University College London

Aspects of embayed beach morphology in a micro-tidal setting in Malta

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PhD Research Degree in Geography
March 2018
DECLARATION

I, hereby confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Michael Schembri

________________
Signature of Student

The research work disclosed in this thesis is partly funded by the Malta Government Scholarship Scheme.
ACKNOWLEDGEMENTS

I would like to extend thanks to the many people who throughout the course of this research have, directly or indirectly, contributed to the work presented in this thesis.

Special mention goes to my principal supervisor, Dr Helene Burningham, who has been a truly dedicated mentor through the whole process. Her knowledge on the subject and guidance have been instrumental in the development of this research.

Similar, profound gratitude goes to my secondary supervisor, Prof. Jon French, for his insightful feedback and advice.

Special mention goes to Ian Patmore for his help and dedication with all things lab related.

Last but not least, I would like to thank my parents and Louisa for their relentless support throughout this long but inspiring journey. Their support has been unconditional and therefore I dedicate this thesis to them.
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Blue Clay</td>
</tr>
<tr>
<td>DSAS</td>
<td>Digital Shoreline Analysis System</td>
</tr>
<tr>
<td>EEA</td>
<td>European Environment Agency</td>
</tr>
<tr>
<td>EPR</td>
<td>End Point Rate</td>
</tr>
<tr>
<td>ERDF</td>
<td>European Regional Development Fund</td>
</tr>
<tr>
<td>GL</td>
<td>Globigerina Limestone</td>
</tr>
<tr>
<td>LCD</td>
<td>Littoral Cut-Off Diameter</td>
</tr>
<tr>
<td>LCL</td>
<td>Lower Coralline Limestone</td>
</tr>
<tr>
<td>LRR</td>
<td>Linear Regression Rate</td>
</tr>
<tr>
<td>MITC</td>
<td>Ministry for Infrastructure and Communications</td>
</tr>
<tr>
<td>MTA</td>
<td>Malta Tourism Authority</td>
</tr>
<tr>
<td>MUS</td>
<td>Malta University Services</td>
</tr>
<tr>
<td>NSM</td>
<td>Net Shoreline Movement</td>
</tr>
<tr>
<td>NSO</td>
<td>National Statistics Office</td>
</tr>
<tr>
<td>SCE</td>
<td>Shoreline Change Envelope</td>
</tr>
<tr>
<td>UCL</td>
<td>Upper Coralline Limestone</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

a  Indentation of the embayment
Ab  Beach area
a/Ro  Indentation index
Bw  Maximum beach width
Hb  Breaker wave height
Ro  Length of the headland spacing
Ro^0  Orientation of the length between the headland spacing
S1  Length of the embayed beach shoreline
S1/Ro  Embaymentisation index
S1/S2  Bay filing index
S2  Length of the embayed beach
S3  Linear distance between the edges of the embayed beaches
S3^0  Orientation of the linear distance between the edges of the embayed beaches
δ'  Embayment scaling parameter
ABSTRACT

Embayed beach response is very often constrained within a specific geological and structural framework that can determine the nature of beach morphology and beach behaviour in response to dynamic forcing. The morphometric characteristics of 29 micro-tidal embayed beaches in Malta and Gozo were analysed for associations between headland and beach morphometry. Significant correlations exist between the embaymentization index (S1/Ro) and indentation index (a/Ro). The length of embayed beach shoreline is also well correlated with the embayment shoreline. Long-term shoreline behaviour was also analysed over a period of 60 years for eight of the embayed beaches. Anthropogenic interventions have contributed to significant shoreline retreat at Armier and Gnejna. Natural erosion of the low rocky shoreline has led to significant shoreline retreat at White Tower. Short-term variations in embayed beach morphology were analysed from 19 beach profiles surveyed over a period of two years to consider cross-shore and alongshore patterns of change. Storms events are the most important factor contributing to short-term morphological change. Variations in beach volumes allowed the quantification of the long-term net sediment exchange at these embayed beaches and the delineation of littoral cells. Morphological change is also dependent on the type and amount of available sediment. This is particularly important in embayed beaches, where sediment exchange is often limited. The sediment textural characteristics within these embayed beaches were used to describe the sedimentary environments, sediment provenance, transport mechanisms and also differentiate wave energy environments. Embayed beach sediments in Malta and Gozo are dominated by medium to very coarse sand with variable amounts of terrigenous rock fragments and carbonate sands of marine biogenic origin. Sediment exchange between embayed beaches is often limited and very much dependent on embayment configuration.

Keywords: beach morphodynamics, embayed beaches, micro-tidal, Maltese islands
IMPACT STATEMENT

The research presented in this thesis provides a detailed description and analysis of the physical environment within which the embayed beaches in Malta are situated. The results and insight presented in this thesis can potentially have wide ranging benefits and can be used for a number of applications such as:

Academia
This research is advancing the existing body of knowledge on small embayed beaches within a micro-tidal setting both on the national and regional scale. Few studies have dealt with embayed beach morphodynamics within the Mediterranean region in such a comprehensive approach. Methods and concepts which have been proposed in this research for embayed beaches in Malta can also be adapted for other embayed beaches in a similar setting.

Policy Development
It is assumed that the results of this research will allow coastal managers to be in a better position to understand the major physical processes operating on embayed beaches in Malta and therefore allow for a more comprehensive approach to coastal zone policy development both in the short and the long-term planning processes.

Governance
The results of this research can be utilised by coastal zone managers to setup the necessary government and management structures to ensure that the day to day running of embayed beaches in Malta is carried out in the most effective and sustainable manner, whilst keeping in mind the demands of the local and tourist population.

Social and economic functions
Embayed beaches in Malta play an important role within the socio-economic development of the country as they attract large amounts of locals and tourists. The insight brought forward by this research will allow for a better valorisation of the socio-economic importance of these embayed beaches and therefore increase their relevance as a natural asset which needs to be protected and managed sustainably.

Environment
The knowledge of the physical processes acting upon embayed beaches in Malta being brought forward by this research will also benefit the natural environment. Maltese sandy beaches are of conservation importance given that they host habitat-restricted species, some of which have limited local and regional distributions, and are internationally protected.
# TABLE OF CONTENTS

1  Embayed beach morphology in a micro-tidal setting .................................. 21  
   1.1  Introduction .......................................................................................... 21  
   1.2  Embayed beaches on low drift coastlines ........................................... 21  
   1.3  Physical features of indented coastlines ............................................. 23  
   1.4  Origin and formation of embayed beaches ........................................... 24  
   1.5  Morphodynamics of embayed beaches ................................................. 25  
   1.6  Hydrodynamic conditions within headland-bay contexts ................. 29  
   1.7  Geological constraints ......................................................................... 35  
      1.7.1  Lateral constraints ......................................................................... 35  
      1.7.2  Vertical constraints ...................................................................... 38  
   1.8  Stability of headland-bay beaches .................................................... 40  
   1.9  Sedimentary and sedimentological factors .......................................... 42  
   1.10 Conclusion .......................................................................................... 47  

2  The embayed beach setting of the Maltese islands .................................. 48  
   2.1  Geographic setting .............................................................................. 48  
   2.2  Geology and structural framework .................................................... 49  
   2.3  The Maltese coastline ......................................................................... 54  
      2.3.1  Cliffs .............................................................................................. 55  
      2.3.2  Rdum areas ................................................................................... 56  
      2.3.3  Low rocky coastline ...................................................................... 58  
      2.3.4  Semi-circular coves ...................................................................... 59  
      2.3.5  Drowned valleys .......................................................................... 59  
   2.4  Embayed beaches of the Maltese islands .......................................... 60  
   2.5  Research aims and objectives ............................................................ 64  
   2.6  Choice of site selection ...................................................................... 66  

3  Research Design and Methodology ......................................................... 69  
   3.1  Approach adopted for this research .................................................. 69  
   3.2  Characteristics of embayed beach setting .......................................... 69  
   3.3  Analysis of shoreline change ............................................................. 72  
   3.4  Beach morphology and morphodynamics ......................................... 74
3.5  Sediment Analysis ............................................................... 76
3.6  Meteorological and hydrodynamic datasets .................................. 79
3.7  Choice of statistical techniques .................................................. 80

4  Structural control on beach morphology ........................................... 81
4.1  Headland-bay morphometry ........................................................ 81
4.2  Headland embaymentisation .......................................................... 87
4.3  Beach planform morphometrics ..................................................... 91
4.4  Bathymetry .................................................................................. 95
4.5  Hydrodynamic context ................................................................. 97
   4.5.1  Metocean context and model set-up ........................................ 97
   4.5.2  Wave modelling results .......................................................... 100
   4.5.3  Depth of closure ................................................................. 103
4.6  Conclusion .................................................................................. 105

5  Meso-scale behaviour of headland-bay beaches .................................. 106
5.1  Shoreline change analysis ............................................................... 107
   5.1.1  Net Shoreline Movement ...................................................... 108
   5.1.2  Range of shoreline position ................................................ 116
   5.1.3  Shoreline trends ................................................................. 120
   5.1.4  Evidence for progressive or cyclical behavior ...................... 128
5.2  Climate forcing ........................................................................... 139
   5.2.1  Wind and wave climate ...................................................... 140
   5.2.2  Sea level change ............................................................... 141
5.3  Anthropogenic interventions ......................................................... 144
5.4  Conclusions ............................................................................... 145

6  Beach morphodynamics .................................................................. 147
6.1  Beach morphology and morphological change .................................. 147
   6.1.1  North Gozo ........................................................................... 147
   6.1.2  North Malta .......................................................................... 153
   6.1.3  West Malta .......................................................................... 160
6.2  Beach volumes and sediment budgets ........................................... 166
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Summary of key findings</td>
<td>250</td>
</tr>
<tr>
<td>9.2 Emerging research questions and future work</td>
<td>253</td>
</tr>
<tr>
<td>10 References</td>
<td>255</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1: Examples of highly curved embayed beaches. (a) Seringat Islands, Singapore, and (b) Niembru Llanes, Spain ................................................................. 22
Figure 1.2: Relationship between the temporal and spatial scales involved in embayed beach evolution ................................................................. 24
Figure 1.3: Formation of natural embayed beaches ........................................... 25
Figure 1.4: Schematic showing the typical morphology of a beach profile, including the terminology applied to the different zones of the beach profile ... 26
Figure 1.5: Schematic showing the typical seasonal summer and winter beach profiles of a sandy beach ................................................................. 27
Figure 1.6: Platform evolution of beach states .................................................... 28
Figure 1.7: Model sequence of beach profiles and beach types for headland bay beach morphology in a swell environment ........................................... 28
Figure 1.8: Volume variations calculated for two beaches along the Santa Catarina coast in Brasil showing out-of-phase changes in beach volume at opposing end of the beach .................................................................. 32
Figure 1.9: Schematic diagram showing the occurrence and parameterisation of an embayed megarip ........................................................................... 33
Figure 1.10: Embayed beach state conceptual model for asymmetrical headland protection ................................................................. 34
Figure 1.11: Schematic diagram of shoreline rotation ......................................... 36
Figure 1.12: Underwaater photo showing the formation of a scour step ............ 39
Figure 1.13: Diagram showing conceptual cross-shore profiles of geologically constrained beaches ................................................................. 40
Figure 1.14: The relationship between wave energy, grain size and beach slope ................................................................................................. 44
Figure 1.15: Conceptual diagram of cross-shore sediment size changes in an embayment ................................................................. 45
Figure 1.16: Conceptual model of the sediment budget of an embayed beach 46
Figure 2.1: Location of the Maltese Islands within the Mediterranean sea .......... 48
Figure 2.2: Monthly periodicity of the total annual precipitation from 1961 to 1990 ................................................................................................. 49
Figure 2.3: Bathymetric map of the central Mediterranean Sea and map of the main terrestrial geological formations and faults systems of the Maltese islands ................................................................................................. 51
Figure 2.4: Locations in the Maltese islands which are important in terms of geology and geomorphology

Figure 2.5: Lithostratigraphic diagram of the succession of the Maltese islands

Figure 2.6: Map of the dominant geology outcropping at the coastline and map of the Maltese islands showing the dominant coastal landforms and the location of the main beaches

Figure 2.7: The Qarraba promontory is one of the most important examples of the contribution of rudum areas to the development and formation of beaches in terms of structure and sediment provision

Figure 2.8: Map of the Maltese islands showing areas where low rocky coastlines and semi-circular coves are present

Figure 2.9: Map of the Maltese islands showing areas where drowned valley systems are present

Figure 2.10: Location of the embayed beaches where investigation of the key physical controls where carried out

Figure 2.11: Location of the eight embayed beaches where a more detailed analysis of shoreline change, beach morphodynamics and sedimentology was undertaken

Figure 3.1: Block flow diagram showing the structure of this research and how each of the research questions identified in Chapter 2 shall be addressed through subsequent chapters

Figure 3.2: Schematic representation of the parameters used to characterise the planform of embayed beaches

Figure 3.3: Bay-shape classification based on the indentation index (a/Ro)

Figure 3.4: Plot showing the available shorelines for the analysis of shoreline change (a/Ro)

Figure 4.1: Location map of the 29 embayed beaches for which morphometric parameters and indices were considered

Figure 4.2: Variation in headland spacing (Ro), indentation and the embayment (a) and length of shoreline (m) amongst the 29 beaches considered for the morphometric analysis

Figure 4.3: Dendogram clustering of all the morphometric parameters

Figure 4.4: Boxplots representing the variations in the morphometric data

Figure 4.5: Principal component analysis plot of the morphometric parameters

Figure 4.6: Scatterplots showing the association between a number of headland parameters

Figure 4.7: Scatter plot of the embaymentisation index against the indentation index for a number of beaches in Malta, Spain and Elba
Figure 4.8: Maps showing the spatial distribution of the embaymentisation index and indentation index ................................................................. 91
Figure 4.9: Scatter plot showing the correlation between beach area and maximum beach width and each area and length of beach shoreline .......... 92
Figure 4.10: Scatter plot showing the correlation between beach shoreline and beach headland spacing and length of beach shoreline and embayment shoreline length ................................................................. 93
Figure 4.11: Scatter plots showing the correlation between a number of embayment morphometry parameters ........................................ 93
Figure 4.12: Scatter plots showing the correlation between length of beach shoreline and shoreline length within the embayment .................. 94
Figure 4.13: Map showing the spatial distribution of the bay filling index ..... 95
Figure 4.14: Submarine morphology within and outward of the embayments... 96
Figure 4.15: Wind rose showing the prevalent wind directions in the Maltese islands ............................................................................ 98
Figure 4.16: Map of the Maltese islands showing the location of the 4 offshore locations for which wave data was obtained from the UKMO wave model .... 99
Figure 4.17: Wave conditions at the 29 beaches at approximately the 10 meter contour line ............................................................................. 101
Figure 4.18: Spatial distribution of the non-dimensional scaling parameter .... 103
Figure 5.1: Map of the Maltese islands showing the location of the eight beaches for which shoreline change analysis was undertaken .............. 106
Figure 5.2: Maps showing the location and variations in shoreline position for the period ranging from 1955 to 2016 ................................................. 107
Figure 5.3: Analysis of the distance between the oldest and youngest shoreline at San Blas .............................................................................. 109
Figure 5.4: Analysis of the distance between the oldest and youngest shoreline at Ramla .................................................................................. 110
Figure 5.5: Analysis of the distance between the oldest and youngest shoreline at Armier .................................................................................. 111
Figure 5.6: Analysis of the distance between the oldest and youngest shoreline at Little Armier ........................................................................ 112
Figure 5.7: Analysis of the distance between the oldest and youngest shoreline at White Tower ........................................................................ 113
Figure 5.8: Analysis of the distance between the oldest and youngest shoreline at Golden Sands ................................................................. 114
Figure 5.9: Analysis of the distance between the oldest and youngest shoreline at Ghajn Tuffieha ................................................................. 115
Figure 5.10: Analysis of the distance between the oldest and youngest shoreline at Gnejna .................................................................115
Figure 5.11: Patterns of change in shoreline position at the eight beaches under study for the period ranging from 1955 to 2016 .................................................................117
Figure 5.12: Plot showing the correlation between the envelope of shoreline change and the net shoreline movement for the period ranging from 1955 to 2016.................................................................118
Figure 5.13: Plot of the envelope of shoreline change against mean beach width for the period 1955 to 2016.................................................................119
Figure 5.14: Plot of the alongshore shoreline erosion and accretion rates at San Blas and Ramla beach ........................................................................................................................................120
Figure 5.15: Plot of the alongshore shoreline erosion and accretion rates at Armier, Little Armier and White Tower ........................................................................................................................................122
Figure 5.16: Plot of the alongshore shoreline erosion and accretion rates at Golden Sands, Ghajn Tuffieha and Gnejna .................................................................124
Figure 5.17: Plot of the correlation between the linear regression rate and the end point rate........................................................................................................................................126
Figure 5.18: Comparison of the range of the rate shoreline change within embayed beaches to the main morphometric indices .................................................................127
Figure 5.19: Comparison of the change in shoreline position over time at San Blas and Ramla beach ........................................................................................................................................129
Figure 5.20: Comparison of the change in shoreline position over time at Armier, Little Armier and White Tower ........................................................................................................................................131
Figure 5.21: Comparison of the change in shoreline position over time at Golden Sands, Ghajn Tuffieha and Gnejna beach ........................................................................................................................................132
Figure 5.22: Time series of satellite imagery for the period between July 2015 and April 2017........................................................................................................................................134
Figure 5.23: Identification of possible hinge points at San Blas beach ....135
Figure 5.24: Identification of possible hinge points at Ramla beach ..........136
Figure 5.25: Identification of possible hinge points at Armier .................137
Figure 5.26: Identification of possible hinge points at Little Armier ..........138
Figure 5.27: Identification of possible hinge points at White Tower ..........139
Figure 5.28: Identification of possible hinge points at Golden Sands.......140
Figure 5.29: Identification of possible hinge points at Ghajn Tuffieha .....141
Figure 5.30: Identification of possible hinge points at Gnejna .................142
Figure 5.31: Monthly wind direction and wind speed together with the monthly maximum recorded wind speed at Luqa station, Malta ........................................................................................................................................143
Figure 5.32: Monthly variations in sea level for the period between 1995 and 2012

Figure 5.33: Shoreline change rates for each individual transect as a function of type of geomorphic landform and anthropogenic development

Figure 6.1: Location of the eight beaches where detailed morphodynamic assessments were carried out

Figure 6.2: Location of San Blas and Ramla beach together with the outcropping geology in the area

Figure 6.3: The small pocket at San Blas with the significant presence of boulders along and at the sides of the beach shoreline

Figure 6.4: Photograph of Ramla beach showing the protruding headlands on the eastern side of the embayment

Figure 6.5: Morphological development of the San Blas beach profiles

Figure 6.6: Morphological development of the Ramla beach profiles

Figure 6.7: Location of Armier, Little Armier and White Tower beach together with the outcropping geology

Figure 6.8: Development of extensive sea grass banquets at Armier beach

Figure 6.9: Morphological development of the Armier beach profiles

Figure 6.10: Morphological development of the Little Armier beach profiles

Figure 6.11: Morphological development of the Little Armier beach profiles

Figure 6.12: Development of extensive sea grass banquets at White Tower beach

Figure 6.13: Morphological development of the White Tower beach profiles

Figure 6.14: The location of Golden Sands, Ghajn Tuffieha and Gnejna beach together with the outcropping geology

Figure 6.15: Morphological development of the Golden Sands profiles

Figure 6.16: Sea grass deposits at Gnejna beach

Figure 6.17: Dissipative beach Profile at Golden Sands

Figure 6.18: Ghajn Tuffieha beach during fair weather conditions

Figure 6.19: Morphological development of the Ghajn Tuffieha beach profiles

Figure 6.20: Morphological development of the Gnejna beach profiles

Figure 6.21: Principal components scatter plot of the 2 most important components accounting for the variability in beach profile volume data

Figure 6.22: Scatter plot showing the correlation between beach profile length and beach profile volume

Figure 6.23: Plots of the variations in beach profile volume over time
Figure 6.24: Net sediment exchange at Ramla and San Blas beach during three different time periods .................................................................173
Figure 6.25: Net sediment exchange at Armier, Little Armier and White Tower during three different time periods .................................................................174
Figure 6.26: Net sediment exchange at Golden Sands, Ghajn Tuffieha and Gnejna during three different time periods .................................................................176
Figure 6.27: Mean monthly variations in wind speed from 2011 to 2013 ......177
Figure 6.28: Wind conditions during 2011, 2012 and 2013 as recorded at the Luqa station in Malta .................................................................179
Figure 6.29: Modelled wave statistics for Ramla and San Blas beach........180
Figure 6.30: Modelled wave statistics for Armier, Little Armier and White Tower beach .........................................................................................181
Figure 6.31: Modelled wave statistics for Golden Sands, Ghajn Tuffieha and Gnejna beach .........................................................................................183
Figure 7.1: Spatial variation in the sediment size distributions of Maltese beaches showing the full distribution and the gravel, sand and mud proportions ..................................................................................................................189
Figure 7.2: Spatial representation of the main grain size parameters .........191
Figure 7.3: Cluster analysis of the grain size distribution data for the 26 embayed beaches .........................................................................................192
Figure 7.4: Plot showing the results of the principal component analysis for the sediment samples collected from the 26 embayed beaches.........................193
Figure 7.5: Comparison of beach sediment grouping with regional geology ..194
Figure 7.6: Boxplots showing the associations between the main textural parameters and the dominant coastal geology ................................................................195
Figure 7.7: Associations between the main morphometric parameters, mean sediment size and sediment distribution .............................................................................196
Figure 7.8: Boxplot showing particle size for the 8 beaches under study......197
Figure 7.9: General bivariate plots of the sediment textural characteristics for all the samples collected at Ramla and San Blas beach .........................................................198
Figure 7.10: General bivariate plots of the sediment textural characteristics for all the samples collected at Armier, Little Armier and White Tower ............199
Figure 7.11: General bivariate plots of the sediment textural characteristics for all the samples collected at Golden Sands, Ghajn Tuffieha and Gnejna ........200
Figure 7.12: General bivariate plots of the sediment textural characteristics for all the samples collected at the eight embayed beaches ................................200
Figure 7.13: Photographs of sediment samples collected from the berm/backshore of the beach profiles .................................................................202
Figure 8.1: Map showing the importance of structural control on the formation of embayed beaches in Malta .................................................................222
Figure 8.2: Planform view of the structural differences exhibited by a selected number of embayed beaches amongst the four different groups.................225
Figure 8.3: Submarine embaymentisation at Santa Marija bay and Marsalforn...............................................................................................................226
Figure 8.4: A marl shore platform on the western section of Ramla l-Hamra is completely exposed following a period of intense wave action and similarly quaternary deposits are exposed on the eastern side of Armier beach .......228
Figure 8.5: Partial exposure of the marl shore platform which vertically constrains the morphological adjustment of the beach profile on the right side of Gnejna ........................................................................................................228
Figure 8.6: Changes in planform configuration for embayed beaches in the Maltese islands ..................................................................................230
Figure 8.7: Storm waves reaching the coastal bluffs surrounding the backshore area of Ghajn Tuffieha beach.................................................................232
Figure 8.8: Armier beach following an intense storm event during November 2011........................................................................................................232
Figure 8.9: Generalise evolution of beach profile morphology for Maltese embayed beaches.......................................................................................234
Figure 8.10: Golden Sands beach showing a well developed landward sloping berm corresponding to the first phase of beach morphological developed ....235
Figure 8.11: Extensive development of beach casts at Dahlet Qorrot in Gozo........................................................................................................236
Figure 8.12: Enhanced beach erosion at the western side of Ramla beach ...237
Figure 8.13: Possible interactions between fields of Posidonia oceanica and beach profile in an embayed beach setting.................................................239
Figure 8.14: Morphological change of Malta’s palaeoshorelines during the last sea level rise from 70m to -10m.........................................................240
Figure 8.15: Conceptual model of the sediment budget of embayed beaches in the Maltese islands ...........................................................................243
Figure 8.16: Temporary formation of streams discharging beach sand into the nearshore zone at Armier and Ramla .................................................246
LIST OF TABLES

Table 3.1: Beach profiles were collected approximately every four months as shown (mm/yy)..................................................................................................................76

Table 3.2: Comparison of the most common methods for sediment size analysis...............................................................................................................................78

Table 4.1: Morphometric parameters and indices of the 29 beaches located in Malta and Gozo.................................................................................................................................82

Table 4.2: Categorisation of beaches according to the embayment classification scheme .................................................................................................................................89

Table 4.3: Categorisation of beaches according to the indentation classification scheme .................................................................................................................................90

Table 4.4: Categorisation of beaches according to the bay filling classification scheme .................................................................................................................................95

Table 4.5: Percentage exceedance of offshore significant wave height on an annual basis and during the summer period .................................................................................99

Table 5.1: Categories used for the classification and analysis of net shoreline movement .............................................................................................................................108

Table 5.2: Minimum, maximum and mean annual rates of shoreline change across five different timescales of analysis ..............................................................................125

Table 6.1: Mean, maximum and minimum profile volumes and volume change statistics between 2011 and 2013.............................................................................167

Table 7.1: Primary grain size statistics of Maltese beach sediments ................188

Table 7.2: Values for the littoral cut-off diameter for the eight embayed beaches in ascending order ..................................................................................................................209

Table 8.1: Comparison of the mean parameters of the studies beaches in Malta and Spain ..........................................................................................................................226

Table 8.2: Descriptive textural parameters of embayed beaches in Malta and Migjorn and Tramuntana regions in Menorca, Spain ................................................................238

Table 8.3: Mean grain size for the eight beaches considered for a more detailed analysis of beach sediments .................................................................................................239

Table 8.4: Comparison of the value for the shoreline change envelope and net shoreline movement for a number of beaches from 1955 to 2016 ........................................242
1 Embayed beach morphology in a micro-tidal setting

1.1 Introduction

The coastline represents the juncture where land meets the sea. Coastlines are the world’s most important and intensely used areas settled by humans (Kay & Alder, 1999) and represent one of the most important revenue sources for worldwide economy. Nowadays, coastal environments attract and concentrate a wide range of socio-economic activities which without correct planning, can cause stress to the littoral zone leading to degradation of the environment (Valdemoro & Jimenez, 2006). This is especially true in small island economies, where the coastal zone is an important resource, particularly for tourism and as a local amenity.

Defining coastal zone features and subdivisions can be difficult due to temporal variability or gradational changes between features which obscure precise boundaries. In addition, the nomenclature used for defining coastal features is not standardized, and various authors describe the same features using different names (U.S. Army Corps of Engineers, 2002). This ambiguity is especially evident in the terminology and zonation of shore and littoral areas. The range of arguments for the classification of coasts is extensive and although various attempts have been made at the creation of comprehensive coastal classification systems (Valentin, 1952; Davis, 1980 and Finkl, 2004), no general classification system has been agreed upon by the scientific community. This is in part due to the coast being one of the most diverse and dynamic environments found anywhere on Earth. In this research, the coastal zone is defined as the transition zone where the land meets water, the region that is directly influenced by marine or lacustrine hydrodynamic processes (U.S. Army Corps of Engineers, 2002).

1.2 Embayed beaches on low drift coastlines

Complex physiographic features can be found along many narrow coastal strips around the world, which include rocky coasts, gravelled and sandy beaches, estuaries, deltas, salt marches, and mangrove swamps. Among these features, sandy beaches, in various shapes and sizes, are very attractive to the general public. Some of the most recognizable sandy beaches are embayed beaches, which are mostly characterised by distinct compartments bounded by rocky outcrops or headlands as shown in Figure 1.1. These embayed beaches represent about 50% of the world’s coastline (Short & Masselink, 1999) and in the literature have attracted a wide variety of terms such as zeta bays (Halligan, 1906; Zenkovich, 1967), half-heart bay (Silvester, 1960),
crenulate-shaped bays (Finkelstein, 1982; Hsu and Evans, 1989; Silvester and Ho, 1972), spiral beaches (Krumbein, 1944; Leblond, 1972), hooked beaches (Rea and Komar, 1975), headland bay beaches (Klein and Menezes, 2001; Leblond, 1979; Moreno and Kraus, 1999; Phillips, 1985; Wong, 1981; Yasso, 1965), pocket beaches (Komar, 1998; Silvester et al., 1980; Uda et al., 2002). For the purpose of this research, the term embayed beaches shall be adopted to signify small beaches (50m to hundreds of meters long), that are naturally sheltered from the open sea as a result of one or more headlands protruding from the surrounding coastline.

Figure 1.1: Examples of highly curved embayed beaches. (a) Seringat Island, Singapore, and (b) Niembro, Llanes, Spain. (Image data: Google, DigitalGlobe 2013). (Source: Daly et al, 2014).

Around the world, embayed beaches form part of some of the most attractive segments of rocky coasts and are the base of tourist activity of several small islands such as those found in the Mediterranean, Caribbean and Southeast Asia. (Schwartz, 1982). Limited in width, they are frequently backed by bluffs and fed by small creeks. The tourist use of the coast exposes these valuable areas to intense urbanization that reduces the resilience of the system as will be demonstrated further on in this research. As a result of rising sea levels and widespread human impacts to beach sediment budgets, many sandy coastlines are eroding (National Research Council, 1995). During the last century erosive phenomena increased sharply in Europe (European Environment Agency (EEA), 2001) becoming one of the most important problems affecting beaches. It is therefore important, to gain an understanding of beach responses to varying environmental conditions and stresses (Fletcher, et al., 1997), especially by making the best use of scientific knowledge and predictions of possible impacts on the environment.
1.3 Physical features of indented coastlines

Embayed beaches comprise one of the most widely distributed coastal geomorphic forms around the world and are amongst the most dynamic systems on the Earth’s surface. Their importance as a buffer zone between land and sea and as a recreational and economic resource has stimulated studies by earth scientists for centuries. Although much has been learned about how embayed beaches form and how they are modified, the coastal environment is incredibly complex, and each location responds to unique geologic conditions and physical processes. Variations in headland morphology, orientation, wave climate and sediment supply have resulted in the formation of an incredible variety of embayed beaches (Short, 1996).

The variation of these factors, across space and over time, creates a varied array of embayed beaches that are forced by, and respond to, these changes in conditions. Embayed beaches can be examined at a range of time scales, depending on the formative processes. These processes can range from the instantaneous timescale to tidal, diurnal, seasonal and increasingly longer periods as a result of the changing wave, tidal, wind and climate regimes and processes influencing sea level, climate and tectonics. Figure 1.2 shows the relationship between the temporal and spatial scales involved in embayed beach evolution. Coastal change can be rapid; local beach shoreline configuration can be significantly modified over hours and days. Over a longer period, larger scale shifts in beach shoreline position occur.

Unlike other coastal systems, embayed beaches are typically considered as closed systems since there is limited exchange of energy and matter beyond the headland bay beach. The boundaries of embayed beach systems are determined by the local topography and shape of the coastline. Natural embayed beaches are unique coastal landforms and have existed long before human interference on the world coasts. Large coastal structures such as breakwaters have led to the creation of artificial embayed beaches.
1.4 **Origin and formation of embayed beaches**

Various processes can lead to the formation of headlands bay beaches, the most common being in places where rocks of varying resistance lie at right angles to the sea (Schwartz, 2005). The rate at which a coast is eroded depends partly on the resistance of the rock. Harder more resistant rock is eroded more slowly by wave action than less resistant rock thus leading to an alternating alongshore succession of headlands and bays (Figure 1.3). In time, as the sea cuts the bay back, less powerful waves reach the coast as they travel over a long expense of bay. Headlands thus experience the more powerful waves and help attenuate the wave energy being diffracted into the bay, favouring the deposition of sediment in this low energy environment.

Headland bay beaches can also form as a result of partial submergence of river valleys. The submergence of these valleys can occur either as a result of eustatic or isostatic changes (Bowman et al, 2014). The structural geology of the area can also play an important role in the formation of headland bay beaches. Block faulting within the coastal zone can lead to the formation horst-graben structures that can eventually function as headland bay beaches.
The man made counterpart to the natural formation of embayed beaches is artificial embayed beaches. Breakwaters, groins and jetties are all structures that act in a similar manner as natural headlands and impose a physical barrier in the nearshore zone and can dramatically alter patterns of erosion, transportation and deposition of sand along the coastline. Breakwaters, whether built for harbor protection or shore protection, create calm water which promotes the accretion of sediment and the formation of beaches.

The sediment present in headland bay beaches can originate from a number of sources. Often, the sediment is supplied by erosion of the adjacent coastline, in particular the headlands, which are subjected to a concentration of wave energy. Wave refraction causes headlands to be the focus of wave energy and thus the focus of erosion. Wave energy is weakened along the wider stretches in the bays, so waves deposit sediment in bays which in turn helps protect that part of the coastline from further erosion (Schwartz, 2005). Additionally, fluvial sediment can also be an important contributing factor to the accumulation of sediment in a headland bay beach. Dams on rivers supplying sediment to headland bay beaches can have a huge impact on the sediment budget and can lead to increased erosion as was the case in some of California’s embayed beaches (Patsch & Griggs, 2006). Longshore transport can also be one of the several sources of beach sediment, bringing sediment from updrift beaches and depositing them in the sheltered environment of headland bay beaches (Goodwin et al, 2013).

1.5 Morphodynamics of embayed beaches

The morphology and dynamics of a beach are a function of the sand, size, wave climate (including height and period), tide range, and major topographic features (Short, 1999). Each of these variables, however, has considerable spatial and temporal variation, resulting in a range of beach types. At the level of an individual beach, temporal change in wave height and period and tidal cycles induce beach response and change. At a regional scale, changes in both sediment and breaker wave height
induce further spatial and temporal changes, while at a global level a wide range of variable combinations and beach response occurs (Short, 1996). Open-coast beaches that experience significant alongshore sediment transport are generally much more sensitive to these changing conditions than headland bay beaches (Sedrati & Anthony (2007).

Beaches around the world often exhibit similar morphological features. Figure 1.4 depicts a typical cross-section of a beach perpendicular to the shore. Four general zones of a typical beach profile that extends from the cliff or dune to the end of the nearshore zone are usually defined (Sorensen, 2006). An offshore point at which wave activity almost becomes insignificant marks the boundary between the nearshore and offshore zone. This zone is often referred to as the depth of closure and typically marks the seaward end of a typical beach profile.

Figure 1.4: Schematic showing the typical morphology of a beach profile, including the terminology applied to the different zones of the beach profile (after Sorensen, 2006).

The seaward extent of the beach profile is however a vague concept given that it is very much dependent on the temporal changes of the wave environment. The longer the wave period, the deeper, and therefore more seaward, will the depth of closure (Leatherman, 1991; Stive et al, 1992; Karus et al. 1999). The location of the depth of closure, whether entrapped within the embayment or offshore beyond the headlands, may indicate the status of sediment exchange between an embayment and adjacent coastal sectors. This can therefore reveal whether embayed beaches are closed physiographic units which are independent of other coastal sectors in terms of beach processes or are partly open systems which interact with adjacent coastal sectors (Storlazzi and Field, 2000; Muller et al., 2006; Anfuso et al., 2013).

Waves typically break in the surf zone section of the beach profile and rush up the steep section of the beach, namely the foreshore zone, or beach face. Increased level
of wave activity usually brings about scarps and the backshore portion of the profile may include more than one berm. At the shoreward end of a typical beach profile, dunes may form, as a result of wind-blown sand which is often trapped by vegetation or backshore cliffs. Typically a calm wave profile (summer profile) is established after a period of low wave energy during which the beach face becomes steeper as a result of the slight shoreward movement of sediment as shown in Figure 1.5. Increased waved activity leads to the formation of a storm wave profile (winter profile) as a result of sand being transported seaward due to the high energy waving action during storms (Dean and Dalrymple, 2002; Sorensen, 2006).

A range of morphological classifications of beaches exist that recognize the occurrence of distinct beach morphologies, or beach states/types, and link these to parameterizations of the key environmental conditions, namely wave climate, tidal regime and beach sediment characteristics. Beach classifications models are useful because they provide a conceptual framework within which beach and surf zone environments can be studied and understood (Scott et al. 2011). The most widely used of such models is the so-called Australian beach model, originally devised independently by Wright et al. (1979) and Short (1979) and subsequently refined by Wright and Short (1984) and Wright et al. (1987). Figure 1.6 depicts the planform evolution of beach morphology as proposed by Wright and Short (1984) and subsequently modified by other authors.

Very few studies have attempted to develop a classification of beach morphodynamics for embayed coastlines. Klein and Menezes (2001), developed a classification of beach
morphodynamics for the microtidal headland bay beach environment of the central-north coast Santa Catarina, Brazil based on a number of morphodynamic and morphometric parameters. The beaches presented a multitude of environmental settings due to their distinct geographical orientation, level of exposure to incident waves and sediment distribution. Klein and Menezes (2001), classified the beaches as: (1) exposed, (2) semi-exposed or (3) sheltered. In the exposed beach, the indentation ratio, which is defined as the ratio of maximum embayment indentation to the spacing between the headlands, is small and waves approximate parallel to the coast with angles less than 40 degrees. Exposed beaches were further subdivided into three types, reflective beaches, intermediate beaches and dissipative beaches.

Figure 1.6: Planform evolution of beach states based on Short (1979, 1999b), Wright and Short (1984), Sunamura (1989 and Lippman and Holman (1990b).
For sandy beaches within an embayed beach setting, Klein and Menezes (2001) concluded that reflective beaches have coarse sand and greater nearshore slope with a very narrow coastal plain. The beachface in reflective beaches is steeper and without a berm near the headland. On the other hand intermediate beaches are characterized by medium sand and medium nearshore slope and possibly also include the formation of a bar. Finally dissipative beaches are composed of fine sand and the nearshore morphology changes very gently as the coastal plain is very well developed. In semi-exposed beaches the indentation ratio is large and the wave obliquity, the angle of wave attack with respect to the shore normal, is usually greater than 40 degrees. The morphodynamics of semi-exposed beaches are a function of wave break and grain size and relative tidal range whereas sheltered beaches are only influenced by diffracted waves or locally-generated waves. Klein and Menezes (2001) further subdivided sheltered beaches into reflective beaches; composed of coarse and medium sand; and dissipative beaches as can be seen in Figure 1.7.

1.6 Hydrodynamic conditions within headland-bay contexts

Understanding the morphodynamics of headland bay beaches is not possible without first examining the hydrodynamic conditions that take place within the embayment (Silva, et al., 2010). In spite of being protected by promontories and headlands, embayments are not necessarily low energy environments (Collins, et al., 1979; Sayo, 1991; Dail, et al., 2000). Embayed beaches can be exposed to high wave energy due to low dissipation on a steeply sloping sea bottom. Large set-ups can be formed in embayments due to accumulation of water during storm events (Sallenger, et al., 2002).

The amount of wave action that is experienced by embayed beaches is primarily determined by the climatic conditions of the area. Given the morphological setting of many embayed beaches, wave action is very much dependent on the orientation of the embayment with respect to the prevailing climatic conditions. In stormy conditions wave action within embayments is even more pronounced leading to larger impacts on the beach. Nordstrom (1980) and Hegge et al. (1996) have highlighted how while exposed beaches undergo a more or less cyclic pattern of morphological change, with phases of erosion and deposition occurring over short periods ranging from several days to weeks, sheltered beaches show a longer frequency response, usually corresponding to seasonal changes in wave energy. According to Hegge et al. (1996) wave conditions prevailing in sheltered pocket beaches are generally insufficient to facilitate full beach
recovery between periods of storm activity with full recovery to pre-storm conditions only possible after a long period of quiescence.

Figure 1.7: The model sequence of beach profiles and beach types for headland bay beach morphology, in a swell environmental developed by Klein and Menezes (2001). The figure shows examples of beaches from Santa Catarina State, Brazil.
Where incident swell waves are shore-normal, the longshore current is supposed to be very weak in the surf zone of an embayed beach unlike on open beaches (eg: Thornton, et al., 1996; Levoy, et al., 2001; Anthony, et al., 2004; Castelle, et al., 2006a; Sedrati et al, 2007). Nonetheless, a number of studies have also highlighted the important role of wind forcing in controlling nearshore and foreshore processes and beach morphological change (eg: Pattiaratchi, et al., 1997; Masselink & Pattiaratchi, 1998b; Sedrati & Anthony, 2007). As suggested by Ozkan-Haller, et al., (2001), infragravity waves are also expected to develop standing edge wave patterns, due to reflections on both sides of the beach, that could force the generation of rhythmic morphologies, such as beach cusps, that would ‘fit’ the beach (Huntley & Bowen, 1978; Inman & Guza, 1982; Holman & Bowen, 1982).

In response to changes in wave direction, fluctuations of beach volume and width can be out-of-phase between opposite ends, due to beach rotation phenomena (Short, 1999) (Short, et al., 2000). Beach studies reported by Klein, et al., (2002) and Vintem, et al., (2006) for the coast of Santa Catarina in Brazil showed out-of-phase volume change behaviour between two opposite ends of headland-bay beaches (Figure 1.8). These out-of-phase volume changes can occur at different scales, showing distinct patterns according to the particular morphodynamic characteristics of each beach. For example at Taquaras and Taquarinhas beach out-of-phase variations between opposite ends suggest an apparent rotation of the beach planform, as a response to changes in predominant wave direction (Klein, et al., 2002).

Thomas (1986) has identified the following characteristics upon which wave action in embayed beaches is dependent:

1. Extent and configuration of the embayment
2. Aspect relative to the range of wind directions
3. Bathymetry within and around the embayment
4. Fetch

Wave parameters and the way they are affected by headlands may be such that embayed beaches are subject to longshore drift gradients. Martens et al., 1999 found that in embayed beaches as wave height increases and shoreline length decreases, a critical threshold is reached where the wave dominated beach model is increasingly modified by end effects. On beaches with no headlands, ‘normal’ surf zone circulation prevails. When headlands or artificial structures are present and widely spaced and/or the beach receives low waves, the headlands impact surf zone circulation only adjacent to the headlands with normal circulation occurring in between.
As wave height increases and/or headlands are close together, the entire beach circulation may eventually become impacted by the end effects (Martens et al., 1999). In extreme conditions with wave height exceeding a few meters, large scale, topographically controlled rip systems prevail (Short 1985).

The occurrence of large scale rips was first described by Shepard and Inman (1950), and particularly McKenzie (1958), who observed that on embayed beaches increasing wave height strengthens rip intensity while reducing the number of discrete rips, and that during high wave conditions strong rips tended to occur in similar topographically controlled locations. Short (1985), working on some of the same beaches as McKenzie in Sydney, Australia called these large scale topographically controlled rips ‘megarips’.
The megarips that develop as a result of the morphological setting of embayments can also influence beach erosion and the seaward extent of surf zone circulation.

Whereas normal beach rips usually begin to dissipate seaward of the breaker zone, megarips have been observed to flow at high velocity up to 1km seaward of the breakers (Martens et al. 1999). This phenomenon has important implications for beach erosion and seaward transport of sediments, nutrients and organisms. As the velocities are higher, the rip currents can carry more, and coarser, material, and as they penetrate further out to sea, they can carry this material a greater distance from the shore and to greater depths. The net result is more rapid and more severe beach erosion on such beaches with the eroded sediment being deposited further seaward and consequently taking longer to return to shore (Short et al., 1995). It may even be lost from the system to longshore or inner shelf deposits (Roy et al., 1994).

Short (1996) devised a classification of embayment circulation to determine the degree of headland impact on beach circulation (Figure 1.9). This can be achieved through the use of the non-dimensional embayment scaling parameters ($\delta'$=$S1^2/100RoHb$) where $S$ is the shoreline length within the embayment, $Ro$ is the distance between the embayment headlands and $H_b$ refers to the breaker wave height. The impact on embayment circulation is determined by $\delta'$.

![Figure 1.9: Schematic diagram showing the occurrence and parameterisation of an embayed megarip (in Short, 1996. Modified from Martens et al. in press).](image)

When $\delta'$ is greater than 19, normal beach circulation occurs, when $\delta'$ is between 8 and 19 transitional circulation occurs whereas when $\delta'$ is less than 8, cellular beach
circulation occurs. Transitional circulation occurs when the embayment size and shape begin to increasingly influence the surf zone circulation by causing longshore current to turn and flow seaward against each headland. At this stage some normal beach circulation away from the headlands is still occurring. When headlands control the circulation within the entire embayment, cellular circulation occurs. This results in the formation of a dominant longshore flow and strong seaward flowing megarips occurring at one of both ends of the embayment (Short, 1996). Gallop et al. (2009) found that large rip currents on embayed beaches can persist for a surprisingly long time depending on the scale of the surf zone relative to the intensity and duration of the storm event. Silva et al. (2010) show numerically that a semi-elliptic shaped headland-enclosed beach can drive a persistent rip current exactly at the centre of the beach, and provide photographic evidence of shoreline morphology adjusting to this rip pattern. Contrastingly, Castelle and Coco (2012) use numerical simulations of morphological change of an embayed beach to show the persistent development of rip channels at the headland and reveal that their presence can propagate alongshore across the whole embayment. McCarroll et al. (2016) developed an asymmetrical headland protected beach state conceptual model (Figure 1.10) which shows the importance of varying headland morphologies in the intensification of the alongshore gradients in surfzone width and beach state.

![Figure 1.10: Embayed beach state conceptual model of Short and Masselink (1999) for symmetrical headland protection (top row) and new conceptual model developed McCarroll et al. (2016) for asymmetrical headland protection, based on observation of Bondi beach, Australia (bottom row). The left panel represent pre-storm conditions, the middle panels depict storm morphodynamics and the right panel idicate the post storm morphology. (Source: McCarroll et al. 2016).](image-url)
1.7  Geological constraints

Every beach exists in a specific geological framework and it is that framework which determines the boundaries within which the beach forms and fluctuates as it is worked upon by dynamic forces (Jackson and Cooper, 2009). These dynamic forces are themselves mediated by certain geological parameters including rock outcrops, which controls bed roughness, influence wave breaking and moderate water flow through the beach.

In recent years, the role of geological factors as a control on beach morphodynamic state has been highlighted at the short timescale (Thieler et al., 2001; McNish, 2004; Jackson et al., 2005) and longer timescale (Cooper and Pilkey, 2004). Geological factors appear to constrain beach behaviour and morphodynamic state through (a) the presence of a geological framework that inhibits the ability of a beach to fluctuate laterally and/or vertically, (b) the reduction of the available space for the accumulation of sand leading to insufficient sediment volumes for the beach to change from one beach morphological state to another, (c) by modifying the flow of material and energy through the beach system (Jackson and Cooper, 2009). Loureiro et al. (2012) used empirical orthogonal function analysis to determine the evolution of coastal areas controlled by headlands, rocky outcrops or underlying bedrock. The authors used datasets of morphological change from six embayed beaches from south-western Portugal. The beaches consisted of two groups of three closely located embayments, with beaches within each group exposed to identical offshore forcing. However due to the presence of rocky outcrops or underlying rocks, each beach experienced different morphological changes. Their study showed that natural geological boundaries constrain the morphological behaviour of embayed beaches, determining diverse spatial and temporal variability patterns. Regional conformity in morphodynamic behaviour that might be expected in sites forced by comparable physical process regimes is inhibited by these geological controls.

1.7.1  Lateral constraints

Despite their common occurrence (Short and Masselink, 1999), relatively few observations demonstrate the importance of headlands in controlling beach morphology. Embayed beaches are known to rotate in response to changes in the alongshore energy flux (Short et al., 2000; Klein et al., 2002; Ranasinghe et al., 2004a; Ojeda and Guillén, 2008; Bryan et al., 2009; Loureiro et al., 2012) or cross-shore sediment exchange processes (Harley et al., 2011).
The phenomenon of beach rotation has been observed on a number of beaches (Bird, 1993; Shyuer-Ming and Komar, 1994; Short et al., 1995). In most cases it is attributed to a seasonal or periodic shift in wave climate, in particular wave direction. Waves arriving from one direction induce longshore sediment transport which eventually accumulates against the downdrift headland. A shift in wave approach that drives sediment transport in the opposite direction leads to a reversal in the foci of erosion and deposition, hence a rotation in planform. The rotation may be seasonal (Bird, 1993; Shyuer-Ming and Komar, 1994) or over longer periods (Short et al., 1995). Net shoreline accretion and erosion may occur at either end, with no net change in the sediment budget, and net erosion may occur during periods of relatively low wave activity, when adjoining beaches are well accreted.

Small shifts in wave direction may induce large shoreline movements, particularly in long embayments (Gordon, 1987). Beach rotation can also be a mechanism for releasing pulses of sand around headlands, known as headland bypassing. Headlands can act as natural obstacles to longshore transport and result in a downdrift accumulation of sediment. If the embayed beach experiences both longshore drift and beach rotation, a mechanism there exists to periodically enable sediment to escape around the headland (Short and Masselink, 1999). A schematic representation of beach rotation and sediment headland bypassing is shown in Figure 1.11.

Figure 1.11: Schematic diagram of shoreline rotation. The initial position (solid black-line) rotates to the new one (dashed black line) under steady wave conditions resulting in an overall shoreline movement $R$ at the edge of the domain (Source: Turki et al, 2013).
In an analysis of embayed beach rotation based on over 30 years of beach profile surveys at Collaroy-Narrabeen Beach, Australia, Harley et al. (2011) found that the beach rotation signal is dominated by sediment exchange in the cross-shore rather than the alongshore direction, thus suggesting a more subtle conceptual model of beach rotation. Beach rotation is usually seasonal but periodic shifts related to wave climate have also been reported (Komar et al., 2000; Ranasinghe et al., 2004). Beach rotation can also occur as a fast response to individual storms possibly coupled to human activities such as the transfer of sand from one part to another part of the beach (Ojeda and Guillen, 2008).

Beach rotation has also been associated with changing climatic conditions, for example, in a detailed study of Narrabeen Beach, New South Wales, Australia, Ranasinghe et al. (2004), showed that variations during strong positive/negative Southern Oscillation Index phases (El Niño/La Niña) influenced beach rotation. Other variables also influence rotation, as shown by Anthony et al. (2002) at Montjoly Beach, Cayenne, French Guiana, where patterns of nearshore mud bank migration induced rotation. Similarly, Thomas et al. (2011b) linked beach diminution and migration, associated with spit collapse, to multi-century shoreline rotation within the area of their study.

Variations in the direction of approaching waves may not necessarily lead to beach rotation. In a study on the morphodynamic behavior and beach rotation processes of two headland beaches in Brazil, Vintém et al. (2004) found that different patterns of sediment remobilization occurred on beaches classified as in a reflective and intermediate state. In the reflective beach, beach rotation processes were induced directly by change in the predominant direction of incident waves, whereas in the intermediate beach, sedimentation and erosion patterns were distributed across the beach profile leading to large sand quantities being removed in dynamic submerged bars. Thus morphological variations on the subaerial section of the intermediate beach were not as evident.

Previous studies of beach rotation phenomena as developed by Short et al. (2000), detected a pivotal point with minimal variation, about which the beach rotates. In a study of the short-term beach rotation processes along the coast of Santa Catarina, Brazil, (Klein, et al., 2002) did not detect a pivotal point, but rather a transitional zone. Cycles of erosion and deposition in different sections of the beach were detected during the same study period, suggesting complex behaviour of headland bay beaches.
1.7.2 Vertical constraints

The lowering of a beach following a storm event is a commonly reported phenomenon as the beach assumes a lower gradient and thus dissipates excess energy across a wider surf zone (Komar, 1998). If this beach readjustment encounters a solid substrate before this depth is reached it would be unable to drop to a level that achieved equilibrium with storm dynamics and would therefore adjust itself in different ways through other morphological adjustments or the generation of secondary fluid movements (Komar, 1998). The presence of shallow, buried bedrock below the beach surface will also potentially exert an influence on beach dynamics by altering the alongshore and cross-shore sediment transport patterns and budgets, and provide an impermeable surface that prevents infiltration of swash (thus enhancing backwash) whilst rendering the beach more prone to saturation and seaward transport of sediment (Cooper, 1991; Rey et al., 2004).

Few studies have, so far, explored the effects of geological control in beach systems underlain by rocks, often classified as perched beaches (Gallop el al., 2011b). Recent studies on the effects of bedrock on beach swash processes have highlighted the significance of porous bed dynamics, and the interactions between waves, the beach and groundwater (Horn, 2006; Masselink and Puleo, 2006). Bedrock presence may affect swash zone dynamics, by (a) affecting the interactions between sea and groundwater; (b) influencing the flow and pressure distribution into the sediment body, as well as the infiltration and exfiltration equilibrium, by limiting the downward water flow through the bed; and (c) accelerating water saturation of the porous sediment body above the beachrocks, and, thus, potentially reducing the beach sediment threshold of motion (Butt et al., 2001). Vousdoukas et al. (2009) studied the dynamics of a microtidal beach in the context of beachrock outcrops in Vatera Beach, Greece, through the collection and analysis of morphological and sedimentary data and hydrodynamic and morphodynamic modelling. The results from the morphodynamic modelling demonstrate that beachrock can significantly affect beach profile response to incoming waves. The model confirmed the formation of significant scour steps, particularly under energetic wave conditions. Scour steps usually appear at the offshore margin of the beachrock, due to the discontinuity in the bed sediment supply as shown in Figure 1.12. Offshore of the step the bathymetry is normally smooth until the closure depth (Vousdoukas et al, 2009). Moreover, the model revealed that the presence of beachrock in beaches leads to coarser sediments and steeper profiles and thus makes the beach more susceptible to intensive morphological changes (Vousdoukas et al., 2009).
Although in some cases beachrock has been reported to act as natural coastal defences (e.g. Dickinson, 1999), offshore beach sediment loss and, thus, beach erosion, is likely to be enhanced in beaches with beachrock. Material loss during extreme events is unlikely to be rapidly replaced by littoral transport where the onshore cross-shore supply is restricted by scour steps that can form even during low to moderate energy conditions. Vousdoukas et al. (2009) observed the following morphological evolutionary sequence for embayed beaches with bedrock constraints: (i) gradual erosion of the sediments veneering the initially buried bedrocks; (ii) bedrock outcropping and (iii) significant bathymetric changes offshore of the areas where the bedrock outcrops.

Many beach morphodynamic models reflect only unconstrained conditions and therefore the application of current models to geologically constrained beaches is inappropriate. Jackson and Cooper (2009) proposed a conceptual model of beach mobility based on qualitative observations along the Outer Ards (Northern Ireland) beach systems (Figure 1.13). The authors purported that a multi-stage scenario of beaches exists within this coastal system and identified 3 types:

1) Semi-constrained – beaches operating in a geologically influenced profile where the underlying volume is operating under a more finite regime and as a result, beach mobility is enhanced,

2) Highly constrained – beaches that have a highly significant underlying geological control present.
3) Unconstrained – beaches that at no stage does the sedimentary profile envelope intersect or interact with the basement geology,

![Diagram showing conceptual cross-shore profiles of geologically constrained beaches existing above the geological framework (P1), within the geological framework (P2) and an unconstrained beach in an adjacent locality (P3). As a beach surface (P1) is lowered (P2) the role of the underlying geology become progressively more important as it compartmentalizes the cross shore sediment body and alter the wave sediment interactions (Source: Jackson and Cooper, 2009).](image)

However, quantitative information about the thickness of sediment veneers below which vertical geological control becomes unimportant is still very much undetermined (Jackson and Cooper, 2009), and field data describing vertical boundary effects is still scarce (Gallop et al., 2011a).

### 1.8 Stability of headland-bay beaches

Embayed beaches are generally considered to be one of the most stable littoral forms (Schiaffino, et al., 2013). The stability of an embayed-bay is determined by the balance between the incoming and outgoing sediment in the beach (Hsu et al. 2008). If the embayment is in equilibrium with the hydrodynamic conditions, refraction is such that no net longshore transport occurs due to obliquely incident waves, because all waves break normal to the beach along the entire embayment. When the hydrodynamic conditions within the nearshore zone change, an imbalance is created in the forces acting on the nearshore zone, causing longshore currents which flow away from areas of maximum wave height to regions of minimum wave energy. Outgoing currents can be expected at the extremities of the embayment (Short, 1999). This imbalance causes transport gradients which lead to cross shore sediment transport which drives changes to the beach profile and beach planform. In view of this, a number of concepts on what constitutes a stable beach in equilibrium both in profile (Dean, 1991; Larson and Kraus,
1989) and planform (Hsu and Evans, 1989), have been put forward in the last few decades.

The equilibrium beach profile concept has been defined as the final form that the beach profile adopts under constant wave conditions and to a given grain size (Larson, 1991). Many of the existing equilibrium beach profile models are based on the dissipation phenomenon (Bodge, 1992; Bruun, 1954; Dean, 1977; Munoz-Perez et al., 1999). Inman et al. (1993) first proposed an equilibrium beach profile model assuming that the incident wave energy is dissipated by waves breaking inside the surf zone and by bottom friction outside. These authors established a two-section equilibrium profile in which the surf and shoaling zones can be differentiated. Several field and laboratory studies have already shown that the beach does not dissipate the entire incident energy. Part of it is reflected by the profile to deeper waters (Mandsard and Funke, 1980; Miche, 1951; Tatavarti et al., 1988). Elgar et al. (1994) estimated from field data that the reflected energy in a beach can be as much as 18% of the total incident energy.

Beaches that are in equilibrium in profile with the nearshore processes generally exhibit a number of characteristics (Dean, 1991), which include:

a) They tend to concave upwards
b) Smaller and larger sediment diameters are associated with milder and steeper slopes respectively
c) The sediments tend to be sorted with the coarse and finer sediments residing in the shallower and deeper water respectively
d) The slopes of the beach tend to be flatten with an increase in wave steepness

Since the 1940s, geographers and coastal engineers have attempted to derive simple empirical expressions, as well as complicated mathematical and numerical models, to fit the curved planform of embayed beaches and vary their stability. Several empirical models and formulae for static equilibrium planform have been proposed, including Yasso (1965), Silvester (1970a,b), Hsu et al. (1987, 1989b), Hsu and Evans (1989), and Tan and Chiew (1994). Among these approaches, an empirical bay shape equation, termed the ‘parabolic bay shape equation’ (Hsu & Evans, 1989) has emerged as the most acceptable expression for practical applications to headland bay beaches in static equilibrium that can maintain a bay periphery without sediment input (Gonzalez & Medina, 2001) (Gonzalez & Medina, 2002). These models are useful in testing the bay stability, but they are subject to limitations in accounting for the general similarity of the static equilibrium planform of crenulate-shaped bays.
For embayed beaches produced by oblique persistent swells, four broad equilibrium categories have been proposed by Hsu et al. (2008):

a) dynamic equilibrium – occurs when there is continual sediment supply and balance between sediment input and output;
b) static equilibrium – occurs when there is almost negligible sediment input and output;
c) unstable – occurs when the beach in an eroding state because of the reduction in sediment supply; and
d) natural beach reshaping – occurs when the repositioning or extension of a headland or coastal structure updrift of the embayment leads to erosion accompanied by accretion.

These stability classes are time-dependent and any considerations of beach stability have to be time-dependent. It should be kept in mind that there is only one static bay shape for an embayed beach with a fixed wave diffraction point related to a wave crest line of the persistent swell at one point in time. Many existing embayed beaches that have remained in dynamic equilibrium for decades could be mistaken as in static equilibrium, or stable in general terms. For a headland bay beach in dynamic equilibrium, sediment supply from updrift and/or a source within the embayment is required to maintain its stability; otherwise the shoreline would retreat as supply reduces (Hsu et al., 2010). If sediment supply is stopped or reduced, either by the damming of a river or the building or a harbor updrift, a bay beach would gradually indent landward until static equilibrium is reached. This is the stage at which the embayed beach would not be affected by any further erosion as a result of the reduced sediment supply but only be subjected to the onslaught of storm waves (Hsu et al, 2010).

1.9 Sedimentary and sedimentological factors

Beaches are composed of anything that can be transported by waves (Davies and Fitzgerald, 2003). Most beaches comprise sediment derived from the erosion of terrestrial rock, although carbonate beaches (composed of shell or coral fragments) are also common in places. The composition of beach sediments reflects the nature of the source material and can often be used to assess relative contributions and transport paths from the sources to the beaches. Waves and nearshore currents continuously rework the accumulated beach sediment, rounding the particles and sorting them by
size, shape and density. Sediment transport is important for the formation of beach features since the beach takes on a form that reflects the totality of water and sediment movements (Komar, 1998).

Sediments in the littoral zone may be composed of any material that is available in significant quantities and is of a suitable grain size to remain on the beach. The composition therefore closely reflects the various sources and their relative importance. Headland bay beaches with limited source areas and limited sediment exchange may be dominated by exotic minerals within their sediments (Komar, 1998). Shells and shell fragments are important in many beach sediments, especially those in tropical regions and warm seas where biological productivity is high and chemical weathering of the terrestrial rocks tends to be intense. Moberly et al. (1965) found that, for the Hawaiian Islands as a whole, foraminifera form the chief carbonate fraction in most beaches, followed by molluscs, red algae and echinoid fragments. In most cases the remains of these organisms are broken into small fragments and worn smooth by wave action into sand particles of white calcium carbonate. Shell material may also be abundant in beaches at high latitudes because the supply of terrigenous sand is either very low or of the wrong grain size for the particular beach as determined by the wave energy (Komar, 1998). The source of sediment for pocket beaches along the Mediterranean is mainly from rocky headlands bounding each beach. Sand is thought to remain in these sediment tight systems which have little input or output of sediment (Pethick, 1984), other than from their confining headlands.

Sediment grain size is one of the most important features for beach morphodynamics and hydrodynamic behaviour. Sediment hydraulic characteristics depend on grain size and differences in sediment permeability (higher on gravel than on sand) (Horn & Walton, 2007) influence longshore and cross-shore sediment transport. Analysis of sediment size and characteristics can reveal many aspects of the dynamics of a particular beach. The relationship between the rapidity of beach changes and the size of the beach material has been identified by Shepard in studies on Californian beaches in the 1950s. The hypothesis put forward by Shepard (1950) is that for coarse sand beaches, beach changes are greater and more rapid than for fine sandy beaches. The coarser the beach material the greater there will be fluctuations in beach slope (King, 1959).

That beach slope is a direct function of grain size and the degree of wave exposure was demonstrated graphically by Flemming & Fricke (1983). Figure 1.14 illustrates that this empirical relationship is narrowly constrained, both for dissipative (exposed) and reflective (sheltered) conditions. For intermediate beach states, the points defining the
relationship between beach slope and mean grain size (and vice versa) occupy positions between the reflective and dissipative domains (Flemming, 2011). Sediment grain size and tides often introduce complication to the above model and fine sand beaches often have reduced slopes and dissipative conditions, especially at low tide. Coarser sediment beaches with steep slopes often remain in reflective mode, as they require inherently higher wave energies to achieve dissipative states (Flemming, 2011).

![Figure 1.14: The relationship between wave energy, grain size and beach slope (Source: Flemming and Fricke, 1983)](image)

Bagnold (1940) states that the beach angle depends only on the size of the grains composing the beach, and is independent of the wave height (cited in King, 1959). Studies carried out in Italy by Dal Cin (1969) determined whether erosion and accretion of beaches could be calculated by using grain size parameters. The conclusions showed that beaches undergoing net erosion tend to have less fine sediment because this was being transported offshore by currents. The same beaches were also revealed to have a better sorting of sediment since there was selective sediment transport taking place. Araya and Vergara (1986) state that the process of beach accretion is normally associated with a decreased mean particle size and a flat beach slope, whilst erosion is associated with a higher mean particle size and a steep beach slope. Indeed, hydrodynamic parameters (especially wave height) driven by meteorological factors
(especially wind speed and direction) determine sediment size distribution and beach slope gradient of sandy beaches.

The sorting of sediments along a beach profile produces cross-shore variations in particle characteristics that are readily apparent and accordingly have attracted a number of studies. The coarseness of sediment reflects the bottom topography and the local intensity of turbulence and wave-energy dissipation. The largest sediment particles generally are located in the zone of the most intense wave breaking, with a decrease in grain sizes both toward deeper water and shoreward across the surf and swash zones (Komar, 1998). A conceptual model of cross-shore sediment size changes in an embayment is presented in Figure 1.15.

![Figure 1.15: Conceptual model of cross-shore sediment size changes in an embayment (Source: Bowman et al. 2014).](image)

Another form of sediment gradation is that known as lateral sorting, which takes place parallel to the shore. This is related to the distribution of energy on the beach and the type of water movement (King, 1961). Observations of the sediment at Chesil Beach, Dorset showed that the variations in sediment size along the shore are related to a lateral increase in wave energy, which was more pronounced on the exposed coast at Portland Bill (Bird, 1984). Thus, it appears that longshore variations in grain sizes can be produced in at least four ways: (1) parallel variations in the wave energy; (2) selective rates of transport, with the finer grains generally outdistancing the coarser; (3) selective removal of the finer grain sizes from the beach (carried onshore by winds or offshore by waves) leaving the remaining beach sediment coarser in median size; (4) the interplay of waves reaching the beach from different directions with contrasting energy levels. Many examples of longshore variation in grain sizes likely result from combinations of these mechanisms (Komar, 1998).
The behaviour of the beach is closely dependent on the amount of available sediment. Since beaches receive material from various sources, they would grow continuously except for the equilibrium of supply and loss from onshore/offshore and longshore transport. This movement, together with sources of sediment input, loss and storage make up the sediment budget of a beach system (Pinet, 2009). If the sediment budget of a beach is balanced, the beach will be relatively stable, whereas if there is an oversupply or deficit of sediment either accretion or erosion will occur (Leont'yev, 2008). The idea that morphological change is dependent on the amount of available sediment is particularly important in embayed beaches, where sediment exchange is often limited. The sediment budget concept provides an effective basis for representing the key components of sediment exchange within an embayed beach.

The factors contributing to the increase or decrease of the available sediment within an embayed beach are schematised in Figure 1.16.

![Figure 1.16: Conceptual model of the sediment budget of an embayed beach (KPAL, 2009)]

The headlands that bound pocket beaches may act as barriers to longshore sediment transfers between adjacent beaches (Short & Masselink., 1999; Storlazzi & Field, 2000; Dolique & Anthony, 2005; Bowman et al., 2009; Dehoucke et al., 2009). Longshore
sediment fluxes may also be limited as a result of significant refraction as these beaches commonly absorb incident wave energy from a limited directional window (Bowman, et al., 2009). Individual pocket beaches may vary, therefore, in terms of their sediment dynamics, from typical swash-dominated to drift dominated configurations; these configurations denoting, respectively, propensity for the absence and dominance of longshore drift (Davies, 1980).

### 1.10 Conclusion

Although embayed beaches are very common worldwide and to date there is a considerable volume of literature on these coastal environments, few studies have focused on investigating the spatio-temporal variation of embayed beach morphology in a micro-tidal setting such as the Mediterranean Sea. Most of the studies on headland bay beaches deal with macro-tidal environments such as Australia (McCarroll et al. 2016), California (Scholar et al. 1997) and South America (Silveira et al. 2010), which experience a different hydrodynamic regime to the micro tidal hydrodynamic characteristic of embayed beaches in the Mediterranean Sea. Moreover the limited amount of studies that have been carried out on the headland bay beaches in the Mediterranean sea are mostly limited to the Western Mediterranean such as the work carried by Basterretxea et al. (2004) in Mallorca, Spain and that by Bowman et al. (2014) on the island of Elba, Italy. To date, studies carried out on Maltese embayed beaches either did not span the amount of time necessary to identify the specific processes acting on such beaches or did not take into consideration the overarching importance of the geological setting on embayed beach morphology.
2 The embayed beach setting of the Maltese islands

2.1 Geographic setting

The Maltese archipelago consists of a small group of low-lying islands that are located in the central Mediterranean Sea, between the island of Sicily and the North African coast. The archipelago consists of three main islands: Malta, Gozo and Comino and a number of small islets. The islands have a total land area of 316 km$^2$ with Malta being the largest island in the archipelago with a total land area of 245 km$^2$. The length of the whole archipelago is 45km. The islands lie approximately 96 km south of Sicily and about 290km north from the Northern coast of Africa (Figure 2.1). Much of the large area of sea surrounding the Maltese islands is shallow in depth in comparison to other parts of the Mediterranean and the islands are situated on a shallow shelf called the Pelagian Platform. The topography of the continental shelf in this area is characterised by a plateau in the middle part, with an average depth of 150m (Drago et al; 2010).

![Figure 2.1: Location of the Maltese Islands within the Mediterranean Sea (Source: Left Panel – Background imagery adapted from Google Earth Imagery; Right Panel – Author)](image)

The climate of the Maltese islands is typically Mediterranean with mild, wet winters and hot, dry summers. The average annual precipitation is 553 mm (NSO, 2011) with a standard deviation of 156mm, meaning that rainfall is highly variable from year to year. This leads to some years being excessively wet, the highest annual precipitation ever recorded was 874 mm, while others are extremely dry, the lowest annual precipitation ever recorded was 274 mm (NSO, 2011). The seasonal distribution of rainfall defines a wet period (October to February) and a dry period (March to September) as shown in Figure 2.2. The islands are windy, only some 8% of the days of the year are calm.
The Maltese islands are entirely composed of Tertiary limestone with subsidiary marls and clays. Quaternary deposits, mostly Pleistocene in age, are limited to few localities and the form of cliff breccias, caves and valley loams, sands and gravels. The geological formations of the islands are very distinctive lithologically and this is reflected in the topography and vegetation (House et al., 1961).

The limestones originated mainly by the accumulation of biogenic carbonate sands and muds on the floor of a shallow shelf sea. Following compaction and cementation, the rocks were uplifted and faulted around 10 million years ago due to collision of the African plate with the Eurasian plate. The pattern of faulting and uplift/ down-throw initially created a series of horst and graben structures (up-thrown blocks and downthrown basins). Subsequently, differential erosion by sub-aerial and marine processes has given rise to a landscape of varied relief and a rock-dominated coast with cliffed headlands and intervening narrow embayments (Guilcher & Paskoff, 1975; Paskoff & Sanlaville, 1978; Paskoff, 1985).

2.2 Geology and structural framework

The Maltese archipelago is located in the east of the Pelagian Sea, on a rise that separates the eastern and western Mediterranean basins. The rise, known as the Hyblean Plateau, is an extreme southerly continuation of the Apulian Plateau and an advanced salient of the African plate, resembling a continental borderland where it abuts the Calabrian arc (Stanley and Wezel, 1985). A morphostructural boundary is formed to the east by the Malta Escarpment and its continuation southwards, the
Medina and Misratha Escarpments. These are divided into upper and lower steps, separated by a marginal plateau. The maximum relief of this submarine rift system is 2.5 km, and developed from the deformation and rifting of a thick sedimentary platform, which was previously eroded and planed during the late Miocene epoch (Stanley, 1972). These escarpments are dissected by large submarine valleys, which are controlled by faulting, such as the Melita, Misratha and Tripolitania canyons (Embleton, 1984). The fracture pattern of the Maltese islands has been created by tectonic processes governed by the relative motions of the European and African plates. Two rift systems of different ages and trends dominate the structural setting of the Maltese Islands. As shown in Figure 2.3 (A), a horst and graben structure has been developing on western Malta, Comino and eastern Gozo resulting from the older rift generation that traverses the Islands striking at about 50º to 70º. This structure constitutes the oldest tectonic movements observable on the Maltese Islands. The second-generation rift, associated with the Pantelleria Rift, strikes Malta at about 120º and Gozo between 80º and 90º (Illies, 1981). Rifting mainly originated during the Late Miocene and Early Pliocene, with continued activity in parts up to the present (Illies, 1981).

The fracture pattern across the Maltese islands is dominated by two intersecting fault systems that alternate in tectonic activity. A NE-SW to ENE-WSW trending fault, the Great Fault, traverses the Islands and is crossed by a NW-SE trending fault, the Maghlaq Fault with a vertical displacement of at least 240 m to the SW (Figure 2.3 (B)). This vertical displacement of the islands in a SW direction is a key factor in the progressive evolution of the coastline and the resulting geomorphological features present at the coast today. In general the faults, all vertical or sub-vertical, are part of a horst and graben system of relatively small vertical displacement. The major faults all influence the entire Oligo-Miocene succession and there is considerable evidence that movement has been continuous since Miocene times. Over time, tectonic activity has played a dominant role in the development of the coastal geomorphology of the Maltese archipelago. The formations of the Maltese Islands are composed of fractured Oligo-Miocene carbonates of marine origin occasionally weathered and eroded by karstic action. Pliocene deposits are completely absent; whilst some sporadic Quaternary deposits occur in limited areas, mostly consisting of valley scree, raised beach deposits, sands and gravels of Pleistocene age.
Figure 2.3: (A) Bathymetric map of the central Mediterranean Sea, Pelagian Platform, showing the location of the Maltese islands and the principal morpho-structural features (isobaths at 500m intervals (Smith and Sandwell, 1997; Catalino et al., 2008). The coastline during the Last Glacial Maximum (LGM) is denoted by a solid orange line. (B) Map of the main terrestrial geological formations and fault systems of the Maltese Islands (Government of Malta, 1993) and an isobaths map of the Maltese coastal waters.
The geological sequence of the islands is such that the geological formations occur in simple succession (Figure 2.5). Starting from the oldest in chronological order, the successions consist of:

a) The Lower Coralline Limestone (LCL) formation - a thick section of algal foraminiferal limestone divided into four distinct members (Pedley et al. 1978). The Lower Coralline is extremely heterogenous with frequent lateral passages from patch reef deposits to lagoonal and forereef facies such as the lateral transitions from the coarse grained biocalcarenites of the Xlendi Member to the finer compact yellow limestones of the Maghlaq member at the base of the Lower Coralline Limestone.

b) The Globigerina Limestone (GL) formation overlies the LCL formation and is predominantly composed of pelagic carbonate limestones, with abundant planktonic forams. It outcrops over large areas of central and southern Malta and Gozo and varies in thickness from 23 m near Fort Chambray (Gozo) to 207 m around Marsaxlokk in the south east of Malta (Figure 2.4). On the basis of two laterally persistent phosphorite conglomerate hardgrounds, the Globigerina formation is subdivided into three members: the Lower, Middle and Upper Globigerina Limestone.

Figure 2.4: Locations in the Maltese islands which are important in terms of geology and geomorphology.
c) The Blue Clay (BC) formation consists of blue/grey pelagic marls interbedded with thick paler bands with a higher carbonate content (less than 30%) than the darker clay-rich bands. Kaolinite is the main clay mineral present within the formation, followed by chlorite, palygorskite, illite and smectite. The maximum thickness of the Blue Clay is approximately 75 m, recorded at Xaghra (northern Gozo) and on the western coast of Malta (North of Fomm ir-Rih Bay) as shown in Figure 2.4.

Figure 2.5: Lithostratigraphic diagram of the succession of the Maltese islands (Turi et al., 1990). The thickness of the formation is proportional to the maximum exposed thickness (Pedley et al., 1976).
d) The Upper Coralline Limestone (UCL) formation is a shallow-water carbonate platform sequence, exhibiting complex facies deposited in a very shallow marine environment from shallow subtidal to intertidal and supratidal. It reaches a maximum thickness of 104 m at Comino and Mellieha. Four members of the Upper Coralline Limestone formation have been defined, all characterised by several lithological variations, laterally and vertically. These are: the Ghajn Melel Member (the oldest), Mtarfa Member, Tal-Pitkal Member and Gebel Imbark Member (the youngest).

e) Quaternary deposits, mostly Pleistocene in age, are mainly concentrated along the coastal sectors of the island and are normally found as valley loams, breccias or fossiliferous deposits (Trenchmann, 1938) or as thin near-surface deposits, such as red soils and colluvial sediments (Pedley, 2011).

The stratified lithology of the Maltese islands often leads to the presence of two or more rock formations being exposed at the coast which given the differential erosion rates of the formations, often leads to formation of distinct geomorphologies.

The structure and lithology of the Maltese archipelago have also shaped the landscape through a number of geomorphological processes, the most noticeable from a coastal perspective being fluvial processes, which formed ephemeral streams which discharge within embayments, and the formation of cliffs, low rocky coastlines and shore platforms.

2.3 The Maltese coastline

The complex geological history, tectonic activity and diverse lithology has resulted in a coastline which is remarkably varied given the small size of the Maltese archipelago. All the major rock formations found in Malta are exposed at different locations along the coastline. On the western coast of Malta the entire geological succession of carbonate sedimentary formations is exposed in cliffs up to 253 m high. Further north, on the island of Malta and Gozo, there are at least five completely or partially drowned grabens, which give rise to a series of embayments, whilst the east coast of Malta exhibits morphology of submergence. The western cliffs on the island of Malta are flanked by deeply incised valleys, which have cut back into the upland areas. The southwest edge has been least affected by such action and the regular line of cliffs is broken only in one place, where the valley complex of Imtahleb forms a deep embayment.
The structural setting and lithology of the island give rise to a number of coastal features along the coastline of the Maltese archipelago, which features can be broadly divided into five categories. These include cliffs, rdum areas, low rocky coastline, semi-circular coves and drowned valleys. Beaches, consisting of sand, gravel or pebble deposits are not a dominant coastal feature within the Maltese coastal geomorphological landscape and only make up around 2.4% of the total coastline (Axiak et al., 1999). The presence and nature of these beaches is very much determined by the structural setting, lithological succession and coastal geomorphology of the island. Figure 2.4 illustrates the predominant coastal features in the Maltese archipelago, which are described in detail below.

2.3.1 Cliffs

Steep cliffs, more than 50 m high and in some place more than 200 m, represent half the length of the Maltese coastline (Guilcher and Paskoff, 1975; Paskoff and Sanlaville, 1978). They characterise southern and southwest Malta, eastern Comino, and most of the coast of Gozo (Ellenberg, 1983). Vertical plunging cliffs are generally cut in the Lower Coralline Limestone and lack shore platforms at their toe. These cliffs are vertical, rectilinear and probably of tectonic origin (Paskoff and Sanlaville, 1978).

Where cliffs are cut in the Globigerina Limestone they are fronted, in most cases, by shore platforms produced by mechanical action of waves, mainly through hydraulic pressure that dislodge and remove blocks from stratified and joint rocks. In the southern part of Malta, between Marsaxlokk and St. Thomas Bay, the Globigerina Limestone features a perfectly vertical cliff that reaches a height of more than 50 m (shown in Figure 2.6). The globigerina limestone in this region is quite uniform which helps to maintain the steepness of the cliff, and rather soft, allowing marine erosion to work efficiently (Paskoff and Sanlaville, 1978). Coastal areas dominated by cliffs preclude the formation of beaches; continuous clifflines and low levels of indentation here provide little accommodation space for the deposition and accumulation of beach deposits, and the nearshore bathymetry transitions quickly to significant depths (in excess of 20 m).
Figure 2.6: (Upper panel) Map of the dominant geology outcropping at the coastline which given the stratigraphic sequence of Malta’s rock formations can differ from the formation present at the land surface. (Lower panel) Map of the Maltese islands showing the dominant coastal landforms and the location of the main beaches. Coastal areas not included within this map have experienced considerable modifications to the natural setting as a result of human intervention.

2.3.2 Rdum Areas

The rdum areas constitute a type of marine cliff related to a specific geological structure that is prone to mass movements and characterised by extensive slope-failure deposits (Biolchi et al, 2016). The rdum areas occur where Blue Clay crops out at sea level and is overlaid with the massive strata of the Upper Coralline Limestone.
The Clay is easily eroded by wave action while rainwater percolates through fissures of the limestone into the underlying clay. This causes the Blue Clay to become plastic and unstable. Jointing and faulting in the Upper Coralline Limestone causes the latter to dislodge and eventually break up, falling on the clay. This type of landform is characterised by boulders screes at sea level and larger landslides at the foot of the scarp face. As a result, cliff retreat is probably slow, since a certain time is necessary for the removal of these boulders through erosion. The huge limestone blocks, which can easily have an approximate volume of 4 m$^3$ and an estimated weight of 10 tonnes (Furlani et al, 2011), are too large to be displaced by the sea and form a strong protective buttressing to the clayey part of the cliff. This type of cliff probably retreats much less quickly than Globigerina Limestone cliffs (Paskoff and Sanlaville, 1978). Rdum areas are especially found north of the Victoria Lines Fault and in eastern Gozo. These areas may give rise to very small pockets of sand (in the region of 2 to 5 m wide), which develop in between the large boulders buttressing the clayey slopes. More importantly rdum areas are very often crossed by faults and therefore present significant discontinuities along the coastline. In some cases, especially on the northwest coast of Malta (Figure 2.7) and the northeast coast of Gozo, rdum areas form important headlands within embayments, favouring the deposition of sediment and the formation of beaches. These areas also have large quantities of readily available boulders, which are exposed to wave attack and therefore this type of coastal feature is also important from a sediment production point of view.

Figure 2.7: The Qarraba promontory is one of the most important examples of the contribution of rdum areas to the development and formation of beaches in terms of both structure (providing shelter to adjacent beaches) and sediment provision (Source: Soldati et al, 2014).
2.3.3 Low rocky coastline

In northeast Malta and northern Gozo, cliffs are largely absent. Long tracts of low rocky, eroding coastlines (Paskoff, 1985) are found. Pools and lapis give an extremely irregular topography to shore platforms, particularly when they are cut in Coralline Limestone. Chemical and biological weathering are the prevailing processes in the formation of such coasts. Evidence of abrasion is absent. Structural controls account for the simultaneous development of several platforms at different levels up to more than 10 m above the sea. This is evident in northern Gozo, where the Globigerina Limestone crops out. On these exposed coasts, boulder deposits ranging from a few decimetres to metres (Furlani et al, 2011), in size have been dislodged by storm waves and lie scattered on the shore platform. The development of beaches in low rocky coastlines is practically absent as a result of the low level of indentation of such coastal landforms. For example in the straight section of low rocky coastline located in the south eastern part of Malta, from Rinella Fort up till Zonqor point, there is an absence of beaches (Figure 2.8). Within low rocky coastal landforms, beaches only form where these are intersected with another dominant coastal landform; drowned valleys. This is discussed in further detail below.

Figure 2.8: Map of the Maltese islands showing areas where low rocky coastlines and semi-circular coves are present.
2.3.4 Semi-circular coves

Semi-circular coves, such as Qawra, near Dwejra point, Dwejra Bay in western Gozo, the two creeks on the western coast of Malta, and Paradise Bay on the northwestern coast of Malta (Figure 2.9), represent a conspicuous feature of the Maltese coastline. They originate from widely distributed karstic landforms inundated by the sea (Paskoff, 1985). Post-Miocene solution of the carbonates has reached an advanced stage, producing well developed sinkholes and extensive subterranean cavern and gallery systems in all formations, but especially in the Coralline Limestone. Most often, marine deposits, in the form of sand, gravel or pebble deposits, are found in the inner portions of these coves. Beaches have progressively developed in some of these coves with the most prominent being Dweja and Paradise bay. However from a broader regional perspective, the presence of semi-circular coves is not the most important causative factor for the formation of beaches.

2.3.5 Drowned valleys

Malta and Gozo display inlets that are partially drowned valleys. The northeastern tilt of the island coupled with changes in sea level have led to the submergence of some drainage channels on the coast, giving rise to the formation of headlands, creeks and embayments. This is most evidently seen on the northeastern coast of Malta since the tilt of the islands is in that direction. Drowned valley systems can be broadly classified into three and include:

1) Wider and well developed inlets, such as Salina Bay in northeast Malta and Marsascala Bay in southeast Malta (Figure 2.9), and correspond to finger-shaped, broad and more open valleys, subaerially eroded in the soft Globigerina Limestone and subsequently submerged. Especially important is the system of drowned valleys that form the creeks of the two main harbours of Malta, Marsamxett Harbour and Grand Harbour, separated by the Valletta headland (Figure 2.9).

2) Narrow and well developed inlets (also known as calanques) such as those found in Wied ix-Zurrieq in southern Malta and Mgarr ix-Xini and Xlendi Bay in south and southwest Gozo (Figure 2.9). These inlets are narrow, shore-inundated valleys with steep sides cut in Lower Coralline Limestone.

3) Less developed inlets such as those found in the northern part of Malta, specifically in the area of Marfa ridge, where the most important examples of this kind of coastal formation are the beaches of Armier, Little Armier and Whiter Tower beach (Figure 2.9).
Within this context of a stratified lithological succession heavily affected by more general structural processes and the resulting coastal landforms, beaches have formed around the coastline of the Maltese islands in response to the interplay of these various factors. The occurrence of beaches in the Maltese archipelago is more dependent on the presence of embayments, which offer the shelter necessary for the deposition and accumulation of sediment, rather than the occurrence of a particular geological formation.

2.4 Embayed beaches of the Maltese Islands

In the last two decades, a number of local non-governmental organisations (NGOs) have focused their efforts on the protection of Malta’s beaches, which has led to the establishment of a number of coastal protected areas. Of particularly importance was the role played by the Gaia Foundation, not only for protecting a number of beaches in the Maltese islands, but also for commissioning a number of studies on these protected areas. The Gaia Foundation commissioned Malta University Services Ltd. in 1997 to undertake an assessment of the Ghajn Tuffieha area and to make specific recommendations regarding its management. In this regard a geo-environmental baseline survey was carried out providing a description of the geomorphology of the area, including the regional setting, structure and stratigraphy. The preliminary
conclusions of this baseline survey indicate that the absence of sand ridges on Ghajn Tuffieha bay exclude the possibility that the beachface is propagating seaward (MUS, 1997). Also, the narrow berm of the beach contrasts sharply with the abundant supply of sediment within the embayment, suggesting that retrogradation is most likely taking place and that shrinkage of the beach is likely to have reached its maximum level. This is also supported by the absence of aeolian dunes in the bay (MUS, 1997). This was followed by a similar study - a geo-environmental survey of the Ramla Bay in Gozo (Scerri, 2003) - also commissioned by the Gaia Foundation. The objective of this study was to provide a baseline reference for any future geo-environmental studies of the area (Scerri, 2003).

One of the drivers behind the need to achieve baseline understanding of these beaches is due to the fact that Maltese islands are a popular tourist destination, especially during the summer months, and sandy beaches are one of the major attractions. In 2004, the Malta Tourism Authority (MTA) undertook a beach replenishment project at St George’s Bay (St Julians, Malta) so as to increase the available beach space in one of the most frequented coastal areas. The associated beach replenishment project involved the deposition of coarse sediment (mean grain size of 2 mm) at the head of St George’s Bay to create an artificial beach. An extensive 2 year environmental monitoring programme was commissioned by the MTA to monitor the potential impacts of the replenishment works on the marine environment, the results of which were presented at the 2nd International Conference on the Management of Coastal Recreational Resources in 2006, Malta. The results of the beach profile and bathymetric surveys did not indicate any major transport of sediments to the sublittoral, following the beach replenishment works. However, in places, minor differences (of the order of 10-30 cm) in the thickness of sediment making up the beach and in the location of the shoreline, together with small differences in the bathymetry of the bay were noted (Borg et al., 2006). Microscopic examination of the sediments indicated that the sediment present in the bay is predominantly calcareous and had a high content of biogenic material, which included the skeletal remains of invertebrate fauna, namely sea urchins, molluscs, foraminifera, brachiopods and bryozoans (Borg et al., 2006). According to Borg et al. (2006) plant fibres originating from seagrass (Posidonia oceanica) and carbonaceous material that appeared to have an anthropogenic origin were also present within the sediment.

More recently, the MTA planned to undertake another beach replenishment program along a rocky stretch of coastline immediately south of Qawra Point, Salina Bay. Numerical modelling was undertaken by Firman et al. (2011) to support the Environmental Impact Studies required for the development permit for the creation of
this recreational beach. An assessment of the stable beach profile was undertaken to provide an indication of the overall footprint of the beach within the bay and hence it’s maximum seaward excursion. Cross-shore sediment transport models were used to determine the drawdown of the beach during severe storm conditions. The results of the modelling indicated that a drawdown of sediment onto the *Posidonia oceanica* meadows (an Annex I priority habitat under the European Union Habitats Directive) is likely. In this regard the development of a beach at this location was considered to place some risk to the nearshore sea-grass and possible methods to mitigate this were investigated (Firman et al., 2011).

In the 2009, a road network improvement program by the Ministry for Infrastructure and Communications (MITC) led to the commissioning of a study on Ghadira Beach to identify the impact of the existing road, which currently runs at the backend of the beach. As part of this study, a quantitative assessment of net changes in waterline position and beach width since 1957 was made by comparing vertical air photographs and maps with vertical air photographs from 2007. The results indicate that between 1957 and 2007 the water line moved landwards by 8-25 m at eight of the nine measurement points established during the assessment. Seaward movement of the beach only occurred at one location, on the northern part of the South Beach of Ghadira Bay, resulting from a redistribution of sand from the eastern end to the western end of the beach (KPAL, 2009). Over the same time period, the measured beach width increased at seven of the nine monitoring points (by 3-25 m). Only at the southeastern end of the Bay, near the Sea Bank Hotel, did the beach width decrease. The authors attribute this apparent paradox of landward movement of the water line, combined with widening of the beach, as a result of the landward realignment of the road in the 1980s. An analysis of the beach sediment indicated that the beach at Ghadira bay is largely made up of sand sized particles, with < 0.5% mud and < 12% gravel size material. The vast majority of the samples contained < 2% gravel, with most of the ‘gravel’ consisting of broken shell material (KPAL, 2009). Most of the samples collected were described as well sorted, very well sorted or moderately sorted; with only one sample being poorly sorted and no systematic onshore – offshore or alongshore trends were evident from the analysis of the beach sediment. Tests for acidic residue content were made by the authors on all the samples and the results indicated that the calcium carbonate content of the beach sediment ranged from 95.5% to 98% and the acid insoluble residue consisted of dark greyish mud (<63 μm in size) and fine grained organic matter. It is also important to note the range of particle types identified by the authors which included fragments of coralline limestone, modern marine algae, foraminifera, echinoderm spine fragments and shell debris. Most of the grains were subrounded to sub-angular and sub-equant in form. KPAL (2009) concluded that the lack of well-
rounded grains is indicative of a limited transport history and a relatively low wave energy environment.

Most recently, a granulometric analysis of the Maltese beach deposits was carried out to provide baseline information on how beach sediment size may relate geo-spatially and morphometrically (Deidun et al., 2013). The objective of the study was to construct a repository of median grain size values for the entire stretch of Maltese sediment coastline and to evaluate the degree of concordance between three different methods (sieving, stereo microscopy and through image processing) for the analysis of grain size. The authors found that in each method, a few coastal areas tended to exhibit a more dominant median grain size, when compared to other areas with the same amount of samples; mainly Mellieha Bay, Gozo Xatt l-Ahmar and Marsaxlokk Harbour area. At a finer scale, the three techniques matched in median grain size for the following six beaches: Malta l-Ahrax Campsite, Malta l-Ahrax Armier, Karlkara Beach and Ghajn Tuffieha. The three techniques also agreed that gravel sized sediment is not a common sediment size characteristic of Maltese beaches (Deidun et al., 2013). The authors concluded that the distribution of different median particle sizes on Maltese beaches does not reflect any geographic pattern, but is mainly dependent on the underlying geology, on the ongoing deposition and erosional processes and the degree of wave exposure and aspect of each beach. Also, by comparing the three different methods it was concluded that grain size analysis is very much dependent on the method used since spatial differences with respect to both the type of median sediment size and the pattern of median sediment size were noticed between the three methods (Deidun et al., 2013).

Embayed beaches are an important resource to the Maltese islands in several ways. Most tourist arrivals are concentrated in the summer months; for example in 2015, 56% of all tourist arrivals occurred in the period May-September (MTA, 2016). This greatly exacerbates human impact on local sandy beaches since some 58% of all beach visitors are nonlocals (MECO, 2000) and some 85% of tourists spend time on local beaches (Mangion, 2001). Tourism, directly and indirectly accounts for 25% of the country’s GDP (MOT, 2015), therefore any tourism related amenity, including local embayed beaches, are considered valuable economic assets. Beaches also protect the coastline against erosion by absorbing wave energy, the primary agent of coastal erosion. Therefore, an understanding of the basic sediment transport processes on pocket beaches and along their coastlines is necessary for sound and effective management of these coastal areas. Most of the Maltese coastline is composed of narrow rocky shelves with offshore rocks, sea stacks, rocky cliffs with sea caves or arches, or near vertical wave cut cliffs, and therefore sand beaches occupy only a
small portion of the coast. The absence of significant tides in the Mediterranean sea, and the generally weak coastal currents, restrict significant beach morphology changes to severe weather episodes when wave related processes are enhanced.

One of the most characteristic features of Maltese beaches is that, as in many Mediterranean coasts, the nearshore sandy seabed is colonized by the endemic reef-building seagrass *Posidonia oceanica* which is known to affect nearshore sediment dynamics (Marba, et al., 2002). Seagrass and other vegetation attenuate wave and current energy, therefore diminishing sediment resuspension, erosion and transport (Fonseca & Calahan, 1992; Worcester, 1995; Mendez et al., 1999). Seagrass also affect and enhance particle deposition (Gacia et al., 1999; Terrados & Duarte, 1999; Gacia & Duarte, 2001). All these processes, although not yet fully understood, have obvious implications on the morphology and variability of the adjacent beach on a seasonal time scale.

### 2.5 Research aims and objectives

Given the importance of embayed beaches, both from an environmental and socio-economic perspective, and the lack of studies focusing specifically on the spatio-temporal variation of embayed beach morphology in a micro-tidal setting such as the Mediterranean Sea, further research is required on the specific characteristics of embayed beaches within such environments. This is especially true in the Maltese islands where embayed beaches are an important natural resource, both due to their unique geomorphological setting and natural diversity, and also provide a major contribution to the island’s socio-economic development. The dearth of scientific literature on the subject within the area makes research on embayed beach morphology of the utmost importance. Through the years, a number of embayed beaches in Malta have suffered the effects of anthropogenic pressures, which led to the modification of the beach profile and planform and the gradual erosion of a number of beaches. This was mainly the result of the lack of knowledge on local coastal systems, which resulted in contentious planning decisions having adverse effects on the stability of these beaches.

A better understanding of these environmental systems will go a long way towards providing the scientific knowledge necessary to develop a sustainable approach to the management of this natural resource. This research will therefore investigate the beach morphology of a number of embayed beaches with the aim of identifying the spatio-
temporal characteristics of embayed beach morphology in the Maltese islands and address the existing knowledge gap on the subject.

The Maltese islands offer an interesting case study for the investigation of embayed bay beach morphology in the Central Mediterranean. Tectonic processes, the islands' geomorphological structure, climate and hydrodynamic processes combine to create a unique set of embayed beaches which although can seemingly occur to be unimportant at the global or regional scale are definitely significant and important at the local scale. Beach morphology and dynamics are a function of many physical factors including sand size, wave climate, tidal range and major topographic features, the variability of which, results in a large range of beach morphodynamic features. In order to elucidate further the morphodynamics of embayed beaches within Malta, the central aim will be achieved through research on the following specific objectives:

1. **Investigate the key physical characteristics of, and controls on, embayed beaches in the Malta**

   The significance of geometry in natural embayments has been at the centre of attention in only a few coastal studies and needs to be analysed in detail. Malta is a very appropriate site to 'explore' coastal embayments because of its numerous embayed beaches with various planform geometries and different levels of exposure to incident wave energy. The present study will therefore assess the significance of the geological and structural framework with respect to the formation and evolution of beaches as well as the importance of embayment morphometry on the development of beaches within an embayed beach setting.

2. **Examine the development and behaviour of embayed beach shorelines**

   Shoreline geometry and position are perhaps the most fundamental indicators that can inform the evaluation of spatio-temporal variations in coastal regions. Shoreline changes at different timescales will be analysed quantitatively to characterise the processes driving embayed beach erosion and accretion.

3. **Characterise the morphodynamics of headland-bay beaches within a micro-tidal setting**

   Simultaneous observation of beach morphology has not carried out in the past for the headland bay beaches in the Maltese islands. Hence this research will
examine the beach morphology and morphological change of a number of embayed beaches in order to determine how beach morphology varies in different physical contexts. The assessment of beach morphodynamics will also shed light on the importance of sediment exchange between adjacent beaches.

4. Analysis of the sedimentology within an embayed beach setting

Sediment textural characteristics for a number of embayed beaches will be used to describe and define sedimentary environments, sediment provenance, transport history, depositional conditions and also for differentiating wave energy environments. The understanding of the beach sedimentary environment is an important prerequisite for the understanding of the morphosedimentary associations within Malta’s embayed beach setting.

2.6 Choice of site selection

The Maltese archipelago provides a unique setting in terms of availability of embayed beaches given that all of its beaches occur in an embayed beach setting. Embayed beaches in the Maltese islands are rather small, mostly being less than 400m in length, when compared to other natural and embayed beaches in the Mediterranean region. Nonetheless they provide a varied range of settings both in terms of size, structural setting and orientation. The choice of sites was determined by the specific objectives of this research. The investigation of the key physical characteristics and controls on embayed beaches was carried out at a national scale and included all the significant beaches in the Maltese archipelago (29 embayed beaches in total) as shown in Figure 2.10.

Detailed analysis of shoreline change and beach morphodynamics were undertaken at a more local scale and focused on eight headland bay beaches as shown in Figure 2.11. These can be loosely classified into three groups based upon their location. Group 1 is located on the north coast of Gozo and consists of Ramla and San Blas beach. Group 2 consists of three beaches, which are fairly similar in size, Armier, Little Armier and White Tower Bay and are located on the North coast of Malta. Group 3 consists of Golden Sands, Ghajn Tuffieha and Gnejna Bay and this group of beaches is located on the west coast of Malta.
Figure 2.10: Location of the embayed beaches where investigation of the key physical controls was undertaken.

Figure 2.11: Location of the eight embayed beaches where a more detailed analysis of shoreline change, beach morphodynamics and sedimentology was undertaken.
The choice of the eight beaches considered for the analysis of shoreline change and beach morphodynamics was motivated by the following criteria:

1. There is a good distribution in terms of the actual size of the beaches with significant variations in beach lengths and beach widths.
2. There is a considerable variation in the physical configuration of the embayment. The unique settings and exposures of the headland bay beaches results in the beaches being subject to incident wave energy from a limited directional window which is dynamic and is timescale dependent.
3. Different geological formations are exposed within the headland bay beaches. The occurrence and extent of different geological formations can affect the overall sediment budget both in terms of quantity and textural characteristics.

The analysis of sediment textural characteristics was carried out at different spatial and temporal scales. Sediment samples were collected from 26 beaches located in Malta and Gozo during summer 2014 in order to characterise the general textural characteristics of beach sediment in the Maltese islands and also determine whether the structural setting of the embayment is significant in terms of variation in beach sediment textural characteristics. A more detailed sediment sampling program was carried out at the eight beaches identified earlier on whereby sampling was carried out along a number of transects with the specific aim of providing additional insight into sediment characteristics and beach morphodynamics.
3 Research Design and Methodology

3.1 Approach adopted for this research

To achieve the research aims and objectives, the design of this research focused on the collection of the field and remote sensing data necessary for the achieving the objectives identified in Section 2.5. Figure 3.1 illustrates how the research methodology and subsequent results chapters have been structured in a way to allow the analysis of the four research objectives identified earlier on in Chapter 2. In this chapter the methodologies proposed for the collection and analysis of results are described. The four results chapters;

- Chapter 4 on structural control on embayed beach morphology
- Chapter 5 on the meso-scale behaviour of embayed beaches
- Chapter 6 on embayed beach morphodynamics
- Chapter 7 on the sedimentology of embayed beaches

subsequently and collectively contribute to the discussion (Chapter 8) of the various aspects of embayed beach morphology in the Maltese islands. The discussion focuses on the various processes acting on embayed beach morphology both at the spatial and temporal scale.

3.2 Characteristics of embayed beach setting

The investigation of the key physical characteristics of embayed beaches in the Maltese islands was carried out on 29 beaches located around the Maltese islands. The inclusion of the most significant (in terms of embayment dimensions) embayed beaches in the analysis of the general morphometric characteristics provides the context for a more detailed assessment of the role the physical setting on the morphodynamics on embayed beaches in the Maltese Islands.

The analysis of beach planform and geomorphological characteristics can take a variety of forms. Earlier studies by Silvester and Hsu (1993), Short (1999) and Klein and Menezes (2001), and more recently Bowman et al. (2009), characterised the planform geometry of headland bay beaches through measurements of headland and beach orientation, degree of embayment and exposure to the incident wave energy. In this study the two-dimensional planform characteristics of headland bay beaches were defined through the following parameters:
Figure 3.1: Block flow diagram showing the structure of this research and how each of the research questions identified in Chapter 2 shall be addressed through subsequent chapters.
a) The length of the headland spacing (Ro) and its orientation (Ro°)
b) The indentation of the embayment (a), which is a control line normal to the most pronounced bay retreat
c) The length of the embayed shoreline (S1)
d) The length of the embayed beach (S2)
e) The linear distance (S3) and orientation (S3°) between the edges of the embayed beaches
f) Beach area (Ab) and;
g) The maximum beach width (Bw)

The parameters used to characterise the planform of embayed bay beaches are also illustrated in Figure 3.2.

![Figure 3.2: Schematic representation of the parameters used to characterise the planform of embayed beaches. The beach is indicated in light gray (Source: Adapted from Bowman et al. 2014).](image)

Detailed measurements of the physical characteristics were performed using a GIS software package (ArcGIS ver 10.3) on 1:2500 orthophoto sets provided by the Mapping Unit within the Planning Authority. The results allowed for further analysis of the physical characteristics of embayed beaches mainly through:

1. The application of the indentation index used for the calculation of beach embaymentisation which is based on the length of the headland spacing (Ro)
and the indentation of the embayment (a). This index for estimating beach embaymentisation is based on the a/Ro criterion (Hsu et al., 1989b,c). Bowman et al., (2014) developed a classification scheme for a number of embayed beaches in Elba based upon the indentation index. The proposed classification scheme (Figure 3.3) ranges from extremely low values (values from 0 – 0.125) to extremely high (values > 8) of indentation.

2. The application of the embaymentisation index (S1/Ro) based on the length of the headland spacing (Ro) and the length of the embayed shoreline (S1). It has been suggested that this index enhances the objectivity of analysis of bay indentation and highlights spatial variations within the same shoreline (Spagnolo et al., 2008). Thus the greater the variability of this index within the same coastline the more likely it is that the littoral forces are acting or interacting differently as a result of the effect of inherited morphology (Bowman, et al., 2009).

3. The application of the bay filling index (S1/S2 index, Bowman et al., 2009) which shows what part of the coastline is veneered with sediments.

![Figure 3.3: Bay-shape classification based on the Indentation index (a/Ro). (Source: Bowman et al., 2014).](image)

### 3.3 Analysis of shoreline change

The shoreline changes in the study area were analysed in ESRI ArcGIS v10.3 software through the use of the Digital Shoreline Analysis System (DSAS) extension (version 4.0) which enables the user to calculate a number of shoreline rate-of-change statistics.
from multiple historic shoreline positions. The identification of the past shoreline positions was made through the use of a combination of aerial photographs obtained from the Water Services Corporation, the Planning Authority and satellite imagery obtained from Google Earth. All the imagery was geo-referenced and projected into the same coordinate system using, ED1950, and the respective shorelines were digitised in ArcGIS. The boundary between the land and water was selected as the shoreline proxy for each image. Transects were cast at a distance of 5m as shown in the Figure 3.4 to ensure that any alongshore changes in beach shoreline are well represented. Given the high resolution of the imagery used for the shoreline change analysis, the uncertainty was calculated at ±2m.

Figure 3.4: Plot showing the available shoreline for the analysis of shoreline change with transects cast at 5m intervals (Source: Author).

The methods used to calculate the shoreline rates of change were based on measured differences between shoreline positions over time. The following statistical methods were used in DSAS:

(i) Net Shoreline Movement (NSM) to measure the distance (m) between the oldest and youngest shorelines. Values for NSM were calculated for 5

(ii) Shoreline Change Envelope (SCE) to measure the total change (distance in m) in shoreline movement for all available shoreline positions

(iii) The linear regression rate-of-change statistic (LRR) which fits a least square regression to all shorelines for each transect and gives a rate of change (which can be both positive and negative) in meters per year. Linear regression rates for each transect were calculated for 5 different time scales (1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016).

(iv) The End Point Rate (EPR), which calculates rates of shoreline erosion or accretion by dividing the distance of shoreline movement by the time elapsed between the oldest and most recent shoreline, was used to increase the robustness of the analysis of shoreline change through the comparison of the LRR and EPR statistics.

The results of the net shoreline movement and shoreline change envelope were plotted in ArcGIS and the same categories were used for all beaches so as to facilitate the comparison of the results across beaches. Rates of the linear regression rate-of-change statistic were plotted for each transect to display the alongshore variability of erosion and accretion rates within each beach.

3.4 Beach morphology and morphodynamics

Detailed morphodynamic investigations were undertaken at the eight headland bay beaches identified in Section 2.3. The assessment of beach morphology is normally carried out through the measurement of beach profiles. Beach profiles enable the identification of the different processes which operate along a particular stretch of coast by providing information on the beach steepness and morphological features which in turn can provide information on the size of the beach material and the type of wave acting on the beach itself (Komar, 1998).

Along the years a number of approaches have been developed to obtain complete profiles across the nearshore zone. The measurement of most beach profiles involves standard practices of surveying including levelling, Kinematic GPS and total stations. Levelling of profiles used to be the most common method of beach profiling. Methods for measuring beach profiles by means of levelling range from low tech variations, such as the use of Emery boards, to more sophisticated approaches, such as the use of auto levels. The advantage of levelling is that most of the equipment is light and
inexpensive and can provide a reasonable accurate measure of the profile. Also profiles can be obtained quickly and the equipment can be carried to distant survey sites. However since all recording and generation of profiles has to be carried out manually, the processing of the collected data can take longer than other methods. The most frequently used method of data capture of beach profiles is by total station. The speed of data acquisition is faster than for levelling since the instrument generally has to be set-up less frequently. Although it has been considered as the most accurate surveying instrument it cannot be operated properly in poor visibility circumstances (Lee et al, 2013). The use of GPS technology for beach profiling has advanced rapidly during the past few years. The main advantage of GPS over other techniques is in the speed of data capture. Also the system is well suited to low light conditions and can be used in complete darkness. Whatever the operational accuracy and performance of the instrument, the quality of the data collected greatly depends on how the equipment is setup, the method of operation, the survey site and the personnel operating the equipment (Lee et al, 2013).

In this study levelling was used for the measuring of beach profiles given that it can provide comparable results to the other methods discussed above. Beach profiles were measured from the back of the beach, from a permanent benchmark, and ended at about wading depth (approximately at 1 meter water depth). Benchmarks were set by identifying fixed structures which in most cases were stone walls or concrete platforms. To measure the changes in gradient along the beach profile a Topcon AT-B3 Automatic 28X Auto Level was set up on a tripod on the benchmark. Once the auto-level was levelled, readings were taken for changes in elevation from the benchmark to the location of the surveying staff. To improve the horizontal distance accuracy of the auto level, the distance to the surveying staff was measured using an industrial laser distance meter (Bosch GLR825). Readings of changes in profile gradient and the distance to the benchmark were taken with every major break of slope and morphological feature. Where changes in the break of slope were more frequent, an increased number of measurements for changes in gradient and the distance to the benchmark were taken.

During the measurement of each profiles, the shoreline position was determined by the downrush limit, which was selected after observing the swash motion for several minutes. Most of the data on beach profile was collected on calm days therefore the difference between the uprush and downrush was minimal, thus reducing the margin of error. No consideration was given to the tide levels when beach profile data was collected since the micro-tidal environment of the Maltese islands has little effect on the
beach profile. More than one profile was measured in each of the beaches considered for this study so as to capture any alongshore variability in beach morphology. The number of profiles within each beach varied from two to three profiles depending on the length of the beach.

Beach profiles were approximately collected every four months and the surveying period commenced on November 2011 until the end of 2013. Collection of beach profiles from the eight beaches was carried out as indicated in Table 3.1. More frequent beach profiling could yield a more accurate description of the changes in beach morphology, but due to time and weather constraints, a profiling interval of four months was selected as this can provide a good indication of beach morphodynamics at the seasonal scale.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Survey Date</th>
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</thead>
<tbody>
<tr>
<td>Ramla l-Hamra</td>
<td>11/11 03/12 06/12 09/12 02/13 05/13 08/13 11/13</td>
</tr>
<tr>
<td>San Blas</td>
<td>11/11 03/12 06/12 09/12 02/13 05/13 08/13 11/13</td>
</tr>
<tr>
<td>Armier</td>
<td>11/11 03/12 05/12 09/12 02/13 04/13 08/13 11/13</td>
</tr>
<tr>
<td>Little Armier</td>
<td>11/11 03/12 05/12 09/12 02/13 04/13 08/13 11/13</td>
</tr>
<tr>
<td>White Tower</td>
<td>11/11 03/12 05/12 09/12 02/13 04/13 08/13 11/13</td>
</tr>
<tr>
<td>Gnejna</td>
<td>11/11 02/12 04/12 07/12 11/12 03/13 05/13 09/13 12/13</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>11/11 02/12 04/12 07/12 11/12 03/13 05/13 09/13 12/13</td>
</tr>
<tr>
<td>Golden Sands</td>
<td>11/11 02/12 04/12 07/12 11/12 03/13 05/13 09/13 12/13</td>
</tr>
</tbody>
</table>

Table 3.1: Beach profiles were collected approximately every four months as shown above (mm/yy).

3.5 Sediment Analysis

One of the most important characteristics of sediment is the size of the particles (McLaren & Bowles, 1985). A particle’s size is usually defined in terms of its diameter. Traditionally the diameter of a particle was determined by the mesh size of a sieve or defined by its fall velocity although in recent years newer methods have been adopted as described further below. The division of sediment sizes into different size classes such as silt, sand and gravel is arbitrary and many schemes have been proposed over the year. Nowadays, the classification which is most generally used is the one devised by Wentworth (Krumbein and Sloss, 1963).

Sediment samples may be collected using a variety of methods and equipment, depending on the type of sample that is required. Different sampling methods achieve different levels of representativeness. Selective sampling targets a particular section, layer or morphological feature of a beach whereas composite sampling involves a
broader characterisation, both horizontally and vertically, of the beach sediment. Apart from the sampling methods, due consideration should also be given to the sediment size analysis method. This is since the sampling method has to be adapted to the sediment characterisation method. Table 3.2 compares some of the most common methods of sediment grain size analysis.

In this study grab samples were collected manually from the beach surface from the topmost part of the sediment (2 to 3 cm depth). Given that the topmost layers of the beach sediment are representative of the transport processes occurring within the short to medium timescale, manual sampling was considered to be adequate for the purpose of this study. Sediment samples for the general assessment of beach sedimentology in the Maltese islands were collected from the berm or backshore of the beaches during the summer months of 2014. Sediment samples for the detailed morpho-sedimentary analysis in the eight beaches were collected along each of the beach profiles at specific morphological zones (backshore, berm area, foreshore and surf zone) between 2011 and 2014. Sometimes samples were also collected from the breaker zone, depending on the water depth. All the sediment samples were then placed in plastic containers, sealed and labelled accordingly. The position of each sediment sample was recorded with a GARMIN 60CSx GPS unit. The objective of this sampling scheme was mainly to characterize the changes in surficial sediments along the cross-shore and alongshore components of the beach. More than 500 samples of beach sediment were collected during the course of this research.

Various studies have shown that the grain size distribution of sediment contains information regarding the source (Pyokari, 1999), mode of transport (McClaren & Bowles, 1985) and energy level of the transporting processes (Komar, 1998). Various methods have been employed to decipher this information from grain size frequency distributions of sediments. Most methods used statistical granulometric parameters such as sample mean, mode, sorting and skewness to characterize the sediment deposit under study (Taney, 1961a), as well as methods to dissect the sediment population into subpopulations that presumably represent different transport modes (Visher, 1969; Bein and Sass, 1978). Efforts have also been made to link (or predict) the distribution of the texture of natural sediment with environmental attributes such as the hydrodynamics, beach slope and topographic relief (Miller and Zeigler, 1964; Murray, 1967; Graf, 1976). In this study the analysis of the sand sized fraction of the beach samples (<2 mm) was carried out through laser diffraction, specifically by means of a Malvern Mastersizer 2000 laser particle-sizer. The coarse grained fraction (>2mm)
<table>
<thead>
<tr>
<th>Methods</th>
<th>Main Advantages</th>
<th>Main Disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image analysis based on statistical methods</td>
<td>Quick method of obtaining a single textural descriptor (mean or median).</td>
<td>Doesn't allow the representation of the sediment grain size distribution including the derived statistical parameters.</td>
<td>Rubin (2004), Barnard et al. (2007), Buscombe (2008), Bosnic et al. (2011), Cascalho et al. (2012).</td>
</tr>
<tr>
<td>Image analysis based on grey morphological openings</td>
<td>Adequate method for obtaining the sediment grain size distribution and respective statistical parameters based on sediment images.</td>
<td>Time consuming and involves heavy computational routines.</td>
<td>Lira (2011), Pina et al. (2011).</td>
</tr>
<tr>
<td>Sieving</td>
<td>Adequate method for size determination in the pebble and sand ranges based on the weights of the grain size classes.</td>
<td>The results obtained are partly dependent on particle shape and consequently substantial deviation of the particle from the shape of a sphere may lead to underestimation of the characteristic intermediate diameter. Can be very time consuming if a large number of samples is being analysed.</td>
<td>Krunbein and Pettijohn (1938), Folk (1974), Buller and McManus (1979).</td>
</tr>
<tr>
<td>Laser diffraction</td>
<td>Adequate to perform particle size analysis where the final results (grain size distribution and statistical parameters) are expressed in terms of the equivalent diameter based on volume.</td>
<td>It is only suitable for sediments finer than medium sand. For coarser sediments this method needs to be complemented by another technique (e.g. sieving). Costly equipment that needs regular calibration and maintenance.</td>
<td>Loizeau et al. (1994).</td>
</tr>
<tr>
<td>Sedimentation tube</td>
<td>Adequate to determine the sediment grain size distribution and respective statistical parameters in an accurate way, based on the particle settling velocity.</td>
<td>Less accurate results when the sediment contains appreciable quantities of heavy minerals with densities greater than quarts and mica flakes whose shapes differ from the spherical. Sensitive equipment that needs regular calibration and maintenance.</td>
<td>Gibbs (1974), Komar and Cui (1984).</td>
</tr>
</tbody>
</table>

Table 3.2: Comparison of the most common methods for sediment size analysis
of the sediment was dried in a convention oven (overnight) and the distribution determined through wire-mesh sieves. After sieving, the coarse grained fractions were individually weighted and recorded and the relative percentages of the sand and gravel fractions of the different distribution categories were calculated. Prior to the analysis, removal of organic matter from the grab samples was not necessary. Statistics based on the grain-size frequency distribution of each sample were obtained with the Gradistat spreadsheet (Bloot and Pye, 2001).

The parameters used to describe a grain size distribution mainly consisted of the (a) the average size, (b) the spread (sorting) of the sizes around the average, (c) the symmetry or preferential spread (skewness) to one side of the average, and (d) the degree of concentration of the grains relative to the average (kurtosis). Attempts to differentiate between different transport modes (Visher, 1969) were made by plotting log probability distributions through the use of DPlot.

3.6 Meteorological and hydrodynamic datasets

Wind data (wind speed and direction) for the period between 1979 and 2016 was obtained from the Met Office MIDAS Luqa Station. Wind data was available on a 3 hourly basis throughout the whole period. Luqa station is located in the central part of Malta and in view of the lengthy time series during which observations were made from this site, this station has long been defined as the reference point for Malta’s climatological data. Moreover the type of instrumentation used for measuring these parameters changed little with time, therefore reducing errors related to changes in instrumentation (NSO, 2011). Monthly sea level data was acquired from the Ports and Yachting Directorate at Transport Malta.

Wave data was obtained from the Simulating Waves Nearshore (SWAN) model (Delft University of Technology, 2017), which simulates wave conditions in the coastal sea around the Maltese islands. SWAN is a third-generation wave model that solves the spectral action balance equation taking into account the effects of spatial propagation. Grid points, corresponding to the 10m and 5m bathymetric contour, were selected within the embayments and wave statistics were computed for these locations.

Bathymetric data was obtained from airborne LiDAR and Sonar data (ERDF LIDAR data, 2012) at 10m resolution covering the Maltese islands’ bathymetry to one nautical mile away from the coastline.
3.7 Choice of statistical techniques

Statistical analysis of the primary data collected throughout the course of this research was mostly carried out in PAST – Paleontological Statistics, ver 3.16 (Hammer et al. 2001). Although a number of very good statistical software are available such as SPPS (IBM Corp, 2013) and Minitab (Minitab Inc, 2010), PAST was preferred since it includes functions such as ordination and morphometry which proved particularly useful in the analysis of the embayment morphometric data. The choice of statistical techniques used to analyse the data was guided by the nature of the data itself. Data reduction techniques and ordination methods were used to summarise and characterize the raw data. Exploratory analysis was used to determine if the components in the data sets were correlated with other underlying variables. As much as possible graphical representations were preferred to the output of basic raw data as the visual interpretation of the data proved to be more effective in the analysis of the data.

A brief description of the statistical methods utilized for the analysis of the data generated during the course of this research is outlined below:

- Principal component analysis is a data reduction technique which finds hypothetical variables which account for as much of the variance in the multidimensional data as possible (Davis, 1986, Harper 1999). It does this by looking for groups among the inter-correlations of a set of variables. Principal component analysis was used to characterise the variance in the embayment morphology, changes in beach volume and beach sedimentology.

- Cluster analysis was used in this research as an exploratory tool to measure the similarly embayed beach morphometrics. The mean linkage algorithm was used as clusters are joined based on the average distance between all members in the two groups. Euclidian distance was used for similarity measure as it is a robust and widely applicable measure.

- Ordinary least squares was used to fit a line of best fit and model the relation between beach width and changes in beach volume. The resultant linear equation was then used to calculate changes in beach volumes as a result of shoreline erosion or accretion.

- All correlations computed throughout this study are based on Spearman’s rs. This test is a non-parametric measure of correlation and therefore makes no assumption about the distribution of the values. The correlation is based on the ranked observation of the two variables and ranges vary from +1 (positively correlated) to -1 (negatively correlated).
4 Structural control on beach morphology

4.1 Headland-bay morphometry

The morphometric parameters of 29 embayed beaches in the Maltese islands are analysed in this chapter, the location of which is shown in Figure 4.1. Previous studies such as Klein and Menezes (2001) suggest that the plan geometry approach provides a useful first step in the study of embayed coastlines as it can make important contributions to the identification of exposure of the coastal segment to incident waves, beach morphological changes, sediment bypassing and shoreline accretion or erosion (Bowman et al, 2009). The geometric approach being addressed in this chapter is therefore a relevant initial research stage prior to detailed field experiments carried out in subsequent chapters. The key parameters considered for this study (Table 4.1) are: the length of the control between the headlands of the embayment (Ro), the orientation of this control line between the headlands (RO°), the indentation of the embayment from the control line (a), the length of the coastline within the embayment (S1), the length of beach shoreline (S2), the direct beach length between the end points of the beach (S3), the orientation of the direct beach length (S3°), the maximum beach width (Bw) and beach area (Ab). A schematic representation of these parameters is also shown in Figure 3.2 in Chapter 3.

![Figure 4.1: Location map of the 29 embayed beaches for which morphometric parameters and indices were considered.](image-url)
Table 4.1: Morphometric parameters and indices of the 29 beaches located in Malta and Gozo which were considered for this study.

The results show that headland spacing (Ro), which is one of the most important structural features conducive to the development of headland bay beaches, ranges between 70 m and 1755 m, with 62% of beaches having a headland spacing ranging from 150 m to 500 m (Figure 4.2). The indentation of the embayments (a) varies from 47 m at Marsalforn Beach to 2603 m at Ghadira Beach, the largest sand beach in Malta. A similar study focusing on the morphometric parameters of headland bay beaches on Elba Island (a Mediterranean island of a comparable size to Malta) (Bowman et al., 2014), found that headland spacing (Ro) ranged between 103 m and 1130 m whereas indentation (a) ranged from 45 m to 474 m. When analyzing the total length of the shoreline in the Maltese embayments (S1), this ranged from 196 m at
Marsalforn beach to 6762 m at Ghadira beach. Bowman et al. (2014) found that the length of the shoreline in the embayed beaches on Elba ranged from 79 m to 1917 m.

Figure 4.2: Variation in headland spacing (Ro), indentation of the embayment (a) and length of shoreline (m) amongst the 29 beaches considered for the morphometric analysis.

In order to understand whether the morphometric parameters of the different embayed beaches can be used as a basis for classification of different headland bay beach types, a hierarchical clustering routine based on the unweighted pair-group average (UPGMA) was run on the morphometric data. The results, as shown in Figure 4.3, indicate that embayed beaches can be grouped into four broad categories based on the differences and similarities that exist within the morphometric parameters across all 29 systems. In the choice of the cut-off distance of the four categories, consideration was given to the similarity/dissimilarity of the embayed beaches to the other groups. The variations between the different four groups for a selected number of morphometric parameters are shown in Figure 4.4.

Group A consists of 6 beaches with a mean headland spacing of 320 m and a mean indentation of 316 m. The mean shoreline length within the embayment is of 996 m, more than three times the distance between headland spacing and bay indentation. Mean beach shoreline length is of 189 m, very similar to the direct beach length (178 m), whereas mean beach width and mean beach area are 39 m and 4,932 m² respectively. Group B consists of 20 beaches which are more diminutive in nature and
this is reflected in the different mean values of the various morphometric parameters. Mean headland spacing (Ro) in Group B is 230 m whereas mean bay indentation is at 176 m. The length of the beach shoreline within the embayment (S1), at 536 m, is almost double the distance between the embayment headlands. The beaches within this group have the smallest values for the beach morphometry characteristics (S2, S3, Bw and Ab) with the mean beach shoreline length being 78 m, the maximum beach width 21 m and the beach area 1085 m².

Figure 4.3: Dendogram clustering using un-weighted pair group average (UPGMA) of all the morphometric parameters showing the four main groupings in the data (Group A, Group B, Group C and Group D). The colour codes correspond to the different groups, with the mean morphometric parameters of each group being summarised in the table below the dendogram.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Ro</th>
<th>a</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Bw</th>
<th>Ab</th>
<th>a/Ro</th>
<th>S2/S1</th>
<th>S1/Ro</th>
<th>S3*</th>
<th>R*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>319.3</td>
<td>315.8</td>
<td>995.7</td>
<td>188.7</td>
<td>178.2</td>
<td>39.3</td>
<td>4931.8</td>
<td>1.0</td>
<td>0.2</td>
<td>3.1</td>
<td>64.7</td>
<td>125.7</td>
</tr>
<tr>
<td>Group B</td>
<td>229.5</td>
<td>178.2</td>
<td>536.4</td>
<td>77.8</td>
<td>75.7</td>
<td>21.0</td>
<td>1084.7</td>
<td>0.9</td>
<td>0.2</td>
<td>2.7</td>
<td>73.0</td>
<td>75.9</td>
</tr>
<tr>
<td>Group C</td>
<td>741.5</td>
<td>329.0</td>
<td>1146.5</td>
<td>301.0</td>
<td>298.5</td>
<td>85.5</td>
<td>13692.0</td>
<td>0.5</td>
<td>0.3</td>
<td>1.6</td>
<td>116.5</td>
<td>111.0</td>
</tr>
<tr>
<td>Group D</td>
<td>1775.0</td>
<td>2603.0</td>
<td>6762.0</td>
<td>602.0</td>
<td>593.0</td>
<td>54.0</td>
<td>23646.0</td>
<td>1.5</td>
<td>0.1</td>
<td>3.8</td>
<td>158.0</td>
<td>169.0</td>
</tr>
</tbody>
</table>

Group C consists of just two embayed beaches, Ramla I-Hamra and r-Ramla tal-Mixquqa. In these two beaches the headland spacing (Ro) is almost double the maximum bay indentation (a) therefore resulting in low values for beach embaymentisation (a/Ro). The mean shoreline length within the embayment for Group C stands are 1147 m. The mean beach shoreline length (S2) in Group C is 301 m, considerable higher than the mean values of Group A and Group B. The beach width
(Ab) in both Ramla l-Hamra and r-Ramla tal-Mixquqa is considerably higher than the values exhibited in all the other groupings whereas mean beach area is in the order of 13,692 m². Ghadira beach, which is the only beach within Group D, is clearly different to all the other 28 beaches considered for this study, especially when it comes to the following morphometric parameters: the distance between the embayment headlands (Ro), embayment indentation (a), the length of shoreline within the embayment (S1), the length of beach shoreline (S2) and the total beach area (Ab).

Principal component analysis was used to identify the key morphometric parameters responsible for the variance that exists within the data. The results of this analysis are shown in Figure 4.5 and indicate that most of the variance within the morphometric data is explained by one component. The plot of the 29 different beaches in Figure 4.5A indicates a strong discretisation of the beaches along the horizontal axis with beaches such as Ramla l-Hamra and r-Ramla tal-Mixquqa being on one end of the spectrum and beaches such as San Niklaw, Imgiebah and Balluta on the other end, indicating that the magnitude of the beach area is key to the variance that exists in the data. More than 42% of the variance within the data is the result of varying beach area (Ab) amongst the 29 beaches (Figure 4.5.C). The second most important parameter, accounting for more than 23% of the variance relates to the embayment morphometry.

Figure 4.4: Boxplots representing the variations in the data amongst the four groups of embayments for selected morphometric parameters. (A) Headland spacing, (B) Embayment indentation, (C) Shoreline length and (D) Beach area.
Figure 4.5: (A) Principal component analysis plot of the morphometric parameters showing the variance of the different beaches with respect to the two most important morphometric parameters. (B) Principal components analysis plot of the morphometric parameters showing the similarity/dissimilarity amongst the embayed beaches with respect to the two most important morphometric parameters. (C) Scree plot showing the percentage variance of the components identified through the PCA.
The initial run of the principal components analysis indicated that Ghadira beach is different in terms of its magnitude (especially when it comes to beach area) to the rest of the beaches in Malta and therefore was considered as an outlier and not included in the final run of the principal components. Omitting Ghadira beach reduced the excessive influence of beach area as the main descriptor of the variance within the data. In fact the importance of beach area (the dominant principal component decreased from over 50% in the initial run to around 42% in the final run.

4.2 Headland embaymentisation

When comparing the correlation of the different parameters characterising headland morphology, Figure 3.8A shows that bay indentation (a) and headland spacing (Ro) are well correlated ($R^2 = 0.85$), whilst Figure 3.8B indicates that the length of the embayment shoreline (S1) and bay indentation (a) are strongly correlated ($R^2 = 0.99$). The length of the embayment shoreline (S1) is not very well correlated ($R^2 = 0.59$) to the distance between headlands (Ro) (Figure 4.6C). The indentation index (a/Ro) amongst the embayed beaches ranged between 0.35, at Little Armier, to 2.41, at Xwejni beach in Gozo, i.e. from very low to highly indented according to the classification scheme for embayment indentation as proposed by Bowman et al. (2014). The indentation index (S1/Ro) ranged between 1.38 and 6.33, higher than the Australian mean regional ratio which varies from 0.66 to 0.86 (Short, 2010) and the range identified by Bowman et al; (2014) for the embayed beaches in the island of Elba (1.32 to 3.01). The indentation index (S1/Ro) and embaymentisation index (a/Ro) are highly correlated as can be seen in Figure 3.8D, ($R^2 = 0.98$) which could be the result of the similar planform charactertics of embayed beaches in Malta. Similar high correlations ($R^2 = 0.92$) between the main embaymentisation parameters (a/Ro and S1/Ro) were observed by Bowman et al. (2009) for 72 pocket beaches along the Catalan coast and for a similar study on pocket beaches on the island of Elba (Bowman et al. 2014) whereby correlations of $R^2=0.95$ where observed.

The main embaymentisation parameters for Maltese beaches were also compared to the main embaymentisation parameters in a number of other Mediterranean beaches. The scatter plot in Figure 4.7 plots the embaymentisation index (S1/Ro) against the indentation index (a/Ro) for the embayed beaches in Malta, Spain (Bowman et al. 2009) and Elba (Bowman et al. 2014). For the Spanish beaches, the mean values of the five broad categories as proposed by Bowman et al. (2009) where plotted. Figure 4.7 shows that almost all the embayed beaches in Malta fall within the range of values of the five categories proposed by Bowman et al. (2009) except for the beaches of San Niklaw, il-bajja ta' San Gorg and Xwejni bay which are more indented than the mean.
value for high-indented beaches in Spain. The comparison also shows that embayed beaches in Malta tend to be slightly more indented than embayed beaches on the island of Elba, indicating the likely impact of structural control on the physical setting and formation of these headland beaches.

The degree of embaymentisation and indentation of headland bay beaches was also analysed from a spatial perspective to determine whether the variation within the key morphometrical parameters is a result of broader regional processes. Figure 4.8 maps out the spatial distribution of the embaymentisation index (S1/Ro) and indentation index (a/Ro) for the 29 beaches considered for this study. The classification of the embaymentisation values was developed as part of this research whereas the indentation index values were categorised according to the classification scheme devised by Bowman et al. (2014).
According to the embayment classification scheme, the beaches considered for this study fall within 3 main categories which are *Low* (embayments with an embayment index lower than 2), *Medium Low* (embayments with an embayment index ranging from 2 to 4) and *Medium High* (embayments with an embayment index ranging from 4 to 8). Table 4.2 lists the beaches according to the embayment classification scheme.

### Table 4.2: Categorisation of beaches according to the embayment classification scheme.

<table>
<thead>
<tr>
<th>Embayment Index (S1/Ro)</th>
<th>Low (&lt; 2)</th>
<th>Medium Low (2 to 4)</th>
<th>Medium High (4 to 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arniar</td>
<td>Bajja ta' Birzebbuga</td>
<td>Bajja ta’ San Gorg - SJ</td>
<td></td>
</tr>
<tr>
<td>Il-Bajja ta’ San Gorg- BZ</td>
<td>Balluta ver1</td>
<td>San Niklaw</td>
<td></td>
</tr>
<tr>
<td>Hondaq ir-Rummien</td>
<td>Crkewwa</td>
<td>Xwejni</td>
<td></td>
</tr>
<tr>
<td>Ingiebah</td>
<td>Dahiet Qorrot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ir-Ramla ta’Cirkewwa</td>
<td>Ghadira</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Littia Arniar</td>
<td>Ghajn Tuffieha</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marsaform</td>
<td>Gnejna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramla I-Hamra</td>
<td>IG-Daha tar-Rinela</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramla tal-Qortin</td>
<td>Mistra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-Ramla tal-Mxquqa</td>
<td>Qala San Marku</td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Bas</td>
<td>Qbajjar</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 4.7: Scatter plot of the Embayment index (S1/Ro) vs. Indentation index (a/Ro) for a number of embayed beaches in Malta, Spain (Bowman et al. 2009) and Elba (Bowman et al. 2014). The black dots show the mean values of the five indentation categories as classified by Bowman et al. (2009) for 72 pocket beaches along the Catalan coast.
More than half of the beaches fall within the *Medium Low* embaymentisation category. This category includes a wide variety of beaches ranging from Ghadira beach, the largest beach in Malta, to smaller beaches such as r-Ramla tal-Bir, indicating that the morphometry of embayed beaches retains a similar setup irrespective of the size of the embayment.

The map in Figure 4.8.A also shows that the degree of embaymentisation is not related to the presence of a particular geological formation at the coastal zone or the presence of one of the dominant coastal features described earlier on.

The analysis of the spatial distribution of the indentation index (Figure 4.8.B) according to the classification proposed by Bowman et al. (2014) indicates that beaches in the Maltese islands fall within four different categories which are *Low* (indentation index values of less than 0.5), *Medium Low* (Indentation index values ranging between 0.5 and 1.0), *Medium High* (indentation index values ranging from 1.0 to 2.0) and *High* (indentation index values ranging from 2.0 to 4.0). Table 4.3 lists the beaches according to the indentation classification scheme. About 41% of the beaches fall within the *Medium Low* category whereas both the *Low* and *Medium High* category have similar proportions, with each category accounting for 27% of the beaches. Only one beach, Xwejni, falls within the *High* indentation category. As with the embaymentisation index, the spatial distribution of the indentation index does not match the presence of a particular geological formation or dominant coastal feature within the coastal zone.

<table>
<thead>
<tr>
<th>Indentation Index (a/Ro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (&lt; 0.5)</td>
</tr>
<tr>
<td>Medium Low (0.5 to 1.0)</td>
</tr>
<tr>
<td>Medium High (1.0 to 2.0)</td>
</tr>
<tr>
<td>High (2.0 to 4.0)</td>
</tr>
<tr>
<td>Armier</td>
</tr>
<tr>
<td>Bajja ta’ Birzebbuga</td>
</tr>
<tr>
<td>Balluta</td>
</tr>
<tr>
<td>Xwejni</td>
</tr>
<tr>
<td>Il-Bajja ta’ San Gorg - BZ</td>
</tr>
<tr>
<td>Cirkewwa</td>
</tr>
<tr>
<td>Ghadira</td>
</tr>
<tr>
<td>Dingli</td>
</tr>
<tr>
<td>Dahlet Qorrot</td>
</tr>
<tr>
<td>Go-Dahla tar-Rnella</td>
</tr>
<tr>
<td>Ir-Ramla ta’Cirkewwa</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
</tr>
<tr>
<td>Bajja ta’ San Gorg - SJ</td>
</tr>
<tr>
<td>Little Armier</td>
</tr>
<tr>
<td>Gnejna</td>
</tr>
<tr>
<td>Qala San Marku</td>
</tr>
<tr>
<td>Marsalforn</td>
</tr>
<tr>
<td>Hondoq ir-Rummien</td>
</tr>
<tr>
<td>Ramla Tat-Torri</td>
</tr>
<tr>
<td>Rambia l-Hamra</td>
</tr>
<tr>
<td>Metra</td>
</tr>
<tr>
<td>R- Rambia tal-Bir</td>
</tr>
<tr>
<td>San Blas</td>
</tr>
<tr>
<td>Qbajjar</td>
</tr>
<tr>
<td>San Nikkew</td>
</tr>
<tr>
<td>Ramla tal-Qarraba</td>
</tr>
<tr>
<td>Ramla tal-Qorri</td>
</tr>
<tr>
<td>R-Ramla tal-Mexquqa</td>
</tr>
<tr>
<td>Santa Marija</td>
</tr>
</tbody>
</table>

Table 4.3: Categorisation of beaches according to the indentation classification scheme
4.3 Beach planform morphometrics

Embayed beaches in Malta are rather short. The shoreline length (S2) of the beaches considered for this study ranged from 32 m to 602 m. The mean beach length for the island of Malta is 134 m whereas that for the island of Elba is 414 m. Maximum beach width (Bw) ranged from 5 m at Balluta bay to 89 m at r-Ramla tal-Mixquqa. Considerable variation also exists with regards to the beach area (Ab) with values ranging from 121 m$^2$ at Balluta bay to 23646 m$^2$ at Ghadira beach. The mean beach area for embayed beaches in Malta is of 3528 m$^2$. 

Figure 4.8: (A) Map showing the spatial distribution of the embaymentisation index (S1/Ro) amongst the 29 beaches considered for this study. (B) Map showing the spatial distribution of the indentation index (a/Ro) amongst the 29 beaches considered for this study. Indentation index values were categorised according to the classification scheme devised by Bowman et al, (2009).
A comparison of the main beach morphometric parameters indicates beach width (Bw) and beach area (Ab) are moderately correlated ($R^2 = 0.736$) indicating that an increase in beach width is likely to result in a corresponding increase in beach area (Figure 4.9.A). A strong positive correlation exists between beach area (Ab) and beach shoreline length (S2) ($R^2 = 0.944$) whereby it is expected that the area of the beach will increase in size with an increase in beach shoreline length (Figure 4.9.B). In both instances, removing the outliers from the correlation did not improve the correlation.

Figure 4.9: (A) Scatter plot showing the correlation between beach area (Ab) and maximum beach width (Bw). (B) Scatter plot the correlation between beach area (Ab) and length of beach shoreline (S2).

A comparison of the most important headland (headland spacing, bay indentation and embayed beach shoreline) and beach morphometry parameters (beach area and beach shoreline length) shows that a positive correlation exists (Figure 3.12) between the length of beach shoreline (S2) and headland spacing (Ro) ($R^2 = 0.863$) and the length of the beach shoreline (S2) and the length of the embayed shoreline (S1) ($R^2 = 0.838$). Therefore an increase in the distance between the embayment headlands is likely to result in an increase in the length of beach shoreline within the embayment. Similarly an increase in the length of embayed shoreline is likely to result in an increase in the length of beach shoreline.

The main beach morphometric parameters were also compared to the embaymentisation index (S1/Ro) and indentation index (a/Ro). The results in Figure 4.11 show that no form of correlation exists between the length of beach shoreline (S2) and the main parameters describing embayment morphology (indentation and embaymentisation index). This is also the case for beach area (Ab).
The Bay filling index (S2/S1) demonstrates how much of the embayed coastline is veneered with beach sediments. The values for Malta are very low, ranging from 0.06 in San Niklaw to 0.39 in Ghajn Tuffieha. The bay filling indices in Malta are significantly lower than those reported for other Mediterranean embayed beaches. For example in
the study carried out by Bowman et al; (2014) the values for Elba ranged from 0.18 to 0.90, with almost half of the studied bays having a bay filling index of less than 0.5. Figure 4.12.A plots the correlation between the length of beach shoreline (S2) and the total shoreline length within the embayment (S1) for the beaches in Malta and Elba. Beach morphometric data for the island of Elba was sourced from Bowman et al. (2014). In both locations, there is a positive correlation between the length of embayed shoreline (S1) and beach shoreline length (S2), with the beaches in Elba showing a higher degree of correctional between the two parameters. A similar comparison was also carried out for beach shoreline length (S2) and the direct beach length between one end of the beach and the other (S3) (Figure 4.12.B). There is a high correlation between these two beach morphometric parameters for the embayed beaches in Malta ($R^2=0.99$) as is also the case in the island of Elba, indicating that shoreline configuration of the beaches located within these embayments tends to have a linear shape with no or very limited curvature present along the beach shoreline.

Figure 4.12: (A) Scatter plot showing the correlation between length of beach shoreline (S2) and the total shoreline length within the embayment (S1) for a number of beaches in Malta and Elba. (B) Scatter plot showing the correlation between the length of beach shoreline (S2) and the direct beach shoreline length (S3) for a number of beaches in Malta and Elba. The mormophometric data for the embayed beaches in Elba was sourced from Bowman et al; (2014).

The extent to which the shoreline of embayments is filled with beach sediment was also analysed from a spatial perspective the results of which are plotted in Figure 4.13. The results of the bay filling index were classified into the following three categories: Low (values less than 0.125), Medium Low (values ranging from 0.125 to 0.25) and Medium High (values ranging from 0.25 to 0.5). As shown in Table 4.4, most of the beaches (79%) have Low or Medium Low values for the bay filling index. Medium High values were recorded in only five beaches. As with the embaymentisation and indentation indices described earlier on, the spatial distribution of the bay filling index does not match the presence of a particular geological formation or dominant coastal feature along the coastal zone.
Figure 4.13: Map showing the spatial distribution of the bay filling index (S2/S1) for the 29 beaches considered for this study.

Table 4.4: Categorisation of beaches according to the bay filling classification scheme

<table>
<thead>
<tr>
<th>Beach Code</th>
<th>Beach Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (&lt; 0.125)</td>
<td>Medium Low (0.125 - 0.25)</td>
</tr>
<tr>
<td>Bajja ta’  Birzizzbuga</td>
<td>Gnejna</td>
</tr>
<tr>
<td>Il-Bajja ta’ San Gorg - BZ</td>
<td>Hondoq ir-Rummien</td>
</tr>
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<td>Jr-Ramla tac-Cirkewwa</td>
</tr>
<tr>
<td>Darhel Qorrot</td>
<td>Little Armier</td>
</tr>
<tr>
<td>Ghadira</td>
<td>Marsalforn</td>
</tr>
<tr>
<td>Id-Dahla tar-Rinella</td>
<td>Ramla tal-Qarraba</td>
</tr>
<tr>
<td>Bajja ta’  San Gorg - SJ</td>
<td>Ramla tal-Qortin</td>
</tr>
<tr>
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<td>Ramla tal-Torri</td>
</tr>
<tr>
<td>Qala San Marku</td>
<td>R-Ramla tal-Mixquqa</td>
</tr>
<tr>
<td>R-Ramla tal-Bir</td>
<td>Santa Marija</td>
</tr>
</tbody>
</table>

4.4 Bathymetry

The bathymetry and topography of the Mediterranean plays an important role in determining the degree of exposure to wave action of the different coastal water stretches in the Maltese Islands. For the purpose of assessing exposure a general description of the immediate depths of coastal waters around the Maltese Islands will suffice.
Figure 4.14: Submarine morphology within and outward of the embayments

Figure 4.16 clearly illustrates the differences in depth between the Northern, and north eastern approaches of Malta to the western and south western approaches. The north and north eastern coastal stretches are characterised by shallow depths and a gently sloping shoreface which gradually increases to the 50m depth contour as one progressively moves seawards. Embayed beaches located on the eastern coast of
Malta, such as Ghadira, Dahlet Qorrot and Qbajjar, generally exhibit a gentler sloping shoreface. In contrast, to the south-west and west of the Maltese Islands the shoreface is characterised by underwater cliffs and boulders screes resulting in greater bathymetric depths closer to the shoreline, therefore leading to a steeper approach. A study by Borg et al. (1997) focusing on two sites on the south-western coast of the Maltese islands indicates that the seabed along this stretch of coast is characterised by vertical drop-offs with boulder fields at their base. As can be seen in Figure 4.16, the 50m contour is in close proximity, very often less than 200m from the embayment headland, to the coastline particularly in the North western parts of Gozo and Western coast of Malta. This is clearly evident in embayed beaches such as Gnejna, Ghajn Tuffieha and Mixquqa.

It can therefore be concluded that bathymetry of embayed beaches located on the western coast of Malta leads to these beaches have a greater exposure to incoming waves due to the steeper shoreface. Embayed beaches on the north and north-eastern Maltese coastline are more 'sheltered' from incoming waves due to a gentler sloping shoreface.

4.5 Hydrodynamic context

4.5.1 Metocean context and model set-up

The physical characteristics of Maltese coastal waters are dictated by larger synoptic climatic features which take place at a Mediterranean scale. Being an enclosed sea, the general topography of the Mediterranean basin and the spatial distribution of the land and sea masses influence pressure systems, sea surface temperatures, currents, sea circulation, winds and most importantly waves.

Waves in the Maltese islands are mostly the result of regional and local winds. The wind rose (NSO, 2010) shown in Figure 4.15 indicates that the most common wind direction in the Maltese Islands is northwesterly (Mistral), which accounts for around 21% of annual wind records. Wind blowing is also frequent from the west (14%), southwest (9%), the south-southwest (8%) and north-northwest (7%). The mean wind speed over the islands in terms of strength and frequency is 8.5 knots (4.4 ms) (Alpha Briggs, 2008). Wind speed may not necessarily be greatest from the most predominant directions. Wind rose plots show that the strongest winds originating in the northeast, the southeast and east-southeast sectors are almost equally strong, albeit less frequent.
Wave action is strongly linked to the prevailing wind conditions and fetch. In the Malta channel the wave field is typically most energetic in the area below 36.5°N due to the partial sheltering by the Sicilian coast (especially from Mistral and northerly winds). The strongest waves occur in the north, west and south west of the Maltese Islands. Wave incidence is predominantly from the North-north-west and the north. Information on significant wave heights (SWH) and direction for the sea area up to 20 nautical miles around the Maltese islands is documented by Scott Wilson Kirkpatrick and Co. Ltd (2003) on the basis of various datasets and modelling. This study applied UK Meteorological Office (UKMO) Wave model data sets generated between 1988 and 2002 and wave data were obtained for 4 offshore locations as indicated in Figure 4.16.

As shown in Table 4.5, on an annual basis, wave heights of 0.5 m are exceeded for 68% percent of the period at points A, B and C and 70% at Point D. Wave heights of 1 m are exceeded on 38% percent of the period at points A, B and C and 39% at Point D. The percentage exceedance of wave heights in the order of 1.5 m ranges between 20 and 21 % at all the four points whereas for wave heights in the order of 2 m, the percentage exceedance at points A to D ranged from 11 to 12 %. During the summer season the percentage exceedance of wave heights in the order of 0.5 m ranged between 56 to 57 % at all four points. For wave heights of 1 m, the percentage exceedance ranged from 26 to 27 % at all the four points whereas wave heights of 1.5 m where exceeded between 12 and 13 % of the time at all the four points.
Figure 4.16: Map of the Maltese islands showing the location of the 4 offshore locations for which wave data was obtained from the UKMO wave model (Malta Maritime Authority, 2003).

Table 4.5: (Left Panel) Percentage exceedance of offshore significant wave height on an annual basis at Points A-D indicated in Figure 3.18 for the period 1988-2002. (Right Panel) Percentage exceedance of offshore significant wave height during the summer period at Points A-D indicated in Figure 3.14 for the period 1988-2002) (Malta Wave Height Study, 2010).

<table>
<thead>
<tr>
<th>Wave Height (m)</th>
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<th>Point B</th>
<th>Point C</th>
<th>Point D</th>
</tr>
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<th>Wave Height (m)</th>
<th>Point A</th>
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Based upon the information of the prevailing wind conditions and the output of the wave height characteristics for the seas around Malta as defined by Scott Wilson Kirkpatrick and Co. Ltd (2003) two wave model runs were carried out using SWAN to simulate the following two scenarios:

- Waves generated from the northeast (60°)
- Wave generated from the northwest (300°)
Both runs started with a 1 m wave height and a 6 seconds wave period together with a 6.5m/s wind speed on the outer grid of the model. Wave conditions for each of the embayed beaches were calculated according to the above two scenarios based upon a position close to the 10m contour within the embayment. On an annual basis the percentage exceedance of this kind of wave setup stands around 38%.

4.5.2 Wave modelling results

The results of the wave modelling exercise (Figure 4.17) show that at 10m depth, the wave height for waves emanating from a NE direction ranged from 0m to 0.62m whereas wave period ranged from 2.96 to 7.27 seconds. For waves emanating from a NW direction the wave height at 10m depth ranged from 0m to 0.59m whereas wave period ranged from 0 to 8.16 seconds. The results of the wave modelling exercise indicate the importance of headland morphology, shoreline orientation and indentation in modifying the wave setup. Waves originating from a NE direction are most significant on the NE coastline of the Maltese islands given the orientation of the archipelago. Embayed beaches which are particularly susceptible to this kind of wave setup include most of the embayed beaches in Gozo (Marsalforn, il-Bajja tal-Qbajjar, Xwejni, Ramla l-Hamra, San Blas and Dahlet Qorrot) where wave height ranged between 0.44 m and 0.62 m. In Malta Mgiebah and St Georges bay are also very susceptible to this kind of wave setup due to the embayment orientation. The model results also show that the sheltering affect of the island lead to a considerable diffraction and attenuation of the wave setup. Embayed beaches which are located on the western coast of Malta such as r-Ramla tal-Mixquqa, Ghajn Tuffieha, Qarraba and Gnejna experienced limited to no wave activity. For waves emanating from a NW direction, wave diffraction plays a more important role given that the archipelago’s long axis is orientated in a NW direction. Under this kind of wave setup, the embayed beaches which are most susceptible to a higher wave setup include r-Ramla tal-Mixquqa, Ghajn Tuffieha, Qarraba and Gnejna, given that the orientation of these embayments is in a northwesterly/westerly direction. In Gozo, Xwejni and Marsalforn bay are also susceptible to high wave heights even though the embayment have a NE orientation. This is a result of the increased exposure of the North coastline of Gozo due to wave diffraction. Under this wave setup, most of the beaches located on the eastern coast of Malta exhibit considerable wave sheltering both as a result of the sheltering effect of the island as well as the increased wave protection offered by the embayments.
Figure 4.17: Wave conditions at the 29 beaches considered for this study at approximately the 10 meter contour line within the embayment for two different scenarios. (A) Wave height (m) and direction for wave conditions generated from a NE direction ($60^\circ$). (B) Wave height (m) and direction for wave conditions generated from a NW direction ($300^\circ$).

Based on the results of the wave modelling exercise, the non-dimensional embayment scaling parameter ($NDESP$) $\delta' = S1^2 / 100 R_0 H_b$ proposed by Short (1999) was applied to the beaches under study (Figure 4.18). This parameter can be used to predict if topographic rips are likely to form parallel to headlands but cannot be used to infer
where rips will form in the interior of embayments. The non-dimensional scaling parameter relates the length of the embayed beach shoreline to the incident breaking wave energy, in other words, the larger the value of $\delta'$ the lower is the energy confronting each beach segment. On the contrary, low embayment scaling values indicate a wide beach exposure (Ro) and high $H_b$ per relative short shoreline ($S_1$). According to Short (1999), in bays that present high scaling $\delta' > 20$ the circulation is natural and therefore unconstrained by end effects. Mega-rips are expected to form when scaling is small $\delta' < 8$ as a result of high incident wave energy on a relatively short embayed shoreline.

The modelled wave height at the 10m bathymetric contour within each embayment together with the embayment morphometry data was used to calculate $\delta'$ for waves emanating from a NE and NW direction. The results show that waves from a NE direction are likely to have little effect on the circulatory patterns within most of the embayed beaches in Malta. In fact 21 of the 29 beaches have $\delta'$ values higher than 20, even though some of these embayments are aligned in a NE direction and therefore are more susceptible and exposed to such wave conditions. The average indentation index value for these beaches stands at 1.05, higher than the average index value in other Mediterranean beaches. Seven other embayed beaches are likely to develop some form of rip currents under these kind of wave conditions given that the $\delta'$ values ranged from 8 to 20. These include Armier, Cirkewwa, Dahlet Qorrot, Hondoq ir-Rummien, Imgiebah, Little Armier and Qbajjar. The average indentation index for this group of beaches is 0.6. Only one beach, Marsalforn, is likely to be affected by mega-rips under these wave conditions given that the scaling parameter is less than 8. The indentation index (a/Ro) of the Marsalforn embayment stands at 0.4 and is one of the lowest indentation index values for the embayed beaches in Malta. Therefore this beach is one of the most exposed to incident breaking wave energy from a NE direction.

Wave generated from a NW direction are most likely to have a lesser impact on the hydrodynamic circulatory patterns within embayments given that 26 out of the 29 embayed beaches considered for this study have $\delta'$ values in excess of 20. This is also the case for beaches such as Gnejna, r-Ramla tal-Mixquqa and Ghajn Tuffieha, which given the orientation of the embayment, are expected to be more exposed to incident wave energy from a NW direction. Under this kind of wave setup, only three beaches, Little Armier, Marsalforn and r-Ramla tac-Cirkewwa are susceptible to the development of rip currents. This is also the result of all three beaches having lower indentation index values, the average indentation index is 0.41, and therefore are more exposed to the incident wave energy.
The results indicate that the deep indentation of the embayed beaches in Malta, is probably contributing towards added beach protection and energy dissipation and therefore counteracting the development of mega-rips.

4.5.3 Depth of closure

The location of the depth of closure in an embayment demonstrates whether wave activity is entrapped within the bay or is spread beyond it and therefore it is considered as the maximum water depth at which significant sediment motion occurs (Bowman et al, 2014). The depth of closure can be computed by two methods: (a) analytical approximations such as those developed by Hallermeier (1978), which is based on wave statistics at a particular location or (b) empirical methods such as cross-shore profile surveys. Defining a single depth of closure for a particular site can be
complicated. This is since the active portion of the shoreface varies in width throughout the year depending on wave conditions and therefore is not constrained to a fixed point, but moves depending on waves and other hydrodynamic forcing.

The formula proposed by Hallermeier (1978), \( h_{in} = 2.28H_s - 68.5(\frac{H_s^2}{gT^2}) \), was used to estimate the depth of closure for the embayed beaches based on the annual significant wave height where \( H_s \) is the significant wave height that is exceeded for 12 hours per year, \( T \) is the wave period associated with \( H_s \) and \( g \) is the acceleration of gravity. The wave conditions for a return period of 1 year where sourced from a wave prediction study carried out at Marsascala Bay (Wallingford, 1993b) and corresponded to a significant wave height of 4.2m and a wave period of 8.2 seconds. The indicative depth of closure based on the significant wave conditions with a 1 year return period corresponds to 7.7 m. A comparison of the estimated depth of closure with the submarine morphology indicates that in most cases the depth of closure is located well within the embayment and therefore the active zone occurs entirely within the boundaries of the embayment. This means that according to the classification devised by Bowman et al (2014), 72% of the embayed beaches analysed are considered as Closed given that the depth of closure is entrapped within the embayment. At Qbajjar, Ramla, San Blas and Dahlet Qorrot, sediment bypassing of the embayment in one direction is possible given that the active zone extends along the rocky shoreline of the embayment almost up till the headland point and therefore these embayments can be considered as Semi-Closed. Satellite imagery of these embayed beaches reveals that a considerable volume of sand is deposited along the sides of the embayment, indicating that the active zone is quite extensive and that sediment exchange between the beach and these zones is an important process for the overall sediment budget of the embayment. Armier and Little Armier are classified as Open given that the depth of closure is seaward of the small headland dividing these two adjacent embayments and therefore sediment exchange between these two beaches is possible. This is also the case for Golden Sands and Ghajn Tuffieha.

In a similar study by Bowman et al (2014) on 23 embayed beaches in the island of Elba, the results demonstrated that: 1) seven of the embayed beaches are closed and therefore bed activity occurs entirely within the embayment, 2) nine bays are semi-closed and therefore sediment bypassing can occur in one direction, 3) seven bays are open and can exchange sediments with adjacent coastal sectors. The relatively higher proportion of embayed beaches which are considered as closed from a hydrodynamic point of view indicates the likely impact of structural control on the physical setting of these beaches due to higher indentation values. This was also illustrated in Figure 3.9 earlier on.
4.6 Conclusions

The key morphometric parameters of 29 embayed beaches in the Maltese islands were analysed to determine the variance that exists in embayment morphometry. Embayed beaches in Malta generally exhibit smaller headland spacing values (Ro) and higher indentation values (a) leading to embayments which are more indented than those found in other Mediterranean islands. High correlations exist between bay indentation (a) and headland spacing (Ro) as well as the length of the embayment (S1) and bay indentation (a). The embaymentisation index (S1/Ro) and indentation index (a/Ro) do not show any spatial correlation, implying that the location of embayed beaches is not the result of an over-arching geophysical process but the result of a combination of local geomorphological conditions.

Based on their morphometric characteristics, embayed beaches in Malta can be grouped into the following four distinct categories:

- Embayed beaches where headland spacing is equivalent to the indentation of the embayment
- Embayed beaches where the headland spacing is greater than the indentation of the embayment and therefore are more exposed
- Embayed beaches where the headland spacing is almost twice the length of the bay indentation and therefore are the most exposed
- Embayed beaches where the bay indentation is greater than the headland spacing and therefore are the least exposed

Significant positive correlations exist between the length of beach shoreline (S2) and headland spacing (Ro) and the length of beach shoreline (S2) and the length of embayed shoreline (S1). The length of beach shoreline (S2) and beach area (Ab) do not exhibit any correlation with the embaymentisation index (S1/Ro) and indentation index (a/Ro). The orientation of the embayments was confirmed as an important parameter in terms of wave sheltering from the dominant wave climate. In terms of hydrodynamic circulation, wave emanating from a NE direction are likely to generate some form of rip currents in beaches with low indentation index values. None the less most of the hydrodynamic activity is bounded by the extent of the embayment, limiting the amount of sand which can be lost from the system.
5 Meso-scale behaviour of embayed beaches

This section focuses on the analysis of shoreline position derived from geo-referenced aerial and satellite imagery. As illustrated earlier on in Figure 1.1, coastal change can occur at various temporal and spatial scales, and shoreline change is one of those processes which, depending on the spatial scale of analysis, is present at all timescales. The analysis of shoreline change and the quantification of this change can therefore help identify the processes causing shoreline erosion and accretion and allow for better coastal area management.

Shoreline change analysis was carried out at the eight beaches shown in Figure 5.1. Rates of shoreline change were generated in ArcGIS with DSAS version 4, an ArcMap extension developed by the USGS (Thieler et al; 2009). DSAS employs the single-transect method (ST) to calculate change rates and rate uncertainties at regularly spaced transects (measurement locations) alongshore.

![Figure 5.1: Map of the Maltese islands showing the location of eight beaches (highlighted in red) for which shoreline change analysis was undertaken.](image)

Aerial imagery was available for all eight beaches during the years 1955, 1988, 1998, 2004, 2008 and 2012; 1968 imagery was also available for all sites except Gnejna, San Blas and Ramla l-Hamra. Satellite imagery was available for most beaches for 2006, 2007, 2009, 2011, 2013, 2015 and 2016. Most of the aerial imagery was made available by the Water Services Corporation or else procured from the Mapping Unit at
the Planning Authority whereas all the satellite imagery was sourced from Google Earth Imagery. The datum used for all the imagery and digitized shorelines was ED1950 and the units used are meters.

5.1 Shoreline change analysis

Historical trend analysis was undertaken to examine the meso-scale tendency of the shorelines of eight embayed beaches in Malta. High water shorelines were digitized from aerial imagery dated between 1955 and 2016. Shoreline changes were assessed at for a total of 305 transects, achieving a longshore resolution of 5 m. In the shoreline change analysis due consideration was also given to the uncertainty that arises as a result of the digitization process. In this regard the uncertainty of the aerial photographs and satellite imagery was calculated at ±2m based on the scale of the imagery. The planform characteristics and variations in shoreline positions for the period ranging from 1955 to 2016 are shown in Figure 5.2.

Figure 5.2: Maps showing the location and variations in shoreline position for the period ranging from 1955 to 2016 for the following beaches: (A) San Blas, (B) Ramla l-Hamra, (C) Armier, (D) Little Armier, (E) White Tower, (F) Golden Sands, (G) Ghajn Tuffieha and Gnejna (H).
5.1.1 Net Shoreline Movement

The analysis of net shoreline movement (NSM), which reflects the net change in position between subsequent dates, was carried out at the following timescales:

- A longer term analysis (approximately 60 years) covering the whole period from 1955 to 2016 and for which aerial imagery and satellite imagery were available
- Movement at the medium time scale (approximately 30 years) for the periods 1955-1988 and 1988-2016
- An analysis of net shoreline movement at a more recent, shorter time scale for the periods 1988-2006 and 2006-2016.

Different timescales were considered for the analysis of the NSM so as to avoid masking important changes occurring at various timescales throughout the 60 year period. The results of the NSM were classified into eight different categories indicating various levels of net shoreline movement (Table 5.1). The same categories were used for all the embayed beaches and across all the different timescales of analysis to ensure comparability of the results. Results of NSM ranging from +2 to -2 m, which is equivalent to the margin of error for the analysis, were grouped within the same category to address errors related to uncertainty.

<table>
<thead>
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<tbody>
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<td>10 m to 20 m</td>
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</tbody>
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Table 5:1 Categories used for the classification and analysis of net shoreline movement

The analysis of net shoreline movement at San Blas beach (Figure 5.3), on the northeast coast of Gozo, reveals that most of the beach front underwent accretion between 1955 and 2016, with a mean shoreline movement of 8.5 m. On a medium time scale, the beach front underwent erosion between 1955 and 1988 followed by accretion between 1988 and 2016. In fact from 1955 to 1988, the mean shoreline movement was of -4.3 m whereas between 1988 and 2016 the mean shoreline movement was 12.9 m. For shorter time scales, net shoreline movement at San Blas between 1988 and 2006 ranged between -1.6 m and 3.4 m, therefore exhibiting limited accretion whereas between 2006 and 2016 shoreline movement ranged between 9.1 m and 14.3 m with accretion occurring throughout the whole length of the shoreline. It is
important to note that in all the different times scales of analysis, shoreline retreat or accretion at one end of the beach is mirrored by the same behaviour at the other sections of the beach, albeit at different rates. Therefore the results of the analysis seem to imply that shoreline behaviour at San Blas beach - whether erosional or accretional - is consistent alongshore.

Ramla beach (Figure 5.4), just to the west of San Blas, exhibits greater alongshore variation in shoreline change between 1955 and 2016, with the western side of the beach exhibiting slight erosion (maximum shoreline change is of -4.1 m) and the central and eastern part of the beach exhibiting accretion (shoreline change values ranging from 3.4 m to 12.2 m).

On a medium time scale, from 1955 to 1988 the beach front mostly underwent erosion (mean shoreline movement during the period was -4.8 m), whereas between 1988 and 2016 the beach shoreline underwent accretion (mean shoreline movement during the period was 9.6m). Between 1988 and 2006 the net movement of the shoreline was more variable with most parts of the shoreline exhibiting various levels of accretion and the rest exhibiting erosion. Net shoreline movement during the period ranged between -6.3 m and 7.3 m. In the decade between 2006 and 2016, the shoreline at Ramla beach

Figure 5.3: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at San Blas beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.
underwent accretion with a mean shoreline movement during the period of 7.1 m. Unlike San Blas, shoreline behaviour at Ramla beach tends to be variable alongshore.

Armier beach (Figure 5.5), on the north coast of Malta, underwent considerable erosion along the whole length of the shoreline between 1955 and 2016, with an average recession of 12.5 m. Retreat was also exhibited at the medium time scale. Between 1955 and 1988 shoreline retreat ranged from -3 m on the western part of the beach to -10.7 m on the eastern part of the beach. Similarly, shoreline retreat between 1988 and 2016 ranged between -10.4 m on the western side of the beach to -2.6 m on the eastern side. Shorter timescales of analysis indicate that between 1988 and 2006 the mean net shoreline movement was of -9.1 m, but more recently, accretion between 2006 and 2016 has moved the shoreline seaward by an average of 3.3 m. The medium and shorter time scale of analysis indicates that shoreline movement at Armier beach, which can be both positive or negative, has a strong alongshore variance with net shoreline movement at the eastern end of the beach being considerably greater than the western end of the beach.

Neighbouring Little Armier (Figure 5.6) beach underwent slight erosion during the period 1955-2016, with a mean shoreline movement of -4.1m. On a medium time scale

Figure 5.4: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at Ramla beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.
(1955 - 1988) the shoreline remained relatively unchanged as the mean net shoreline movement for the period was -0.3m.

Figure 5.5: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at Armier beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.

Between 1988 and 2016 however, landward retreat of the shoreline was more evident, with a mean shoreline movement of -3.7m. Between 1988 and 2006, and then 2006 and 2016, the Little Armier shoreline exhibited similar patterns of shoreline retreat ranging from -7.3 m to -8.9 m during the first 8 years, and -4.6 m to -6.2 m in the latter 10 years. The analysis of net shoreline movement at Little Armier indicates that the beach shoreline moved very little from 1955 to 1988, but that erosion ensued since the 1980s.

At White Tower beach (Figure 5.7), the northern most beach within the group of beaches located on the Mtarfa peninsula, the beach shoreline underwent considerable erosion. The mean net shoreline movement during the whole period (1955 to 2016) was -23.3 m and the longshore shoreline movement ranged from -18.8 m to -30.6 m. On a medium time scale, the beach front underwent considerable landward retreat between 1955 and 1988 with the mean net shoreline movement during the period being -18.7m. The highest values of net shoreline movement were registered at the
southern section of the beach shoreline, -25.9 m, with net movement values gradually reducing to -14.94 m on the northern section of the beach.

Figure 5.6: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at Little Armier beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.

From 1988 to 2016 the mean movement of the shoreline was of -4.6 m, indicating a further landward retreat of the shoreline position. Between 1988 and 2006 the mean net movement of the shoreline was of -1.4 m whereas between 2006 and 2016 this stood at -0.8 m. The results of the net shoreline movement at White Tower indicate that contrary to what is exhibited at Little Armier, the landward movement of the beach shoreline was greatest during the period ranging from 1955 to 1988. Following 1988, changes in the position of the shoreline where of a lower magnitude, with possibly the position of the shoreline stabilizing in recent years.

From 1955 to 2016, net shoreline movement at Golden Sands (Figure 5.8) was not uniform and longshore variation is evident. Variation in the net shoreline movement during the period ranged from 4.2 m in the northern section to -5.2 m in the southern section of the beach. Between 1955 and 1988 the mean net shoreline movement was 0.4 m, with an alongshore variability ranging from -3.1 m to 5.7 m. Similarly, between 1988 and 2016 the mean net shoreline movement was of -1.3 m but considerable alongshore variation is evident with net values ranging between -9.6 m and 4.2 m.
Figure 5.7: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at White Tower beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.

Between 1988 and 2006 the shoreline retreated by a net mean movement of -7.8 m, with values for net movement ranging from -3.4 m to -14.1 m. In recent years, from 2006 to 2016, the mean shoreline accreted and moved shoreward by 2.8 m, albeit with longshore differences ranging from -2.1 m on the southern part of the beach to 8.9 m, in the northern part of the beach. The results show that at Golden Sands, changes in the position of the shoreline at one end of the beach are not necessarily reflected in other sections of the beach shoreline both in terms of magnitude of change and in terms of process (eroding as opposed to an accreting shoreline).

Net shoreline movement at Ghajn Tuffieha (Figure 5.9) from 1955 to 2016 reveals that most of the shoreline either remained relatively stable or exhibited accretion, with values ranging between -1.4 m and 5.3 m. From 1955 to 1988 erosion probably has led to an average value of net shoreline movement of -1.8 m. On the contrary between 1988 and 2016 the shoreline underwent accretion with the mean shoreline movement for the period being 3.1 m and the highest values being exhibited in the central section of the shoreline (up to 9m of shoreward movement).
The overall accreting trend of the shoreline is also exhibited at smaller timescales of analysis. Between 1988 and 2006 the mean net shoreline movement was 2.3 m whereas between the 2006 and 2016 this stood at 3.2 m. During both timescales, accretion was greatest in the central section of the shoreline. The results of the different timescales of analysis at Ghajn Tuffieha indicate that the beach seems to have remained stable throughout the whole study period with a slight shoreward movement of the shoreline as a result of accretion.

From 1955 to 2016, net shoreline movement at Gnejna (Figure 5.10) underwent considerable erosion, with the mean shoreline movement for the period being -13.6 m. On a medium time scale of analysis, the shoreline underwent erosion between 1955 and 1988 and similarly, although to a lesser extent, between 1988 and 2016. From 1988 to 2006 the net movement of the shoreline varied longshore between 3.1 m on the western part to -3.8 m on the eastern part of the beach. In recent years, from 2006 to 2016, the mean net shoreline movement stood at -3.9 m, indicating a landward retreat of the shoreline. The results of the analysis at Gnejna indicate that the causative factors leading to the erosion of the shoreline have had a considerable effect on the position of the shoreline which in turn led to a significant landward retreat.
Figure 5.9: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at Ghajn Tuffieha beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.

Figure 5.10: Analysis of the distance between the oldest and youngest shoreline (net shoreline movement (m)) at Gnejna beach for the periods ranging from 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.
5.1.2 Range of shoreline position

The analysis of the range of shoreline position was carried out through the shoreline change envelope (SCE), which reflects the gross change in position between all the available shorelines. The whole range of available shoreline data, from 1955 to 2016, was used for the analysis of SCE, the results of which are presented in Figure 5.11. The results of the SCE were classified into five different categories indicating various levels of gross shoreline change. The same categories were used for all the beaches to ensure comparability. Results of SCE ranging from +2 to -2, which is equivalent to the margin of error for the analysis, were grouped within the same category to address errors related to uncertainty.

The long-term analysis of gross shoreline change at San Blas indicates that between 1955 and 2016 all the sections of the shoreline exhibited a high degree of variability. The mean gross change value for San Blas during the period was 14.4 m. The results indicate that the shoreline at San Blas beach is susceptible to a high degree of change. However when comparing the results of the SCE with those of the NSM it is evident that changes in shoreline position do not necessarily imply that the beach shoreline is eroding or accreting. The analysis of gross shoreline change at Ramla indicates that between 1955 and 2016 all the sections of the shoreline exhibited a high degree of variability, with the envelope of change being highest on the eastern part of the shoreline. The results also indicate that change in the relative position of the shoreline is expected to be highest on the eastern side of the shoreline and lowest in the central sections of the beach.

At Armier all the sections of the shoreline exhibited a high degree of variability with change values ranging from 17.6 m to 26.8 m and the mean value for the period being 21.7 m. The shoreline change envelope at neighbouring Little Armier was similar throughout the whole section of the shoreline, with the mean gross change value 14.4 m. The results show that the alongshore variability in gross shore change values is rather limited, which is in part due to the small size of the beach. Though Little Armier is a small beach by Maltese standards, the amount of shoreline variability throughout the period was comparable to larger and more exposed beaches. Between 1955 and 2016 White Tower exhibited a high degree of variability. The mean gross change value for White Tower during the period was 28.8 m, the highest value of gross change from the group of beaches considered for the shoreline change analysis.
Figure 5.11: Patterns of change in shoreline position (reflecting the envelope of shoreline change (m)) at the eight beaches under study for the period ranging from 1955-2016.
The envelope of shoreline change at Golden Sands indicates that between 1955 and 2016 the mean gross change value for the period was 13.8 m. When considering the extent of Golden Sands beach, the envelope of variability of the shoreline is considerably lower than what is evidenced in other embayed beaches in Malta. Lower variability across the different timescales increases the possibility that the shoreline is in a relatively stable condition with respect to the wave setup. At Ghajn Tuffieha, SCE between 1955 and 2016 ranged between 4.6 m and 12.1 m. The greatest fluctuations in the position of the beach shoreline occurred in the central and northern section of the shoreline. The mean gross change for the period was 8.7 m. At Gnejna, the envelope of change between 1955 and 2016 ranged between 11.5 m and 22.1 m. The greatest fluctuations in the position of the beach shoreline occurred to the east of the central section of the shoreline. The mean gross change for the period was 18.6 m.

The long-term results (1955 to 2016) of the analysis of NSM and SCE were compared to determine the extent to which there is a correlation between the net and gross changes in shoreline position along the eight embayed beaches considered for this study. The results, presented in Figure 5.12, show that net shoreline change does not always reflect the maximum change experienced by the beaches over the last 60 years. Changes in the position of the shoreline throughout the period, as shown by the SCE, are often greater than the net shoreline movement. This phenomenon is most evident as Ramla, Golden Sands and Ghajn Tuffieha.

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Figure 5.12: Plot showing the correlation between the envelope of shoreline change and the net shoreline movement for the period ranging from 1955 to 2016.
The importance of geological factors as a control on the morphodynamic state of the beach was determined through the analysis of the envelope of shoreline change at each of the eight beaches with respect to the width of the beach (Figure 5.13).

Figure 5.13: Plot of the envelope of shoreline change at each of the eight beaches considered for this study for the period 1955 to 2016 against the mean width of the beach during the period.

The results show that there is no significant correlation ($R = 0.147$) between the beach width and the envelope of profile change recorded during the period from 1955 to 2016. Variability in the position of the shoreline is not dependent on the width of the beach. Instead, the results show that in most cases, variability in the position of the shoreline often tends to be comparable across the whole length of the shoreline, irrespective of the width of beach. This is probably the result of the small nature of Maltese beaches, which due to their embayed morphology and limited shoreline extent (the average shoreline length of Maltese beaches is 134 m) alongshore variability is not significant enough to create noticeable long-term variations in shoreline change between one end of the beach and the other. Similar results are exhibited by Pinto et al (2009) for an embayed beach in Portugal where beach width variations for a number of profiles along Armacao de Pera beach show complex behaviours with changes in beach width exhibiting different responses to offshore wave forcing.
5.1.3 Shoreline trends

Shoreline erosion and accretion rates were measured by means of the linear regression rate of change statistic (LRR). Positive rates of change indicate that the shoreline is accreting, whereas negative change rate indicate that the shoreline is retreating. The analysis of shoreline erosion and accretion for the eight beaches under study was carried out for the same timescales considered for the NSM earlier on. The linear rate-of-change statistic was preferred to the end point rate given that in its computation, the linear rate-of change statistic considers all the available shorelines and therefore is expected to provide more realistic rates of change.

The results of the alongshore rates of change in shoreline position at San Blas beach are shown in Figure 5.14 for different timescales. The long-term analysis shows that the shoreline has been relatively stable throughout the period with very low rates of shoreline accretion exhibited throughout the whole length of the shoreline.

Figure 5.14: Plot of the alongshore shoreline erosion and accretion rates (m/yr) at San Blas and Ramla beach during five different timescales: 1955-2016, 1955-1988, 1988-2016, 1988-2006 and 2006-2016.
At the medium timescale of analysis, from 1988 to 2016, the shoreline exhibited higher rates of accretion throughout the whole length of the shoreline. This was also the case from 1988 to 2006. Rates of shoreline change, in the form of accretion, were highest during this last decade, from 2006 to 2016, with shoreline accretion being most pronounced in the central and western parts of the beach. During this period rates of shoreline accretion ranged from 0.4 m/yr to 0.9 m/yr. At Ramla beach (Figure 4.14), rates of shoreline change from 1955 to 2016 were very low (mean rate of 0.01 m/yr) almost no alongshore variability, indicating that the shoreline has been relatively stable during the period. From 1988 to 2016, rates of shoreline change indicate that the shoreline was accreting at a mean rate of 0.2 m/yr. Rates of shoreline accretion were highest at the western and eastern part of the beach. On a shorter timescale of analysis, from 1988 to 2006, the rates of shoreline change were more varied, with some parts of the beach exhibiting erosion and other part exhibiting accretion. The highest rates of accretion (0.41 m/yr) were exhibited on the western part of the beach whereas the highest rates of erosion during the period were exhibited on the eastern part (-0.35 m/yr). During the last decade, the rates of shoreline change at Ramla beach indicate that the shoreline is accreting, albeit with significant alongshore variation. Beach accretion rates were highest at the eastern parts of the shoreline (2.03 m/yr) and lowest in the central section (0.09 m/yr).

The long-term analysis (1955 to 2016) of shoreline change rates at Armier (Figure 4.15) indicates that the shoreline has retreated landward at mean rate of 0.25m/yr. During this period, rates of shoreline erosion were highest on the eastern part of the shoreline (in particular from transect T24 to T27). At the medium timescale of analysis, from 1955 to 1988 and from 1988 to 2016, the shoreline was still exhibiting rates of erosion. Between 1955 and 1988, rates of erosion were highest on the eastern part of the beach and lowest on the western part. On the contrary, between 1988 and 2016, rates of erosion were highest on the western part and lower on the eastern part of the beach. On a shorter timescale of analysis, from 1988 to 2006, the shoreline at Armier exhibited even higher rates of erosion, (-0.46m/yr), with limited alongshore variation in shoreline erosion rates. In was only during the last decade, from 2006 to 2016, that the shoreline at Armier beach exhibited rates of accretion. The mean shoreline accretion rate during the period was 0.41m/yr with shoreline accretion rates being highest on the eastern side of the beach. At Little Armier (Figure 5.15) rates of shoreline change from 1955 to 2016 indicate that the shoreline has experienced a very slow rate of erosion (mean erosion for the period is -0.09m/yr). From 1955 to 1988 the shoreline was practically stable with rates of change being very low during the period (accretion rates of 0.01m/yr). From 1988 to 2016 and 1988 to 2006 shoreline change rates were
practically the same, with the shoreline exhibiting low rates of erosion during both periods (mean values of -0.22m/yr and -0.21m/yr respectively).

During the last decade, from 2006 to 2016, shoreline erosion rates at Little Armier where higher with the mean value for the period being -0.44m/yr. It is important to note that at Little Armier, very limited alongshore variability exists in the rates of change throughout the different timescales of analysis. Rates of change at Little Armier beach
are very much the same throughout the whole length of the beach shoreline. At White Tower beach (Figure 4.15), the results of the multi-decadal analysis (1955 to 2016) shows that the shoreline has been eroding at an average rate of -0.38m/yr with very limited alongshore variability in the rates of erosion ranging from -0.44m/yr to -0.35m/yr. From 1955 to 1988, rates of shoreline erosion where higher with the mean rate for the period being -0.55m/yr, with rates of erosion being higher at the western part of the beach (Transects T1 to T4) and lower on the eastern part (Transects T22 to T25). Shoreline change rates between 1988 and 2016 were relatively the same throughout the whole length of the shoreline (-0.21m/yr) with limited alongshore variability. From 1988 to 2006, White Tower beach exhibited the lowest rates of erosion with the mean rate for the period being -0.11m/yr. During the last decade, from 2006 to 2016, rates of shoreline change increased once again with the beach exhibiting a landward retreat at a mean rate of -0.51m/yr. During this period, shoreline erosion rates where highest on the northern section of the shoreline (T19 to T21).

Figure 4.16 presents the results of the alongshore rates of change in shoreline position at Golden Sands, Ghajn Tuffieha and Gnejna. The long-term analysis shows that the shoreline exhibited low rates of erosion, mean retreat rate during the period was of 0.1m/yr, with limited alongshore variation. From 1955 to 1988 the shoreline position was relatively stable throughout the whole length of the shoreline. In the subsequent 30 years, from 1988 to 2016, the shoreline was progressively being eroded at a mean rate of -0.2m/yr, with erosion rates being more pronounced on the southern part of the shoreline (T1 to T10). The highest rates of shoreline erosion were exhibited between 1988 and 2006. Mean annual shore erosion rates during the period stood at -0.3m/yr, with this retreat being more pronounced on the southern part of the beach (T1 to T9). During the last decade, from 2006 to 2016, shoreline change rates included significant alongshore variations with one half of the beach exhibiting erosion rates, from T1 to T20, and the other half exhibiting accretion rates, from T21 to T43. The long-term analysis of shoreline change at Ghajn Tuffieha (Figure 4.16) indicates that the very low rates of shoreline erosion and accretion during the period have practically led to the beach shoreline remaining in a stable position. This is also the case for the medium timescale of analysis. Very low rates of shoreline change during the periods 1955 to 1988 and 1988 to 2016 have led to the beach shoreline remaining in stable position. On a shorter timescale, from 1988 to 2006, the beach exhibited low rates of accretion with the mean accretion rate for the period being 0.16m/yr. In the last decade, from 2006 to 2016, the shoreline at Ghajn Tuffieha was accreting at a mean annual rate of 0.41m/yr with the highest accretion rates being registered at the Northern part of the beach (from T55 to T58). At Gnejna beach (Figure 5.16) rates of shoreline change from 1955 to 2016 stood at a mean annual rate of -0.24m/yr with limited alongshore
variability in erosion rates. Similar rates and patterns of erosion are exhibited between 1988 and 2016. The mean annual erosion rate during the period was -0.18m.

Between 1988 and 2006, shoreline change rates exhibited a higher degree of variability with the western and central sections of the beach exhibiting low rates of accretion (from T1 to T22) and the eastern part of the beach (from T26 to T41) exhibiting...
erosional rates. On the contrary, between 2006 and 2016 the highest rates of shoreline erosion were exhibited in the western and central sections of the beach (T3 to T20) with increasingly low rates of beach erosion on the eastern part of the beach.

The results of the linear regression rate-of-change statistic (LRR) were compared to the end point rate (EPR) statistic as shown in Table 5.1.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Linear Regression Rate (m/yr)</th>
<th>End Point Rate (m/yr)</th>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>Mean</td>
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</tr>
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</table>

Table 5.2: Table showing the minimum, maximum and mean annual rates (m/yr) of shoreline change across five different timescales of analysis. Rates of shoreline change were calculated by means of the linear rate-of-change statistic (LRR) and the end point rate (EPR).

A comparison of the LRR and EPR shows that in most cases the rates of change as calculated by both methods are comparable. For transects where the LRR statistic provides positive rates of change, this is also replicated by the EPR statistic, albeit at slightly different magnitudes. Similarly where the LRR statistic provides negative rates of change, the EPR also exhibits negative rates of change. The linear correlation between the LRR and EPR statistic is also shown in Figure 5.17. Based on the combined interpretation of the LRR and EPR statistics across the different timescales the eight beaches considered for the analysis of shoreline change can be grouped into two distinct groups. The first group consists of embayed beaches which throughout the
analysis have progressively shown rates of erosion both at the long, medium and short term scale. These beaches, which are Armier, Gnejna and White Tower have experienced a landward retreat during these past 60 years as a result of a combination of natural and anthropogenic phenomenon.

The second group consists of embayed beaches which throughout the analysis have progressively shown a combination of very low rates of erosion or varying rates of accretion at the long, medium and short term scale of analysis. This group consists of Little Armier, Ghajn Tuffieha, Golden Sands, Ramla and San Blas and the beach shorelines within this group are definitely in a stable state and therefore highly unlikely that the shoreline retreated landward during these past 60 years. This discrepancy in embayed beach shoreline change at different timescale of analysis was also evidenced by Balouin et al, (2014) when evaluating the shoreline position of 44 pocket beaches in Corsica. The historical evolution (1948 to 2012) indicates that 13 beaches are accreting where 16 are eroding, whereas the recent evolutionary trend, from 2007 to 2012, indicates that 16 are accreting and 23 are eroding.

![Figure 5.17: Plot of the correlation between the linear regression rate (m/yr) and the end point rate (m/yr) for the eight embayed beaches. Rates of shoreline change as calculated by the two methods show a linear correlation.](image)

The range of shoreline change exhibited within the embayed beaches was analysed with respect to the main embayment morphometric indices (indentation index, embaymentisation index and bay filling index). Figure 5.18 indicates that variations in the position of the shoreline are not correlated to embayment morphometry and that
Figure 5.18: Comparison of the range of the rate shoreline change (m/yr) within embayed beaches to the main morphometric indices: (A) Indentation index, (B) Embaymentisation index and (C) Bay filling index.
this lack of correlation is consistent at different timescales. Other, more important physical factors are responsible for determining the range of shoreline change within embayed beaches. Embayment orientation to the dominant wave conditions could possibly be a better descriptor of the range of shoreline change.

5.1.4 Evidence for progressive or cyclical behaviour

Sites of specific change can be explored in further detail through the examination of discrete transect data. This section presents a comparison of the time series of changing shoreline positions relative to the initial available shoreline position for selected transects located on the sides of the embayed beaches.

The comparison of changing shoreline positions at San Blas beach is shown in Figure 4.19. The plot shows that changes at one end of the shoreline are not necessarily coupled by similar changes on the other end of the beach. The results of the time series also indicate that there are instances where both sides of the beach are exhibiting shoreline erosion, such as in 1988 and 2013, or accretion, such as in 2015 and 2016, although at different magnitudes. In 1998 and 2011, the western part of the shoreline (T2) is exhibiting shoreline erosion whereas the eastern part (T20) is exhibiting accretion. The opposite process, whereby the western part of the shoreline is accreting and the eastern part is eroding could not be identified from the time series data. The western side of the shoreline (T2) is more prone to shoreline retreat as a result of erosion and therefore this part of the beach is exhibiting a cycle of erosion followed by a return to more stable shoreline position. On the other hand the eastern side of the beach (T20) exhibits a cycle of accretion followed by a return to a more stable position. The results also show that although beach rotation may be present, this phenomenon is not clearly exhibited in the data, probably as a result of the beach rotational processes being out of phase and therefore the temporal resolution of shoreline positions is not detailed enough to identify this process.

As in neighbouring San Blas, the plot for Ramla beach (Figure 5.19) shows that changes at one end of the shoreline are not necessarily coupled by similar changes at the other end of the beach. The time series plot indicates that from 1955 to 2016, there are instances where shoreline retreat at the western side of the beach (T2) is coupled by an even greater retreat in shoreline position on the eastern side of the beach (T77). This was the case in 1998, 2006, 2008, 2009 and 2013. In 1988 and 2013 both sides of the beach are exhibiting erosion. However unlike San Blas, in 1988 and 2013, shoreline retreat at one end of the beach was coupled by similar magnitudes of shoreline retreat at the other end of the beach. In 2015, the shoreline at both sides of the beach accreted at a similar magnitude whereas in 2016, shoreline retreat at the
western part of the beach (T2) was coupled by shoreline accretion on the eastern part of the beach (T77). The results also show that the position of the shoreline on the western part of Ramla beach (T2) exhibits a lower envelope of shoreline change than the eastern shoreline (T77). In fact the envelope of variability at T2 ranged from 6.1m to -7.6m from the initial position of the shoreline whereas at T77 this ranged from 5.5m to -20.4m during the period.

Figure 5.19: Comparison of the changes in shoreline position over time, starting from 1955 up till 2016, at specific beach transects in San Blas and Ramla beach.

At Armier, the plot in Figure 4.20 indicates that from 1955 onwards, the shoreline position on the eastern side of the beach (T26) was consistently more prone to shoreline erosion and retreat than the western side (T2). Variations in the position of the shoreline at one end do not necessarily imply a corresponding change in the position of the shoreline at the other end of the beach. From 2007 to 2008, the shoreline position at T2 exhibits a landward retreat of approximately 4m, whereas the shoreline position at T26 practically remained stable. From 2008 to 2011, the shoreline position at T2 accreted and moved seaward whereas at T26, the position of the
shoreline retreated and moved landward. The results also confirm what was already indicated in the previous analysis of shoreline change that the shoreline at Armier has gradually retreated landward and probably reached a point where nowadays the shoreline is in a more stable position.

At adjacent beach of Little Armier, Figure 4.20, changes at one end of the beach shoreline were coupled by similar changes on the other end of the beach. Therefore whenever one side of the shoreline is accreting, the other side is also accreting and moving seaward. This processes also applied for episodes of shoreline retreat. Changes to the position of the shoreline with respect to its initial position in 1955, whether positive or negative, are of the same magnitude. The close coupling of these changes at the opposing ends of the beach is probably the result of the limited shoreline length, which limits alongshore variability and the development of significant differences the position of the shoreline.

The comparison of changing shoreline positions at White Tower beach is shown in Figure 5.20. The time series plot confirms what was already indicated earlier on in this chapter that the shoreline at White Tower beach has progressively retreated from its original position in 1955 until a more stable shoreline position was reached. The results of the time series also indicate that the southern part of the beach (T2) is less likely to exhibit significant changes in the position of the shoreline when compared to the northern part of the beach (T25). In fact between 2011 and 2016, the envelop of shoreline change at T2 ranged between -29.2m and -31.m whereas at T25 the position of the shoreline during the period ranged from -19.2m to -28.1m from the original position of the shoreline. In this regard, changes in the position of the shoreline, both positive or negative, at one end of the beach do not necessarily imply a corresponding change on the other end of the beach shoreline.

The results of the time series of shoreline positions at Golden Sands (Figure 5.21) indicate that changes in the position of the shoreline at one end of the beach, whether positive or negative, are often coupled by similar changes at the other end of the beach, although at different magnitudes. This was the case in 1968, 1988, 2004, 2006, 2009, 2011, 2012 and 2013. In some instances, the beach shoreline at T2 retreated landward whereas the shoreline at T40 accreted seaward. This was the case in 2008, 2015 and 2015. In these circumstances, it was always a case of the shoreline retreating at T2 and accreting at T40. The results also show that the beach shoreline at Golden Sands has remained relatively stable throughout the period, only to be disrupted by intermittent cycles of erosion and accretion.
Figure 5.20: Comparison of the changes in shoreline position over time, starting from 1955 up till 2016, at specific beach transects in Armier, Little Armier and White Tower beach.
Figure 5.21: Comparison of the changes in shoreline position over time, starting from 1955 up till 2016, at specific beach transects in Golden Sands, Ghajn Tuffieha and Gnejna beach.

At Ghajn Tuffieha (Figure 5.21) the results indicate that there were instances where both sides of the beach were exhibiting similar changes in shoreline position, whether accreting or eroding. This was the case in 1998, 2008, 2011 and 2016. In other instances both sides of the beach were exhibiting a retreat in the position of the shoreline, with the northern part of the beach (T58) exhibiting higher magnitudes of
retreat. In 2004, 2013 and 2015 the southern part of the beach shoreline (T20) accreted whereas the northern part of the beach shoreline (T58) remained relatively stable. The results also show that the beach has remained relatively stable throughout the period with temporary cycles of beach erosion and accretion.

The results of the time series analysis for Gnejna beach, Figure 5.21, show that in most cases, changes at one end of the beach shoreline, whether it is accretion or erosion, are also exhibited at the other end of the beach. However, the magnitude with which this change in the position of the beach shoreline occurs varies from one side of the beach to the other. The plot also shows that the beach has retreated landward throughout the years until a more stable shoreline position was reached.

To determine whether beach rotational processes should be considered further, an initial visual assessment of a time series of satellite imagery (Sentinel 2 imagery with a ground resolution of 10 m) was carried for the three beaches located on the western coast of Malta (Golden Sands, Ghajn Tuffieha and Gnejna). The time series of 18 images (Figure 5.22) spanning the period from July 2015 to April 2017 indicates that beach rotational processes at Golden Sands are not as readily apparent. The imagery resolution however does not allow for a quantitative analysis of this process. In this regard an attempt was made to quantitatively identify and determine the possible hinge points responsible for beach rotational processes through the use of the available aerial photography and satellite imagery (Google Earth imagery).

Various methods have been proposed for the analysis of beach rotational processes, but to date there is no standard approach. Quantitative data on the possible location of hinge points was obtained from shoreline intersections for the period ranging from 1955 to 2016. The identified intersection were plotted as points and the density of points showing the location of shoreline intersections was quantified based on a grid made up of 5m² grid squares. The assumption is that the higher the number of shoreline intersections within each grid square the higher the probability that a particular location acts as a hinge point upon which the shoreline rotates.

The highest density of shoreline intersections at San Blas occurs on the east section of the shoreline as indicated in Figure 5.23. However, as demonstrated earlier on in Figure 5.19, given the uneven pattern of shoreline erosion and accretion at San Blas and the alongshore differences that occur from one side of the beach to the other, it is highly probable that the beach does not have a single fixed point of rotation. Therefore the hinge point is probably susceptible to both alongshore and cross-shore movement (due to erosion and accretion of the beach shoreline) as a result of changes in the dominant wave climate.
At Ramla beach the highest density of shoreline intersections occurs at the central part of the shoreline, as shown in Figure 5.24. The close proximity of the shorelines within the central section of the Ramla shoreline also supports the theory that the pivotal point of the shoreline is located in this section of the shoreline given that it’s expected that any shoreline rotation occurs around a fixed point. Therefore the envelope of shoreline change within this section of the shoreline should be of a lower magnitude when compared to the other sections of the shoreline. The results imply that the shoreline pivot point identified at Ramla is most likely located at the central section of the shoreline.
Figure 5.23: Identification of possible hinge points at San Blas beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m$^2$ grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

At Armier the highest density of shoreline intersections occurs on the eastern section of the shoreline are indicated in Figure 5.25. As shown earlier on in Figure 5.20, at Armier beach, variations in the position of the shoreline at one end do not necessarily imply a corresponding change in the position of the shoreline at the other end of the beach. Therefore it is highly probable that hinge point moves according to the current position of the shoreline. In times when the shoreline has retreated, the primary hinge point is located midway between the central and eastern part of the shoreline. The location of this hinge point coincides with the presence of an area where the bedrock outcrops in times of beach erosion.
Figure 5.24: Identification of possible hinge points at Ramla beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m² grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

The western part of the beach is most likely to be significant in times when the beach shoreline has accreted.

At Little Armier, Figure 5.26, the highest density of shoreline intersections occurs in a section of the shoreline which is just off the central section of the beach. Given that the shoreline at Little Armier tends to accrete and erode in a uniform manner along the whole section of the coastline, it is highly probable that the hinge point moves landward or seaward together with the rest of the position of the shoreline.
Figure 5.25: Identification of possible hinge points at Armier beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m$^2$ grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

At White Tower beach, the last of the group of beaches located on the northern coast of Malta, the highest density of shoreline intersections occurs on the southern section of the beach shoreline as indicated in Figure 5.27. Changes in the position of the shoreline tend to pivot around the southern end of the beach, with the beach shoreline on the northern part of the embayment having a greater envelope of shoreline change.
Figure 5.26: Identification of possible hinge points at Little Armier beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m² grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

The highest density of shoreline intersections at Golden Sands (Figure 5.28) occurs at the sides of the beach shoreline. Beach rotation probably occurs around the central section of the beach, with the hinge point probably moving landward or seaward depending on the position of the shoreline. This is also the case in Ghajn Tuffieha (Figure 5.29) and Gnejna (Figure 5.30) where the zone of transition around which minute changes in beach orientation occur is most probably located in the central section of the beach.
5.2 Climate forcing

Malta’s wave climate can be described in the context of the topography of the Mediterranean basin where the flow of the lower atmosphere into the basin occurs mainly through mountain gaps, except over the southern shores east of Tunisia (NSO, 2010). In the Central Mediterranean region both Sicily and the Tunisian peninsula can play an important part in the local weather. Under certain prevailing conditions, Sicily can act as a barrier against strong low-level northerly winds. Transient North African low pressure systems have the potential to produce strong winds over the Central Mediterranean (NSO, 2010).
Figure 5.28: Identification of possible hinge points at Golden Sands beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m² grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

5.2.1 Wind and wave climate

Long-term climate data, from 1979 to 2016, acquired through the Met Office MIDAS Stations was analysed to determine whether changes in the wind statistics have progressively led to changes to Malta’s wave climate. The plot of monthly wind direction and wind speed (Figure 5.31) does not show any apparent changes in long-term wind conditions. Average wind direction and wind speeds have practically remained the same throughout the whole period. In recent years, values for the maximum recorded wind speed seem to be more stable with limited variations year on year.
Figure 5.29: Identification of possible hinge points at Ghajn Tuffieha beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m$^2$ grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

5.2.2 Sea level change

The smaller extent of the Pelagian Sea and Straits of Sicily in the central Mediterranean when compared to the western (Algerian-Provencal basin) and eastern sections (Libyan sea and Levantine Basin) give rise to distinctive weather patterns that pertain to the region and which directly affect the changes in sea level (NSO, 2011). The main influence on sea level is determined by the general synoptic situation over the whole Mediterranean basin, with geostrophic gradients being produced in the Sicilian Channel by different pressure regimes between the western and eastern Mediterranean basins. Besides meteorological forcing other factors are expected to
Figure 5.30: Identification of possible hinge points at Gnejna beach. The red circles indicate possible hinge points for shoreline rotation. (A) Available shorelines for the period 1955 to 2016. (B) Points showing the intersection of one shoreline with another shoreline. (C) Density of shoreline intersections within a 5m² grid square. The greater the density of points within a particular grid square the higher the possibility that the beach is rotating around a particular pivotal point.

Contribute to sea level variability. These factors mainly depend on effects derived from the influence by the general circulation and from mesoscale eddies propagating on the Sicilian shelf.

Monthly sea level data provided by the Ports and Yatching Directorate for the period between 1995 to 2012 (Figure 5.32) indicates that fluctuations in sea level usually are in the order of 20 cm to 30 cm. Seasonal changes in the mean sea level show a major minimum in March and a major maximum towards the last months of the year.
The analysis of densely sampled meteo-marine observations collected in the region of Mellieha Bay by Drago (2009) on the northwestern area of Malta demonstrates that the tidal amplitude in the vicinity of the Maltese Islands is small. The mean spring tidal range is 20.6 cm and is reduced to 4.6 cm during neap tide. Water level variations are dominated by energy inputs from long-period oscillations of non-tidal origin. The time series plot of water level data indicates that the seawater level has been relatively stable throughout the period with no significant changes in sea level and therefore in recent years, from 1995 onwards, changes in the position of the shoreline cannot be attributed to sea level rise.

Sea level data prior to 1995 was not available and therefore the relative contribution of changes in sea level to shoreline change cannot be determined. None the less, the general observed rate of sea level rise in the Mediterranean during the last century was significantly lower than the global average. Based on measurements of available tide-gauges the sea level increased until the 1960s, at a rate of approximately 1.2mm/yr (UNESCO, 2011) and dropped a few cm between 1960 and 1993 probably as a result of atmospheric pressure forcing.
Figure 5.32: Monthly variations in sea level for the period between 1995 and 2012. The general trend in sea level is provided by the black line. The sea level data was provided by the Ports and Yachting Directorate within the Malta Transport Authority.

Between 1993 and 2000, a rapid sea level rise of 4-5cm took place, after which, there was no change. Climate models also indicate that given the expected increase in atmospheric pressure an average reduction of -0.2mm/yr is expected as a result of this forcing (UNESCO, 2011).

5.3 Anthropogenic interventions

In order to gain further insight into the natural and anthropogenic influences on the behaviour of the shoreline, variations in the rates of change according to the coastal landform and anthropogenic features located at the backend of the beach were analysed. In this regard each transect was classified in one of three different categories - bluff, dune and seawall - in order to explore the relationship between rates of change and backshore context. This analysis was carried out at two different timescales, a long-term analysis spanning the period from 1955 to 2016, and a short term analysis from 2006 to 2016 (Figure 5.33).

The results of the long-term analysis indicate that rates of change along the different categories vary widely amongst beach profiles which are backed by seawalls. The
shoreline change rate of beach profiles falling within this category ranged from -0.44m/yr to 0.11m/yr. Most of the profiles backed by seawalls exhibited rates of erosion except for the profiles located in San Blas. Higher rates of erosion could imply that the beach sections backed by seawalls are adjusting and retreating to a more stable shoreline position. On the contrary, variation in shoreline change rates was lowest in profiles backed by bluffs. Shoreline change rates in these profiles ranged from 0.09m/yr to -0.28m/yr. For the short term analysis, 2006 to 2016, the rates of change were most widely distributed for beach profiles backed by dunes. Change rates at dune backed profiles ranged from 2.03m/yr to -0.61m/yr during the period, with dune backed profiles exhibiting the highest rates of accretion. Unlike the longer timescale of analysis, profiles backed by seawalls exhibited the least variation in rates of change between 2006 and 2016. During this period rates of change for profiles backed by seawalls ranged from 0.77m/yr to -0.58m/yr. The lower rates of change for seawall backed profiles could indicate that these beach sections have already eroded and retreated to a more stable shoreline position.

![Figure 5.33: Shoreline change rates for each individual transect as a function of type of geomorphic landform and anthropogenic development.](image)

**5.4 Conclusions**

A historical shoreline change analysis was undertaken for eight embayed beaches in Malta with the analysis showing contrasting behaviours for beaches exposed to the same forcing parameters. Whereas beaches such as San Blas, Ramla, Little Armier, Golden Sands and Ghajn Tuffieha have remained relatively stable in terms of shoreline...
position from 1955 to 2016, beaches such as Armier, White Tower Armier and Gnejna exhibit significant shoreline erosion and landward retreat (ranging from 5 to 40m).

Nonetheless all eight embayed beaches exhibited a high degree of variability from 1955 to 2016 indicating that all embayed beaches are susceptible to a natural cyclic process of shoreline erosion and subsequent recovery. The range of shoreline change exhibited by each embayment is not conditioned by the main morphometric indices of embayment indentation (a/Ro), embaymentisation (S1/Ro) and bay filling index (S2/S1).

Comparisons of changes in shoreline position over time have shown that beach rotational processes are not so readily apparent and in most cases there is a close coupling of shoreline change at opposing ends of the beach. This is probably the result of the reduced headland spacing (Ro) and length of embayed beach shoreline which limit the directional window of wave attack and the development of longshore sediment transport gradients.
6 Beach morphodynamics

6.1 Beach morphology and morphological change

The morphology of eight embayed beaches in Malta and Gozo is explored in this chapter (Figure 6.1). These eight beach systems are located in different physical contexts, and exposed to different environmental conditions. A key question in this research is to what extent the local context and physical processes influence beach morphology and dynamic variability. The beaches occupy three different coastal regions across the Maltese Islands: the north coast of Gozo, the north coast of Malta (the north facing coast of the Marfa Ridge), and the west coast of Malta.

![Figure 6.1: Location of the eight beaches where detailed morphodynamic assessments were carried out](image)

6.1.1 North Gozo

The beaches of San Blas and Ramla, on the north coast of Gozo, are the largest beach systems of Gozo, covering around 2,500 m² and 20,000 m² respectively (Figure 6.2). The beaches are located on the northern part of Gozo and exposed to northerly and north-easterly winds. Ramla and San Blas beaches are located adjacent to each other and are separated by a significant headland called Irdum tar-Ramla, which protrudes around 450m seaward of Ramla beach. San Blas beach is the smallest pocket beach
considered for this study and has formed at the mouth of San Blas valley (Il-Wied ta’ San Blas). The valley is dominated by the presence of the Blue Clay formation that is present along the entire length of the valley system. San Blas beach is flanked by two natural headlands, Rduim tar-Ramla on the western side, and Irdum il-Kbir on the eastern side, that offer some degree of protection to the embayment. All along the embayment, the plateaus of these headlands, Il-Qortin tar-Ramla and il-Qortin ta’ Isopo, are eroded leading to the development of rockslides, slumps and rockfalls made up of upper coralline limestone, which has detached from the edge of the plateaux. This leads to the accumulation of large boulders of upper coralline limestone, varying in volume from a few cm³ to 4m³ (Furlani et al, 2011) at the coast (as shown in Figure 6.3), which increases the dissipative potential of the headland and also provide a readily available source for carbonate beach sand.

Raml Beach is the largest pocket beach considered for this study and similar to San Blas beach, has formed at the mouth of the second largest valley system in Gozo, the Ramla valley (Il-Wied tar-Ramla). The valley mainly consists of globigerina limestone which is flanked by Blue Clay at the sides throughout the whole length of the valley. An intermittent stream occasionally discharges freshwater onto the beach. During periods of extreme rainfall, storm water runoff within the valley reactivates the valley channel and discharges the beach sand into the sea leading to the formation of a temporary stream channel approximately 2 meters wide by 1 in depth. As in San Blas, Ramla beach is flanked by the natural headlands, Irdum tal-Marin on the western side of the embayment and Irdum tar-Ramla on the eastern side (Figure 6.4). The shoreline morphology of the embayment headlands is characterised by the accumulation of large boulders consisting of Upper Coralline Limestone formation. The beach at Ramla is mainly backed by well developed sand dunes which extend up to a maximum of 100m landward in the central sections of the beach. The western part of the beach is backed by low cliffs, ranging from 2m to 4m, comprising clay and marl deposits. These lithologies are relatively unstable and subject to erosion in times of intense wave action. The relative contribution of these clay and marl deposits to the overall beach sediment budget shall be considered in Chapter 7.

Profiles at San Blas beach were collected on the western and eastern side of the beach as shown in Figure 6.5.A and started from the rear of the beach until approximately wading depth. The profiles at San Blas exhibit high degrees of variability over time, especially on the western side of the beach (B1), where maximum beach elevation change was in the region of 3.7m. The beach profiles at San Blas were most developed at the start of the beach profiles survey period (November 2011), following which the beach exhibited considerable morphological change.
Figure 6.2 The location of San Blas and Ramla beach on the north coast of Gozo together with the outcropping geology in the area.

Figure 6.3: The small pocket beach at San Blas with the significant presence of boulders along and at the sides of the beach shoreline (photo taken on 26th March 2012)
During the survey period, the beach morphology at San Blas was characterised by considerable sea grass deposits. This was especially evident on the 18th September 2012 at profile B2 where sea grass deposits modified the morphology of the profile, leading to the development of an artificial berm. In some periods Profiles B1 and B2 exhibit the formation of bars and troughs. This is most pronounced in profile B2 in November 2011, where considerable bar development occurs at around 25m from the control point. In May 2013, the bar and through formation in the foreshore of B1 was the result of sea grass deposits. The beach profile data shows that the beach is slow to recover from high intensity storm events which completely modify the state of the beach. This delayed response of the beach morphology leads to the profiles at San Blas not exhibiting significant differences between winter and summer conditions.

The profiles at Ramla beach are more of a dissipative nature with the presence of a longshore bar which is constantly migrating and adjusting to changing hydrodynamic conditions. This bar is present throughout the whole year and along the entire section of the beach shoreline. Profile R1 is vertically constrained by the presence of the underlying marl which limits the beach’s ability to vertically adjust to the changing conditions. This explains the reduced variability in the beach morphology at R1 when compared to the other beach profiles at Ramla (Figure 6.6.D). This led to the development of a sudden step in the beach profile at the shoreline, in the region of 30cm to 40cm, and which gives a particular shape to the beach profile.
Figure 6.5: Morphological development of the San Blas beach profiles. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelope of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelope of profile change, mean profile and standard deviation at B2.
Figure 6.6: Morphological development of the Ramla beach profiles. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
At profile R2 considerable changes in the berm morphology occur. Most of the time the profile at R2 assumes a typical ‘summer’ profile comprising a landward sloping berm produced by summer swell washing over the berm crest and depositing sand (Figure 6.6.E). Although swell profiles are mostly associated with summer conditions, the highest berm formation occurred in March 2012, following which the sharp berm crest was subsequently eroded in the later months. The occurrence of this berm coincides with the occurrence of a relatively stormy two months in 2012 (February and March). Profiles at R3 indicate a much more active and dynamic beach morphology with changes in beach morphology being consistently high throughout the whole length of the profile (Figure 6.6.H). As with the other profiles at Ramla Bay, the profiles measured at R3 indicate the presence of a migrating longshore bar (Figure 6.6.G).

6.1.2 North Malta

The beaches of Armier, Little Armier and White Tower are located on the north coast of Malta, specifically on the north coast of the Marfa Ridge peninsula (Figure 6.7). Armier and Little Armier are oriented towards the north whereas White Tower beach is oriented in a north-westerly direction. All three beaches are located within natural embayments which protect the beaches from incoming waves and are also sheltered from incoming waves from the small island of Comino, which is located approximately 2km north of the beaches. The structural configuration of the natural headlands sheltering these beaches provides for an interesting case study given that the headland configuration offers different degrees of embaymentisation. All three beaches are constrained by two headlands, Ta’ Macca on the west and Torri l-Abjad on the east, which protrude seaward for about 325m and 425m respectively and limit the directional wave setup. The embayment in between these two headlands is then subdivided by a smaller headland, is-Sur ta’ l-Ahrax, which delimits White Tower beach from the other two beaches and protrudes seaward about 225m. An even smaller headland made up of low rocky coastline then separates Armier beach from Little Armier. The dominant outcropping geology throughout the whole area is the Upper Coralline Limestone which is also the main source for the sand which has accumulated in the embayment.

Armier beach has formed at the mouth of a small valley system and is backed by a combination of low lying agricultural land and manmade infrastructure (including retention walls, beachside restaurants and a small parking area. Of particular importance at Armier is the concrete quay (shown in Figure 6.7) which was built on part of a natural low lying rocky headland located on the eastern side of the embayment. This led to the creation of an artificial reflective headland within the natural embayment. Little Armier is the smallest of three embayed beaches and is flanked by a low lying
(2m to 3m) gently sloping rocky coast on the west side and a small headland on the east side (is-Sur ta’ l-Ahrax). The rear of the beach has been extensively modified and is surrounded by a low retaining wall aimed at limiting the amount of sand which is blown landward during strong north-westerly winds. An access road and car park flanks this retaining wall on the landward side of the beach. White Tower beach is the most sheltered of these three beaches due to the sheltering effect and orientation of the Sur ta’ l-Ahrax and Torri l-Abjad headlands. The shore of these headlands is made up of a low lying gently sloping rocky coast. The beach is backed by an access road which delimits the extent of the beach and the dune system which has developed at the rear of the beach.

![Diagram showing the location of Armier, Little Armier and White Tower Beach on the Marfa Ridge (north coast of Malta) together with the outcropping geology in the area.](image)

**Legend**

**Geological Formations**

- UPPER CORALLINE LIMESTONE FORMATION

**Figure 6.7:** The location of Armier, Little Armier and White Tower Beach on the Marfa Ridge (north coast of Malta) together with the outcropping geology in the area.

The profiles at Armier show varying degrees of steepness with Profile A2 exhibiting a higher seaward sloping beach profile than A1. The berm and backshore morphology is more mobile along profile A1 with changes in elevation in the order of 0.5m occurring at approximately 20m from the control point during the period under study. Both profiles exhibited a low in the berm on 18th March 2012, followed by a sharp berm crest and a steeply sloping beach face. Such a profile is typical of a storm (winter) profile for this location. The landward sloping berm is produced by waves depositing sea grass banquets. Following intense storm events, extensive sea grass banquets, almost exclusively made up of *Posidonia oceanica* material, can be deposited on the beach as shown in Figure 6.8. Subsequently these deposits are partially or fully eroded away as
can be seen in subsequent profiles at A1 and A2. The variability in the backshore beach morphology is also dependent on the location of the bedrock. At A2, the limited variability between subsequent profiles in the backshore is the result of the presence of rocky outcrops which limit the vertical displacement of the beach. In most cases both profiles exhibit a process of beach erosion and recovery which does not depend on a particular season, but is more depended on the dominant wave climate during the period.

Figure 6.8: Development of extensive sea grass banquets at Armier beach. The algal banquets shown in this photo have created a beach step of approximately 50cm in height (photo taken on 26th March 2012).

The profile data for Little Armier (Figure 6.10) indicates that L1 is a reflective beach profile with limited to no backshore area. An offshore bar and trough was measured on 19th May 2012 and the amplitude between the trough and the top of the bar was approximately 50cm. This was subsequently eroded away or migrated further offshore since this morphological feature was not recorded in subsequent profile surveys. At L2, a distinction can be made between the onshore and offshore section of the profile. The great variability at the backshore is not the result of the changing hydrodynamic conditions but as a result of the windblown sand accumulating at the rear of the beach as a result of the retaining wall which delimits the landward extent of the beach. This is subsequently dredged back and redistributed along the beach prior to the summer months. As in Armier beach, sea grass deposits accumulate during periods of stormy weather leading to the development of banquets along the whole length of the shoreline.
Figure 6.9: Morphological development of the Armier beach profiles. (A) Location of beach profiles, (B) Relative cross-shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
Figure 6.10: Morphological development of the Little Armier beach profiles. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
Profiles measured at White Tower, T1 and T2, exhibit dissipative beach profiles with the formation of bars and throughs not captured by the profile surveys (Figure 6.13). At White Tower beach, the backshore areas are quite stable with limited variability occurring during the study period. At T1, extensive berm development occurred on the 19th November 2011, 19th May 2012 and 26th February 2013 (Figure 6.12) as a result of sea grass deposits. The extensive deposits of sea grass banquets at profile T2, which assumes the shape of a landward sloping sharp crested berm, formed as a result of waves washing over the berm crest, depositing sea grass and then ponding in the low of the mid-berm. Of all the eight beaches surveyed during the period, the morphological development of White Tower beach was the most affected by the deposit of sea grass and the formation of banquets.

Figure 6.11: Photo of Little Armier beach clearly showing the retaining wall and access road flanking the rear of the beach. Both sides of the beach are flanked by a low lying rocky coastline (26th February 2013).

Figure 6.12: Development of extensive sea grass banquets at White Tower beach (photo taken on 26th February 2013)
Figure 6.13: Morphological development of the White Tower beach profiles. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
6.1.3 West Malta

The beaches of Golden Sands, Ghajn Tuffieha and Gnejna are located on the west coast of Malta (Figure 6.14). Golden Sands is oriented towards the south west whereas Ghajn Tuffieha and Gnejna have a more north westerly orientation. All three beaches are located within natural embayments which shelter the beaches from incoming waves. Golden Sands is bounded by the Nahhalija headland to the North and a smaller headland to the south, which also separates Golden Sands from Ghajn Tuffieha. Golden Sands is a well developed beach, when compared to other sandy beaches in Malta, with an extensive backshore area ranging up to 70m from the beach shoreline. The rear of the beach consists of a combination of beach facilities on the northern section, a dune system in the central section and vegetated bluffs on the southern section. Golden sands is also located at the mouth of a small valley system, which in times of extreme rainfall can lead to the formation of a temporary stream channel right across the beach.

The sandy beach at Ghajn Tuffieha occupies half of the bayhead in the form of a wedge shaped belt, approximately 150m long and 25m wide, tapering gradually towards the south. The northern part of the embayment is composed of an Upper Coralline Limestone plateau, which features a cliff face (approximately 28 m high) and plunges directly into the sea where blue clay is absent. The rear of the beach is made up of extensive blue clay slopes which descend from the base of the upper coralline plateau to sea level. To the southern part, the Ghajn Tuffieha embayment is delimited by a promontory, known as Il-Qarraba (Figure 6.14), composed of an upper coralline limestone cap rock (ranging from 8 m to 23 m in thickness) and blue clay slopes which descend to sea level. The Qarraba promontory also delimits the Ghajn Tuffieha and Gnejna embayments.

Gnejna beach is bounded by the Barumbara headland to the west and the Qarraba promontory to the north. Although the embayment configuration at Gnejna considerably limits the angle of direct wave exposure, Gnejna beach is directly exposed to waves emanating from a north-westerly direction, which in Malta’s case is the most significant wave setup. Gnejna has developed at the confluence of two valley systems (Wied il-Hmir and il-Wied tal-Mgarr). The dominant outcropping geology at the coast in the Gnejna embayment is the Globigerina Limestone formation. The beach at Gnejna is backed by a combination of low lying Globigerina Limestone cliffs, remnants of past terraced fields, small dune systems and anthropogenic infrastructures. Anthropogenic influence on the embayment is most evidently seen on the right part of the embayment.
where over the years kiosks, slipways and a car park where constructed to accommodate the increasing number of locals and tourists.

As with San Blas and Ramla beach in Gozo, most of the headlands in the area are characterised by the presence of large boulders made up of upper coralline limestone which detach from the edge of the plateaus and find their way to the coast through rockslides, slumps or rockfalls. The presence of these boulders also provides an important source of readily available sand for the beaches in the area.

Figure 6.14: The location of Golden Sands, Ghajn Tuffieha and Gnejna beach on the west coast of Malta together with the outcropping geology in the area.

The profiles measured at Golden Bay, Figure 6.15, show a berm which is at its widest in the central sections of the beach, as seen along profile M2. The berm ranges from 30m to 70m from the control point. The backshore area is significantly reduced to the sides of the embayment with profile M3 exhibiting no backshore. Maximum variability in the morphology of the beach occurs at the beachface in all of the surveyed sections of the beach (M1, M2 and M3), with this variability being highest at M2, where the recorded change from the maximum and minimum measured distance was of 1.2m. The beach profiles also indicate cycles of beach erosion and accretion, which are
Figure 6.15: Morphological development of the beach profiles at Golden Sands. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
Figure 6.16: Gnejna beach (photo taken on 11th March 2012).

Figure 6.17: Golden Sands during stormy weather. The beach face assumed a dissipative beach profile (photo taken on 15th March 2013).

Figure 6.18: Ghajn Tuffieha beach (photo taken on 20th July 2012)
Figure 6.19: Morphological development of the Ghajn Tuffieha beach profiles. (A) Location of beach profiles, (B) Relative cross-shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
Figure 6.20: Morphological development of the Gnejna beach profiles. (A) Location of beach profiles, (B) Relative cross shore position, (C) Changes in Profile B1, (D) Envelop of profile change, mean profile and standard deviation at B1 (E) Change in Profile B2, (F) Envelop of profile change, mean profile and standard deviation at B2.
mostly accentuated in the central sections of the beach (Figure 6.17). Profiles measured at Ghajn Tuffieha show considerable variation, with V1 being more dissipative in nature whereas V2 assumes a more reflective profile. Variability in the profile morphology along V1 was at its highest at the berm as a result of extensive deposits of sea grass leading to the development of banquets. The analysis of the beach profiles at Gnejna show that at G1 the beach is constantly in a reflective state whereas at G2 the beach mostly assumes a dissipative profile. At G3, the reflective beach profile is practically maintained throughout the year. The backshore area at G3 exhibits high variability as a result of storm events. By the end of the surveying period, the beach profile at G3 was still in a heavily eroded state. At G3 the profile is also exhibiting the formation of bar and troughs. In some instances, such as on 20th July 2012 and 6th November 2012, multiple formations are exhibited. The profile data also captures the shoreward movement of the bars along the profile as they migrate shoreward during fair weather. This is most evidently exhibited by the relative close proximity to the shoreline of 3 successive bars and troughs on the 20th July 2012.

6.2 Beach volumes and sediment budgets

The volume of the beach profiles located in the eight beaches considered for this study were then estimated and the results are shown in Table 6.1. From the end of 2011 to 2013 the average profile volume ranged from 3.24m³/m to 109m³/m. The profiles with the highest mean volume during the study period were located in Golden Sands (M2), Ramla (R2) and Armier (A2) with mean volumes of 109.77m³/m, 78.74m³/m and 73.07m³/m respectively. Beach profiles with the lowest mean volumes were measured at San Blas (B1 and B2) at 3.91m³/m and 3.66m³/m, and Gnejna (G3) at 3.24m³/m. Values for the cumulative volume change of the beach profiles over the period indicate a high degree of sediment flux with sediment being repeatedly eroded from the beach to be deposited at a later stage. Cumulative volume change during the period ranged from 5.2 m³/m at R1 in Ramla to 117m³/m at G1 in Gnejna. The mean volume to cumulative volume change ratio indicates the propensity of a particular beach profile to exhibit change in volume of sediment. Ratios ranged from 0.2 at profile R1 in Ramla to 7.5 at profile B2 in San Blas. High ratio values were also registered at Profile G3 in Gnejna and Profile V2 in Ghajn Tuffieha. The ratios also seem to indicate that the lower the measured mean profile volumes throughout the period the higher the probability that a beach profile is likely to exhibit significant volume changes when compared to the mean profile volume. The net volume change during the period accounts for the positive and negative changes in the beach profile volume from the end of 2011 to
By the end of 2013, almost all beaches experienced erosion as can be evidenced by the negative net volume change. Positive volume changes were measured only in beach profiles R2, L2 and V2.

### Table 6.1: Mean, maximum and minimum profile volumes together with volume change statistics for the period ranging between the end of 2011 and 2013.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Beach Profile</th>
<th>Mean Profile Length (m)</th>
<th>Mean Vol (m$^3$/m)</th>
<th>Max Vol (m$^3$/m)</th>
<th>Min Vol (m$^3$/m)</th>
<th>Range of Volume Change (m$^3$/m)</th>
<th>Cumulative Volume Change (m$^3$/m)</th>
<th>Net Volume Change (m$^3$/m)</th>
<th>Cumulative Volume Change/Mean Volume Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramla</td>
<td>R1</td>
<td>20.0</td>
<td>22.9</td>
<td>24.8</td>
<td>21.8</td>
<td>3.1</td>
<td>5.2</td>
<td>-2.1</td>
<td>0.2</td>
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<tr>
<td>Ramla</td>
<td>R2</td>
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<td>85.8</td>
<td>71.1</td>
<td>14.7</td>
<td>47.6</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
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<td>R3</td>
<td>28.5</td>
<td>31.7</td>
<td>37.3</td>
<td>27.7</td>
<td>9.6</td>
<td>22.5</td>
<td>-3.2</td>
<td>0.7</td>
</tr>
<tr>
<td>San Blas</td>
<td>B1</td>
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<td>3.9</td>
<td>12.4</td>
<td>0.8</td>
<td>11.6</td>
<td>19.3</td>
<td>-7.3</td>
<td>4.9</td>
</tr>
<tr>
<td>San Blas</td>
<td>B2</td>
<td>8.0</td>
<td>3.7</td>
<td>11.6</td>
<td>0.8</td>
<td>10.8</td>
<td>27.6</td>
<td>-7.8</td>
<td>7.5</td>
</tr>
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<td>42.4</td>
<td>24.9</td>
<td>17.4</td>
<td>62.0</td>
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</tr>
<tr>
<td>Armier</td>
<td>A2</td>
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<td>73.1</td>
<td>80.9</td>
<td>64.8</td>
<td>16.1</td>
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</tr>
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<td>Little Armier</td>
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<td>10.0</td>
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<td>2.2</td>
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<td>50.1</td>
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<td>White Tower</td>
<td>T1</td>
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<td>9.0</td>
<td>10.8</td>
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<td>11.4</td>
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<tr>
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<td>T2</td>
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<tr>
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<td>42.1</td>
<td>54.2</td>
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<td>67.3</td>
<td>-7.6</td>
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<td>Gnejna</td>
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<td>3.2</td>
<td>6.8</td>
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<td>13.7</td>
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<td>4.2</td>
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<td>44.3</td>
<td>23.4</td>
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</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>V2</td>
<td>10.1</td>
<td>5.7</td>
<td>9.0</td>
<td>3.1</td>
<td>5.9</td>
<td>17.4</td>
<td>2.0</td>
<td>3.1</td>
</tr>
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<td>Golden Sands</td>
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<td>44.2</td>
<td>52.3</td>
<td>38.0</td>
<td>14.3</td>
<td>23.1</td>
<td>-9.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Golden Sands</td>
<td>M2</td>
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<td>109.8</td>
<td>133.3</td>
<td>89.8</td>
<td>43.6</td>
<td>113.3</td>
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<tr>
<td>Golden Sands</td>
<td>M3</td>
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<td>23.4</td>
<td>27.3</td>
<td>17.9</td>
<td>9.4</td>
<td>17.7</td>
<td>-5.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

In order to characterise the variance that exists in the beach profile volume data, principal components analysis was used to find the hypothetical variables which can explain the variability in this data. The results show that most of the variability in the data can be accounted for by the two most important components (98.36%). A scatter plot of the two most important components is shown in Figure 6.21. Component 1 is by far the most important determinant for the variation that exists in the data, accounting for 88.76% of the variance in the beach profile volume data. This component is most probably related to the maximum beach profile volume recorded during the study period. The 2nd component which is responsible for 9.6% of the variance in the beach profile volume data relates to the ratio of the cumulative volume change of the profile with respect to the mean volume throughout the period under study. The cumulative volume change of beach profiles such as R2, M1, R1 and A2 does not exceed the mean volume of the beach profile. On the contrary the cumulative volume change of beach profiles such as G1 and L2 exceeds the mean volume of the profile during the study period, indicating a high degree of sediment erosion and deposition. This
The scatter plot of the principal components analysis indicates that there is great similarity in the beach volume data between the group of profiles made up V2, G3, B1, B2, L1 and T1 (Group A). All of these profiles are characterised by a short mean profile length, low mean volumes ranging from 3.2 m$^3$/m at G3 to 9 m$^3$/m at T1. Group B consists of profiles R1 and R3 in Ramla, T2 in White Tower and M1 and M3 in Golden Sands. This group consists of profiles with a mean profile length ranging from 20m to 36.8m and a mean volume ranging from 22.9m$^3$/m to 44.2m$^3$/m. Group C consists of four beach profiles, V1, A1, G2 and L2, with a mean profile length ranging from 27.6m to 46.3m and a mean volume ranging from 31.7m$^3$/m to 42.1m$^3$/m. Group D is made up of two profiles, R2 in Ramla and A2 in Armier, with a mean profile length of 49.5m and a mean profile volume of 75.9 m$^3$/m. Profile G1 in Gnejna and M2 in Golden Sands are somewhat different to the rest of the profiles given that they have a significantly higher cumulative volume change throughout the study period compared to the rest of the beach profiles.

The groupings in the data as shown in the principal component analysis do not indicate that there is a spatial component to the observed changes in the beach volume data. The main determinants of change in beach profile volume are more related to the mean profile length and the propensity of that particular profile to changes in volume rather than the location of the beach profile with respect to the dominant wave setup and
embayment configuration. The beach volume data and subsequent analysis also shows that there are contrasting differences in volume and volume change between beach profiles measured in the central sections of the beach and beach profiles measured at the sides of the beach. This is most evidently seen in at Golden Sands and Ramla where profiles M2 and R2 are significantly different to the rest of the beach profiles collected in the same embayments both in terms of mean volumes and range of volume change. The funnel shaped planform morphology of these beaches allows for the greater accumulation of beach sediment in the central sections of the beach as a result of greater accommodation space. This greater body of sediment is more prone to changes in volume, given that it is often less sheltered than the sides of the beach, however it is also more resistant to extreme storm events and therefore these profiles are able to recover at a greater rate than the profiles located at the sides of the embayments.

Figure 6.22 plots the mean profile length against mean volume recorded during the period and shows that there is positive and linear correlation between beach profile length and beach profile volume ($R = 0.93$), meaning that beach profile volume is very much dependent and closely related to the length of the beach profile, irrespective of the headland configuration, wave setup, beach orientation and morphology.

![Figure 6.22: Scatter plot showing the correlation between beach profile length (m) and beach profile volume (m$^3$/m) for the eight beaches considered for this study. The blue lines indicate the 95% confidence intervals.](image-url)
The beach profile volumes collected from the end of 2011 to 2013 were also analysed over time to investigate temporal variations in beach profile volume both within the embayment and also between adjacent embayments. The variations in beach profile volume for each beach profile are presented in Figure 6.23.

The time series of beach profile volume at Ramla, Figure 6.23(A), indicates that the volume of the beach profiles was fairly stable throughout the period, with R2 being the most active in terms of volume change. The plot also indicates that changes in one beach profile do not necessarily affect the volume of the beach profile in other sections of the beach. For example, beach profile volume at R2 increased from 75.4m$^3$/m to 84m$^3$/m in May 2013, followed by a reduction in beach profile volume in August 2013 to 75.7m$^3$/m. Similar changes in volume were not exhibited in profiles R1 and R3. Similarly, at San Blas, the changes exhibited at one end of the beach are not necessarily exhibited at the other end of the beach (September, 2012). A comparison of the volume changes observed between 2011 and 2013 at Ramla and San Blas beach does not indicate that short term changes in beach volume in one of the beaches is likely to affect and alter the beach volume of the adjacent beach.

At Armier both profiles exhibit important changes in beach profile volume with the most significant change in volume occurring between September 2012 and February 2013. The plot also shows that changes in profile volume at one end are also exhibited at the other end of the beach. At Little Armier, Figure 6.23C, the volume at Profile L1 was relatively stable throughout the period, whereas profile L2 is more dynamic with the profile volume ranging between 20.8m$^3$/m and 50.1m$^3$/m during the period. The time series of beach profile volumes at White Tower beach indicates that the profile volume of both T1 and T2 during the period was relatively stable. A comparison of the volume changes observed between 2011 and 2013 at Armier, Little Armier and White Tower does not indicate that short term changes in beach volume in one of the beaches is likely to affect and alter the beach volume of the adjacent beaches. The time series analysis also shows that Armier and Little Armier, in particular profiles A1, A2 and L2, are likely to exhibit similar changes in beach volume, given that they are likely to be exposed to similar hydrodynamic conditions.

The time series of beach volume change show contrasting differences in volume change for Golden Sands between the central beach profile, M2, and profiles M1 and M3. The volume at M2 is more dynamic with changes in volume during the period ranging between 89.7m$^3$/m and 133.3m$^3$/m. On the contrary, changes in volume at profile M1 and M3 are more subtle with both sides of the beach exhibiting similar
Figure 6.23: Plots of the variations in beach profile volume over time for the eight beaches considered for this study. The extent of the x and y axis has been standardised to ensure comparability between beaches and their respective profiles.
changes in volume. At Ghajn Tuffieha, changes in beach profile volume are most pronounced at V1, with a reduction in the volume between November 2012 and March 2013 possibly leading to an increase in the beach profile volume at V2 during the period. The profiles show contrasting differences in volume at Gnejna, with profile G1 and G2 exhibiting similar temporal variations in beach volume, whereas changes in volume at G3 are more limited. This could be the result of the lack of sediment at this end of the beach. A comparison of the volume changes observed between 2011 and 2013 at Golden Sands, Ghajn Tuffieha and Gnejna does not indicate that short term changes in beach volume in one of the beaches is likely to affect and alter the beach volume of the adjacent beaches. The time series of beach profile volume changes also indicates that while all three beaches are exposed to the same set of hydrodynamic conditions, given that these three beaches are located on the north-west coast of Malta, the embayment morphology plays an important role in altering the wave setup leading to important differences in beach volume variations between beaches.

Given the high correlation between length of beach profile and profile volume, the analysis of beach volume change was extended to longer time periods to determine whether changes in the overall sediment budget of the three different groups of beaches are occurring on a longer time span than that considered for the analysis of beach profile volume change. To this end, the results of the net shoreline movement for three different time periods, 1955-2015, 1988-2016 and 2006-2016, were used to determine the net sediment exchange in the eight beaches considered for this study. Estimates of sediment exchange where calculated using an Ordinary Least Squares (OLS) regression based upon a 95% confidence interval.

The results of the analysis of net sediment exchange for San Blas and Ramla beach are presented in Figure 6.24. Net sediment exchange at Ramla and San Blas beach was positive throughout the three difference timescale of analysis, indicating that the beaches have always shown signs of accretion and therefore an increase in the beach sediment budget, albeit at different magnitudes. This phenomenon also sheds light on the regional sediment budget of the area. Given that both beaches have exhibited accretion and an increase in overall sediment volume and considering the embayment morphology, it is highly unlikely that beach sediment is exchanged between one embayed beach and the other. Therefore the results also imply that each of the embayed beaches could possibly constitute a littoral cell whereby the boundaries of the littoral cell are delineated by the embayment headlands.
Net sediment exchange for the three beaches located on the north of Malta (Armier, Little Armier and White Tower beach) varied depending on the time scale of analysis (Figure 6.25). The long term analysis shows that between 1955 and 2016 net sediment exchange was negative in all three beaches. White Tower exhibited the highest quantities of net sediment losses at 4,731m$^3$ followed by Armier at 2,636m$^3$. Sediment losses during the period were considerably lower at Little Armier at 304m$^3$.

During the medium term period of analysis, from 1988 to 2016, all beaches exhibited a negative net sediment exchange, albeit at lower magnitudes. The highest losses of beach sediment occurred at Armier, followed by White Tower and Little Armier. Between 2006 and 2016 the analysis of net sediment exchange indicates that Armier beach accreted with a total of 667m$^3$ of sediment whereas both Little Armier and Whiter Tower exhibited erosion and sediment loss.
The comparison of the three different timescale of analysis indicates that Armier and White Tower have lost considerable quantities of sand over the years with the overall sediment budget of these two beaches only stabilising in recent years. On the contrary the sediment budget of Little Armier has been relatively stable throughout the years.

Figure 6.25: Net sediment exchange at Armier, Little Armier and White Tower beach during three different time periods: 1955-2016, 1988-2016 and 2006 and 2016.
given that the net negative sediment exchange is comparable across different timescales. When considering the net sediment accretion and erosion volumes as well as the embayment morphology of the three beaches, it is highly probable that sediment exchange between Armier and Little Armier is an important factor in the overall sediment budget of these two beaches, although the timescale and rate at which this exchange of sediment is occurring cannot be determined. There is the possibility that sediment from Armier and Little Armier is exchanged with beach sediment at White Tower, although as stated before, the timescale and rate at which this exchange of sediment is occurring cannot be determined. The possible linkages in the sediment budget of the three embayed beaches therefore points towards the plausible theory that from a sediment point of view all three beaches are within the same littoral cell, within which a separate sub-cell for Armier and Little Armier beach exists.

Net sediment exchange at Golden Sands, Ghajn Tuffieha and Gnejna depends on the timescale of analysis (Figure 6.26). From 1955 to 2016 both Golden Sands and Gnejna exhibited net negative sediment exchange, although the volumes of net sediment losses varied greatly. During the period Ghajn Tuffieha exhibited net positive sediment exchange with the beach sediment increasing by 813m$^3$. Similarly, during the medium timescale of analysis, from 1988 to 2016, both Golden Sands and Gnejna exhibited a net negative sediment exchange whereas Ghajn Tuffieha exhibited a net positive sediment exchange and therefore an increase in the beach sediment budget. From 2006 to 2016, Gnejna exhibits signs of beach erosion with a total of 1,269m$^3$ of beach sediment being lost during the period, whereas both Golden Sands and Ghajn Tuffieha accreted and exhibit an increase in the amount of beach sediment.

The comparison of the three different timescale of analysis indicates that Ghajn Tuffieha beach always exhibited positive net sediment exchange volumes, indicating that throughout the years the volume of beach sediment has been slowly increasing. At Golden Sands, the overall beach sediment budget is probably stable with cycles of sediment erosion and accretion probably leading to different values of net sediment exchange throughout the years. On the other hand Gnejna beach lost considerable quantities of sand over the years and from the net sediment exchange analysis it is difficult to determine whether the beach sediment budget for this beach is currently in a stable state or if sediment erosion is still an important factor.

The analysis also sheds light on the regional sediment budget of the area. When considering the net sediment exchange volumes as well as the embayment morphology of the three beaches, it is highly probable that sediment exchange between Golden Sands and Ghajn Tuffieha is an important factor in the overall
Figure 6.26: Net sediment exchange at Golden Sands, Ghajn Tuffieha and Gnejna during three different time periods: 1955-2016, 1988-2016 and 2006 and 2016.

sediment budget of these two beaches, although the timescale and rate at which this exchange of sediment is occurring cannot be determined. One can also conclude that it is highly unlikely that sediment exchange is occurring between Gnejna beach and the adjacent beaches, Ghajn Tuffieha and Golden Sands, mainly due to the embayment configuration which is both more embayed and indented with respect to the other two beaches. These considerations also shed light on the regional sediment budget of the area. The results imply that the area can be divided into two littoral cells, with one cell
consisting of Golden Sands and Ghajn Tuffieha and the other cell being made up Gnejna.

6.3 Climate forcing

6.3.1 Short-term variability in wind and wave climate

The average wind speed in 2011 was 3.7m/s whereas the average wind direction was 208°. Similarly in 2012, the average wind speed was 3.9m/s whereas the average wind direction was 220°. The average wind speed in 2013 was slightly higher at 4.4m/s whereas the average wind direction was 223°. The results of the wind conditions during this three year period conform to the long term observations of wind conditions in Malta. The mean annual wind speed during the period 1961 to 1990 was 4.5m/s (NSO, 2011). However the wind data shows considerable variation in the monthly averages. Figure 6.27 plots the mean monthly wind speed conditions from 2011 to 2013 as measured form the Luqa station.

![Figure 6.27: Comparison of the mean monthly wind speeds (m/s) between 2011 and 2013 at the Luqa station, Malta.](image)

The plot shows that during this period, the highest variability in the mean monthly wind speed was exhibited in January with wind speed values ranging from 2.7m/s in 2011 to 5.6m/s in 2013. On the other hand, the highest mean monthly wind speeds over the three year period were exhibited in February at 4.6m/s. The highest mean monthly wind speeds throughout the whole period were recorded in March 2013 at 6.1m/s. Mean monthly wind speeds from January 2013 to June 2013 were also consistently higher than the mean speeds recorded for the same months in previous years. Long
term observations of wind speed conditions at Luqa from 1961 to 1990 also confirm that January is the month with the highest variability in the mean monthly wind speed (NSO, 2011).

A more thorough assessment of the wind conditions throughout the period was subsequently carried out to get a better understanding of wind conditions with respect to the location of the eight embayed beaches considered for this study. In this regard the assessment focused on winds blowing from north-westerly and north-easterly directions. Winds blowing from a north-westerly direction are more likely to be most significant in terms of changes to beach morphology at Golden Sands, Ghajn Tuffieha and Gnejna given that they are located on the western coast of Malta whereas San Blas and Ramla beach are mostly susceptible to changes in beach morphology as a result of winds blowing from a north-easterly direction, given their location on the north coast of Gozo. Armier, Little Armier and White Tower are located on the eastern part of the Marfa Ridge, and although not directly exposed to north-easterly winds, given the orientation of the beach embayments, winds from this direction are most likely to be the most significant in terms of beach morphological changes. The decision to focus the in-depth assessment of the wind conditions on winds blowing from a north-westerly and north-easterly direction was also based on long term statistics of the most common wind directions in Malta. The most common wind direction in Malta is the north-westerly which blows on an average of 20.7% during the year. The other winds are not as dominant, with the least dominant wind over the Maltese islands blowing from the North (NSO, 2011).

Figure 6.28 presents a detailed time series of the wind conditions recorded at Luqa station from 2011 to 2013. Wind speeds greater than 6.5m/s and with a direction ranging from 280° to 320° are highlighted in blue. Wind speeds greater than 6.5m/s and with a direction ranging from 40° to 80° are highlighted in purple. The analysis focused on wind speeds greater than 6.5m/s (12.6 knots) given that such wind conditions are likely to be significant in terms of beach morphology. The time series of wind data for the period shows that in 2011, winds with a speed greater than 6.5m/s and with a direction ranging from 280° to 320° were recorded on 54 different days. Similarly in 2012 the number of days when such winds were recorded totalled to 56. In 2013, strong winds coming from a north-westerly direction where more frequent as these were recorded on 70 days during the year. Winds with a speed greater than 6.5m/s and coming from a north-easterly direction (40° to 80°) were less frequently recorded during the period with only 8 days during 2011, 9 days in 2012 and 15 days in 2013. The results also indicate that the wind conditions from the December 2012 to June 2013
were more conducive the generation of storms arising from a NW direction as opposed to the same period between 2011 and 2012.

Figure 6.28: Wind conditions during 2011, 2012 and 2013 as recorded at the Luqa station in Malta.

The high frequency of days with wind conditions greater 6.5m/s therefore merits further investigation from a hydrodynamic point of view. In this regard nearshore waves for the eight beaches under study were simulated with SWAN. Wave simulations were carried out for waves originating from a north-westerly and a north-easterly direction as a result of winds blowing at 6.5m/s. All runs started with a 1m wave height and wave period of 6 seconds. The results of the wave modelling excersise carried out at Ramla and San
Blas for waves originating from a north-easterly direction (60°) are presented in Figure 5.29. Wave conditions at Ramla and San Blas were extracted from the wave modelling results at the positions shown in Figure 6.29.A and Figure 6.29.B, which approximately coincide with the location of the 10m and 5m bathymetry contour. The wave simulations indicate that wave heights at 10m depth are almost the same for Ramla and San Blas at 0.55m and 0.57m respectively, with limited affect of the embayment morphology on the wave setup given that in both instances, the 10m sampling point coincides with the most outward point in the embayment.

Figure 6.29: Modelled wave statistics for Ramla and San Blas beach at approximately the 10m and 5 meter contour line within the two embayed beaches. The location of the 10m and 5m wave parameters sampling locations are indicated by the yellow and red circles respectively.
At 5m depth, the effect of embayment morphology is more significant on wave diffraction. The wave height within the Ramla embayment at the 5m contour line is reduced to 0.41m whereas in San Blas the wave height is 0.5m.

The results of the wave modelling exercise carried out at Armier, Little Armier and White Tower for waves originating from a north-easterly direction (60°) are shown in Figure 6.30.

Figure 6.30: Modelled wave statistics for Armier, Little Armier and White Tower Blas beach at approximately the 10m and 5 meter contour line within the three embayed beaches. The location of the 10m and 5m wave parameters sampling locations are indicated by the yellow and red circles respectively.
Wave conditions at each of the beaches were extracted at the positions shown in Figure 6.30.A and Figure 6.30.B, which approximately coincide with the location of the 10m and 5m bathymetry contour. The wave simulations indicate that wave heights at 10m depth are lower when compared to the wave conditions in the Ramla and San Blas embayments. The wave simulations in Figure 6.30.C indicate that the maximum wave heights in the area are concentrated on the northern most part of the Marfa ridge (Ahrax Point) leading to considerable wave sheltering for the embayed beaches located on the northern side of the Marfa Ridge. This leads to a lower significant wave height at the 10m contour line, even though the location of the 10m wave sampling point is well beyond the influence of the beach headlands. The wave heights at the 10m and 5m contour line for these three beaches are shown in Figure 6.30.D. At the 5m contour line, there is a further lowering in the modelled wave height, especially at White Tower, indicating that this beach is very well sheltered from wave conditions coming from a north-easterly direction.

The results of the wave modelling exercise carried out at Golden Sands, Ghajn Tuffieha and Gnejna for wave originating from a north-westerly direction (300°) are presented in Figure 6.31. Wave conditions at each of the beaches were extracted from the modelled wave data at the positions shown in Figure 6.31.A and Figure 6.31.B, which approximately coincide with the location of the 10m and 5m bathymetry contour. The wave heights at the 10m and 5m contour line for these three beaches are shown in Figure 6.31.D. The wave simulations indicate that wave heights at 10m ranged from 0.49m at Gnejna to 0.56m at Ghajn Tuffieha. Of the three beaches in this area, Ghajn Tuffieha is the most exposed beach to wave conditions coming from a north-westerly direction. Wave height at the 5m contour line was 0.53m with limited wave diffraction as result of north-westerly orientation of the embayment. Wave diffraction within the Gnejna embayment led to a lowering of the wave height to 0.34m at the 5m sampling point with a significant wave shadow occurring on the western part of the beach as a result of wave diffraction from the Ras il-Pellegrin headland.

6.3.2 Nature and frequency of storms

Storms can have a significant impact on the morphology of embayed beaches. The nature and frequency of storms between the end of 2011 and 2013 were analysed with respect to changes in beach morphology. For the purpose of this analysis, storms were identified based on the measured wind conditions at the Luqa station. Periods where wind speeds in excess of 6.5m/s and blowing from a north-westerly (280° to 320°) and north-easterly direction (40° to 80°) and which lasted longer than 15 hours where
defined as storm events. Storms generated under these conditions were defined as significant in terms of beach morphological change.

At the end of 2011, November and December, the wind conditions were such that no significant storms occurred. The first significant storm in 2012 occurred during February. On the 6th of February 2012 a storm resulting from wind blowing from a north-westerly direction lasted for approximately 24 hours and the measured peak wind
speed was 14.4m/s (28 knots). Similarly on the 16th February 2012 wind from a north-westerly direction blew for 24 hours with peak wind speeds of 11.8m/s (22.9 knots). March led to the first storm in 2012 from a north-easterly direction which lasted for almost 21 hours with peak wind speeds of 15.9m/s. The storms occurring during February and March 2012 led to noticeable morphological changes at Ramla and San Blas with a measureable retreat in shoreline position and reductions in beach volume (Figure 6.23). Marked changes in beach morphology during the period were also recorded at Golden Sands, in particular the central section of the beach shoreline (Profile M2) as also shown in Figure 6.15. Milder but more prolonged storm events were also recorded in April 2012, duration of 27 hours with peak wind speeds 11.8m/s, and May 2012, duration of 30 hours with peak winds speeds of 10.8m/s. No other significant storms as defined earlier on in this research were identified throughout 2012, except for December. This led to the recovery of the beach volume at Ramla, San Blas and Golden Sands during the milder summer period as shown in Figure 6.23. December was particularly significant in terms of beach morphological change given that wind speeds from a north-westerly direction and in excess of 6.5m/s were registered on 13 calendar days.

In 2013, January was the worst month in terms of stormy weather with over 63 hours of stormy weather coming from a north-westerly direction being recorded on three different days at the middle and the end of the month. Peak wind speeds during this period reached 14.9m/s. Another significant north-easterly storm occurred in March 2013 with a cumulative duration of 42 hours and peak wind speeds of 14.9m/s. Additional significant storms from a north-westerly direction were recorded in April, May, August and December of 2013. The August storm, with a total duration of 27 hours and a peak wind speed of 12.3m/s, is particularly significant in terms of beach morphology given that these wind conditions probably generated the same hydrodynamic conditions which one would expect to occur during the winter season. The prolonged period of stormy weather during the first quarter of 2013 and subsequent intermittent storm events throughout 2013 led to the erosion of the beach at Ramla and in particular San Blas (Figure 6.23). Similar effects on beach morphology are evidenced at Golden Sands during the period with the central section of the beach (Profile M2) exhibiting a measurable landward retreat (Figure 6.15) and reduction in profile volume (Figure 6.23). The observed retreat is likely the result of a combination of more energetic wave conditions during the period and also shorter durations between successive storm events, preventing the beach from recovery. Changes in beach morphology were less pronounced along profiles M1 and M2. The beaches adjacent to Golden Sands, ghajn Tuffieha and Gnejna, exhibited contrasting
morphological changes during the same period and the association of morphological changes to hydrodynamic changes proved difficult. Throughout 2013, significant storms from a north-easterly direction were limited and only recorded in June and November 2013.

Stormy weather during the winter months can lead to significant deposits of sea grass mats on the beachface. This can alter considerably the morphology of the beach as evidenced by the increase in beach volume at Armier and Little Armier (Figure 6.23) during the winter months (December 2011 to March 2012 and December 2012 to March 2013). The subsequent reduction in beach volume is a result of the removal of the sea grass deposits from the beachface during the summer period. These deposits have probably reduced the effect of stormy weather on beach morphology. At White Tower, no significant changes in beach morphology could be related to changes in hydrodynamic conditions during the period.

The analysis of the wind statistics indicates that along the Maltese coastline, most energy is expected to be diffracted from northwestern headlands. Therefore beaches with a north/northwest orientation are more susceptible to direct incident wave conditions and associated change in morphology. However, the beaches exhibited contrasting morphological changes when exposed to similar wave conditions. This is since the asymmetry of the incident waves, which is a result of the headland diffraction, does not cause a dominant asymmetric response in beach morphology. Therefore the observed gradual alongshore morphological transitions in the embayed beaches do not fit the direction of the dominant incident waves. This sheds light on the importance of headland control on the morphology of embayed beaches.

### 6.4 Conclusions

The morphological development of the eight embayed beaches shows a process of erosion and accretion which is not construed by specific time intervals (summer and winter seasons) but is more dependent on the occurrence and frequency of storm events. The presence of beachrock in constraining the morphological response of the beach is also a determining factor as well as the presence of beach casts in the form of seagrass banquets. The timing of the deposition of these beach casts is significant in terms of subsequent morphological development.

The analysis of beach volumes indicates that all beaches are considerably mobile in terms of beach morphology, with the central sections of the embayed beaches being more susceptible to morphological change than the extremities of the embayment.
where often embayed beaches tend to narrow out, thus having a limited supply of sand.

The regional sediment budget analysis indicates that San Blas and Ramla beach each constitute a littoral bounded by the embayment headlands. Both beaches have shown a positive increase in their respective sediment budget across different timescales. On the contrary Armier, Little Armier and White Tower exhibited contrasting differences in net sediment exchange and probably form part of the same littoral cell, with Armier and Little Armier forming a separate sub-cell within this group of embayed beaches.

The analysis of wind statistics and wave modelling indicates that the alongshore morphodynamic evolution of embayed beaches does not fit the direction of the dominant incident waves emanating from the NW, emphasizing the importance of headland control on the morphology of embayed beaches.
7 Sedimentology of embayed beach systems

Sedimentology can go a long way towards providing a better understanding of beach processes, morphology and dynamics (Bird, 1996). The main aim of this chapter to characterise the sediments of embayed sandy beaches in the island of Malta and Gozo. The analysis of beach sedimentology first focused on 26 embayed beaches in Malta and Gozo to capture beach sediment characteristics across the Maltese islands beaches. This was followed with a more in depth analysis of sediment texture, composition, provenance and transport in 8 of the embayed beaches.

7.1 Regional patterns of sedimentology

The analysis of sediment size and texture can reveal many aspects of the dynamics of a particular beach (Aboudha, 2003). Sediment grain size is one of the most important features for beach morphodynamics and hydrodynamic behaviour. Sediment hydraulic characteristics depend on grain size and lithology, and differences in sediment permeability influence longshore and cross-shore sediment transport. Sediment properties also govern the rapidity of beach changes with respect to changes in hydrodynamic conditions. In the first part of this chapter the analysis of grain size distributions focuses on sediment samples collected from 26 embayed beaches around Malta and Gozo during summer 2014. Sediment samples were gathered from the berm or backshore area and grain size distributions were measured using a combination of a laser granulometer (for sediment less than 2mm) and sieving (for sediment greater than 2mm).

7.1.1 Sediment texture and composition

Grain size is the most fundamental property of sediment particles, affecting their entrainment, transport and deposition (Blott et al; 2001). Particle size parameters of 26 embayed beaches in Malta are summarized in Table 7.1. The mean grain size of all samples combined is 824.5μm however particle size can vary greatly depending between beaches. In fact, the mean particle size for the samples collected ranged from 2775 μm at Marsaxlokk to 193 μm at Balluta. In most cases, the mean sediment value is very similar to the D₅₀ percentile. It is only at Cirkewwa, Marsaxlokk and Xwejni that significant differences exist between the mean and D₅₀. The larger mean sediment value in these three beaches is the result of a beach sediment distribution that is coarse skewed. The width of the sediment distribution can be characterised by dividing the D₉₀ percentile by D₁₀ percentile; Qalet Marku, Cirkewwa, Marsaxlokk and Xwejni had wide distributions whilst Mgiebah had the narrowest sediment distribution.
Table 7.1 Primary grain size statistics of Maltese beach sediments. The $D_{10}$, $D_{50}$ and $D_{90}$ refers to cumulative percentile values above which the specified percentage the grains are coarser. The $D_{90}/D_{10}$ is a measure of the distribution width between the $D_{90}$ and $D_{10}$ percentiles.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Mean (um)</th>
<th>$D_{10}$ (mm):</th>
<th>$D_{50}$ (mm):</th>
<th>$D_{90}$ (mm):</th>
<th>($D_{90} / D_{10}$) (mm):</th>
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<td>Armier</td>
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<td>266.2</td>
<td>467.9</td>
<td>991.7</td>
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<td>132.7</td>
<td>193.3</td>
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<td>Cirkewwa</td>
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<td>426.0</td>
<td>1109.3</td>
<td>18789.9</td>
<td>44.11</td>
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<td>Ghadira</td>
<td>407.5</td>
<td>196.4</td>
<td>364.9</td>
<td>1091.7</td>
<td>5.560</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>396.2</td>
<td>272.3</td>
<td>395.8</td>
<td>576.2</td>
<td>2.116</td>
</tr>
<tr>
<td>Gnejna</td>
<td>607.9</td>
<td>417.2</td>
<td>607.0</td>
<td>884.2</td>
<td>2.119</td>
</tr>
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<td>Golden Sands</td>
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<td>408.4</td>
<td>593.8</td>
<td>875.9</td>
<td>2.144</td>
</tr>
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<td>Little Armier</td>
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<td>218.9</td>
<td>329.7</td>
<td>502.7</td>
<td>2.297</td>
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<tr>
<td>Marsalforn</td>
<td>891.0</td>
<td>537.5</td>
<td>880.0</td>
<td>1485.5</td>
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<td>Marsaxlokk</td>
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<td>Paradise Bay</td>
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<td>428.7</td>
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<td>2.349</td>
</tr>
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<td>Pretty Bay</td>
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<td>462.9</td>
<td>806.2</td>
<td>1393.0</td>
<td>3.009</td>
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<td>Pwales</td>
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<td>364.2</td>
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<td>Qalet Marku</td>
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<td>1874.9</td>
<td>11886.9</td>
<td>49.70</td>
</tr>
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<td>Obajjar</td>
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<td>351.6</td>
<td>715.7</td>
<td>1379.7</td>
<td>3.925</td>
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<td>2.171</td>
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<td>3.653</td>
</tr>
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<td>297.7</td>
<td>509.7</td>
<td>890.6</td>
<td>2.991</td>
</tr>
<tr>
<td>San Bias</td>
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<td>340.8</td>
<td>521.9</td>
<td>892.5</td>
<td>2.619</td>
</tr>
<tr>
<td>San Giljan - San George</td>
<td>2264.1</td>
<td>629.9</td>
<td>1974.5</td>
<td>9292.5</td>
<td>14.75</td>
</tr>
<tr>
<td>San Gorg Birzebugia</td>
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<td>197.6</td>
<td>464.9</td>
<td>1077.8</td>
<td>5.454</td>
</tr>
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<td>San Tumas - Mscalul</td>
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<td>239.2</td>
<td>532.7</td>
<td>1115.3</td>
<td>4.662</td>
</tr>
<tr>
<td>White Tower Bay</td>
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<td>237.7</td>
<td>384.7</td>
<td>625.2</td>
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<td>Xwejni</td>
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<td>724.4</td>
<td>1226.6</td>
<td>20310.5</td>
<td>28.04</td>
</tr>
</tbody>
</table>

The sediment distribution histograms (Figure 7.1) show that most embayed beaches have a unimodal distribution with bimodal or trimodal distributions only being present in selected number of beaches (Xwejni, Cirkewwa, Qalet Marku, St George’s Bay and Marsaxlokk). Sediment samples with bimodal or trimodal distributions indicate that the hydrodynamic conditions within these embayments were subject to change. The deposition of fine sands is normally associated with low energy conditions, whereas increased wave activity is normally associated with the transport of coarser sand. This phenomenon is not constrained to a specific location or related to a particular embayment configuration. Anthropogenic interventions in the form of quays and/or boat slipways at Cirkewwa, St George’s Bay and Marsaxlokk have probably altered the sediment population of these beaches leading to a coarsening of the sediment within these beaches. Ramla l-Hamra, Mgiebah, Balluta, Ghajn Tuffieha, Golden Sand and Gnejna have similar grain size distributions albeit centred around different mean sediment values.
In 20 of the embayed beaches, the sediment samples consisted entirely of sand (more than 99% of the sample). Only five beaches had significant portions of gravel; Xwejni (29.1%), Cirkewwa (42%), Qalet Marku (48%), St George’s Bay (49.7%) and Marsaxlokk (50.2%). The silt and clay size fraction within the analyzed beach sediments was practically nonexistent except for very small quantities at Qalet Marku (2%) and San Tumas in Marsascala (2.2%).

Figure 7.1: Spatial variation in the sediment size distributions of Maltese beaches: A) full distribution and B) relative to the Udden-Wentworth scale - proportion of Gravel (2mm to 64mm), Sand (0.063 to 2mm) and Mud (<0.063).
The embayed beaches in Malta and Gozo are mainly characterised by medium sand (42% of all locations) followed by coarse sand (34% of all locations) (Figure 7.2.A). Overall the beach sediments are well sorted (30%), moderately well sorted (23%) or moderately sorted (23%). The statistical measures of the sample distributions indicate that most beaches had a symmetrical distribution (65%) with the rest either being coarse skewed or very coarse skewed. Also, most beach sediment samples were mesokurtic (80%) indicating that most of the grains within the sample are concentrated around the mean. The spatial distribution of the main grain size parameters indicate that exposure to the most dominant wave conditions (from a north-westerly and westerly direction) could possibly lead to a coarsening of the mean sediment size. This is most evident in the beaches located on the Northern part of Gozo (Xwejni, Qbajjar, Marsalforn and San Blas) and the western part of Malta (Golden Sands and Gnejna). Also sediment tends to be less sorted with an increase in sediment size (Qbajjar, Cirkewwa, Qalet Marku, St George’s Bay and Marsaxlokk). The degree of sediment sorting can also shed light on the amount of wave energy (Osborne and Simpson, 2005). Sediment sorting is inversely related to energy dissipation and where the latter is at its maximum, sediment sorting is the poorest.

Unweighted pair-group average (UPGMA) clustering was used to organise the beaches into groupings on the basis of grain size distribution. The results, shown in Figure 7.3, indicate a clear separation of beach sediments into four groupings. Group A consists of just one beach, Balluta, whereas Group B is the largest of the clusters with 14 beaches in total. Group C and group D consist of 6 and 5 beaches respectively. Figure 7.3 plots the grain size distribution bar plots, with the samples ordered in the groupings identified through the cluster analysis. The plots indicate that the clustering of beach sediment samples is in terms of the sediment sample composition. The sediment sample at Ballutta (Group A) consists almost entirely of fine sand, which when compared to the other beach samples, is quite unique in the Maltese islands and therefore explains why this beach is in a group of its own. Sediment samples within Group B mostly consist of medium sand and coarse sands whereas Group C is made up of sediment samples with a higher proportion of coarse sand and very coarse sand (ranging from 69% at Rinella to 92% at Marsalforn). Group D represents samples that mostly comprise very coarse sand, fine gravel and coarse gravel. The same clusters are also evidenced in the principal components analysis shown in Figure 7.4. The PCA also confirms that separation between the different sediment clusters is based on the proportion of medium sand and very coarse sand. This first component clearly separates groups A/D from B/C and accounts for 52% of the variability that exists in the data. The second component, which accounts for 30% of the variability in the data, separates the groups based on the proportion of fine sand and coarse sand.
Figure 7.2: Spatial representation of the main grain size parameters measuring the average size (A), the spreading of the sizes around the average (B), the symmetry or preferential spread to one side of the average (C) and the degree of concentration of the grains relative to the average (D).
Figure 7.3: Cluster analysis of the grain size distribution data for the 26 embayed beaches (upper panel) together with simplified grain size distribution bar plots with the samples ordered according to the groups identified through the cluster analysis (lower panel). The groupings show a clear separation in terms of sediment distribution composition.
Figure 7.4: Plot showing the results of the principal component analysis for the sediment samples collected from the 26 embayed beaches. As shown earlier in this chapter, clear separation exists between the four groups of embayed beaches.

The identified beach sedimentology groups were compared to the regional geology to determine the importance of the outcropping geology for the delineation of beach clusters (Figure 7.5). The results show that the outcropping geology, both along the coastline, and further inland for beaches which are located at the mouth of a valley system, does not determine the sediment size distribution. Exposure to the dominant wave conditions and the interaction of the wave climate with the embayment configuration is definitely a more important controlling factor when it comes to the regional differences in beach sediment.

The main textural parameters for the sediment samples (mean, sorting, skewness and kurtosis) were plotted against the dominant coastal geology within the embayment as shown in Figure 7.6. The boxplots show that the different lithologies impose little control on the type and size of sediment found within the embayment. Values for beaches with Lower Coralline limestone as the dominant coastal geology exhibit a wide variation in terms of mean sediment size and sorting due to the presence of Balluta (a fine sand and well sorted beach) and Qalet Marku (a very coarse sand and very poorly sorted beach). This variation in sediment size indicates that beach sediment composition is more dependent on other factors (such as embayment indentation and orientation) rather than dominant lithology within the embayment.
Figure 7.5: Comparison of beach sediment grouping with the regional geology: (A) North Gozo, (B) North Malta, (C) South-East Malta, (D) North West and North Eastern Malta and (E) Central Malta.

The range of beach sediment sizes measured throughout the 26 embayed beaches indicates that not all sand-sized sediment exists on these embayed beaches. Therefore defining the range of sediment inputs within a system is paramount prior to the definition of any sediment budget. Glogoczowski and Wilde (1971) and Hicks (1985) were the first to recognize that a minimum sediment grain size threshold, termed by Hicks (1985) as the littoral cut-off diameter (LCD) exists.
The method of Best and Griggs (1991) was used to define the littoral cut-off diameter for the 26 embayed beaches in Malta. This method takes the average $D_{10}$ value (the grain size for which 90% of a sample is coarser and 10% is finer) and then subtracts one standard deviation from that number to arrive to the LCD. The calculated littoral cut-off diameter for the whole region is 189 μm. This LCD is slightly greater than the 125 μm identified by Limber et al., (2008) for a number of beaches along California’s coast.

Very few beaches contain sediment distributions with grains smaller than the calculated littoral cut-off diameter, the only exception being Balluta beach (54% of the sediment within the sample was less than the LCD), Pwales (18%), St Georges bay in Birzebbugia (10%) and Qalet Marku (7.9%). Balluta, Pwales and St Georges bay are embayed beaches which are located in deep embayments and therefore are very well sheltered from the dominant wave climate. The sediment sample collected from Qalet Marku might have contained some wind-swept sediment, which explains the broad range of grain sizes identified within this sample.
7.1.2 Regional comparison of morphosedimentary relationships

Associations between embayment morphometry and their respective sediment parameters were analysed by correlating the mean sediment size and width of the sediment distribution (D$_{10}$-D$_{90}$) with the main beach morphometry parameters.

![Figure 7.7: Associations between the main morphometric parameters, mean sediment size and sediment distribution](image)

The plots in Figure 7.7 do not show any significant correlations between embayment morphometry and the textural characteristics of beach sediment. This lack of correlation indicates that regional variations in beach sediment are not determined by the width, indentation and length of coastline within the embayment but are more probably related to the orientation of the embayment with respect to the dominant wave conditions and the degree of wave sheltering.
7.2 Site-scale variation in beach sedimentology

A more in depth analysis of beach sediments was carried out at the eight beaches referred to earlier on in Chapter 5 and 6. The location of these eight beaches is shown in Figure 6.1. Surface samples of beach sediment were collected from these beaches between the end 2011 and 2014 along cross-shore beach profiles at different morphological units with each beach.

7.2.1 Sediment textural characteristics

The mean value for all the beach sediments samples during this time period for the eight embayed beaches was of 663 μm, but values for beach sediment size varied considerably between beaches over this time period. Figure 7.8 shows the range of mean sample values for all the sediment samples collected at the eight different beaches. The box plots show the full range of variation in the sediment samples. Median values ranged from 333.2μm at White Tower to 727.5μm at Gnejna. The range of beach sediment recorded at a beach is also an important descriptor of the possible morphodynamic processes occurring at the beach. The difference between the 25th and 75th percentile was greatest at Armier at 591μm, whereas a much lower range was recorded at San Blas over the period at 120μm. The maximum and minimum values indicate that sediment samples at the eight beaches ranged from fine sand to fine pebbles according to the Udden-Wentworth scale.

![Figure 7.8: Boxplot showing particle size for the 8 beaches under study. The box and whisker diagram show the minimum, first quartile, median, third quartile and maximum size values for all the beach sediment values collected during the period of analysis.](image-url)
Combinations of biplots involving the four main textural parameters, mean, sorting, skewness and kurtosis have been used extensively in distinguishing between sedimentological characteristics of different beach types (Dora et al. 2014; Rashedi et al. 2016). Six combinations of biplots were plotted for each group of beaches as shown and described further below.

Bivariate scatterplots of the sedimentary parameters at San Blas and Ramla are shown in Figure 7.9. Figure 7.9A shows that the sediment is dominated by a medium sand population that is often well sorted, and minor quantities of coarse sand that are moderately well sorted. At Ramla, beach sediment samples tend to coarsen and become less well sorted as one moves from the central sections of the beach to the sides of the embayment. Also, sediment from San Blas is often slightly coarser than sediment at Ramla. Most of the samples collected from these beaches have a symmetrical distribution (82%) with the rest generally being coarse skewed. Similarly most samples are mesokurtic. Overall the bivariate scatterplots indicate that the sediment populations of both San Blas and Ramla are very similar.

Beach sediments at Armier, Little Armier and White Tower (Figure 7.10) exhibit a greater variation in grain size and sorting than at San Blas and Ramla. At Armier beach sediment tends to be slightly coarser (especially along transect A1) but also less sorted
than those at Little Armier and White Tower. Samples at White Tower mainly consisted of fine and medium sand (82%) as opposed to Armier (67%) and Little Armier (42%) and are usually better sorted. Samples within this group of beaches are mostly symmetrical or coarse skewed, except for Armier where the sediment distributions presented a greater variation (from very fine skewed to very coarse skewed). Most of the sediment samples had a mesokurtic concentration around the sample mean in all three beaches.

Figure 7.10: General bivariate plots of the sediment textural characteristics for all the samples collected at Armier, Little Armier and White Tower. (A) Mean versus sorting, (B) Mean versus skewness, (C) Mean versus kurtosis, (D) Sorting versus skewness, (E) Sorting versus kurtosis, (F) Skewness versus kurtosis.

The sediment within Golden Sands, Ghajn Tuffieha and Gnejna presents contrasting differences in terms of grain size, with most of the samples in Gnejna having coarse or very coarse sand (93%). At Golden Sands, 62% of the sediment samples mainly consisted of coarse or very coarse sand whereas this went down to 33% at Ghajn Tuffieha. Most of the samples within these three beaches were moderately well sorted or well sorted, with samples with a higher mean grain size often being poorly sorted. The sediments within these beaches most often have a symmetrical distribution with a tendency for some samples, especially in Gnejna, to be coarse or very coarse skewed. Measures of the sediment concentration around the sample mean indicate that, in all three beaches, the sediments have a mesokurtic concentration. Overall the bivariate scatterplots indicate that the sediment populations of both Golden Sands and Ghajn
Tuffieha are very similar whereas Gnejna exhibits a more varied sediment population (coarse skewed).

![Figure 7.11: General bivariate plots of the sediment textural characteristics for all the samples collected at Golden Sands, Ghajn Tuffieha and Gnejna. (A) Mean versus sorting, (B) Mean versus skewness, (C) Mean versus kurtosis, (D) Sorting versus skewness, (E) Sorting versus kurtosis, (F) Skewness versus kurtosis.](image)

Bivariate scatter plots of the main textural parameters were plotted for all the beach sediment samples to identify any regional patterns in sediment textures (Figure 7.12). The plot of average sediment size versus sorting, Figure 7.12.A, shows that there is a general tendency for sediment to be less sorted with an increase in sediment grain size. Most of the beach samples collected from these eight beaches are symmetrical or coarse skewed (Figure 7.12.B). Sediment samples with greater mean sediment values often tend to be fine or very fine skewed. Most of the sediment samples distributions are centred around the mean are therefore are mesokurtic, however the distribution of samples with a larger grain size value is often platykurtic or very platykurtic given that the sediment sample contains a varied mix of sediment size values. Moderately sorted sediment samples often have a fine to coarse skewed distribution, with very fine skewed or very coarse skewed samples often being poorly sorted. Sediment sorting tends to become less well sorted with a decrease in kurtosis, Figure 7.12.E, whereas the plot of kurtosis versus skewness does not show any real correlation.
Figure 7.12: General bivariate plots of the sediment textural characteristics for all the samples collected at the eight embayed beaches. (A) Mean versus sorting, (B) Mean versus skewness, (C) Mean versus kurtosis, (D) Sorting versus skewness, (E) Sorting versus kurtosis, (F) Skewness versus kurtosis.

7.2.2 Sediment composition

In order to identify the grain types present, visual observations of the sediment samples were carried out by microscope. In Figure 7.13 photographs of sediment samples from the berm section are shown for the eight different beaches. The photographs indicate that the sediments are mainly composed of calcium carbonate with varying portions of shelly organisms (foraminifera). The identification of the type of foraminifera present within the sediment samples proved difficult due to the grains being subject to dissolution and erosion. Sediment samples from the eight beaches were also placed into a furnace at high heat (550°C) to determine the percentage content of biogenic sediment.

The results in Figure 7.14 indicate that the proportion of biogenic sand within the sample varies with morphology. Lower quantities of biogenic sand are shown in the inactive zone of the beach profile (backshore) as a result of a higher proportion of rock content. The proportion of biogenic sand gradually increases towards the surf zone indicating an active contribution of biogenic material of a marine origin towards the overall sediment composition.
Tests carried out on the mineralogy of beach sediments in Malta by Turi et al., (1990) indicate that calcite is the predominant mineral, with minor quantities of aragonite and high Mg calcite also being present. Other non-carbonate minerals which were identified include quartz, with which variable quantities of apatite, glauconite, gypsum or ferruginous concretions are associated.
7.2.3 Sediments transport modes

A number of studies (Koeshidayatullah et al., 2016) have shown that the use of log-probability plots for the comparison of grain size curves can be used for the identification of sub-populations within the distribution. These sub-populations can then be related to different modes of sediment transport and deposition (Visher, 1969). Figure 7.15 plots the relation of sediment transport dynamics to sub-populations and truncation points in a grain size distribution. The most important aspect in the analysis of log-probability plots is the recognition of straight line curve segments. Four such segments occur on the log-probability curve, each defined by truncation points. The interpretation of this distribution is that it represents four separate log-normal populations with each sub-population being associated to a particular deposition mechanism. Each sub-population is truncated and joined with the next sub-population to form a single distribution.

The following section presents the results of a number of log-probability grain size plots for sediment samples collected from the eight different beaches during the winter and summer season. Sampling was carried out along two or three beach transects, depending on the beach, and each sample was classified according to the beach morphology. The data on sediment samples were plotted on log-probability graphs to infer the transport mechanisms through the characterisation of the fine and coarse truncation points within the sediment samples.
Figure 7.15: Transport mechanisms for beach sands (adapted from Friedman & Sanders, 1982).

Figure 7.16 plots log-probability grain size populations for a number of sediment samples from San Blas. The samples collected from San Blas are characterised by relatively high percentages of material in the traction population. The percentage of this material ranges from 30% to 70% depending on the location along the beach profile and the season. The saltation population ranges from 50% to 70% of the sediment population and is often better sorted than the traction population. Sorting of the traction and saltation sub-populations improves from the winter to the summer season. In all instances, the suspension population is very limited and normally comprises less than 5% of the population.

As in San Blas, samples in Ramla (Figure 7.17) are characterised by a relatively high percentage of material in the traction population. Depending on the location along the beach profile and season the percentage material of the traction population can range from 20% to 60%. The saltation population, which can constitute up to 80% of the population, is usually better sorted than the traction population. The suspension population only constitutes a small proportion of the log-probability plot (less than 5%) and therefore sediment deposition by means of suspension is not a significant deposition process. No evident alongshore differences in the deposition mechanisms exist at both beaches.
Figure 7.16: Cumulative percentage distribution of selected sediment samples along two transects in San Blas beach during the winter and summer season.

The samples collected from Armier (Figure 7.18) are characterised by a relatively high percentage of material in the traction population. The percentage of this material ranges from 10% to 80% of the total sediment population, depending on location and season. The range of the saltation population is from 20% to 80%. As in Armier, sediment samples at Little Armier (Figure 7.19) are mainly dominated by traction and saltation populations. At Little Armier, sorting of the sub-populations improves during the summer months. Improved sediment sorting reduces the variability of the fine and coarse truncation point within the samples. In Figure 7.19.B the coarse truncation point is better defined and approximately located at 300μm whereas in Figure 7.19.C this is located at approximately at 450μm.
Figure 7.17: Cumulative percentage distribution of selected sediment samples along three transects in Ramla beach during the winter and summer season.

Plots the log-probability grain size populations for a White Tower are shown in Figure 7.20. The samples collected at White Tower are also mainly dominated by traction and saltation populations. Sediment collected along profile T1 during the winter season were almost exclusively deposited as a result saltation processes since the traction and suspension part of the population is almost nonexistent. Samples collected from Golden Sands are characterised by relatively high percentages of material in the traction and saltation population.
Figure 7.18: Cumulative percentage distribution of selected sediment samples along two transects in Armier beach during the winter and summer season.

In the breaker zone, the percentage of the traction population can be as high as 99% (Figure 7.21). At Ghajn Tuffieha, (Figure 7.22), samples are characterised by relatively high percentages of material in the traction and saltation population. The traction population can constitute up to 80% of the total sediment population. The lower limit of the coarse truncation point is in the region of 300\(\mu\)m. As with other beaches, the suspension population is not present. The samples collected from Gnejna, (Figure 7.23) are characterised by a relatively high percentage of material in the traction and saltation population. Sub-populations of sediment which was deposited in suspension can be found at very low quantities (less than 5%) at the backshore area along profile G1 (Figure 7.23.A and Figure 7.23.B) and the backshore and surf zone at profile G2 (Figure 7.23.C).

The characteristics exhibited by the log probability grain size plots indicate a depositional material characterised by breaking waves which keeps the depositional interface agitated, and suspension matter is winnowed out and transported seaward by currents. The proportion of the traction and saltation sub-populations depends on the
position of the wave breaking zone and the direction and magnitude of the currents. These combine to allow the mixing between the saltation and the traction sub-populations. Repeated sediment sampling also allowed for the quantification of the Littoral Cut-off Diameter (LCD) (Table 7.2) for the eight beaches in order to determine the effect of the local wave setup on the sediment within the embayment.

![Cumulative percentage distribution of selected sediment samples along two transects in Little Armier beach during the winter and summer season.](image)

Figure 7.19: Cumulative percentage distribution of selected sediment samples along two transects in Little Armier beach during the winter and summer season.

Limeber et al, (2008) have identified a positive correlation between the mean annual significant wave height and the LCD for a number of beaches in California. Values for the LCD indicate that the group of beaches located on the north coast of Malta are the least exposed to wave attack, whereas Gnejna is the beach with the highest exposure to incident wave conditions.
Figure 7.20: Cumulative percentage distribution of selected sediment samples along two transects in White Tower beach during the winter and summer season.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Littoral Cutoff Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Armier</td>
<td>121</td>
</tr>
<tr>
<td>Armier</td>
<td>142</td>
</tr>
<tr>
<td>White Tower</td>
<td>151</td>
</tr>
<tr>
<td>Ramla</td>
<td>230</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>255</td>
</tr>
<tr>
<td>Golden Sands</td>
<td>278</td>
</tr>
<tr>
<td>San Blas</td>
<td>284</td>
</tr>
<tr>
<td>Gnejna</td>
<td>333</td>
</tr>
</tbody>
</table>

Table 7.2: Values for the littoral cutoff diameter for the eight embayed beaches in ascending order. An increase in LCD values is expected to correspond to an increase in exposure to wave conditions.
Figure 7.21: Cumulative percentage distribution of selected sediment samples along three transects in Golden Sands beach during the winter and summer season.
7.2.4 Morphosedimentary associations within headland-bay beach systems

Although a beach can only be composed of the available sediments, grain size distributions can change in time and space. In this regard simplified grain size distribution barplots of the main sediment categories were plotted for the winter and summer season for a number of beach profiles. Sediment sampling along the beach transects was not always possible either due to the presence of thick sea grass mats or else due to the breaker zone being located beyond wading depth.

The grain size distribution barplots for San Blas (Figure: 7.24) indicate a general coarsening of the sediment along the whole length of the profile during the winter when compared to summer as a result of an increase in the proportion of very coarse sand and a reduction in the quantities of medium sand. The coarsest sediment samples tend to be located within the swash or surf zone of the beach profile. At Ramla, (Figure 7.25) coarsening of the beach sediment from winter to summer is only evident at R1.
No real changes can be observed in sediment composition between winter and summer at R2 and R3. As in Ramla, the coarsest sediment samples were repeatedly collected from the swash or surf zone.
Sediments samples collected along profile A2 in Armier (Figure 7.26) during summer and winter are generally coarser than those collected along A1. Beach sediments also tend to coarsen in winter and probably there is an active contribution of beach sediment from the bedrock in the berm area of profile A2 as a result of the lowering of the beach profile and exposure of the bedrock during winter (exemplified by the high percentage content of gravel material).

![Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at San Blas during the winter and summer season grouped by the main beach morphological units](image)

Figure 7.24: Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at San Blas during the winter and summer season grouped by the main beach morphological units

On the contrary at the adjacent beach of Little Armier (Figure 7.27), the sediment distribution and composition of beach sediment is relatively consistent throughout the year, with medium sediment being the dominant size class. This phenomenon is also apparent at White Tower (Figure 7.28).

On the west coast of Malta, the grain size distribution barplots for Golden Sands (Figure 7.29) do not show any evident changes in sediment composition from one season to another. The cross-shore variability in sediment composition indicates that coarser sediments are usually found in the most active sections of the beach profile (swash, surf and breaker zone). At Ghajn Tuffieha (Figure 7.30) most sediment
samples were characterised by a dominant medium sand population followed a varying proportion of coarse sand. The results indicate a slight coarsening in the swash or surf zone area as opposed to the backshore, however no alongshore variability was observed in sediment composition along the beachface.

Figure 7.25: Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at Ramla during the winter and summer season grouped by the main beach morphological units.

Beach sediment in Gnejna (Figure 7.31) contains a higher proportion of coarse and very coarse sand when compared to Golden Sands and Ghajn Tuffieha. The presence of gravel material (ranging from very fine gravel to coarse gravel) is not uncommon especially in the surf and break zones leading to these morphological units having the coarsest sediment populations. Low proportion of very fine sand and silt can were also present in the backshore area along profile G1 and G2 probably as a result of very fine windswept sediment being deposited onto the beach from the adjacent fields.
Figure 7.26: Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at Armier during the winter and summer season grouped by the main beach morphological units.

The angles of the measured beach profiles were compared to the mean sediment size of the respective profile (Figure 7.32). Values for the entire beachface slope ranged from 3° at Little Armier to 15° at Gnejna. The range of values of beachface slope identified by Klein et al. (2005) for a number of beaches along a headland bay coast in southern Brazil (Santa Catarina state) ranged from 0.9° to 11.5°. The plots also indicate that the exposed part of the beach face (backshore and berm section) are generally steeper (average value of 6.4°), than the submerged section of the beachface (average value of 3.8°). Fairly steep beachfaces, with slopes in excess of 10%, were also recorded by Vousdoukas et al. (2009) in Vatera beach, on the island of Lesbos, Greece.
Figure 7.27: Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at Little Armier (upper panel) and White Tower (lower panel) during the winter and summer season grouped by the main beach morphological units.
Figure 7.28: Grain size distribution bar plots of selected sediment samples collected along specific beach profiles at Golden Sand (upper panel) and Ghajn Tuffieha (lower panel) during the winter and summer season grouped by the main beach morphological units.
Poor positive correlations were obtained between beach slope and mean sediment size for the different sections of the beach profile. Beaches with equal slopes exhibited different mean grain sizes whereas beaches with similar grains sizes exhibited considerable variations in beach slopes. Klein et al. (2005) found a positive correlation between beachface slope and grain size with beaches having a steeper slope being composed of coarse sand whereas smoother profiles consisting of fine sands. The results show that a correlation between beach slope and grain size cannot be established for Maltese beaches given that other factors, such as the role of sea grass mats in altering the gradient of the profile and the presence of exposed bedrock in times of profile lowering, need to be taken into consideration.
Figure 7.30: Comparison of mean sediment size and the slope of the beach profile for three different profile sections. (A) Whole length of the profile, (B) The exposed (sub-aerial) section of the profile and (C) The submerged section of the profile.

7.3 Conclusion

Sediment samples collected from 26 embayed beaches in the Maltese islands indicate that the beaches are composed almost entirely of sand with significant portions of
gravel (more than 29% of the sample) occurring in just five beaches. Silt and clay are practically non-existent except for very small quantities (less than 2.3%) in only two beaches. The embayed beaches in Malta and Gozo are characterised by medium and coarse sand and normally are well sorted, moderately well sorted or moderately sorted.

Embayed beaches can be classified into four categories based upon their grain size distributions and can be broadly summarised as follows:

- Beaches where fine sand is the dominant sediment type
- Beaches where medium sand is the dominant sediment type
- Beaches where coarse sand and very coarse sediment are the dominant sediment type
- Beaches where fine gravel and coarse gravel constitute more than 30% of the sediment distribution composition.

The identified sediment groupings do not exhibit any spatial association with the presence of a particular rock formation at the coastline.

The analysis of sediment composition indicates that most sediment is composed of calcium carbonate with varying portions of shelly organisms (foraminifera). Biogenic sediment contribution to the overall sediment composition is highest in the surf zone. Analysis of the sediment transport modes indicates that in most embayed beaches traction is the dominant transport mechanism, followed by rolling and sliding. Sediment carried in suspension usually comprises less than 10% of the sediment population which also sheds light on the importance of wave activity in selective sediment transport.
8 Discussion

8.1 Physical controls on headland-bay beaches

8.1.1 Geological Setting

The coastline of the Maltese islands has been predominantly controlled by tectonic activity, namely faulting, up-arching and subsidence (Alexander, 1988). The structural setting of a coastal site is the most important physical influence on embayed beaches as it controls the presence/absence of specific lithologies, the geomorphology of the embayment, sediment type, sediment availability and wave setup, which in turn control beach morphodynamics. Tectonic activities throughout the Maltese archipelago have produced large scale uplift and subsidence structures. This is most evidently apparent in the north section of Malta’s coastline where a succession of horst and graben structures has led to the formation of a number of embayed beaches (Figure 8.1). The structural setting of beaches such as Ghadira, Anchor Bay, Mgiebah, Pwales, Golden Sands, Ghan Tuffieha and Gnejna has been conditioned by tectonics and regional lithology. These factors have conditioned the formation of embayed beaches both in terms of location and also embayment configuration.

The fracture pattern across the Maltese islands is also important in terms of coastal evolution and embayed beach setting. The Maghlaq fault, which traverses the Islands in a NW-SE direction, has a vertical displacement of 240 m. This vertical displacement led to the islands tilting in NE direction resulting in the western and south-western coast of Malta and the western and southern coast of Gozo having higher elevations than the north-west and north coast of Malta and Gozo. As shown earlier in Figure 2.3B, this process is important both in terms of the geology that outcrops at the coastline (it’s control on coastal configuration, its behaviour in response to wave attack and the geomorphology that subsequently develops) and also in terms of the relief and topography of the islands.

The Maltese coastline has been shaped by other geomorphological processes, the most extensive of which are karstic processes that have led to the development of sinkholes and underground caverns, and fluvial processes that have formed ephemeral river valleys (Alexander, 1988). Of these, fluvial processes are most important for the embayed beach systems due to the erosion of incised valleys which, following the Holocene sea level rise, have led to the development of embayments within coastal
inlets. This was important for the development of beaches such as Ramla, San Blas, Ballutta, Rinella and St George’s Bay in Birzebbugia (Figure 8.1). Within this context however, tectonic processes still have an important role. The vertical displacement of the island, as a result of the Maghlaq Fault, has led to most valley systems discharging on the eastern side of the island, which part of the coastline, coincides with the location of most of the beaches described above.

Figure 8.1: Structural controls on the formation of embayed beaches in Malta are mostly evidently seen in the northern part of Malta where a succession of horst and graben structures has led to the formation of embayed beaches (Source: Author).

The combination of tectonic activity, fracture pattern, geology and geomorphology has over the years led the coastline of the Maltese islands to have varied and complex coastal features. The dominant coastal landforms in the Maltese islands can be broadly classified into 5 categories (Magri, 2006) (semi-circular coves, cliffs, high cliffs, low rocky coast and rdum type cliffs, described earlier in Section 2.3). Within this context, embayed beaches only occupy 2% of the total coastline of the Maltese islands and therefore cannot be considered as a major coastal landform. The dearth and location of beaches on the Maltese islands also implies that the formation of embayed beaches on the Maltese islands is not controlled by the erosion of discordant coastlines but as a result of a combination of tectonic activity, fracture patterns, geology and geomorphology.
8.1.2 Headland Configuration

The morphometric analysis of embayed beaches in Malta indicates that headland spacing and bay indentation is entirely dependent on the pre-existing bedrock topography which has been partially drowned by the Holocene sea level transgression. This is highlighted by the contrasting variations in headland spacing and bay indentation. Headland spacing and bay indentation are well correlated as are bay indentation and the length of embayment shoreline. Categories from embayment indentation ranged from very low to highly indented according to the classification proposed by Bowman et al., (2014). The main embayment morphometric parameters, the indentation index (S1/Ro) and embaymentisation index (a/Ro) are highly correlated comparable to other Mediterranean beaches in Spain (Bowman et al., 2009) and Elba (Bowman et al., 2014).

The spatial distribution of the embaymentisation and indentation index do not indicate any significant correlation with the presence of a particular geological formation or dominant feature within the coastal zone. This also sheds light on the importance of structural control, rather than erosive processes, on the formation and development of embayed beaches, an aspect which was also highlighted by Bowman et al, (2009) for a number of embayed beaches on the Catalan coast. A comparison of the Malta’s headland bay morphometry with other similar Mediterranean islands, such as Elba, indicates that structural control on the morphometry of embayed beaches in Malta is more pronounced (Figure 4.7).

The analysis of the main beach morphometric parameters reveals that the variance that exists in beach area amongst Malta’s embayed beaches, is very much dependent on headland spacing, highlighting the dominant role of embayment morphometry on the development of beaches. Beach areas amongst the 29 beaches ranged from 121 m² at Balluta bay to 23,646 m² at Ghadira beach.

Beach width and beach area are moderately correlated and an increase in beach area is expected to occur with an increase in the maximum beach width, highlighting the role of accommodation space in the landward development of the embayed beach. Results also showed that an increase in headland spacing and embayed beach shoreline are likely to correspond to an increase in the length of embayed beach shoreline.

The bay filling indices in Malta are significantly lower than those reported for other Mediterranean embayed beaches, indicating that most beaches are sediment starved. The key morphometric parameters used to describe embayment morphometry, embaymentisation index (a/Ro), indentation index (S1/Ro) and bay filling index (S2/S1)
did not exhibit any significant spatial variations, highlighting the role of the geological setting in the development of site specific embayment morphometries.

Embayed beaches in Malta can be grouped into four distinct groups based on their morphometric characteristics. A brief description of each group is given below whereas the mean parameters (m) of each group is shown in Table 8.1.

**Group A**
Embayed beaches within this group are characterised by an average headland spacing (Ro) of 319 metres and a beach area ranging from 3,422 m² to 7,077 m². The bay indentation values of beaches within this category are almost equal to headland spacing values. Beaches within this category are generally more indented than those in Category 2.

**Group B**
Embayed beaches within this group which are characterised by an average headland spacing of 229 m and a beach area ranging from 121 m² to 2,234 m². This is the most frequent embayed beach category and consists of the smallest and least indented beaches found in the Maltese islands. Beaches within this category can be considered as the most exposed given the lack of wave sheltering.

**Group C**
Embayed beaches which are characterised by an average headland spacing of 741 m and a beach area ranging from 9,871 m² to 17,513 m². This group of beaches is characterised by significant beach areas compared to those in Category 2 and 3 as well as an extensive landward development of the beach system. In fact both beaches within this category are backed by sand dunes.

**Group D**
The embayed beach (only Ghadira beach falls within this category) where headland spacing is 1775 m and the beach area is 23,646 m². As highlighted earlier on in Section 8.1.1 the morphometric characteristics of Ghadira beach emphasize the importance of structural control on the formation of embayed beaches. The structural differences exhibited by beaches within these four categories are exhibited in Figure 8.2.
Figure 8.2: Planform view of the structural differences exhibited by a selected number of embayed beaches amongst the four difference groups. Beaches within Group A generally have bay indentation values similar to headland spacing values. Beaches within Group B are the smallest and least indented beaches in the Maltese islands. Beaches within Group C are characterised by larger beach areas, when compare to Group A and Group B beaches. Group D consists of Ghadira beach, the largest embayed beach in the Maltese islands (Source: Author).

The mean parameters of the four groups for embayed beaches in Malta were compared to the mean parameters of the five indentation categories proposed by Bowman et al, (2009) for Catalan pocket beaches. A comparison of the values indicates that contrasting differences exist between the embayment categories. From an embayment morphometry perspective, classes with similar embayment indentation values do not necessarily exhibit similar beach morphometry. For example beaches categories which have similar indentation values (both the Indented class in Spain and the Group B in Malta exhibit indentation values of 0.8) have significant differences in the embayed beach shoreline length (S2). Whilst the most indented beaches on the Catalan coast (high-indented) exhibit lower values (163 m) of embayed beach length (S2), in Malta the greatest beach length (602 m) is recorded in the most indented beach (Group D).
Table 8.1: Comparison of the mean parameters of the studied beaches in Malta and Spain (Bowman et al, 2009). All parameters are in metres.

<table>
<thead>
<tr>
<th>Class</th>
<th>a</th>
<th>Ro</th>
<th>a/Ro</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unidented</td>
<td>174</td>
<td>910</td>
<td>0.2</td>
<td>1178</td>
<td>954</td>
</tr>
<tr>
<td>Low-Indented</td>
<td>145</td>
<td>400</td>
<td>0.4</td>
<td>645</td>
<td>438</td>
</tr>
<tr>
<td>Medium-indent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indented</td>
<td>257</td>
<td>322</td>
<td>0.8</td>
<td>819</td>
<td>291</td>
</tr>
<tr>
<td>High-indent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Malta</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group A</td>
<td>315</td>
<td>319</td>
<td>1.0</td>
<td>995</td>
<td>188</td>
</tr>
<tr>
<td>Group B</td>
<td>176</td>
<td>229</td>
<td>0.8</td>
<td>536</td>
<td>77</td>
</tr>
<tr>
<td>Group C</td>
<td>329</td>
<td>741</td>
<td>0.4</td>
<td>1146</td>
<td>301</td>
</tr>
<tr>
<td>Group D</td>
<td>2603</td>
<td>1775</td>
<td>1.5</td>
<td>6762</td>
<td>602</td>
</tr>
</tbody>
</table>

It has been observed that some embayed beaches may preserve their bay-form also in shallow waters up to 20m below sea level. Embayed beaches such as Santa Marija bay in Comino and Marsalforn in Gozo show characteristics of submarine embaymentisation (Figure 8.3). This phenomenon was also observed by Bowman (2009) in a number of embayed beaches along the Catalan coast of Spain.

Figure 8.3: Submarine embaymentisation at San Marija bay and Marsalforn. Distinct submarine headlands can protrude seaward for hundreds of metres.
8.1.3 Accommodation space
Each embayed beach exists within a specific geological framework that determines both the vertical, lateral and landward boundaries within which the beach forms and fluctuates. Beaches located within these geologically constrained environments are likely to respond much more rapidly to moderate wave conditions compared to unconstrained and sediment abundant beaches. This makes such beaches more susceptible to changes in beach morphology and increases their vulnerability to sediment losses, thus making their behavior more difficult to understand or predict (Jackson & Cooper, 2009).

Although no field data was collected on the sediment thickness of the beaches, field observations of exposed beach rock allowed for the identification of local geological constraints on beach morphology. Some of the embayed beaches in the Maltese islands are composed of relatively thin layers of medium to coarse sand, which generally overlie either deposits of lithified quaternary beach deposits or bedrock. These underlying strata act as a vertical constraint to the sub-aerial beach system, modifying its morphological response. Such examples were recorded at Armier, where the eastern side of the beach is vertically constrained by the presence of lithified beach deposits and Ramla l-Hamra, where the western side of the beach is underlain by a marl shore platform that is exposed during periods of increased wave action (Figure 8.4). The type of vertical constraint referred to above falls within the highly constrained category (Category III) as proposed by Jackson and Cooper, (2009). In such cases, the classic beach state classification developed by Wright and Short (1984) is likely to be unsuitable given that the beach sediment volume is severely limited and the beach profile is highly mobile. Strong control on beach profile evolution was also evidenced by Vousdoukas et al., (2007) at Vatera beach in Greece.

Considerable alongshore differences can exist in the vertical constraints of the beach, with the central sections of the beach having greater accommodation space than the sides of the beach. This is particularly evident at Gnejna, given that the beach has developed at the mouth of a small valley system. In the central section of the embayment the bedrock does not vertically constrain the beach from adjusting its morphology to changes in wave activity (Figure 8.5). This leads to the development of distinct beach morphologies between the central section and the sides of the beach, where vertical constraints considerably limit morphological adjustments. Figure 8.3 shows the partial exposure of bedrock at the eastern section of Gnejna.
Figure 8.4: A marl shore platform on the western section of Ramla l-Hamra is completely exposed following a period of intense wave action (Upper Panel). Similarly quaternary beach deposits are exposed on the eastern side of Armier beach (Lower Panel) (Source: Author).

Figure 8.5: Partial exposure of the marl shore platform which vertically constrains the morphological adjustment of the beach profile on the right side of Gnejna.
Lateral geological constraints are also important when analysing the morphodynamic evolution of embayed beaches given that seasonal or period shift in wave direction can induce significant longshore sediment transport processes and beach adjustment in the planform as described in Section 1.7. The comparison of variations in shoreline position at the lateral ends of eight embayed beaches in Malta indicated that changes in the planform configuration of the shoreline can be broadly categorised as follows (also schematised in Figure 8.6):

**Type I:** One side of the embayed beach is accreting or eroding whereas the other side is stationary and does not show any change in terms of shoreline accretion or erosion.

**Type II:** The lateral margins of the embayed beach are either both accreting or both eroding simultaneously. Accretion or erosion can either be the same in terms of magnitude at both ends of the beach or else accretion or erosion is greater at one end of the beach than the other.

**Type III:** One end of the beach is accreting whereas the other end of the beach is eroding. This phenomenon is generally considered as the classic example of beach rotation (Bird, 1993; Shyuer-Ming and Komar, 1994; Short et al., 1995) and in most cases it is attributed to a seasonal or period shift in the wave direction.

Variations in the beach planform indicate a complex response system which cannot be predicted by simple rotational models as proposed by Turki et al. (2013) and shown in Figure 1.11 earlier on. The results in Section 5.1.4 indicate that changes in the beach planform are characterized by the coexistence of both cross-shore and longshore processes. Cross shore processes are however the dominant beach planform change process and is likely to mask any changes caused by longshore processes. Ojeda and Guillén (2008) have found that for embayed beaches in Barcelona, beach rotation due to storm events can be heterogeneous, i.e., in the retreating sections there are segments that undergo shoreline advance and the in advancing sections there are segments that undergo retreat. A factor for explaining this heterogeneous alongshore behaviour of the shoreline is the formation of submerged sedimentary structures, such as sandbars, and their subsequent transformation (Ojeda et al., 2006). The coexistence of both cross-shore and longshore processes as agents of embayed beach planform change was also identified by Pinto et al., (2009) for an embayed beach in Portugal. Their results indicate that cross-shore process operate on smaller timescales, and decrease in importance with an increase in the time window of observation. At larger timescales (inter-annual to inter-decadal), the pattern of beach
planform evolution was more conditioned by longshore processes as predicted by beach rotational models (Pinto et al. 2009).

Figure 8.6: Changes in planform configuration for embayed beaches in the Maltese islands. Changes in planform configuration can be categorised into three different types, depending on the variations in the position of the shoreline position (Source: Author).

Many of the embayed beaches in the Maltese islands are partially backed by coastal bluffs, dunes or seawalls which constrain the backward limit of the beach (Section 5.3). This is also the case in other Mediterranean headland bay beaches (Bowman, 2014). The degree of impact that these features have on the beach is dependent firstly on their nature and size, and secondly, on their location relative to the shoreline and surf zone. Given the small size and limited beach width of Malta’s embayed beaches, it often occurs that under extreme conditions, the berm and backshore section of the beach profile are eroded away and the rear part of the part of the beach becomes part of the swash or surf zone. The presence of coastal bluffs or seawalls at the backshore will have a greater impact on the beach morphology given that wave reflection is accentuated.

This is most evident at San Blas where the limited width of the beach profiles often leads to the beach being completely eroded away flowing intense storm events (Figure 6.5). This can prevent the beach from fully recovering its original beach profile and
becoming vulnerable to erosional processes even as a result of more frequent moderate storm events. Significant alongshore differences can also exist with regards to the landward limit of embayed beaches. Gnejna beach is located at the mouth of a small valley system leading to central section of the beach being the widest section (up to 50m). On the other hand the embayed beach is considerably narrower on the western part (up to a maximum of 10m at profile G3). Given that this section of the beach is narrower, increased wave activity has a greater impact on the overall morphology of the beach profile. Similar alongshore differences in the landward limit of the beach can be evidenced at other embayed beaches in Malta such as Ramla and Golden Sands. Vousdoukas et al. (2009) have also demonstrated this narrowing of the beach as a result of low cliffs backing the eastern part of the embayment. The effect of the type of geomorphic landform delimiting the landward boundary of embayed beaches in Malta was analysed in Section 5.3. From 1955 to 2016, profiles backed by seawalls exhibited greater rates of erosion whereas shoreline change rates were lowest in profile backed by bluffs. At Gnejna, profile G3, (Figure 6.20), is backed by a seawall which during increased wave activity leads to greater erosion of the beachface. Ghajn Tuffieha is the only embayed beach considered for this study where the backward limit of the beach is defined by a coastal bluff that is made up of Blue Clay. This formation can be subjected to erosional processes and collapses as a result of intense wave action leading to an increase in the potential accommodation space of the embayment. Figure 8.7 shows storm waves reaching the coastal bluffs surrounding Ghajn Tuffieha beach.

8.2 Morphosedimentary nature of embayed beaches

8.2.1 Beach morphology
The beach profiles show a process of erosion and recovery which does not depend on a particular season, but is more dependent on the dominant wave climate during the period. Therefore the classification of beach profiles based on the classic winter and summer profiles as described by Bascombe (1953; shown schematically in Figure 1.5) does not reflect the morphological behaviour exhibited by the embayed beaches in Malta.
Repeated profile measured on eight embayed beaches in Malta have never captured beach profiles in a fully dissipative state, although field observation following extreme storm events indicate that embayed beaches can attain a fully dissipative beach profile (Figure 8.8). In most instances, the beaches are transitioning between intermediate beach states and the reflective beach state according to the classification developed by Wright and Short (1984). The speed of this transition depends on the hydrodynamic conditions exhibited at the beach, but given the coarse sedimentary nature of Maltese
beaches, this transition can be quite rapid. None the less, the measurement of beach profiles has shown that the process of profile accretion and recovery might take longer than one year. This can be explained by the idea that wave conditions prevailing in sheltered beaches are generally insufficient to facilitate full beach recovery between periods of storm activity unless there is a long period of quiescence (Hegge et al.1996).

The measurement of beach profiles indicates that in most cases, beaches are in a reflective state. Therefore breakers impinge directly on the shore without breaking on offshore bars. As breakers collapse, the wave uprush surges up a steep foreshore. At the bottom of the steep foreshore a pronounced step composed of coarser material is usually found. Seaward of the step, the slope of the beach profile bed decreases appreciably. Values for beach profile gradients indicate a general tendency for profile gradients to be relatively steeper, probably due to the sediment being coarse skewed. The small size of the beaches and the presence of sea grass deposits probably obstructs the full development of beach cusps. Well defined beach cusps were only recorded at Golden Sands, Ramla and San Blas.

Longshore variation in beach morphology is present in the larger beaches such as Ramla and Golden Sands. This longshore variation can be intensified as a result of storm events which create alongshore gradients in surfzone width and beach state. Longshore variation in beach morphology is also very much dependent on the accommodation space available for the beach morphology to adjust to the changing hydrodynamic conditions (as discussed in Section 8.1.3). Occasionally bar development was recorded along some of the beach profiles, with this being most evident at Gnejna (Profile G3), which profile is adjacent to the beach headland. Similarly, the prevalence of double-bar morphologies adjacent to headlands has been observed in a recent study at Bulli Beach in Australia (Van Leeuwen et al., 2015).

Based on the field measurements and observations, a generalised conceptual model of beach profile morphology evolution has been developed for Maltese embayed beaches (Figure 8.9). The key framework of this model is the differentiation between accreted and eroded beach profiles, and constrained and unconstrained beach morphology evolution. The conceptual model does not distinguish between winter and summer beach profiles given that morphological development of the beach is very much dependent on the wave climate and the antecedent state. The conceptual model proposed in Figure 8.9 differs from other models of profile evolution of beach states such as those proposed by Short (1979, 1999b) and Wright and Short (1984) in that due consideration is given to the importance of beach casts on the morphological development of these beaches.
Figure 8.9: Generalised evolution of beach profile morphology for Maltese embayed beaches. Embayed beaches profiles in the Maltese islands, (whether constrained or unconstrained), generally exhibit four different stages of profile evolution, ranging from a well accreted to a well eroded beach profile (Source: Author).

The generalised evolution of embayed beach profiles in Malta can be described in the following four phases:

Phase A: The beaches are well accreted and exhibit the morphological characteristics of a reflective beach profile whereby the berm is well developed (Figure 8.10). This
type of morphological development is associated with calm wave energy conditions and limited wave activity resulting from storm events. During this phase the morphological evolution of the embayed beach profiles is similar for both constrained and unconstrained beaches and therefore there is no influence on the beach profile of the underlying beach rock. Beaches with similar profiles are generally considered as intermediate beaches according to classification proposed by Wright and Short (1984).

Figure 8.10: Golden Sands beach showing a well-developed, landward sloping berm, corresponding to the first phase of beach morphological development as shown in Figure 8.9. (Source: Author).

Phase B: During this phase, an increase in wave activity leads to the progressive erosion of sand from the exposed part of the beach and its deposition offshore as longshore bars. The collection of field data on the presence and location of sand bars did not allow for the identification of the type of bars present according to the classification proposed by Wright and Short (1984). The importance of the constraints to beach morphological change as a result of the presence of the underlying beach rock becomes more important but is insufficient to have significant effects on the beach morphology. In times of high energy wave action, beach casts (banks of sea-grass (*Posidonia oceanica*) detritus) are frequently washed onshore. The presence of these beach casts can either have a positive effect as it protects the beachface from more intense and erosive wave activity, or else prevent the beachface from recovering and accreting to pre-storm conditions.

Phase C: During this phase, increased wave activity will lead to further erosion of the beach profile and also to the deposit of greater amounts of beach casts. Removal of additional sand may lead to multiple bar formation. In constrained beaches, the
sediment eroded through increased wave activity can actually be replaced by beach casts, further limiting beach recovery, as shown in Figure 8.11. Extensive beach cast development can also lead to the development of scour steps. The development of these scour steps may significantly affect cross shore sediment transport as it hinders the onshore movement of sediment a result of the step and the enhanced turbulence at its base (Vousdoukas et al. 2009).

![Figure 8.11: Extensive development of beach casts (deposits of *Posidonia oceanica* banquets) at Dahlet Qorrot in Gozo leading to the complete removal of beach sediment. In such instances, unless the beach casts are manually removed, the recovery of the beach to its original state can take years (Source: Author).](image)

Phase D: During extreme storm events, both unconstrained and constrained beach profiles assume a fully dissipative state. The high energy conditions erode considerable amounts of sediment, thus significantly changing the morphology of the beachface. In such instances, the high energy conditions can lead to the natural removal of beach casts, therefore providing the beach with an opportunity to slowly recover and accrete during calmer periods. Constrained beaches are impacted heavily during extreme storm events due to the limited availability of sand. This leads to enhanced beach erosion when compared to unconstrained embayed beaches and also the formation of scour steps (Figure 8.12). Embayed beaches with similar profiles are generally classified as reflective according to the classification proposed by Wright and Short (1984). This reflective phase of the beach profile also concurs with the observations made by Klein and Menezes (2001) for embayed sandy beaches in Brazil where reflective beaches are generally steeper and without a berm.
8.2.2 Morphosedimentary dynamics within embayed beaches

The onshore and offshore limits of beach profile response is of interest as it represent the maximum elevation and landward limit of sediment transport. During normal erosion/accretion cycles, the upper limit of significant beach profile change coincides with the wave run-up limit. Under construction conditions, as the beach face builds seaward, this upper limit of sediment deposition is usually well defined in the form of a depositional beach berm. During erosion conditions, the berm bay retreat more or less uniformly. In some cases, the berm may be so high that runup never reaches its crest, in which case an erosion scarp will form above the run-up limit.

Values for the entire beachface slope in Malta ranged from $3^\circ$ at Little Armier to $15^\circ$ at Gnejna. Slope values in the Maltese islands are steeper than the range of values recorded by Klein et al., (2005) for a number of embayed beaches in Brazil where these ranged from $0.9^\circ$ to $11.5^\circ$. The relationship between sedimentary grains size and the slope of the beachface is also important in terms of the morphodynamic stages and wave energy levels present on the beach. Klein et al. (2005) found that dissipative beaches are normally composed of fine sand with a gradual transition towards coarser sand for reflective beaches. Similarly Bascom (1951) studies 40 sandy beaches on the Californian coast and found the flatter beaches are composed of fine sands and steeper ones are composed of coarser sands. The results presented in Figure 7.32
show that a correlation between beach slope and grain size cannot be established for Maltese beaches given that other factors, such as sea-grass deposits and bedrock constraints, need to be taken into consideration.

Sediment size within embayed beaches can vary greatly and is very site specific. The mean sediment size ranged from 193 μm at Balluta to 2775 μm at Marsaxlokk. Most of the embayed beaches analysed (76%) are entirely composed of sand whereas other beaches such as Xwejni, Cirkewwa, Qalet Marku, St. George’s bay and Masaxlokk contain significant portions of gravel. The silt and clay size fraction of sediment is practically non-existent in Mata. Comparisons with the textural parameters of embayed beaches in a similar setting in the Mediterranean region (Puyol et al., 2013) show similar characteristics. Sand is the predominant textural class with low proportions for silt and clay content. Mean gravel content is low in all locations (< 5.5%) with occasional higher gravel content in particular beaches.

<table>
<thead>
<tr>
<th>Malta</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Silt and Clay %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3.3</td>
<td>96</td>
<td>0.4</td>
</tr>
<tr>
<td>Min.</td>
<td>0</td>
<td>49.8</td>
<td>0</td>
</tr>
<tr>
<td>Max.</td>
<td>50.2</td>
<td>100</td>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Menorca</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tramuntana Region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.1</td>
<td>94.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Min.</td>
<td>0</td>
<td>79</td>
<td>0</td>
</tr>
<tr>
<td>Max.</td>
<td>21</td>
<td>100</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Migjorn Region</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.5</td>
<td>95.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Min.</td>
<td>0</td>
<td>53.8</td>
<td>0</td>
</tr>
<tr>
<td>Max.</td>
<td>15.8</td>
<td>100</td>
<td>44.4</td>
</tr>
</tbody>
</table>

Table 8.2: Descriptive textural parameters for embayed beaches in Malta and Migjorn and Tramuntana regions in Menorca, Spain (Puyol et al., 2013).

The sediment size present at any particular location on the beach profile represents the size which is at equilibrium with the wave energy at that point on the profile. Based upon the average grain size of the headland bay beaches, one can deduce the energy wave level at the beach. The mean sediment size for the eight embayed beaches considered for detailed sediment size analysis is presented in Table 8.3.

Considering the results of the mean grain size analysis, it can be concluded that White Tower is the most sheltered of the headland bay beaches considered in this study with Gnejna being the most exposed.
The headland bay beaches considered in this study do not exhibit any clear trends when it comes to beach profile steepness and sediment size. This however needs to be investigated further following the collection and processing of additional data. Preliminary results of beach sedimentology indicate that there are slight differences in the grain sizes of adjacent beaches, indicating that circulation of sediment between adjacent beaches is for the most part restricted, at least for the most part of the year. This however warrants further investigation.

Of importance are the deposits of *Posidonia oceanica* as banquettes on many of the headland bay beaches since these can have a significant result on beach morphology as highlighted in Section 8.2.1. The impact of banquettes on the morphodynamics of the beach depends on the timing when these are deposited. Sea grass such *Posidonia oceanica* can in actual fact function similar to a reef in accentuating wave reflection and creating sheltered areas favouring the settling of more variable grain size sediments as shown in Figure 8.13 (Simeone, 2008).

### Table 8.3: Mean grain size for the eight beaches considered for a more detailed analysis of beach sediments.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Grain Size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Tower</td>
<td>387</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>508</td>
</tr>
<tr>
<td>Little Armier</td>
<td>535</td>
</tr>
<tr>
<td>San Blas</td>
<td>565</td>
</tr>
<tr>
<td>Golden Sands</td>
<td>578</td>
</tr>
<tr>
<td>Ramla l-Hamra</td>
<td>662</td>
</tr>
<tr>
<td>Armier</td>
<td>934</td>
</tr>
<tr>
<td>Gnejna</td>
<td>995</td>
</tr>
</tbody>
</table>

Figure 8.13: Possible interactions between fields of *Posidonia oceanica* and beach profile in an embayed beach setting (Simeone, 2008).
8.3 Scales of change in headland-bay beach systems

8.3.1 Meso to macro scale

8.3.1.1 Sea Level Change

Sea level is particularly important in affecting deposition and erosion along embayed beaches. The Holocene sea level rise flooded coastal valleys to form headland bound embayments. Changes in sea level during the timeframes considered for this study were practically stable and therefore cannot be considered as important agents of coastline change within embayed beaches. However changes in sea level should also be discussed in terms of longer timescales, given that embayed beaches are often more vulnerable to change in sea level. Furlani et al. (2013) found that during the Roman times, sea level was $-1.36 \pm 0.1$ m below present, while in the Midde Ages it was at $-0.56 \pm 0.2$ m, therefore on a longer timescale of analysis, changes in sea level become one of the most important controlling factors of embayment morphology. This phenomenon becomes particularly important given that in most cases, sea level rise will lead to embayed beaches become 'squeezed' between the rising sea levels and the backward limit of the beach.

This phenomenon has been occurring for thousands of years along the Maltese coastline and probably led to the formation of embayed beaches as we know them nowadays (Figure 8.14). The analysis of monthly variations in sea level between 1995 and 2012 (Figure 4.32) indicate that in recent years, seawater level has been relatively stable and no significant changes in sea level were exhibited. Nonetheless, the ever increasing presence of anthropogenic structures, such as seawalls, quays and concrete shore platforms, can severely limit beach adjustment to long terms changes in sea level, therefore leading to increased erosion of the beachface.

![Figure 8.14: Morphological change of Malta’s palaeoshorelines during the last sea level rise from -70m to – 10m, corresponding to a time interval of 12.4 – 7 ka BP (Source: Fularni et al., 2013).](image-url)
8.3.1.2 Climate
The synoptic climatic features which take place at a Mediterranean scale dictate the physical characteristics of Maltese coastal waters. The most common winds arise from a northwesterly and westerly direction with the maximum wind speed not necessarily being highest from the most predominant wind directions. Waves in the Maltese islands are mostly the results of the regional and local winds and predominantly originate from a north-west direction (Mistral). The results of the wave modelling exercise indicate the importance of headland morphology, shoreline orientation and indentation in modifying the wave setup. The models results also show that the sheltering effect of the island leads to a considerable diffraction and attenuation of the wave setup. For waves emanating from a NW direction, wave diffraction plays a more important role given that the archipelago’s long axis is orientated in a NW direction.

Malta has been dominated by a generally arid climate with the limited amounts of rainfall precluding the formation of rivers or streams directly discharging into embayments. Therefore most of the embayed beaches in Malta receive little terrigenous sediments and the supply of sediment from terrigenous sources is not significant in terms of volumetric contribution to the overall sediment budget.

8.3.1.3 Shoreline erosion and accretion
Variability in the position of the shoreline is not dependent on the width of the beach. In most cases, variability in the position of the shoreline often tends to be comparable across the whole length of the shoreline, irrespective of the width of the beach. This is probably the result of the small nature of Maltese beaches, which due to their embayed morphology and limited shoreline extent, alongshore variability is not significant enough to create noticeable long term variations in shoreline change between one end of the beach and the other.

From 1955 to 2016, net shoreline change was not necessarily equivalent to the envelope of shoreline change (Table 8.4). Changes in the position of the shoreline were often greater than the net movement of the shoreline throughout the period. The results indicate that embayed beaches in Malta are highly mobile in terms of shoreline change, highlighting the importance of the temporal scale when analysing shoreline change. Mean shoreline displacement values for 17 embayed beaches on the island of Elba ranged from 0.69 m to 8.14 m (Cipriani et al., 2011), however the timescale of analysis was considerably shorter (24 years) than that considered or this research (61 years). Rates of shoreline erosion and accretion computed through LRR and EPR showed comparable results (Figure 5.18). From 1955 to 2016, Armier, Gnejna and Whiter Tower beach experienced a landward retreat as a result of a combination of natural and anthropogenic phenomenon. The other beaches, Ghajn Tuffieha, Little
Armier, Golden Sands, Ramla and San Blas where either relatively stable or have shown marginal rates of accretion. On the contrary Cipriani et al., (2011), found that coastal erosion and shoreline retreat of embayed beaches in Elba is a regional process which is affecting almost all beaches, regardless of their orientation and degree of exposure to wave energy. This is partly attributed to the reduction of terrigenous sediment, which is an important component in the sediment budget of these embayed beaches (Cipriani et al., 2011).

<table>
<thead>
<tr>
<th>Beach</th>
<th>SCE (m)</th>
<th>NSM (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Blas</td>
<td>14.4</td>
<td>8.5</td>
</tr>
<tr>
<td>Ramla</td>
<td>15.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Armier</td>
<td>21.7</td>
<td>-12.5</td>
</tr>
<tr>
<td>Little Armier</td>
<td>13.8</td>
<td>-4.1</td>
</tr>
<tr>
<td>White Tower</td>
<td>28.8</td>
<td>-23.3</td>
</tr>
<tr>
<td>Golden Sands</td>
<td>13.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>Ghajn Tuffieha</td>
<td>8.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Gnejna</td>
<td>18.6</td>
<td>-13.5</td>
</tr>
</tbody>
</table>

Table 8.4: Comparison of the value for the shoreline change envelope (SCE) and net shoreline movement (m) for a number of beaches from 1955 to 2016.

No significant correlations could be established (Figure 5.18) between the range of shoreline change rates with the main morphometric parameters (indentation index, embaymentisation index and bay filling index) indicating that additional morphometric characteristics of the embayment, such as orientation with respect to dominant wave setup, could be more significant in terms of shoreline change. In fact beaches with significant differences in the indentation index and embaymentisation index, such as Little Armier and White Tower, exhibit similar ranges of shoreline change.

The results have shown that shifts in wave approaches drive sediment transport within the embayment leading small shifts of the shoreline around one or more pivotal point. The location of pivotal points coincides with the location where the beach shorelines exhibit minimal variation. The location of the pivotal point often is not static and can move shoreward or landward, depending on the state of the beach. Moreover the location pivotal points can move alongshore, as can be seen at Ramla bay, therefore in some beaches the pivotal point should be considered more as a zone of transition rather a fixed point around which beach rotational processes occur. At White Tower the pivotal point is located at the end of the embayed beach shoreline, possibly due to the presence of rock outcrops. The significance of this rotational process however needs to be assessed further, possibly by more frequent aerial imagery, given that the timescale
of analysis might not have fully captured the scale at which beach rotational processes are occurring.

### 8.3.1.4 Sediment budgets

The sediment budget of embayed beaches in the Maltese islands is dependent on the amount of available sediment and the interplay of the sediment supply and loss from these beaches. This process, which operates at different timescales and with varying volumes, is being presented in the form of a conceptual model (Figure 8.15). Seven factors contribute to the overall sediment budget (A) of embayed beaches and these are described further below.

![Conceptual model of the sediment budget of embayed beaches](image)

**Figure 8.15:** Conceptual model of the sediment budget of embayed beaches (exposed section) in the Maltese islands (Source: Author). Factors contributing to sediment gains are shown by the green circles, factors contributing to sediment loss are shown by the red circles. The arrow thickness indicates the relative gain/loss of sediment in terms of volume with respect to the other factors on a short term basis. The colour intensity displays the frequency of occurrence of the process.

- Erosion from beach rock and boulders (B)
Erosion of beach rock and boulders found within the embayments are one of the sources of sediment contributing to sediment gains within the sediment budget of embayed beaches. Erosion is a continuous process; however given the hard rock
nature of most Maltese rocks, erosion provides limited supply in terms of volume on the short time scale of analysis but none the less is an important component in the long term sediment budget of all embayed beaches in Malta. In some beaches the importance of erosion towards sediment budget contribution is more significant both in terms of volume and timescale of occurrence. This especially true at Armier, where the eastern side of the beach is underlain by lithified quaternary beach deposits which are easily eroded once sand is removed and the bedrock is exposed. Similarly the erosion of coastal bluffs at Ghajn Tuffieha supplies the beach with additional sediment.

- Inshore movement of sediment by swell waves (C)
In times of fair weather, constructive swell waves contribute to the inshore movement of sediment and beach accretion. This process is continuous and the most significant in terms of quantities of sediment mobilised towards beach accretion.

- Input from seabed (biogenic carbonate material) (D)
The analysis of sediment composition in Section 7.2.2 has shown that the percentage contribution of biogenic sediment within the overall sediment composition of sediment can be quite high (Figure 7.14). The addition of modern biogenic carbonate sediment in the form of calcareous algae, foraminifera, shell debris and echinoderm spines derived from nearshore marine areas was also observed by KPAL (2009) in a study carried out at Ghadira. There is evidence that Posidonia oceanica meadows can play an active role in the sedimentary balance of Mediterranean beaches, both supplying biogenic sediment and also trapping sediments from being further offshore. Canals and Ballasteros, (1997) have shown that Posidonia oceanica beds can produce 60 to 70 g m² year-1 of calcium carbonate, which translates to an important yield when compared to the large areas occupied by this species in the deeper offshore areas. Input from biogenic carbonate material is a continuous process which in terms of volume, is probably more important than the erosion of beachrock and boulders at the shorter timescale of analysis.

- Removal of sediment by beach users, vehicle traffic and beach cleaning activities (E)
Sandy beaches in Malta are amongst the most densely utilised beaches in the world (MTA, 2015) and in recent years beach use has intensified even more as a result of a greater number of tourists, increased population and a greater demand for recreational activity by locals. The thousands of beach visitors which make their way to the beaches every day invariably contribute to the removal of sediment from the beach. This coupled with vehicular access to maintain beach facilities and provide beach cleaning activities contribute to the loss of beach sediment. While the amount of sediment
removal is terms of sediment volume is minimal compared to other sediment loss factors, this process of sediment loss occurs on a day to day basis.

- Offshore movement by storm water runoff discharge (F)
In times of extreme rainfall events storm water runoff leads to the re-activation of the valley channels backing some of the embayed beaches in Malta. This leads to the temporary formation of a stream which discharges all the beach sediment within its flow patch into the nearshore zone. This process is mostly evidently seen in beaches such as Ramla, San Blas, Ghadira, Golden Sands, Ghajn Tuffieha and Armier (Figure 8.16). In such instances, the quantity of sediment removed is considerable; however the frequency of occurrence of such events is very often limited to once or twice a year. Any sediment which is removed is normally replenished by constructive waves in the days following the storm.

- Offshore movement by storm waves (G)
Storm waves lead to the erosion of sediment from the beachface and the formation of offshore bars and troughs. In times of prolonged wave intensity or insufficient good weather conditions, beach sediment can remain trapped within these morphological features and therefore result in the temporary depletion of sediment. The wave energy levels can also be such as to favour the movement of sediment outside the boundaries of the embayment (sediment bypassing) and therefore result in a permanent loss of sediment either to neighbouring embayed beaches or to deeper waters. Loss of sediment through intense wave activity is an ongoing process within the sediment budget of an embayed beach and given its frequency, is one of the most important processes in terms of the volume of sediment lost from the system.

- Landward transport of sand by wind to the beach backend and dunes (H)
The landward transport of sediment from embayed beaches by wind is also an important factor contributing to the loss of beach sediment in embayed beaches. This is particularly significant in beaches which are backed by low lying or vegetated areas such as Ramla, White Tower, Little Armier and Gnejna. The significance of this factor in terms of volume of sediment lost is marginal even so because of the limited occurrence of such events.

This conceptual sediment budget advances current understanding of the factors contributing to sediment gains and losses in embayed beaches in Malta and other embayed beaches in a similar setting. However it is unable to provide realistic figures on the quantities of sediment gain or loss involved for each of these factors. An initial
estimate of the net sediment exchange in a number of embayed beaches at different timescales revealed that:

- Ramla, San Blas and Ghajn Tuffieha have consistently shown an increase in their sediment budget (Figure 6.24 and Figure 6.26)

- Armier and Golden Sands exhibited both sediment gains and losses depending on the timescale of analysis (Figure 6.25 and Figure 6.26)

- Gnejna and White Tower both exhibited a net sediment loss in all the timescales of analysis albeit at different magnitudes (Figure 6.25 and Figure 6.26).

Figure 8.16: Temporary formation of streams discharging beach sand into the nearshore zone (Upper panel: Armier, Lower panel: Ramla). The frequency of such events is very often limited to once or twice a year and occurs following intense rainfall events which generate substantial runoff in the valleys backing these embayed beaches (Source: Author).
The analysis also reveals that in terms of sediment budget most embayed beaches in Malta can be considered as closed systems where sediment exchange is restricted by the boundaries of the embayment. This contrasts sharply with the sediment exchange processes in embayed beaches where the constant supply of sediment through longshore drift or fluvial sediment is the main factor controlling the dynamic equilibrium of embayed beach systems (Klein et al., 2003). Any changes to the longshore drift of sediment, for example from the construction of artificial headlands or dams, will obstruct the flow of sediment leading to a modification in the sediment budget and equilibrium of the embayment. This process of headland bypassing is considered important for the sediment budget and the dynamic equilibrium of embayed beaches in the south west coast of England (Burvingt et al., 2017).

Even though embayed beaches in Malta are considered as closed systems, in times of high wave energy conditions and prolonged wave activity sediment exchange between some adjacent beaches is possible. This phenomenon is probably best illustrated at Armier and Little Armier where periodic sediment bypassing may occur (always storm related) and therefore there is a level of connectedness amongst these beaches. Sediment bypassing can occur amongst these three beaches also due to the favourable morphometric parameters of the embayments. The limited protrusion of the headlands dividing these embayments leads to low indentation index values, (0.5 at Armier and 0.4 at Little Armier) whereas the shallow bathymetry within the embayments (less than 5m depth) is exceeded by the calculated maximum water depth of significant sediment motion (7.7m) and therefore favours sediment movement between these embayments. Similarly sediment bypassing may occur between Golden Sands and GhajnTuffieha. This research was not able to determine the potential quantities of sediment bypassing, but given that this occurs during high energy wave events (low probability events) the quantities involved are not significant in terms of changes to the sediment budget of embayed beaches.

### 8.3.2 Micro to meso scale

This section discusses the short term agents of change within embayed beaches. Changes in headland bay beach morphology are mainly dominated by periodic fluctuations in wave energy that give rise to distinctive beach morphologies. Storm events are by far the most important causative force of short term morphological change in headland bay beaches (Grottoli et al, 2017). During storm events, sediment eroded from the beach is deposited offshore. In periods of limited wave activity and favourable conditions for beach accretion, sediment from these offshore deposits is deposited onto the beach. Storms are rapid agents of change within embayed beach morphodynamics, however subsequent recovery of beach morphology can be more
prolonged. When the calm period between two consecutive storms is shorter than the
time needed for a complete recovery, beach recovery can be multi-decadal (Senechal
et al., 2017).

Embayed beaches constantly adjust their morphology in response to changing
hydrodynamic conditions (Masselink & Kroon, 2009). Changes in the morphological
features occur on temporal scales of hours to a several months and have spatial scales
ranging from a few metres to tens of metres. The principal morphological features of
embayed beaches which are subject to change are:

- Berm. The berm is one of the most dynamic beach morphological features both
  in terms of morphology and location along the beach profile. Berms are more
  prominent in the larger embayments, such as Ramla, Golden Sands and
  Gnejna, and usually are more developed in the widest section of the beach
  (Profile R2, M2 and G2). In the smaller embayments the limited beach width
  restricts the development of well-developed berm morphologies. Berms can
  also be artificially enhanced through the deposition of algae matts which can
  both enhance beach protection during storm events or else prevent the onshore
  movement of sediment.

- Beach step. Small submerged scarps consisting of the coarsest available
  material formed at the seaward edge of the beachface in Ghajn Tuffieha (Figure
  6.19) and Gnejna (Figure 6.20). Their development is associated with relatively
  stationary water levels and low tidal ranges (Masselink & Kroon, 2009).

- Bar and trough. Where measured, bar/through morphology where highly
dynamic and assumed a variety of forms. The development of a crescentic bar
is evident at Ramla (Figure 6.4), although this was not fully captured in all the
beach profiles (Figure 6.6). Multiple bars where occasionally detected, such as
at Profile G3 on the 13th March 2013 (Figure 6.20), however most profiles did
not extend seaward enough to capture this morphological feature. Bar formation
in most cases is attributed to the offshore movement of sediment during storms
and inshore during calm conditions. Further research on whether bar formation,
in instances such as those in Ramla, can be attributed to standing infra-gravity
waves should be considered in the future.

The results of the wave propagation studies show that although wave obliquity can be
high for waves emanating from a North-West and North-East Direction (Figure 6.30 for
Armier, Little Armier and White Tower and Figure 6.31 for Golden Sands, Ghajn
Tuffieha and Gnejna), the effect of high wave obliquities on the creation of significant
longshore drift gradients is not so readily apparent. This is in part as a result of the
limited headland embayment width (Ro) and beach length (S2). As highlighted earlier on in Section 4.5, the mean beach length for the embayed beaches in Malta is 134m, which is considerably smaller than that for the island of Elba (Bowman et al, 2014).

Evidence of alongshore transport mechanisms were not clearly shown both when looking at the sediment transport modes (Section 7.2.3) and the alongshore grain size distributions (Section 7.2.4). This does not exclude the occurrence of longshore sediment transport, however it can be concluded that the most important transport processes for the redistribution of sand across the beach profiles is the onshore-offshore component. The onshore-offshore component is also the process which probably triggers any changes in the orientation of the shoreline with respect to the incident wave conditions. This change in beach orientation can also be considered as a subtle version of beach rotation, however it is less clearly evidenced than the traditional conceptual models of beach rotation (Turki et al, 2013). Beach rotation as a result of the sediment exchange in the cross-shore have also been recorded by Harley et al, (2011) at Collaroy-Narrabeen beach in Australia.

Within the surf zone, cross-shore transport is predominantly dominated by traction and saltation processes (Section 7.2.3). The percentage contribution of each sediment transport process varies according to the morphological feature being considered and hydrodynamic conditions (storm or swell waves). For example sediment samples with a sediment population composed entirely of the traction population (99%) have been recorded in the breaker zone at Golden Sands (Figure 7.21). On the other hand the sediment collected along profile T1 during the winter season was almost exclusively deposited as a result of saltation processes and the traction and suspension part of the population is non-existent (Figure 7.20). In most beaches the suspension population either made up a small proportion of the sediment population or was completely absent (Figure 7.20). This indicates that the depositional environment is kept agitated by breaking waves leading to the winnowing and offshore transportation of the finer sediment.

Fluctuations in sea level in the order of 20 cm to 30 cm where recorded between 1995 and 2012 (Figure 5.32), therefore the tidal amplitude in the vicinity of the Maltese islands is small (Drago, 2009) and can be considered as insignificant in terms of embayed beach morphodynamics. Variations in wave energy levels are more important for water level changes than tidal oscillations.
9 Conclusions

9.1 Summary of key findings

In terms of the research aims and objectives identified in Section 2.5, the following conclusions can be made:

1. Key physical characteristics and controls on embayed beaches in Malta

Embayed beaches in the Maltese islands occur in various forms and locations. They range in size from small pockets of sand such as Balluta, at just 121 m$^2$, to more significant beaches such as Ghadira, at 23,646 m$^2$. The occurrence of beaches throughout the Maltese archipelago is the result of the interplay of the general structural processes acting upon the local stratified geology leading to the formation of characteristic geomorphological settings. The presence of a particular type of formation at the coast on its own is highly unlikely to lead to the development of an embayed beach setting without the influence of tectonic processes. High correlations exist between bay indentation (a) and headland spacing (Ro) ($R = 0.85$) as well as the length of the embayment (S1) and bay indentation (a) ($R = 0.99$). Four distinct categories of embayed beaches were distinguished based on their respective morphometric characteristics:

- Embayed beaches where headland spacing is equivalent to the indentation of the embayment
- Embayed beaches where the headland spacing is greater than the indentation of the embayment and therefore are more exposed
- Embayed beaches where the headland spacing is almost twice the length of the bay indentation and therefore are the most exposed
- Embayed beaches where the bay indentation is greater than the headland spacing and therefore are the least exposed

Wave modelling results showed that the embayment orientation is the most important morphometric factor in terms of the wave setup acting upon embayment morphology. Accommodation space, which is determined by the vertical, lateral and landward boundaries of the embayment, conditions the extent and width of the beachface and also the propensity for morphological change.

2. Shoreline change within an embayed beach context

The analysis of shoreline change within an embayed beach context is timescale dependent. From 1955 to 2016, the eight embayed beaches analysed in Chapter 5
exhibited changes in shoreline, which can be positive or negative, ranging from 5 m to 40 m. Therefore embayed beach shorelines can be highly mobile and therefore the processes of shoreline erosion and accretion is a long term process, spanning multiple years and even decades. During the last 60 years, beach erosion has led to shoreline retreat at Armier (with an average shoreline retreat of 12.5 m), Gnejna (with an average shoreline retreat of 13.6 m) and White Tower beach (with an average shoreline retreat of 23.3 m). Shoreline retreat at Armier was most intense between the 1950s and 1980s following which the position of the shoreline within these beaches has stabilised. The timing corresponds to the building of a concrete platform on the eastern side of the embayment. Similarly enhanced shoreline retreat on the eastern part of Gnejna corresponds to the building of concrete quay. Erosion at White Tower beach is likely the result of natural causes, following the erosion of a low lying headland on the western side of the embayment. San Blas, Ramlia, Little Armier, Golden Sands and Ghajn Tuffieha have remained relatively stable from 1955 to 2016. The range of shoreline change exhibited by each embayment is not conditioned by the main morphometric indices of embayment indentation (a/Ro), embaymentisation (S1/Ro) and bay filling index (S2/S1).

Comparisons of changes in shoreline position over time have shown that changes to the planform configuration of the shoreline can be categorised into three different types, depending on the variations in the position of the shoreline. These can be summarised as follows:

- **Type 1:** Embayed beaches which exhibit accretion or erosion on one side whereas the other side is stationary and does not show any changes in terms of position of the shoreline
- **Type 2:** Embayed beaches which are either both accreting or both eroding simultaneously. Accretion or erosion can either be the same in terms of magnitude at both ends of the beach or else accretion or erosion is greater at one end of the beach than the other.
- **Type 3:** Embayed beaches which exhibit accretion on one side and erosion on the opposing end.

Embayed beach shorelines can exhibit any of the variations described above and each type of variation is not limited to a single beach.

3. **Morphodynamics of headland-bay beaches within a micro-tidal setting**

The morphodynamics of embayed beaches in Malta are very much dependent on the geo-physical framework within which these are constrained. This framework sets the conditions for the range of dynamic processes acting on beach morphology. Most
embayed beaches present characteristic reflective beach profiles with strong interactions with the rear end of the beach system due to the limited beach width. Beach morphodynamics are heavily impacted by storm events leading to the temporary erosion of beach sediment followed by sediment deposition and profile accretion during calmer periods.

The embayed beaches exhibited a range of morphological features, but the significant in terms of frequency of occurrence and scale are the formation of berms, beach steps and bars and troughs. A high correlation (R = 0.9304) exists between the length of the beach profile and volume. Mean profile volumes ranged from 3.66m³/m in San Blas to 109.7m³/m in Golden Sands, highlighting the importance of accommodation space. Embayed beaches are generally most developed in the central sections of the embayment, with the beach gradually thinning out at the sides. Values for the entire beachface profile gradient ranged from 3° at Little Armier to 15° at Gnejna. The exposed part of the beachface (backshore and berm section) is generally steeper than the submerged part of the profile. Tides do not play an active role in the morphodynamics of embayed beaches in Malta given that the mean spring tidal range is 20.6 cm and is reduced to 4.6 cm during neap tide.

A generalised conceptual model of beach profile evolution was proposed which distinguishes between constrained and unconstrained beaches. Embayed beaches in Malta generally exhibited one of four difference stages of profile evolution, ranging from a well accreted to a well eroded beach profile. The conceptual model recognises the importance of beach casts (*Posidonia oceanica*) in the morphodynamic evolution of embayed beaches in Malta.

4. **Analysis of the sedimentology within an embayed beach setting**

Embayed beach sediments in Malta are mainly characterised by the presence of medium and coarse sand and minor proportions of gravel. Beach sediments are mainly composed of calcium carbonates with varying portions of shelly organisms (foraminifera). Mean sediment values ranged from 193 µm at Balluta to 2775 µm at Marsaxlokk. Beach sediments are normally well sorted, moderately well sorted or moderately sorted. Alongshore differences in sediment composition are not so readily apparent, probably due to the limited size of the embayment which limits the formation of significant wave energy gradients between opposing ends of the beach.
Embayed beaches can be classified into four categories based upon their grain size distributions. These categories can be broadly summarised as follows:

- Beaches where fine sand is the dominant sediment type
- Beaches where medium sand is the dominant sediment type
- Beaches where coarse sand and very coarse sediment are the dominant sediment type
- Beaches where fine gravel and coarse gravel constitute more than 30% of the sediment distribution composition.

Regional geology and embayment morphometry are not significant in terms of the spatial variation exhibited by sediment textural characteristics. Traction is the dominant sediment transport process responsible for the alongshore variability in sedimentology. Cross-shore and alongshore analysis of embayed beach sediments indicated contrasting variations in the grain size distribution of sediment. Whereas some beaches where relatively consistent throughout the year, such as Little Armier, others beaches, such as San Blas, indicate a general coarsening of the sediment along the whole length of the beach profile. Values for the LCD for eight embayed beaches ranged from 121 μm at Little Armier to 333 μm at Gnejna. An increase in the LCD normally corresponds with an increase in exposure to incident wave conditions.

### 9.2 Emerging research questions and future work

The data collection and analysis carried out as part of this research has highlighted a number of key questions which need to be addressed in order to obtain a better understanding of the various aspects of embayed beach morphodynamics.

Further investigation is necessary on the dynamics of beach morphology, in particular with respect to the processes of beach erosion and recovery. Beach profiles collected during this research did not capture the full dynamic range of beach morphological evolution. For example, the role of bar development with respect to beach morphology could not be assessed adequately given that in most cases, bar formations were beyond wading depth. A better characterisation of the interplay between bar development and beach morphological evolution can improve existing knowledge on the type of bars present within embayed beaches as well as provide information on wave energy conditions in beach morphodynamics.
This research has made a preliminary characterisation of beach sediment in several embayments across the Maltese islands. Additional emerging research questions which can build on the existing findings relate to the cross-shore sediment size changes that occur within these embayments and how these changes relate to the changing hydrodynamic conditions and different levels of wave exposure. Moreover further investigations can be carried out on the cross-shore sediment size changes in embayments, and in particularly, to how these relate to the findings of this research with regards to the depth of closure. The role of cellular circulation for the cross-shore transport of sand is paramount and also merits further investigation.

Evidence of progressive or cyclic behaviour also needs further investigation given that the temporal resolution used for the analysis of beach rotational processes might not have been sufficient to fully capture and characterise these dynamics. With the increasing popularity and affordability of unmanned aerial vehicles, monitoring of beach rotational processes at an increased temporal resolution is becoming increasingly possible. Moreover the acquisition of high resolution aerial imagery can also allow for a better quantification of beach volume changes.

Finally future work should address the poorly quantified components of the sediment budget in embayed beaches. Preliminary estimates of the inshore and offshore movement of sediment have been provided by this research, however little is known on the other components of the sediment budget. Therefore research should specifically focus on quantifying the processes leading to sediment gain, such as erosion from beach rock, coastal bluffs and boulders, as well as the processes leading to sediment loss, such as anthropogenic removal of sediment, the influence of storm water runoff discharge and wind erosion. The availability of this kind information will help understand better the dynamics of beach morphological evolution in a sediment starved micro-tidal setting.
10 References


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MECO project (Bases for the Integrated Sustainable Management of Mediterranean Sensitive Coastal Ecosystems) funded by the European Commission under its ‘Co-operation with the Third Mediterranean Countries and International Organizations’ (Contract No. ERB IC 18-C198 – 0270).


