level, originating due the erosion of the Upper Coralline Limestone escarpment on top of the Blue Clay slopes on both headlands. The more extensive rock field on the west-side is characterised by smaller rocks, which give the area a highly irregular and variable surface bathymetry. This irregular surface is not represented properly in the map, which is a limitation of the method used. The other side of the bay (east-side), was characterised by fewer and larger boulders close to the shoreline with less variation than the opposite side of the bay. Generally, along the periphery of the two sides of the headlands within the bay, a higher rugosity can be observed than in the centre of the bay, where there is a sandy seabed. The exception to this, are the remnants of the submerged sea-wall and the patches of *Posidonia oceanica* seagrass beds. Secondly, the shape/outline of the sand bar is clearly outlined on the *in-situ* measured bathymetric map (Figure 4.1) and corresponds to the satellite imagery of the bay, if superimposed on one another. This is another clear advantage the *in-situ* map has over the PORG map. The sand bar during the summer period between August and September (when measurements were taken) has a crescentic shape, as opposed to a linear parallel sand bar observed by Azzopardi (2015) after the winter period.
Figure 4.1: Bathymetric Map produced from in-situ measurements, with the shallowest depths in red, graduating down to deeper depths in blue.

Figure 4.2: Bathymetric Map produced data obtained through numerical modelling performed by the PO-Unit, with the shallowest depths in red, graduating down to deeper depths in blue.
4.2 Lagrangian Drifter Currents

A map of all the drifters track measurements of recorded currents was compiled (Figure 4.3). Additionally, the sorted drifter track maps, according to the day of deployments can be found in Appendix A. Also in Appendix A, is a table of all the information about the tracks, including the wind direction of the day with colour coded legend, the times of drifter deployments and retrieval and the duration of each track. A total of 46 hours and 30 minutes of current recordings were measured throughout the collection of data, with the average duration of a single track lasting to approximately 76 minutes.

Figure 4.3: The complete set of drifter tracks recorded throughout the data collection period superimposed on a map with bathymetric contours extrapolated from the bathymetric map interpolation.

The plotted tracks presented, show that under north-westerly winds (red), currents flowing from the NNW from deeper water and approach the embayment obliquely, as was observed on the 5th of July 2015 (Figure A-1). Under NNW winds, longshore currents, as were clearly identified on the 18th of July 2015 and the 26th of September 2015. The directional flow of these tracks mirrors the coastline and/or deviates slightly at some point. The same is true
for the opposing direction from the NNE (yellow) and ENE (green), in which longshore currents are clearly identified, flowing along the contours of the coast. The exception being for currents measured on the 11th of July 2015, whereby the longest track does not show directional preference to coastal configuration but to the wind direction, largely because it was deployed in more open water. Therefore, the results agree with the hypothesis stated, when currents have direct influence from the shallower bathymetry.

4.2.1 Drifter Trajectories: Current Velocities

The extracted $U$ and $V$ velocity vectors, were initially intended to be used in the Rosario-SHYFEM model. Instead, they have been presented as time-series velocity graphs for four selected tracks. Only four tracks were chosen because of the insurmountable amount of the data available for discussion. The data not used has been made available with this dissertation.

For the duration of most tracks taken on the 5th of July 2015 (Figure A-14), the drifter appeared to be stationary for short periods. The highest velocity reached was during the 16:13-16:41 track, with a peak in the $U$ vector velocity exceeding 1m/s. The track 12:17-12:37 was the weakest, with velocity fluctuations not exceeding 0.6m/s. The large peak at the end resulted whilst retrieving the drifter and not the actual current. This could be observed for several other tracks. Both tracks occurring between 12:15 – 12:52 and 16:10 – 16:38 were characterised by minor fluctuations in velocities not exceeding 1m/s.

On the 11th of July 2015 (Figure A-15), the strongest currents came from the tracks 09:28-11:38 and 13:26-14:29, reaching velocities of over 0.8m/s and 1m/s, respectively, both in the westwards direction (signified by the negative value in of the $U$ component). Thusly, a dominant alongshore flow prevailed. The remaining two tracks at 13:27-14:37 and 14:46-16:40 were much weaker, with velocities not reaching more than 0.2m/s. The latter shows a stronger velocity from the positive $V$ component so the flow is dominantly cross-shore. This may resemble a rip current but because of its low velocity, it may not
necessarily classify as a rip current, since rip currents are typically strong and fast as explained by Thornton, MacMahan and Sallenger (2007). Interestingly, track 13:26-14:29, deployed in shallower waters than track 13:27-14:37, was significantly stronger in comparison. This is significant because both tracks were taken at relatively the same time but at different depths.

Out of the four tracks selected on the 29th of August 2015 (Figure A-16), the track between 09:27-11:10 exhibited the highest peak in velocity of 0.58 m/s, travelling in the southerly, cross-shore direction. Surprisingly, this track exhibited the highest velocity when it was in the shallowest waters compared to the other three tracks, which were in much deeper water but all had lower velocities. The track between 13:39-14:34, was slightly slower at 0.52m/s at its peak when travelling westwards in the alongshore direction. This track was in the deepest water of all four tracks.

On the 26th of September 2015 (Figure A-17), the track between 13:41-14:31 shows a highly variable velocity, strongly associated within the U vector rather than the V vector, indicating a strong alongshore direction of travel. This track is the strongest amongst all other tracks on this day, with velocities exceeding 0.2m/s. In contrast to previous tracks discussed, it is relatively weak. On this day, this track, along with the track between 14:50-16:39 were much stronger than the other two, which fluctuated below 0.1m/s. This is significant because unlike the prior three cases, the strongest currents on this day (13:41-14:31) occurred in relatively deeper water compared to other tracks.

The alternating spikes and dips are most likely the cause of strong gusts. The dips in velocity to 0m/s indicate that the drifter was stationary. This could be an error caused by the GPS logger, which may have lost connection, as mentioned in previous chapters. The range of velocities of currents recorded comply to the range presented in the literature reviewed. The general pattern observed from drifter measurements submits to a higher degree of alongshore current flow in shallower waters, flowing from direction of the wind. Some of these longshore currents (such as between 17:50-19:12 on the 26th of September 2015) are the products of wave breaking in the surf-zone and although measurements directly in the surf-zone were not possible to obtain, these resultant longshore currents are representative of the wave induced
current processes. Deployments and therefore, currents, initiated in deeper water tend to follow the direction of the wind and not always reconfigure to the coastal perimeter. From the selected current tracks for time-series comparison, a general trend arose that suggests that the shallow water and nearshore currents are stronger than those currents in the deeper portions of the bay. The results presented do not support the hypothesis, which suggested that currents in shallower water would be weaker than those of deeper waters because of the significant dissipation in wave energy. The only track that complies with the hypothesis was between 13:41-14:31 on the 26th of September 2015. This was not statistically proven, however. From the results present, it may be construed that with stronger currents in the shallow surf zone, greater transport of beach sediments is likely to occur, largely in the longshore direction.

4.2.2 Drifter Trajectories: Current Direction

Despite attempting to record drifter tracks under as many environmental conditions as possible in the field, rip currents were unable to be observed and measured by the drifters during the summer period at Ramla Bay. This does not conclude that rip currents do not occur indefinitely within the bay but infers that they may be extremely rare events in the summer period when the wave climate is drastically dampened in contrast to the higher energy during the winter months. Therefore, the hypothesis with regards to the biophysical configuration of *Posidona oceanica* due to a cellular rip current circulation was incorrect.

The direction of current flow observed from field measurements show that currents often flow along the contours of the coastline. The direction of current flow is dependent on the wave direction to a certain extent. When plot on a scatter plot (Figure 4.4), the outcome of the correlation reveals itself to distort the true relationship by the added skewness incurred by three outliers.
Figure 4.4: First scatter plot of the measured current direction ($y$-axis) against the modelled wave direction ($x$-axis) with outliers included.

The $R^2$ value calculated (0.0176) is closer to 0 than to 1. This suggests that, although the correlation is positive, the relationship is weak. The Root Mean Square Error (RMSE) was calculated for the two variables of the seventeen sets of records listed in Table A-2. This measures the level of association of the data with the line of best fit. The RMSE was computed to be $107.05^\circ$. This indicates that typically, the points are around $107.05^\circ$ off from the line of best fit and because the RMSE value is so high, there is a weak association between the variables.

The Pearson correlation was used to measure the strength of the relationship between two variables. Let the null hypothesis ($H_0$) be that there is no relationship between the direction of current flow and the wave direction if the $p$-value exceeds the 0.05 level of significance. The alternative hypothesis ($H_1$) states that there is a statistical relationship between the wave direction and current direction if the $p$-value is less than the 0.05 level of significance.
Table 4.1: Table of Pearson correlation and level of significance of the relationship between wave direction and current direction with outliers. Produced in SPSS.

<table>
<thead>
<tr>
<th></th>
<th>Wave</th>
<th>Current</th>
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</thead>
<tbody>
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</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.612</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>17</td>
</tr>
<tr>
<td>Current</td>
<td>Pearson Correlation</td>
<td>.132</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.612</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>17</td>
</tr>
</tbody>
</table>

The Pearson Correlation coefficient, $r$, (Table 4.1) was computed in SPSS to be 0.132, which indicates that there is a positive correlation between the wave direction and the current direction. Since, the 0.132 mark is closer to zero than one, it can be concluded that the proportional relationship between the two variables is weak. This reaffirms the result of the $R^2$ value. Furthermore, the $p$-value of 0.612 is significantly greater than the 0.05 level of significance, hence the null hypothesis is accepted. This indicates that there is no statistical significance between wave and current direction.

The three outliers are the likely causes of the statistical insignificance of the data. The outliers observed occurred on the 4th September 2015 from the 18:03-19:51 track, with points taken at 19:01:52 and 19:06:33. Again these points were taken because they were closest to the SWAN grid point (spatially and in time at 18:00). The second set of outliers occurred on the 5th of September 2015 from the 11:02-12:48 track, with points taken at 12:27:06 and 12:42:26. These points were temporally closest to the SWAN grid point at 12:00. To test the alternative relationship that would otherwise be skewed by the outliers, the outliers were removed and the same statistical analysis was repeated.
With the three outliers removed, the correlation remains positive but the relationship is much stronger now (Figure 4.5). The null and alternative hypotheses proclaimed for the first statistical test, still applies to this new test. The Pearson correlation coefficient of 0.896 (Table 4.2) is now closer to 1 signifying a strong positive relationship between the two variables. Since the p-value (0) is less than the 0.01 level of significance, the alternative hypothesis \( (H_1) \) is supported, whereby it can be established that there is a strong associated relationship with wave direction and current direction.
To inspect the possible cause of the emergence of the outliers, a further test was conducted for the data of the corresponding tracks from which the outliers originated from. This was done to measure the statistical significance of the wind vector velocities from SKIRON (a component model of SWAN) with the outlier current vector velocities. The $U$ and $V$ vectors were used because of the directional and magnitude components. The SKIRON model has a much lower resolution than the SWAN model so a single grid point (36.05°N, 14.3°E) that was closest to the bay was taken as a constant for the statistical analysis. By taking the $U$ velocity of sea currents and wind coinciding at the same time, a scatter plot was produced, with the line of best fit added. The level of association was calculated and found to be strong between these points. Therefore, the line of best fit will serve as a baseline reference to compare the $U$ velocities of the outliers points in question. The same was repeated for the $V$ velocity component.

![Scatter plot of $U$ (top) and $V$ (bottom) components of current velocity and wind speed on 04/09/2015 with the $U$ and $V$ components of the two points from the tracks at 19:01 (green) and 19:06 (yellow) to test the relationship of these possible outliers.](image)

$y = 0.0171x + 0.0977$

$R^2 = 0.0437$

$y = 0.0171x + 0.0448$

$R^2 = 0.9695$
For the 4th of September 2015, the $R^2$ values for the $U$ (0.0437) and $V$ (0.9695) scatter plots show the $V$ vector having stronger relationship between the current and wind velocities, than the $U$ vector. The RMSE calculated for the $U$ and $V$ vectors came to be 1.611m/s and 0.831m/s, respectively. The $U$ component RMSE is much larger than the $V$ component RMSE, which amalgamates the result of the $R^2$ value. When comparing the outlier components of 19:01:52 (Figure 4.6), the scatter plot shows a close association of the outlier $V$ components with the line of best fit. However, the outlier $U$ component for the same data is far from the line of best fit of the wind $U$ vector velocity (Figure 4.6). The exact opposite is the case with 19:06:33.

Figure 4.7: Scatter plot of $U$ (top) and $V$ (bottom) components of current velocity and wind speed on 04/09/2015 with the $U$ and $V$ components of the two points from the tracks at 19:01 (green) and 19:06 (yellow) to test the relationship of these possible outliers.
The RMSE of the $U$ and $V$ velocities on the 5th September 2015 current and wind velocities coinciding at the same time was calculated to be $2.3777\text{m/s}$ and $0.2934\text{m/s}$, respectively. Both indicate a relatively close association. This shall be the base which to correlate the outliers with. The scatter plot (Figure 4.7) shows that the two outlier points have a stronger association between the $V$ vectors than with the $U$ vectors. Unfortunately, since the points skew far from the line of best fit of the $U$ components, they must be considered as outliers. This test has shown that since the points remain outliers in relation to the wind velocity and direction, they are verified outliers on the wave-sea current correlation and scatter plot.

Both sets of outlier points (4th and 5th September 2015) are themselves outliers in either the $U$ or $V$ component fields within the SKIRON wind-sea current velocity test and have no close association with the line of best fit. It can be concluded that the SKIRON model is not the cause of the outliers through incorrect modelled data. This was shown by the strong relationship formed by the line of best fit. The drifter points themselves may have been erroneous due to a GPS error. Therefore, the outliers observed in the wave-sea current scatter plot can be taken to be valid. Furthermore, with the first scatter plot of the wave-sea current direction correlation (i.e. with outliers included) being accepted, the final determination would suggest that under general conditions, represented by the selected drifter tracks, there is a positive relationship between the wave-current direction, albeit weak. As determined from the first statistical test (Table 4.1), there is no statistical significance between the wave direction and the current direction. Therefore, the degree of variation in wave direction is less likely to change current direction at the same extent.

By putting these results into context, one could determine that within the shallow nearshore zone, the complex hydrodynamic processes statistically distort the relationship between current and wave direction. However, the second test, without outliers, may also be accepted for currents in deeper waters, whereby the influence of the bathymetry (i.e. beyond the influence of the depth of closure) is irrelevant.
4.3 SWAN Maps

4.3.1 Significant Wave Height

The average SWH across the transect taken from the SWAN grid runs from 0m at the shoreline to 4225m outside the embayment. A long transect was taken to observe how the average SWH varied from deep waters to shallow waters for each month. The results show that SWH decreases as water depth decreases (Figure 4.8). August 2015 experienced the lowest range variation in SWH between shallow and deeper points, with a maximum of 0.58m in deep water and a minimum of 0.25m in shallow water. The extent of variation between deep and shallow water increased with each subsequent month, in which January 2016 experienced the highest variance of SWH, with a maximum SWH of 4.16m and a minimum value of 0.28m. SWHs in December were the exception of this observation, whereby SWHs were averaged between August 2015 and September 2015.

On the larger scale, the interpolated maps of SWH (Figures B-1 to B-7) show, not only a decrease in SWH with water depth but also re-orientation with the coast. The results also reveal the processes of wave diffraction and refraction.
as the wave fields approaching at an oblique angle, converge around the headland and approach the beach at an angle almost perpendicular to the beach but still angled to facilitate minor longshore drift of sediment. The spatial variation in SWH indicates that a directional spread of the wave energy across the bay results in a gradient of radiation stress, which leads to the formation of longshore current, as discussed before. Therefore, the directionality changes in SWH can be linked to the wave direction.

The thickness of the graded bands of the interpolation can be seen to decrease spatially from deeper to shallower waters. This represents the conversion of long-crested to short-crested waves. Long-crested waves, as Sundar, Sannasiiraj and Kaldenhoff (1999) explain, are those waves responding to the decreasing bathymetric depth contours, resulting in the parallel orientation of waves to bathymetric contours. Short-crested waves are the product of the interactions of an irregular bathymetric and collective effects of wave refraction, diffraction and reflections that the waves endure when approach the embayment. Acknowledging the shift to short-crested waves is important for estimating the radiation stresses in the nearshore area.

4.3.2 Wave Direction

During the time scale of the study across six months, the dominant monthly average direction of wave fields propagating towards the coast was from the general NE direction throughout August (Figure C-1), September (Figure C-2) and November (C-4). This does not comply entirely with what was hypothesized. It was expected that the dominant average monthly mean wave direction was to approach from the NW, according to the dominant wind direction from the NW, as mentioned in the Introduction. This may be of significant importance as a means of identifying a possible shift in the general trends of wave climate due to climate change. NW wave fields were observed throughout the limited days of available data in October (Figure C-3). Wave fields from the North and East were prevalent throughout December (Figure C-5) and January (Figure C-6), receptively. When approaching from the North, drastic changes in directionality occur, exhibiting an almost ideal theoretical
scenario (Figure C-5) whereby, the high-energy breaking occurring at the headlands forces currents to flow along the peripheries of the headland into the bay. During August, September, November and January when the predominant mean wave direction propagates from the NE, sediments are likely to be transported to the western side of the beach. Longshore sediment transport during November and January may be more lateral because of the more acute angle the waves break to the beach. With the mean wave direction during October and December showing to propagate in from the NW direction within the surf zone, longshore drift may be assumed to migrate sediments to the eastern part of the beach. However, due to the significant data gap of October and the seemingly erroneous results produced by the model for December, this may not be representative of reality.

The directionality of the wave fields is observed to change, from a seemingly unidirectional propagation in open waters to a highly variable nature within shallower waters. This change is represented by the narrow, vibrant colour array along the peripheries of the coastline within the bay (Figure C-1 to C-6). This is because waves adjust due to decrease in water depths once reaching the depth of closure and due to the boundary configuration of the coast causing refraction and diffraction of the wave field. This aspect supports the hypothesis. It can also be noted from the maps that after bending around the headlands, the waves in actuality propagate within the surf zone at an obtuse angle. This facilitate the longshore drift of sediments along the beach (Figure C-1 to C-6). The longshore sediment transport within an embayed beach, which functions within a semi-closed system, will tend fluctuate to and fro in the alongshore direction. The average wave direction of each month may provide an estimate of the direction of longshore transport of sediments. This is, speculative as other processes may also be playing a role. This field deserves a study in itself.

4.4 Time Series Analysis: Significant Wave Height

A time series of the average SWH for every month was computed across the five points along the transect running centre cross-shore of the bay (Figure D-1 to D-6). Typically, the pattern of the temporal variation across each point (i.e.
different depths), remains relatively identical. However, there is a change in the amplitude that distinguishes the variations across the points (depths), with points in deeper water having a larger amplitude to that of the shallower points.

A high degree of seasonality is evident between the calmer summer period comparable to the more intense winter SWHs (Figure 4.9). It is noteworthy to point out the almost overwhelming overlapping similarity, in terms of pattern and amplitude of SWH characteristics at points two and three, which corresponds to a point in the centre of the bay and at the outer edge of the bay mouth, respectively (Figure D-1 to D-6).

![Significant Wave Height Time-Series](image)

Figure 4.9: Time series of the SWH from August 2015 to January 2016 over point 2, with the atmospheric pressure superimposed in dashed black line.

Since SWAN is the first high resolution coastal model to be applied to Malta, there was a limited amount of data available for the model. The lack of data input from proxy models, such as SKIRON (for wind), resulted in data gaps in SWAN (Table 4.3). Of the six months, the greatest deficiency of output data was for October (81.85%). An adequate analysis may not be conducted for that month. Data for August and December were also considerably absent but a decent representation could be achieved, nonetheless. September, November and January all had almost complete sets of data to provide a truly meaningful representation.
Table 4. Tabulation of the amount of data available from the SWAN model and the percentage of missing data.

<table>
<thead>
<tr>
<th></th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total 3-hourly Intervals</td>
<td>248</td>
<td>240</td>
<td>248</td>
<td>240</td>
<td>248</td>
<td>248</td>
</tr>
<tr>
<td>Missing 3-hourly Intervals</td>
<td>127</td>
<td>26</td>
<td>203</td>
<td>47</td>
<td>89</td>
<td>20</td>
</tr>
<tr>
<td>Percentage</td>
<td>51.21%</td>
<td>10.83%</td>
<td>81.85%</td>
<td>19.58%</td>
<td>35.89%</td>
<td>8.06%</td>
</tr>
</tbody>
</table>

The dashed line (black) superimposed on all time-series for every month represents the daily average atmospheres pressure, in hPa. The plot of pressure (Figure 4.9) shows variations throughout each month and a seasonal rising trend in the average pressure from summer to winter. During the summer months, the frequency of fluctuations is much greater than in the winter months, whereby from November, variations become less frequent. The opposite is true for the magnitude, in which summer months exhibit low amplitudinal variations and range. This natural shift occurs in November when intensive amplitudinal variations become more violent. These drastic dips in pressure represent low-pressure storm events. Although some strong low pressure storms occurred during the summer months, the sheer intensification of winter storms is unparalleled in comparison. This has significant ramifications to the nature of SWH.

During August, the average SWH and atmospheric pressure were both contrastingly lower compared to other months. The offset between the atmospheric pressure and the SWH time-series may be more significant in August than for other months (Figure D-1). The inverse relationship can still be observed however, whereby periods of low atmospheric pressure generally resulting in slightly higher SWHs as opposed to when the pressure was lower. The time-series of the SWH in shallower water remains quite well defined, as opposed to the dampened temporal variation pattern experienced in other months.

The SWH in September 2015 (Figure D-2) is characterised by a double peak spectrum, which corresponds to two strong decreases in pressure around the same time of the month. November (Figure D-4) begins with slightly higher SWH and gradually levels out for the mid-term period of the month, with values straggling below 1m, before dramatically increasing closer to the end of the month, when it reaches it maximum SWH across all points. This pattern is
observable for all points (within the bay and outside) with exemption to point 1. Across the shallowest point, there is minimal variation.

The absence of SWH data available for time-series analysis may alternatively be assessed by means of the average atmospheric pressure. The average atmospheric pressure during October 2015 (Figure D-3) is characterised by two major dips in pressure, occurring around the 10th and 23rd of October. Other dips in pressure occurred on the 15th and 31st but are not as powerful as the latter two. The seemingly inverse relationship between pressure and SWH allows for the presumption that during or around this time of the month SWH would have peaked. Subsequent peaks in high pressure on the 4th, 13th, 17th and 25th of October 2015 would have most likely resulted in a compressed sea surface and reduce the SWH.

December (Figure D-5) is seemingly the exception to the trend on seasonal increase in SWH. There are dramatic fluctuations between higher and low SWHs across all points. The SWH never exceeded 0.8m across all points. This is significant because the maximum SWH is considerably lower than the minimum fluctuating range of November and January. When viewing Figure 4.9, where the scale of the average atmospheric pressure is not misrepresented as is on Figure D-5, it is evident that SWH data modelled by SWAN must be erroneous because of the disproportional amplitudinal relationship between the average SWH and the average atmospheric pressure.

The observable relationship from the time-series graphs leads to the actuality that SWH in the deeper waters than in the shallower waters as was hypothesized. The direct correspondence between maximum peaks of SWH and dips in pressure appear to be offset by a few hours, or sometimes days. This limitation may be caused by the distance of the meteorological station in Rabat, Gozo and Ramla Bay but could also be due to a response lag between the conditions of the atmosphere and the sea surface layer. The pressure may be used as a tool to predict the possible nature and peaks in SWH, where there are significant data gaps in the SWH data. During times of low pressure and storm events, there is maximum variance between the SWH in deeper water (point 5) and shallow water (point 1). When pressure is relatively high the
variance between SWH in deep and shallow water in minor. This incurs that Ramla Bay is strongly protected during storms. This effectively, reduces the scale of sediment transport and erosion of the dunes that would otherwise occur if not for the protection of the headlands. This may also explain why the SWH decreases with depth (Figure 4.8) instead of increasing as was hypothesised. The severe attenuation of SWH between deep and shallower water depths within the embayment caused by the level of protection offered by the headland embayment.

The intensity on wave energy signified by large SWHs during winter periods, in particular November (Figure D-4) and January (Figure D-6), corresponds to sharp decreases in the general atmospheric pressure and in the peaks reached in both November and January. It is during this period, when the beach and morphology of the bathymetry and features, such as the sand bar are likely to shift and change shape. Azzopardi (2015) conducted a study on the morphological variation of the seabed and sandbar at Ramla and found that there are distinctive shifts in the underwater morphology between the summer and winter seasons. Storm events are the cause of this reset of the seabed and sandbar resulting in the attenuation of the extreme curvature of the sandbar (Figure 4.1), forcing it straighten, becoming more parallel to the beach and move shorewards (Winter et al., 2014). The supplementary fluctuations in SWH that are far more minor in terms of amplitude, may be due to the superposition of two wave groups travelling in the same direction, which will cause the wave heights to increase and consequently, the SWH to increase.

The study focused on the SWH conditions and not the regular wave conditions because the SWH represents the average of the largest waves. This is relevant, especially for coastal engineers and managers because larger waves are more likely to have a consequential effect on structures and sediment dynamics (Altunkaynak & Wang, 2012). The process of wave shoaling, whereby the wave heights increase and the velocity of the wave orbitals decrease should produce weaker currents measured within the centre or slightly deeper portions of the bay, where wave shoaling of incoming waves is likely to occur. Currents generated by wave breaking within the surf-zone of originating from the surf-zone are expected to be stronger.
Chapter 5 Conclusion

A study was conducted to investigate and examine the nature of the hydrodynamic processes, pertaining to current flow and wave climate at Ramla Bay. By means of drifter measurements, the flow the circulation of sea-currents within the bay between July and October were mapped. A time-series analysis for a selected number of tracks revealed that the velocities of currents are stronger in the nearshore zone than in deeper portions of the bay, with velocities ranging from 0 to 1 m/s. The general flow pattern of currents followed the alongshore direction, i.e. along the contours of the embayment. Currents in deeper waters were recorded to cross the bay in lieu of following the contours. Attempts to record rip currents using the drifters were unsuccessful, leading to the conclusion that during the summer months, rip currents are virtually inexistent. However, the possibility of strong rip currents (mega rips) during the winter months should not be excluded as a possibility. If this were to occur, a strongly defined cellular circulation would most likely prevail. For this reason, similar surveys should be conducted during both summer and winter months. Laborious statistical tests to determine the relationship between the current direction and the wave direction within the embayment proved to be statistically insignificant in shallow waters. However, to fully understand this relationship, the results would have to be input and compared to modelled outcomes, as was initially intended for this dissertation.

By means of modelled data of the monthly mean wave direction showed that, wave directionality is more variable within the shallower nearshore regions of the bay and that the dominant mean wave direction on average (even in the surf-zone) originates from the northeast direction. This signifies that, the more likely accumulation of beach sediments during this six month period, was likely to occur on the western side of the pocket beach. An inversely proportional relationship between the atmospheric pressure and the SWH is evident across the months. The peaks in SWH occurring throughout certain months, correspond to strong decreases in pressure, i.e. possible storm events. This shows that climatic variances have a strong influence on the nature of significant wave height. The spatial variation of the significant wave height
appeared to dampen within the shallower depths of the embayment, typical since wave energy in shallower wave is drastically dissipated due to wave breaking.

The results acquired, presented and discussed show little support to most of the hypotheses formulated. Some statistical ambiguity did arise with the further testing in attempting to correlate wave direction and current direction. The fact that uncertainties within the modelled data do exist, needs to be acknowledged. These uncertainties arose, particularly with the SWH for December. Additionally, working numerical models may sometimes be unreliable. For instance, the absence of data in the SWAN model and the Rosario-SHYFEM model not operating. Nevertheless, numerical models are sometimes necessary for studies in physical oceanography and coastal management, especially because many complex processes and interactions cannot be measured in the field at all times or at all. Uncertainties in the low accuracy of the methodology to collect in-situ data may be argued. However, the results have showed contextual association of the bathymetric map with that of satellite imagery, as well as previous studies from Azzopardi (2015). For a higher resolution surface bathymetry map, remote sensing would ideally be used.

This research project, has been a pioneering study on the physical characteristics of current and wave climate dynamics at Ramla, in which no such study or data existed prior. This study may now serve as a baseline of such information for future works. Even without the complete inclusion of winter months in this study, the information provided for the summer period, when human activities are highest at Ramla, may still be successfully applied to certain aspects of management. From this study, it is suggested that to further better understand the hydrodynamic processes at Ramla, particularly, on the nature of rip currents, that annual measurements are taken. This information should be regarded in the management studies and decisions, especially those related to sediment dynamics, public safety, project proposals and the fragmentation of Posidonia oceanica seagrass beds. This newly acquired knowledge can now be applied to Coastal Management Plans. Such plans, may be implemented using the sediment cell concept, in which currents and
waves are defining boundaries. This approach will help utilise a study such as this, to implement management strategies to defend the coast in a sustainable manner, whilst accommodating for the conservation of the area, as Ramla is part of the NATURA 2000 network.
References


based on Spatial Interpolation Methods in Not Covered Areas by Region Climate Change Scenario, 99(Itec), 109–112.


## Appendix A – Drifter Tracks

Table A-1: Table of information of drifter tracks.

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of Tracks</th>
<th>Time</th>
<th>**</th>
<th>Duration of Tracks</th>
<th>Wind Direction</th>
<th>*colour code according to the angle of the wind direction during the day track was taken.</th>
<th>**colour code to identify the times of each drifter on the maps, illustrated at the start of each track.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/07/05</td>
<td>1</td>
<td>12:15 – 12:52</td>
<td>●</td>
<td>37 mins</td>
<td>NNW 330°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12:17 – 12:37</td>
<td>●</td>
<td>20 mins</td>
<td>NNW 330°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16:10 – 16:36</td>
<td>●</td>
<td>26 mins</td>
<td>NNW 330°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>16:13 – 16:41</td>
<td>●</td>
<td>28 mins</td>
<td>NNW 330°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/10</td>
<td>1</td>
<td>18:09 – 19:18</td>
<td>●</td>
<td>69 mins</td>
<td>NW 300°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/11</td>
<td>1</td>
<td>09:28 – 11:38</td>
<td>●</td>
<td>130 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13:26 – 14:29</td>
<td>●</td>
<td>63 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13:27 – 14:37</td>
<td>●</td>
<td>70 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>14:46 – 16:40</td>
<td>●</td>
<td>114 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/17</td>
<td>1</td>
<td>18:09 – 19:42</td>
<td>●</td>
<td>93 mins</td>
<td>NNW 340°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/18</td>
<td>1</td>
<td>11:24 – 13:21</td>
<td>●</td>
<td>117 mins</td>
<td>NW 340°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15:56 – 16:16</td>
<td>●</td>
<td>60 mins</td>
<td>NW 340°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/28</td>
<td>1</td>
<td>15:51 – 17:44</td>
<td>●</td>
<td>113 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17:52 – 18:55</td>
<td>●</td>
<td>63 mins</td>
<td>ENE 60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/07/29</td>
<td>1</td>
<td>08:45 – 09:18</td>
<td>●</td>
<td>33 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>09:27 – 11:10</td>
<td>●</td>
<td>103 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>11:22 – 13:17</td>
<td>●</td>
<td>116 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13:39 – 14:34</td>
<td>●</td>
<td>55 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>14:38 – 14:55</td>
<td>●</td>
<td>17 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>15:11 – 16:20</td>
<td>●</td>
<td>69 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>16:27 – 17:07</td>
<td>●</td>
<td>40 mins</td>
<td>ENE 65°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/08/30</td>
<td>1</td>
<td>11:18 – 13:20</td>
<td>●</td>
<td>122 mins</td>
<td>NNE 35°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>14:35 – 15:59</td>
<td>●</td>
<td>84 mins</td>
<td>NNE 35°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/09/04</td>
<td>1</td>
<td>18:03 – 19:51</td>
<td>●</td>
<td>108 mins</td>
<td>W 270°</td>
<td></td>
<td></td>
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<td>SW 220°</td>
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<td></td>
<td>4</td>
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<td>56 mins</td>
<td>SW 220°</td>
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<td>2015/09/26</td>
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<td>●</td>
<td>27 mins</td>
<td>NNW 335°</td>
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<td>12:54 – 13:31</td>
<td>●</td>
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<td>NNW 335°</td>
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<td>13:41 – 14:31</td>
<td>●</td>
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<td>NNW 335°</td>
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<tr>
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<td>4</td>
<td>14:50 – 16:39</td>
<td>●</td>
<td>109 mins</td>
<td>NNW 335°</td>
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<tr>
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<td>5</td>
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<td>●</td>
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<td></td>
<td>6</td>
<td>17:50 – 19:12</td>
<td>●</td>
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<tr>
<td>2015/09/27</td>
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<td>●</td>
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<td>NNW 340°</td>
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<td>2015/10/04</td>
<td>1</td>
<td>12:11 – 13:44</td>
<td>●</td>
<td>93 mins</td>
<td>E 90°</td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>76.52 mins</td>
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</table>

*colour code according to the angle of the wind direction during the day track was taken.
**colour code to identify the times of each drifter on the maps, illustrated at the start of each track.
Figure A-1: Drifter tracks on the 5th of July 2015 with wind direction from the NNW.
Figure A-2: Drifter tracks on the 10th of July 2015 with wind direction from the NW.
Figure A-3: Drifter tracks on the 11th of July 2015 with wind direction from the ENE.
Figure A-4: Drifter tracks on the 17th of July 2015 with wind direction from the NNE.
Figure A-5: Drifter tracks on the 18th of July 2015 with wind direction from the NNW.
Figure A-6: Drifter tracks on the 28th of August 2015 with wind direction from the ENE.
Figure A- 7: Drifter tracks on the 28th of August 2015 with wind direction from the ENE.
Figure A-8: Drifter tracks on the 30th of August 2015 with wind direction from the NNE.
Figure A-9: Drifter tracks on the 4th of September 2015 with wind direction from the W.
Figure A-10: Drifter tracks on the 5th of September with wind direction from the SW.
Figure A- 11: Drifter tracks on the 26th of September with wind direction from the NNW.
Figure A-12: Drifter tracks on the 27th of September 2015 with wind direction from the NNW.
Figure A-13: Drifter tracks on the 4th of October 2015 with wind direction from the E.
Table A-2: Table of the selected drifter track points and SWAN model grid points that have been selected based on closeness of between the two sets of points, spatially and temporally.

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<th>No</th>
<th>Time</th>
<th>SWAN</th>
<th>Drifter</th>
<th>Time</th>
<th>SWAN</th>
<th>Drifter</th>
<th>Wave</th>
<th>θ +/- 180</th>
<th>Lat</th>
<th>Lon</th>
<th>Drifter θ</th>
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Figure A-14: Velocity time-series of the U (top) and V (bottom) components of four drifters on the 5th of July 2015.
Figure A-15: Velocity time-series of the U (top) and V (bottom) components of four drifters on the 11th of July 2015.
Figure A-16: Velocity time-series of the U (top) and V (bottom) components of four drifters on the 29th of August 2015.
Figure A-17: Velocity time-series of the U (top) and V (bottom) components of four drifters on the 26th of September 2015.
Figure B-1: Average Significant Wave Height for August.
Figure B-2: Average Significant Wave Height for September.
Figure B-3: Average Significant Wave Height for October.
Figure B-4: Average Significant Wave Height for November.
Figure B-5: Average Significant Wave Height for December.
Figure B-6: Average Significant Wave Height for January.
Figure B-7: Average Significant Wave Height for the total period of study.
Figure C-1: Average Mean Wave Direction for August.
Figure C-2: Average Mean Wave Direction for September.
Figure C-3: Average Mean Wave Direction for October.
Figure C-4: Average Mean Wave Direction for November.
Figure C-5: Average Mean Wave Direction for December.
Figure C-6: Average Mean Wave Direction for January.
Figure D-1: Time-Series for the Significant Wave Height during August across the five points from the transect.
Figure D-2: Time-Series for the Significant Wave Height during September across the five points from the transect.
Figure D-3: Time-Series for the Significant Wave Height during October across the five points from the transect.
Figure D-4: Time-Series for the Significant Wave Height during November across the five points from the transect.
Figure D-5: Time-Series for the Significant Wave Height during December across the five points from the transect.
Figure D-6: Time-Series for the Significant Wave Height during January across the five points from the transect.