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Travelling in the Roman Mediterranean a GIS approach

Volume 1

by

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This thesis applies new methods to understanding and interpreting the structure of the Mediterranean basin through three different specific studies (chapters 5 to 7), each of which applies several different GIS technologies to create a theoretical model of the wind and wave environment of the Mediterranean during the period of the Roman Empire.

The first of these studies the Mediterranean in terms of its geomorphology, and considers possible movement between areas of the Roman Empire.

The second examines the interconnectivity properties between different port locations in the Mediterranean basin using routes between different known locations and spheres of contact.

The third examines the possible movement patterns along a known axis of travel between two documented port locations in the Mediterranean basin.
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Declaration of Authorship

I, David Andrew Potts, declare that the thesis entitled *Traveling in the Roman Mediterranean a GIS approach* and the work presented in it are my own.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at the University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

where I have consulted the published work of others, this is always clearly attributed;

3. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
4. I have acknowledged all main sources of help;
5. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself,
6. Either none of this work has been published before submission, or parts of this work have been published as: [please list references below]:

Signed …………………………………………………………………………

Date …………………………………………………………………………..
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABM</td>
<td>ABM Agent-Based Modelling</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>API</td>
<td>Application Program Interface</td>
</tr>
<tr>
<td>AW</td>
<td>Atlantic Water</td>
</tr>
<tr>
<td>CART</td>
<td>Classification and regression trees</td>
</tr>
<tr>
<td>DBMS</td>
<td>Database Management System</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>Heat map</td>
<td>A heat map is a graphical representation of data where the individual values are represented as different colours</td>
</tr>
<tr>
<td>Hub port</td>
<td>A port that acts as the centre of a group of ports</td>
</tr>
<tr>
<td>Java</td>
<td>A computer language</td>
</tr>
<tr>
<td>JTS</td>
<td>Java Topological Suite, a library for processing GIS in Java</td>
</tr>
<tr>
<td>Manhattan distance</td>
<td>The path between two nodes on a mesh instead of the direct distance as 'the crow flies'.</td>
</tr>
<tr>
<td>R</td>
<td>A statistical processing language</td>
</tr>
<tr>
<td>Port Cluster</td>
<td>A group of two or more port locations</td>
</tr>
<tr>
<td>Pass through Port</td>
<td>A port long distance route that ship passes through while travelling</td>
</tr>
<tr>
<td>Postgis</td>
<td>A spatial module for Postgres database system</td>
</tr>
<tr>
<td>Postgres</td>
<td>A database system</td>
</tr>
<tr>
<td>Symbiotic port</td>
<td>A port that has a distance relationship with another port location such that it is possible to make a return journey within the same time period.</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangular Irregular Network</td>
</tr>
<tr>
<td>TSP</td>
<td>Travelling Salesman problem</td>
</tr>
<tr>
<td>1\textsuperscript{st}-degree port</td>
<td>A port in a port network that is connected to many other ports</td>
</tr>
<tr>
<td>2\textsuperscript{nd}-degree port</td>
<td>A port in a port network which is connected to the majority of other ports but not as well as a 1\textsuperscript{st} degree port.</td>
</tr>
<tr>
<td>3\textsuperscript{rd}-degree port</td>
<td>A port in port network which is partially connected to other ports but not as many as a 2\textsuperscript{nd} degree port.</td>
</tr>
</tbody>
</table>

Table 1 List of abbreviations.
Acknowledgements

This thesis could not have been finished without the help of many different friends and institutes: the following have given me special help:

My parents and family for everything.

David Wheatley and Simon Keay for acting as supervisors, for supplying the answers to my many different questions, reading many draft copies of this document, for much encouragement and going beyond the call of duty.

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And finally, my thanks to my long-suffering wife Anne, for putting up with so much for so little reward.
Chapter 1

Introduction
1. Introduction

Current studies of Roman travel have focused on the distribution of Roman objects e.g. Rice study of ceramic assemblages and ports (Rice, 2011) Heslin study of Dolia shipwrecks (Heslin, 2008), and Reynolds (1995) analysis of trade in the western Mediterranean. The inference is that, if an object is known to be made in one location, and is found in another location, it is suggested that there must be a spatial relationship between the different locations. Analysis of this type ignores many issues in the physical world, such as changes in the local geography, the spatial distribution of Roman ports, the nature of the localised weather systems and the suggestion that the direct route is not the only route between locations.

The changing nature of the weather patterns throughout the year may affect a journey between different ports, such that a port which is reachable in one season may well not be reachable in another, or the same journey may take a significantly longer or shorter length of time. Although the port data set (de Graauw, 2013) suggests that there is a constant density of port locations along the Mediterranean coastline, it is the nature of the coastal geography in terms of features and wind factors which actually defines the travel potential between different locations.

The proximity of supplying ports and receiving ports is also important for defining the nature of the travel between different areas. This thesis investigates the Mediterranean coastal Roman Empire in terms of the different spatial connectivity between the Mediterranean ports, in terms of known patterns.

This study will attempt to resolve questions such as: are these ports related to each other in terms of their spatial relationship, are there different maritime provinces, was travel possible between these locations throughout the entire year, and does the nature of local and wide area geography define the nature of any association between locations and areas?
In order to resolve these questions, this dissertation aims to examine these issues by the application of different spatial modelling methods to achieve a better understanding of the nature of the Roman maritime environment, derived from the known physical environment of the Mediterranean basin, the known sailing characteristics of Roman merchant vessels (Stecher, 2001, Casson, 1994a, Gambin, 2012), the distribution of ports (de Graauw, 2013), (Houston, 1988), and the wind patterns (Athanassoulis et al., 2004) which occur during the different seasons of the year. The application of GIS modelling methods has been used to investigate or examine many different problems ranging from Identifying brown bear habitats (Kobler and Adamic, 2000), Remote Sensing Image analysis (Huang and Jensen, 1997), the Movement Economy in Pompeii (Poehler, 2017), etc. GIS methods are used in this thesis to explore the relationships between different areas. Delivery and supply metrics in terms of fleet supply are not examined due to the lack of concrete information about the size and distribution of the Roman merchant fleet. Where possible, Roman sources such as the Diocletian trade edict\(^1\) (Arnaud, 2007), will be used to map the relationship between different areas, supplemented with information from object distribution sources (Tomber, 1993), (Reynolds, 1995), (Arnaud, 2005) and (Rougé, 1966).

**1.1 Research Questions**

The purpose of this research is to examine the patterns of travel within the Mediterranean basin during the Roman empire in order to contribute towards a better understanding of travel between different areas and point locations, subject to the variations introduced by the different seasonal weather patterns within the period 30 BC to 500 A.D.\(^2\) This will be achieved by an in-depth study of the geospatial structure of the Mediterranean basin, and applications of GIS technologies to create a software abstraction that can measure the ability to move between two fixed points, subject to known wind data, and to infer possible travel patterns based on this input.

---

\(^1\) A system of price controls that established a price ceiling for different products, freight charges etc.

\(^2\) The Roman Empire controlled the entire Mediterranean coastline during this period.
This first aim is to provide a new understanding of potential travel relations between the different coastal Mediterranean areas of the Roman Empire.

By considering the general possibilities of location to location travel at a macro level, the following set of questions may be considered:

- Are there identifiable regional travel subsystems within the Mediterranean basin, where the patterns of travel might be different from other areas?
- Do the patterns of wind create any zones of travel within a given seasonal period and if so how might these affect the general travel environment throughout the entire Mediterranean basin?
- Are there any travel hot or low spots where the wind patterns may cause an excessive change in the localised travel environment?

Some aspects of travel can only be identified by considering the interactions at a local level between different known locations.

The second aim is concerned with building an understanding of how local travel locations could interact with each other, and if any organisation between different locations. This allows researchers to be focused on a set of questions:

- Do changes in the season affect the position of a port within the trading hierarchy?
- Is travel throughout the Mediterranean constant or is it subject to any form of regional organisation?
- Is the direct route between locations always the best choice of route or would a route that avoids or sails by a feature be a better route?

These issues will be investigated by the study of the Mediterranean basin at a global and local level and focus on the different aspects of the travel regime such as placement of port infrastructure and local weather systems to provide data for the final analysis section which might provide answers to the questions described above.
1.2 GIS technologies

GIS technologies allow an abstraction of data to be examined, modelled and presented in a visual format. Consider Figure 1. A cartogram map of wind values found across the Mediterranean basin, the larger the square shape the larger the wind value.

Figure 1 Mediterranean wind map summer season, the size of the square is proportional to its wind strength basin (author’s interpretation of data from (Athanassoulis et al., 2004)).

In similar context, Preiser-Kapeller (2015) suggests that the maximum daily travel distance for an ancient ship was limited to 100 KM per day, assuming a ship is attempting to sail by known landmarks and return to its starting point within the same sailing day suggests that all would be restricted to an area within a 50 KM buffer of a coastline. This concept is displayed in Figure 2.
Introduction

Figure 2 Buffered 50 KM distance from a coastal shoreline (author’s interpretation of data from (AWMC, 2014)).

Which indicates only some of the island groups may be reached and the only way of crossing the Mediterranean basin would be by making a long circumnavigation of the entire coastline.

Assuming that ship is not attempting to return to its starting point and that it is possible to sail anywhere within 100 KM of a coastline allows a ship to cover a much larger area including being able to reach all possible island groups and being able to island hop from Africa to Europe instead of making long circumnavigation see Figure 3.

Figure 3 Buffered 100 KM distance from a coastal shoreline (author's interpretation of data from (AWMC, 2014)).
Both these maps support a concept of coastal or cabotage travelling, by using a longer daily distance it is possible to consider travel patterns derived from interregional travel.

There are many other GIS methods than just simple map projections, see chapter 3 for a description of the applications of GIS technologies within the scope of this thesis.

1.3 Methodology

The outlined goals of this thesis require the development of a methodology to answer specific questions about the movement patterns of Roman ships travelling between different ports.

The proposed methodology is to map the possible progress of a ship using an application of Dykstra’s algorithm (Cormen et al., 2009:658), (see Appendix 7) and graph theory to model the potential for shipping movement within the Mediterranean basin (see Appendix 5 and 7). An algorithm calculates the most efficient route between two different points, subject to the amount of effort or cost factor of moving between those points being known in advance.

This method has been selected because it allows:

- Easy comparison between partial or total voyages.
- The cost factor can be altered to model factors such as the influence of lee shore winds, etc.
- Can be used to generate one or a given number of routes between different locations.
- The algorithm runs in time $O(|V^i|)$ where $V$ is the number of vertices in the topological map of the Mediterranean basin compared to some methods which take $O(|V^i|)$ or longer (PG Routing Community, 2015).
- Allows factors such as the asymmetric nature of maritime transport networks to be represented.
- Can be used to examine the profile of a selected port on a localised or global area within a port network structure.
Introduction

The cost factor is derived from measuring the movement factors acting on a ship, such as the amount of available wind energy in a given area that may be captured by the ship's sails, the proximity of a port to a given area, the season of the year etc.

1.4 Data sources

Wind data for the Mediterranean basin is available from many different national maritime authorities (such as French Nautical Industries Federation (FIN), or the Spanish Blas de Lezo) etc. Unfortunately, each data source normally only covers a specific national area of the Mediterranean basin often using different metrics and map offsets. For this research, a single source that covered the entirety of the Mediterranean basin was chosen on the assumption that the measurement of the different data patterns would be consistent.

The wind and wave atlas data source (Athanassoulis et al., 2004) covers all seasons of the year and can be used to identify the peak, low and persistent patterns in wind and wave flows (See chapter 4 for a detailed explanation of how the wind and wave model was designed and implemented). These data patterns are important when attempting to discover the movement factors affecting the passage of a ship.

The project port data set is taken from a subset of the de Graauw Geodatabase of ancient ports and harbours, which lists 4491 different ancient ports locations in and near the Mediterranean basin (de Graauw, 2013) and describes if a port has features such as ship sheds, lighthouses etc. The data set does not include any information about the size of the port or how well connected it is any other location within the Roman Empire.

Two “pseudo ports” have been included to provide a reference point to locations outside the western Mediterranean basin.

Other data sources such as the Ancient World Mapping Centre (AWMC, 2014) are used to provided information about roads, towns and river system locations. This information can be used to define the nature of port interconnections with the rest of the Roman world.
The distribution pattern of wrecks and harbours may be important. A shipwreck denotes only the presence of possible shipping activity, it could have sunk for many different reasons such as poor seamanship, bad weather etc. The position of the wreck could also be invalid if a ship was blown off course.

A possible naming issue does occur when using different sources; some locations are called by many different names in different sources. Where possible the common or well-known name is used to describe a location or area.

For example, some sources refer to Constantinople as either Byzantium or, Constantinopolis or the eastern empire as the Byzantine Empire etc. In this thesis, the common names of Constantinople or the eastern empire are used.

1.4.1 The Limits and Use of the model

The intended model will only provide an interpretation of the available modern wind and wave data that could be applied to a Roman period ship and the possible sailing methods employed by Roman sailors. It will be designed to allow for the answering of “what if” types of questions (Oreskes et al., 1994).

The proposed model design will focus on a minimal approach using the concept that a ship is attempting to make the best or shortest possible journey between individual locations. It will avoid attempting to model complex case simulation with multiple ships as these would complicate the case models (see chapters 5 to 7) without returning any extra information about the information being studied.

The intended model will allow for the possibility that some ships may have sailed out of sight of a coastline or only where it was possible to observe a coastline, this type of choice might affect the possible selection of a route. It also assumes that the weather changed during the different seasons.
1.5 Structure of the thesis

This thesis uses the following structure:

Chapter two: reviews the known evidence for the physical and spatial environment in the Roman Mediterranean basin, considers how ships may have moved along known trade routes and the possible nature of port hierarchies.

Chapter three: reviews current research methods which have been previously applied to similar problems in archaeology, and why they might be applicable to answering the research questions listed in this thesis.

Chapter four: explains the methods used to create the movement mode, how the different data sources are accessed, the limitations of the data model and the different algorithms used to create input for the individual case studies.

Chapter five: Uses the model to consider the affordances for movement in the Mediterranean basin in light of the known limitations and influences of the geography, weather patterns of the maritime environment etc.

Chapter six: reviews the record of known port locations in order to further understand possible movement and travel, and considers the structure of travel systems such as port hierarchies.

Chapter seven: While chapters five and six have explored the general patterns and potentials for movement, chapter seven attempts to apply the modelling approach developed in chapter four to a specific axis of movement between two well-known ports subject to the different external constraints on how a navigation route may be used.

Grain was sourced from many different areas of the Roman Empire and supplied free to some citizens of Rome. One of the best documented and understood routes is from Egypt to Rome (Rickman, 1980). The prevailing winds blow from Rome to Egypt, see section 2.3, hence the journey is regarded as being easy to navigate. The return journey was against a constant foul wind which requires a great deal of effort, nevertheless this journey is known to have been made many times (Stecher, 2001).
Arnaud’s examination of the Diocletian edict (Arnaud, 2007), suggests that one of the grain trade routes from Egypt was along the African coastline and then north. Arnaud has also suggested (Arnaud, 2005) that journeys could have been made across the open sea, either directly, or as a series of journeys between different fixed points, e.g. Sicily or Crete.

Chapter eight will consider the findings of chapters 5 to 7 as they relate to the known facts about the Roman empire and present any conclusions. The conclusions will then be compared against the issues identified in the research questions and any research outcomes are examined in detail along with suggestions for any future research.
1.6 Mediterranean Locations

This thesis references many different locations within the Mediterranean basin, and where possible, ancient names have been used. The following map describes the different maritime locations used to describe the nature of voyages throughout this thesis\(^3\).

---

\(^3\) A reference to point in this map includes the entire area around that point.
Chapter 2

Physical and Spatial Environment
2. Physical and Spatial Environment

2.1 The Mediterranean topography

The Mediterranean Sea extends over 1,100 KM in a north-south direction at its maximum, and 3,900 KM in an east-west direction, and covers an area of an approximate 2.5 million sq. KM; it is connected to the Black Sea in the east and the Atlantic Ocean in the west. The sea can be subdivided into two geographical basins separated by the Italian peninsula and Sicily, or twenty-one ancient seas (Parker, 2008:193), see Figure 136.

Water flows into the Mediterranean basin via the Straits of Gibraltar, and via the Don, Dnieper, Dniester, Ebro, Nile, Po and Rhone river systems (Mc Grail, 2014:54). It is normally free of clouds making possible coastal navigation by visual observation of the coastline during daylight, and by stars at night time.

McElderry (1963:12) describes the Mediterranean Sea as being “tideless, or that its tides are so small that they are not worth consideration”. There are exceptions in the Straits of Gibraltar (where due to the effect of tidal push from the Atlantic there is a 0.3-metre average drop) (Easy Tide Hydrographic Office, 2010). There are sections where there are narrow tidal flows, such as those in the Straits of Bonifacio, Gibraltar, Messina, and the Dardanelles, which are all hazards to maritime transport (Rauh, 2003).

The Mediterranean has approximately 2000 islands with Cyprus, Crete, Sardinia, and Sicily among some of the larger. The islands are distributed throughout the Mediterranean basin and could serve as trading points, storm shelters, refuelling points or even as a marine hazard (Gambin, 2012), the size, location and population of the islands being the deciding factor. Rauh (2003) describes the islands as being reachable with one day's travel from the coastline thus making supply and trading easy between island and coastline.
2.2 Coastlines

The geology of the Mediterranean basin is described as

being stable with areas of submergence and uplift quite restricted
with long stretches of coast showing no relative movement at all
during the last 5000 years (Muckelroy, 1980:177).

The implication of this is that natural landmarks, e.g. Cape Bon (Mc Grail, 2014:58), coastal features and coastline, as possibly used by Roman sailors, can be assumed to be in the same places, subject to 2000 years’ worth of weathering. It is assumed that navigating by coastal observations is as valid today as it was during the period of the Roman Empire.

Pryor describes how the coastline of the Mediterranean is formed of cliffs along the northern coast making distinct landmarks which provide good visibility and are relatively kind to the mariner (Pryor, 1988:21). The southern coast is Notorious for its treacherous character. It has many sandbanks and low lying reefs that run out to sea (Pryor, 1988:21). Rauh agrees with Pryor, describing the western coast of north Africa as being a graveyard for ancient shipping, with the coastline having hidden sandbars and presenting a low featureless terrain (Rauh, 2003:22). See Figure 5 where the orange areas represent areas where the Mediterranean coastline cannot be observed.
Morton suggests that

*Even experienced mariners might not have easily remembered the position of so many unmarked submerged rocks with any accuracy; sailors had to rely on spotting them from the deck before it was too late to take evasive action* (Morton, 2001:134).

The implication is that a constant watch must be maintained for hazardous features when navigating near the North African coastline.

Having an observable coastline allows more space and time for manoeuvring and dealing with hazards. For example, the coastlines of the Adriatic Sea are clearly visible and there is a lot of space to recover from an error, but the coastlines of Egypt and Libya only present a narrow space.

Ancient sailors may have been familiar with the coastal landscape and actions of the sea, and, it is to be presumed, would have used them to their best effect. A headland would cause a break in the local wind conditions so that when rounding a headland the full force of winds blowing unimpeded off the sea are felt (Morton, 2001:76). The problem with headlands and wind was sufficiently known for Odysseus to have suffered this problem:
For he brought her close (the ship) to the headland and the wind drove in from the sea (Roberts and Homer, 1976:Book 9 chapter 281).

Odysseus may have been a mythical character, but given the nature of the story about a seafaring incident being told to a seafaring society, it can be assumed that the story was attempting to describe known problems associated with headlands. Ancient knowledge of the sea and its behaviour should be considered when interpreting the results of any computer-generated simulation, see chapter 5 to chapter 7.

2.3 Wave and Wind Patterns

The Mediterranean Sea circulation is derived from the effects of evaporation and changes within the salinity derived from river sources. There is a continuous inflow of surface water from the Atlantic Ocean, derived from the Portugal current (see Figure 6). After passing through the Strait of Gibraltar, the main body of incoming surface water flows eastward along the northern coast of Africa. This current is sub-divided by the Italian peninsula and Sicily, generating several further currents.

- The Atlantic water flowing into the Mediterranean is warmer than the water of the Alboran Sea (between the coastline of Spain and Morocco), which generates a clockwise gyre, forcing a current along the Algerian coastline.
- The Atlantic water stream is split by the island of Sicily and backflows along the western coastline of Italy, and the southern coastline of France back towards Spain. The interaction between this water stream and water flowing along the Algerian coastline generates eddies which create the unstable north Balearic front and Corsica vein. These eddies are unstable in nature with the result that the current strengths may vary.
• A continuing current which eventually reaches the Egyptian/Palestinian coastline and then flows back towards the Aegean. This current is reinforced by the small amount of water entering the Mediterranean Sea from the Black Sea generating a surface current from the Bosporus.
• The Atlantic water arriving into the Gulf of the Lion can introduce a back current towards Sicily.

![Current water circulation in the Mediterranean basin](image)

Figure 6 Current water circulation in the Mediterranean basin (Millot and Taupier-Letage, 2005:40).

These currents are reinforced by the outflow from the major river systems of the Mediterranean, the Nile, Po, and Rhone, with a minor contribution from the Arno, Maritsa, Meander and Tiber (see Figure 7).
Murray compared the weather conditions recorded in *Meteorologica* (Aristotle, 1952) with modern wind observations and concluded:

*If allowances are made for slight variances in the directions and frequencies of individual winds, we can be reasonably certain that the winds throughout the Mediterranean blew from the same general directions and at the same general times of the year as they do today.* (Murray, 1987:159)

So, it can be assumed that the wind conditions have not changed significantly within the Mediterranean basin since the fourth century BCE. This conclusion is supported by Morton who describes the sea conditions as *having been little changed in the Mediterranean since antiquity* (Morton, 2001:16). Hence, again, it can be assumed that current tidal data can be used to simulate the effects of ancient tidal systems.

The weather calendar is subject to a warm season focused on the summer months of June to September, and the cooler period during the months of October to May. The transition between the two periods is slower in the spring and faster in the autumn (Ritossa, 2008:61). This implies that a boat travelling in the spring could choose the best time to make a voyage due to a gradual change in the weather, but a voyage undertaken in autumn could be subject to an unexpected weather change.
The western Mediterranean is subject to the north Atlantic low and Azores high weather systems, and the eastern is subject to the Mongolian high and Indo Persian lower systems. The interactions between these weather systems create the prevailing winds in summer and winter. (see Figure 8 and Figure 9.) The effect is to create a wind geometry that normally blows southeast to south throughout most of the year over most of the Mediterranean basin.

A travelling ship is affected by both tidal and wind forces. In the Mediterranean, there are few places where tidal phenomena are significant (Stecher, 2001:190). The straits of Gibraltar and the Dardanelles are subject to inflows of water which create a current with an average rate of 3kph (Morton, 2001:38) and 6kph (Morton, 2001:68) respectively. These currents ensure that transportation out of the Mediterranean was difficult, although not impossible. The current flow along the straits of Messina made it effectively a one-way passage, with the flow providing a power assist in one direction and a halting force in the other (see Figure 6).

It was, therefore, necessary to endure a lengthy circumnavigation around Sicily to sail in the other direction. Pryor (1988:15) suggests that the legend of Scylla and Charybdis was derived from the notorious whirlpools and tidal rips encountered at Messina. Similar problems could be expected to occur in other areas such as the Straits of Bonifacio.
Figure 8 Prevailing winds patterns in the Mediterranean basin in the winter season (Pryor, 1988:17).

Figure 9 Prevailing wind patterns in the Mediterranean basin in the summer season (Pryor, 1988:17).
Physical and Spatial Environment

Figure 10 Prevailing wind systems for the summer season in the Mediterranean basin (author’s interpretation of data from (Athanassoulis et al., 2004)).

In Figure 10 the general direction of the wind is to the southeast, making journeys from the western to the eastern Mediterranean basin easy. There is a suggested windblown triangle in the western basin operating from the south coast to France, to north eastern Africa, and followed by either an exit to the Atlantic or a return journey along the southern coast of Spain towards France.

Crete can be seen to be a blocking feature to the wind system originating in the Aegean. The islands of Sardinia and Corsica provide a similar feature against the Mistral wind blowing from the direction of France.

Localised coastal breezes can occur, caused by the effects of the land cooling down during the evenings, but these winds only blow for a fraction of the total day, and would not have made a major contribution to the total amount of wind energy encountered during an average voyage.

A major hazard to ancient sailors was the likelihood of sea storms, which can occur with little or no warning in the Mediterranean; the problems of a heavy sea and strong winds could sink any ship no matter how well constructed or well sailed. Homer describes in the Odyssey:

For the force of the wind had brought him to Crete as he was making for the land of Troy and drove him out of his course at Malea. So he
anchored his ship at Amnisos, where is the cave of Eileithyia, in a difficult harbour, and hardly did he escape the storm (Roberts and Homer, 1976:185).

Sea storms occur more in the winter months, this might be why the seas were described as being closed (Vegetius, 2013: IV 39) during the winter months.

Although Figure 5 shows which parts of the coastline are subject to coastal observations, there can be issues with this map which shows an ideal or best possible situation. In the spring and early autumn, it’s possible for large amounts of sand and dirt to be picked up from the Sahara (Dulac et al., 1996), which results in a hazy environment see Figure 11 making the coastline difficult to observe.
The number of dust events is significant, Goudle (2009) quotes a total of 207 days of dust events, i.e. 62% for the year 1999. Another problem is the sea haze caused by land masses heating and cooling. The size and density are unpredictable, but it is only present during the summer months. In the winter months, visibility may also deteriorate due to the results of heavy rain (El-Fandy, 1952). The overall effect of the dust and sea haze is to periodically greatly reduce visibility on some days throughout the year. Both these issues may result in greatly decreased observation of the coastline which has implications if the coastline is being used for navigation.
2.4 Roman Ships

The sailing ability of a Roman ship was, in some degree, determined by its carrying capacity, operating environment and its propulsion method. The ships would have been designed to carry the largest amount of cargo possible while remaining seaworthy. The evidence from Roman-era shipwrecks (Parker, 1992) and mosaic images. Casson (1995:157 and :169) suggests two general classes of ship, the sailing ship, and the general merchant galley. Both types of vessels had different operating abilities.

2.4.1 The Sailing Ship

The sailing ship came in different sizes, some designed to handle longer distance travel routes, and being designed to withstand the stronger winds (see Figure 12) and waves encountered in the open ocean. Their deeper draught ensures that their carrying capacity was greater than the merchant galley, but this feature also prevents them from working the shallower river systems.

Figure 12 Roman sailing ships under full sail with extended sails and steering oars (Piazzale delle Corporazioni Ostia Antica)
Figure 13, shows a ship that appears to have lowered its mast, and is in the process of unloading its cargo. The design of the mosaic suggests this boat is beached, as there is no depiction of a quayside or other port infrastructure in the image. The presence of a pair of steering oars implies that this is a cargo carrying vessel instead of a rowboat. This could mean that any beach could be used as a port, without having to build all the necessary warehouses, quays and other infrastructure normally associated with an operational port.

![Mosaic of a ship unloading cargo](image)

**Figure 13** Sailing vessel unloading a cargo of firewood with a lowered mast and stored sail (Mosaic from a tomb at Hadrumetum (Sousse, Tunisia)).

The Althiburus mosaic (see Figure 14, images one to four), appears to show four different sailing ships with one or more masts and steering oars, a feature not found on the rest of the images.

Due to the size and weight of the vessel and number of crew, it is suggested that a sailing ship would not have used oars as a power source; the manpower required to have any notable effect on the speed of the boat would have removed any possible profit from a journey. It is possible that when a boat was being docked, it could have been towed into place by smaller boats powered by oars (known as lighters). This suggestion is supported by Rougé who describes the merchant’s problems

*in order to turn a profit, these merchantmen had to have fairly sparse crews, but more men were required for coastal craft propelled by both*
oar and sail than for the sailing ships plying the open seas (Rougé, 1981:158).

2.4.2 General merchant galley

From iconographic evidence, these boats appear to have a mixture of either oars or sails (or both) as a method of propulsion. The Althiburus mosaic, see Figure 14, shows ships carrying different types of cargos: (horses, nets, jars etc). The images seem to occur in no fixed order, the floor being an item of decorative artwork. However, this does illustrate the general design of Roman shipping, providing a catalogue of 25 different ship types, the majority of which show the use of oars. Three of the images show the use of oars and sails together, eight with sails at work, four with oars at work and another five where oars may be being used as a power device as well as a steering device. It is suggestive that sail would have been used as the main source of power, with the oars being used only when becalmed or when attempting to enter or leave a port. The mosaic images do provide some indication of size, for example, image 19 which appears to be a fishing boat landing a catch, indicating the general size for this image. But the rest of the images are not drawn to the same scale, images 1-3 show full-sized sailing ships (one towing another ship) which are significantly larger than simple fishing boats.
Figure 14 The Althiburus mosaic, showing some different designs of Roman ships (Maison des Muses, Althiburus (Meijer, 1986:223)).

Arnaud (2011) has interpreted images from some of the stations (see Figure 12, Figure 15) of the Piazzale delle Corporazioni at Ostia along with phrases from the Natural History (Pliny the Elder Book II Chapter CXXVIII in Rackham et al, eds, 1949) as suggesting that ancient boats were capable of sailing at least
90 degrees from the wind\(^4\). The circular voyage of experimental ship Kyrenia2 between Cyprus to Greece (see Figure 17) indicates that this is possible.

These images could merely be an artistic interpretation, but the inclusions of pennants (see Figure 15 and Figure 16) and tell tales (Figure 16), devices for showing the direction and speed of the wind, suggests that these images at least attempting a faithful description of a period ship at work.

![Image of two ships with multiple sails and bowsprits with a building that has been interpreted as a possible lighthouse from Piazzale delle Corporazioni (Ostia Antica (Arnaud, 2011)).](image)

In Figure 14, Figure 15 and Figure 16 some of the ships are shown with one or more masts carrying a single oblong sail per, with a checked sail pattern, rigging, and pairs of steering oars. The pattern on the sails in the images have been interpreted as a device ensuring that the working area of the sail could be

\(^4\) Sailing at 90 degrees to the wind or tacking allow a vessel to be sailed in to the path of a foul wind.
controlled, or as a method of strengthening the sail (see Figure 16) where the sail is being adjusted.

Figure 16 A ship mosaic Domus of Palazzo Diotallevi illustrating the presence of sail tell tales and adjusting the sailing surface area (Rimini, Rimini City Museum.)

Stecher (2001) provides a detailed analysis of the design of the Madrague de Giens wreck, in terms of hull design, steering oar design and possible mast construction. Stecher suggests that design was stable but indicates that the sail configuration would be changed to reflect the nature of the current wind. In a slow wind, 25% more sail cloth would be rigged, in a faster wind 50% of the mainsail area could be reefed away (Stecher, 2001:131).

Attempts (Gianfrotta et al., 1997) have been made to prove that the technology as understood by archaeologists does work. Although not of the same period under consideration in this thesis a copy of the Bronze Age boat (Kyrenia2) was sailed between Cyprus and Greece against foul and favourable winds, using a direct route (see Figure 17). Although the ship was blown off course several times, both trips were successful, proving that the understanding of the
technology was and that voyages of at least this length were possible well before the early Roman period.

Casson (1995) describes documentary evidence from 171 BCE of grain carrying ships on the river Nile averaging in size between 250 and 275 tons with one ship carrying at least 450 tons. Ships carrying complete obelisks (Wirsching, 2000), medium-sized grain carriers (Stecher, 2001) or the specialised ships such as the Dolia bulk wine carriers (Heslin, 2008).
The obelisk carrying ships only transported single stone structures, which seem to have made only singular voyages. At least one of the obelisks carried was used to create the foundations of the Portus lighthouse (Wirsching, 2000:121), which suggests a rather limited use for ships of this size. Similarly, Caligula ordered the construction of two large pleasure barges for use on Lake Nemi (Carlson, 2002). These barges were 70 metres long and 18 metres wide. It is not suggested that these barges were designed for sea travel, but their size confirms the abilities of Roman shipwrights to construct larger vessels. It is not clear if this level of shipping technology was generally available through the entire Mediterranean basin.

This pattern of evidence suggests that Roman era ships were manoeuvrable, were sailed in the direction of a foul wind as well as a favourable wind, at least some could use a flat beach as a temporary port if required, they came in many different sizes and might engage in long-distance or short-distance travel.

2.5 Shipwrecks

Parker’s (1992) study of shipwrecks in the Mediterranean catalogued 1259 different shipwrecks over a period of 2000 years (500BC- 1500AD) and from Straus’s (2013) update, it might be suggested that a given percentage of ships would be wrecked every year, probably due to a combination of bad seamanship, worn out crafts, adverse weather conditions or pirate action. Leidwanger (2017) has stated that the contents of a wreck can be used in indicating where a ship was sailing to or from, but it depends on the journey the ship made between the surface and the sea bed. A sinking ship may capsize and scatter its cargo, or it could hit the sea bed at a significant velocity and explode, scattering its contents across a wide area. The crew may have realised that there is an issue and may have attempted to dump some parts of cargo overboard. Some cargos may not have survived or left traces in the archaeological records, cargos such as grain or liquids carried in barrels which would have rotted away. Some of the cargo’s contents could be ballast, or a heavy cargo acting as ballast. In all scenarios, it can be difficult to identify from the position of the cargo. how it was loaded, or what the total cargo contents were.
Even if an entire cargo has survived the wrecking process it can be difficult to discover at which port it was loaded or what its destination was; depending on the nature of the journey it could be a local port or any port along a long-distance trade route. The position of shipwrecks could be used to suggest an area of risk to shipping, and hence a location to avoid whenever possible, or it can indicate a point of marine activity. Figure 18 shows a heatmap of known shipwrecks plotted over a bathymetric map of the Mediterranean.

![Map of the Mediterranean with shipwreck locations](image)

Figure 18 Sea depths of the Mediterranean basin and the locations of shipwrecks (author’s interpretation of Parker (1992) and Strauss (2013)) (NOAA, 2004).

It should be noted that most wrecks occur in either the areas which are known to be difficult to sail, near ports or in the shallow northern inshore waters of the Mediterranean where diving is common and thus shipwrecks have a great chance of being discovered. It is not known how many undiscovered wrecks exist in deeper water, which makes using the location of wrecks as a general indicator of difficult travel unreliable.

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5 The darker blue sections indicate deeper waters.
2.6 The Sailing Season

As described in section 2.3, the weather in the Mediterranean is divided into two periods, a warm phase subject to long days with stable weather, and a cold season subject to short days with reduced visibility and unsettled weather. As might be expected, most of the long-distance travelling appears to have taken place within the period of stable weather and longer days. It would also be expected that some activity would also take place in the shorter days of spring, autumn, and winter but the amount of this activity is unknown. The Roman military engineer Vegetius (2013:IV 39) states that the sailing season was from 27 May to 24 September where navigation is believed to be safe, until 11 November navigation was unsafe, and until 10 March when the sea was closed. But this is contradicted by Demosthenes where traffic between Alexandria and Rhodes was described as happening (Against Dionysodorus 30: in Carey et al, eds, 2014) in the winter season. It’s more likely that in some parts of the Mediterranean travel and trade continued where the weather was stable enough.

Ritossa(2008:40) describes the Mistral as being violent through the winter, and the Adriatic as being often unsettled, with the north-western and eastern area of the Mediterranean being subject to violent wind storms. This suggests that winter was obviously not the best time to sail. Rauh(2003:21) suggested that the harsh weather conditions would have restricted winter voyages to short excursions across enclosed waters. This implies that long-distance travel and trade was only possible during the summer season and had to be organised in advance. The term `short excursion' can refer to anything from trip down a river to an inshore journey, suggesting some short distance voyages still occurred if the weather permitted. Plotting the areas of significant wave height 6 using data from (Athanassoulis et al., 2004) see Figure 19 and Figure 20) shows a distinct area(s) of the Mediterranean which would have restricted the movement of ships in winter and autumn. In the autumn, the area is located to the south of Gaul, see Figure 19.

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6 A strong wave is a wave with a height greater than 3 meters which occurs more than 10% of the time.
Figure 19 Areas of strong wave activity in the Mediterranean basin during the autumn season (author’s interpretation of data from (Athanassoulis et al., 2004))

The area of strong wave activity is much more extensive in winter, forming a block between Rome and the eastern and western Mediterranean basins, see Figure 20. It would still be possible to sail these areas, but these voyages would be subject to hazards. The different behaviour of the seasons needs to be reflected in any simulation software used in this thesis.
Figure 20 Areas of strong wave activity in the Mediterranean basin during the winter season (author’s interpretation of data from (Athanassoulis et al., 2004)).

There are also other hazards that occur through the year such as lee shore winds, which would blow a ship on shore. The location of these feature changes throughout the year and would be avoided where possible.

2.7 Known Roman Maps

There is limited supporting evidence for the uses of maps by Romans; most surviving evidence is limited to itineraries and documents such as the Peutinger map.

The Antonine itinerary lists *starting and finishing points of each journey and the total distance in Roman miles* (Dilke., 1987). Some evidence about maritime routes is included such as the journey from Rome to Arles (Reed, 1978). It is suggested by Dilke that the purpose of some of the routes reflects either the distribution of the *Annona militaris* or a supplied document to the creation of the Diocletian tax edict (Arnaud, 2007). This suggestion limits the use of itinerary in this thesis, but it does demonstrate a general understanding of the geography of the Roman world, such as the locations of the narrowest points of the Mediterranean basin.
This suggestion is confirmed by the design on the Peutinger map (Talbert, 2010) which presents a layout of Roman roads and settlements from Britain to India and indicates knowledge of spatial locations of different Roman settlements, and mosaic maps such as the one at Madaba in modern Jordan show large-scale pictorial landscapes.

It can suggest that knowledge of itinerary style information would be well known as sources such as Vegetius, suggests that when fighting on a campaign

*the more conscientious generals reportedly had itineraries of the provinces... not just annotated but illustrated as well, so that they could choose their route when setting out by the visual aspect as well as by mental calculation* (Vegetius, 2013:III 6)

### 2.8 Navigation

The importance to sailors of constantly assessing the state of the weather and of the sea, and of adjusting courses to take account of expected changes is paramount. At the same time, they must direct their course using sea markers as navigation signals – spotting coastal towers and temples, patterns of headlands and cliffs, and so on. Most travel patterns would have been itinerant, making roundabout routes and frequent stops. For them, a complete journey might involve not just one direct passage over the open seas, but a series of stages between successive ports of call. Some hazards could force a choice of which course to navigate; Morton notes

*If fear of deep water encouraged inexperienced or nervous sailors to remain near the coast, the threat of piracy might have encouraged others to keep well out the sea. Pirates apparently tended to favour inshore waters* (Morton, 2001:156).

Sailors may have preferred to stay near to a coastline but may have been compelled to navigate further from the shore due to lack of manoeuvring space, the presence of headwinds, lee shores, submerged rocks etc. Navigating near a coastline is far more hazardous than deep water sailing.
One of the most common compromises between the open sea and coastal sea-faring was to follow the general outline of the coast, but to sail directly across the mouths of often deeply recessed bays rather than follow the longer route around their shores, thus avoiding shallow hazards and being able to sight trouble from a longer sea distance. It is reported by Strabo

*The earliest Greeks made voyages for the sake of piracy or of commerce, not, indeed, in the open sea, but along the coast* (Strabo book 1 chapter 3 section 2).

It is possible that some Roman sailors followed the patterns suggested by Strabo, and only travelled by coastal hugging, the implication being that they would not cross an open sea space due to lack of fixed reference points. It has been suggested by Arnaud (2008:62) that a mixture of coastal and open sea routes were used. Taking a direct route requires an understanding of navigation. Davis (2009), suggests that detailed navigation was understood, taking bearings from stars, understanding cloud formations etc.

Even if travel patterns were limited to only coastal sailings, some ‘shortcuts’ may have been employed, see Figure 21, where the sea within square boxes indicates possible crossing areas. Passages out of the sight from land are made across either the straits of Otranto or sea of Sicily (see Figure 4), to avoid a longer circumnavigation off the Mediterranean basin.
This suggests that two sailing profiles need to be considered when attempting to simulate a travel pattern, a path which follows a coastline and another that crosses the open sea.

It is also known that an experienced sailor could by taking sightings from either the Sun or a constellation to steer an accurate north/south course. Until the creation of the marine chronometer in 1761 steering an accurate east/west course was always difficult unless fixed landmarks were available.

### 2.9 Sailing Movement

A merchant ship is designed to carry the largest amount of cargo possible while remaining sea-worthy and being capable of being moved by the effects of the wind alone, unlike a military ship which is designed to travel as fast as possible with a greatly reduced carry capacity. The prevailing wind in most of the Mediterranean is normally south-easterly. A ship attempting a voyage in a different direction could not move upwind directly; it must manoeuvre across the wind direction by tacking or gybing to the wind. Pliny (Book II Chapter
XLVIII in Rackham et al, eds, 1949) describes the method, Vessels by means of slacking sheets can sail in contrary directions with the same winds.

The resultant movement pattern is either a dogtooth (see Figure 22) for tacking or a sine wave for gybing (Figure 23), each diagram represents the locus taken by a ship as it travels from left to right.

![Figure 22 Route of ships path tacking into the Wind.](image)

![Figure 23 Route of the path of a ship gybing to the wind.](image)

The tacking method is more efficient and captures more of the wind with a resultant faster speed but generates a large shearing force as the ship executes the turning manoeuvre. Beating/gybing places far less strain on ship and sails, but at a cost of losing a larger amount of wind strength and increasing the distance that must be traversed, making a journey far longer. Having to sail upwind was a standard manoeuvre which most crews would have been familiar with, which would have been expected to be used whenever necessary, no matter what the current weather pattern (Stecher, 2001:207), with the possible exception of a sea storm. Recent voyages from the experimental Phoenician ship 2008 project (Beale and Taylor, 2013) around the
coastline of Africa did attempt tacking, which was described as ‘Virtually impossible’ (personal communication P. Beale.15/September/2012).

An attempt to sail a replica of the Bronze Age Kyrenia ship discovered that it was possible to tack into the wind between 2-4 knots on the Beaufort scale, but the procedure proved to be difficult (Cariolou, 1997:93), (see Figure 17). It is possible to suggest that there are problems in the recreation of the original technology, that the crews were unfamiliar with the equipment, were ignorant of the procedure or that there is a limitation in the technology. The Kyrenia project discovered the procedure was easier in speeds up to 5 knots but required skill and perfect coordination in wind forces up to force 10 Beaufort (Cariolou, 1997:93). Similar experiences have been recorded while sailing a replica Viking seagoing cargo ship (Bennett, 2009:68). These facts contradict Arnaud (2011), the possible difference being that the crew attempting to sail the recreation boats might have been attempting to make a manoeuvre derived from experience from a modern yacht, instead of an ancient ship.

Any form of manoeuvre other than a straight course is expensive in terms of time and distance, the sails must be reconfigured at each end of the turn, discipline must be tight, and it is often difficult to steer the perfect course with the result that both time and distance are lost. The path taken by the Kyrenia ship from Cyprus to Greece and return shows some of the problems, see Figure 17. The voyages do not follow a straight path, perhaps caused by inexperienced sailing or by one of the storms encountered during the trip (Gianfrotta et al., 1997).

Some merchants may have attempted to avoid a significant amount of tacking or gybing by sailing a large offset, thus only having to occasionally reset their course and sails. The problem in performing this type, of course, is that a ship requires a large operating space. If a ship is attempting to sail within sight of a coastline it might be necessary to perform a constant number of small manoeuvres to fit within the available space. This suggests that any attempt to model the possible movements of Roman ships must be flexible enough to cover an attempt to sail in any direction no matter what direction the wind is blowing in at any given point (see section 4).
2.10 Roman Ports

A port functions as an interface between the sea and the land. The evidence about the layout and functions is limited to ruins that currently exist, given that most harbour sites have been in an almost constant state of redevelopment since they were first built, and some port sites may have predated the Roman civilisation. Several lost documents noted by Blackman (1982a) describe the principles for the construction of a port, so it can be assumed that the layout of some ports would have followed established design principles on how to use the landscape for the best advantage in creating, servicing and defending a port. It is suggested by Ducruet that there are three different types of port model, each working with a different urbanisation pattern (see Figure 24). A ‘city level’ port which interfaces directly with a sea such as Ephesus and a smaller hinterland, a large scale urban development such as Pompeii which may have one or more localised harbour areas or an inland city which has one or more localised ports serving it such Rome being supplied by Ostia and Portus or an inland settlement such as Jerusalem being supplied by Ascalon.

![Figure 24](image.png)

**Figure 24** Different possible port and city relationships (Ducruet et al., 2016)

The scale and accessibility of the hinterland affects the development of the port. Rimmer (1967) suggests that port development along a coastline undergoes five different phases of development, see Figure 25.
The initial phase is a random collection of ports along a coastline each being capable of localised trade. As port and hinterland resources are grown, some port locations become more developed and other locations are abandoned. In Figure 25, a collection of ports transforms into four regional centres linked by inland routes and eventually only ports P2 and P4 are developed. Port P2 offers general shipping access for the entire area and P4 offers some type of specialised trading resources which caused it to survive, where ports P1 and P3 were abandoned.

Figure 25 The five different phases of port development (Rimmer, 1967)
This type of behaviour may be observed in the Roman Mediterranean by the development of a deep-water port at Portus (Blackman, 1982b) which resulted in the movement of port resources away from Puteoli.

This type of development model suggests that the viability of a port location depends partly on its connectivity to its hinterland as well as the constant development of shipping.

2.11 Port systems

The ports in the Roman period may have uniquely functioned as part of an integrated transport network or as a distributed collection of focal points for travel. The Roman imperial period was the only time in history when all ports were in the common political authority of a single state. This has some major implications for our understanding of Roman seaborne commerce. There may have been some local differences in customs, such as the taxation structure. After the collapse of the empire, the Mediterranean became subject to all manner of localised differences in culture and working practices. These issues make it difficult to compare the trade routes and trading behaviour established by Roman merchants to patterns created by later merchants.

Nieto (1997), in his analysis of Roman trading, describes the concept of Primary and Secondary ports with direct and redistribution routes between them. In this model, large ships carry a homogeneous cargo and sail a direct route between primary ports. When a ship docks, the cargo is redistributed to smaller boats resulting in a heterogeneous cargo distribution network. This model allows larger boats such as the Isis (Casson, 1950:43) to carry large bulk cargos and be serviced at a deep-water port. Smaller coastal boats can then be used to navigate river systems such as the Tiber and Rhone, or to make local voyages to smaller secondary ports that serve a hinterland. Such networks can be strongly or weakly connected, see Figure 26 and Figure 27.

In such a system, the secondary ports would be under the economic control of the primary port. A primary port would be expected to have better infrastructure than a secondary port, for example, more storage, cranes, larger
moles, the ability to process cargo, bulk up cargos, resupply a ship, etc. Some form of local market control may have existed to protect prices.

In this model, local sailors would have expert knowledge of local weather systems and the local secondary ports. International sailors would have known the international wind systems and how to deal with hazards found on such voyages.

Figure 26 A high connect network of local port networks.

Figure 27A ringwork of local port networks.
A similar system is a group of ports having a shared area of influence, (see Figure 28). Were travel and trade confined to a small area which may share locations between two or more other areas of influence.

Figure 28 A network of ports sharing a common area.

Figure 29 An uncontrolled port network.

An alternative to Nieto’s theory is to suggest that there was no organised system, no zones of economic control, no localised hubs, no major travel patterns routes, all resources are shared across all ports, see Figure 29. Instead, the general concept of trading and travel was free for all, in which voyages were undertaken where it was suspected that a profit may have been
made. In such a system, travel could either be a long or short journey, ports could be of any size.

There is a general difficulty in discovering which trading system could have been supported; the physical evidence could support either system or a mixture of the two. Peacock (1986) suggests that a redistribution model for Roman travel was also operating alongside a reciprocity or gift exchange model and marketing model. Reynolds also states that hierarchy of cargos existed with goods subdivided into classes of primary, secondary and tertiary, along with the suggestion that it was

*highly unlikely that fine wares or coarse wares were carried as sole cargoes* and that *distance travelled by secondary and especially tertiary goods depends on the value of the primary cargo.* (Reynolds, 2010:127)

Evidence to prove this model would require a detailed study of the remaining evidence for cargo distribution based on shipwreck contents and artefact scatter patterns.

### 2.12 Voyage profiles

Most data about historical sailings describes how long the journey took and possibly when the voyage took place, but little information is supplied about the nature of the journey unless something exceptional took place. It is unknown if the stated information includes the time to load and unload the ship or the time taken to enter and exit the harbour. Docking at a port would have been difficult and avoided where possible as it would require a ship to have been towed into place using a heavy dory⁷ (Casson, 1994a:130), or by the use of a fixed harbour mounting point, a towrope and use of the ships capstan (see Figure 30). Both procedures would have been expensive in terms of time and resources.

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⁷ A rowed tugboat
Figure 30 Roman Ship show a capstan on the left-hand side and cargo being un/loaded Piazzale delle Corporazioni Ostia Antica (Casson, 1994a:132).

The choice of which route to take was an individual choice. Casson describes Cicero’s journey as taking two weeks because Cicero enjoyed a shore-based meal and a night’s sleep in a stable bed (Casson, 1994b:151).

The journey was expected to take three or four days if the direct route had been followed with no overnight stops, but as Cicero was paying for the journey, the route taken would have reflected Cicero’s requirements.

Long distance voyages did occur, the grain trade between Alexandria and Rome, the list of cities listed in the Piazzale delle Corporazioni (see Figure 31) and the trade routes of the Diocletian price edict (see Figure 32 ) confirm that voyages did occur but not how they were made.
Figure 31 known cities with a statio in the Piazzale delle Corporazioni at Ostia (Rice, 2016).

Ultimately the type of voyage profile is decided by the design of the ship, the ability to sail the boat and knowledge of the sailing conditions.

Some designs of boats will be restricted to use in a river system, their design not being able to stand the strain of sea passage, or conversely being too large to enter a river system. In either case a change of ship must be made which requires the presence of a port at a river estuary such as port p2 in Figure 25.

The knowledge of when to start a tack or which course to sail when more than one alternative route was available between two identical locations can greatly affect the amount of time spent travelling. A ship engaged in cabotage style trade or navigating a local small world may only have made a voyage of up to 100 KM per day as suggested by Preiser-Kapeller(2015:124) and Pyor(1988:25-101).
Figure 32 Major sea links according to the Diocletian price suggested by Rougé (Parker, 2008)

A ship making a long-distance voyage between two locations may have stopped off along the route to resupply/take on water, avoid a storm etc. The circumnavigation of Africa voyage made by the Phoenician ship expedition in 2012 (Beale and Taylor, 2013) did make a nonstop twelve-day detour from its official route to avoid the pirates along the Somali coastline; which suggests that it is possible to make long trips within the closed environment of the Mediterranean basin.

A ship making a voyage cannot expect to encounter constant weather conditions, no two voyages will be completely identical due to changeable weather patterns. A ship’s choice of profile could also be affected by the choice to sail near islands as either waypoints, trading posts or possible shelters from anticipated storms (Gambin, 2012).

Ships may have chosen to break a journey during the winter season, when the sea-lanes were closed (see section 2.6). Any cargo would have been unloaded where possible, as cargos such as grain would have otherwise rotted had they been exposed to damp and humid environment of a ship’s cargo hold, where other cargos such as stone, and bulk cargos of amphorae would have placed an unnecessary strain on a ship’s infrastructure. This assumes that the choice of a winter location could have supported this type of activity.
2.13 Major routes

Detailed knowledge of the trade routes used by the Romans is unclear: some documentary evidence is available from the fragments of surviving coastal pilots, but these documents only tend to give the basic information needed by the navigator (Blackman, 1982a). What is unclear is the trading interlinkage, the guidance between different ports, the knowledge necessary to be able to operate as a successful merchant. The main trade routes would have been dictated by the weather systems, the size of the boat being used and the commercial requirements (Papaioannou, 2011:204), (Peacock and Williams, 1986:54-66), (Tomber, 1993:159).

The available evidence consists of, the location of shipwrecks,( see section 2.5), the positions of the known resources (see section 4.1.9) and the geophysical features and navigation (see section 2.8) and the weather (see section 2.6). But Interpretation needs to be carefully considered to avoid issues such as the ‘Last Route theory’ (Parker, 1992) where the makeup of the ship’s cargo is used to determine the port of origin. The composition of the cargo may represent a single charter between two different locations, could be the result of a return cargo, a redistribution to a secondary site, the result of speculative trading, or the ship could have been blown off course.

Some attempts have been made to suggest trade routes in the Mediterranean by drawing on the documented sailing routes of Genoese and Venetian merchants (Mollat, 1993). But there are issues with these attempts: outside of the Roman period, the Mediterranean is a network of different states, some of which were closed, hostile, or welcoming. Any attempt to establish or navigate a trade route would have to deal with these issues, which presumably did not occur during the Roman period when all areas were under a common authority: ships could move anywhere within the Mediterranean basin, without fear of hostile states.

Rauh and McGrail suggest that trade routes were along the northern and southern shores of the Mediterranean coast (Mc Grail, 2014:59), (Rauh, 2003:22). Arnaud’s (2007) interpretation of the price edict, see Figure 33, suggests a different set of coastal bound routes to those of Rougé, see Figure
32. These routes follow Rauh and McGrain’s suggestions about coastal trading. Arnaud’s study of general trade routes suggests a different network of trade routes, much more extensive than the routes suggested by studies of the price edict, see Figure 34.

Figure 33 Trade routes in the Mediterranean basin at the time of the Roman Empire (Arnaud, 2007:232).

Trade routes cannot be assumed to be static, the trading landscape is subject to constant change and flux. For example, until the creation of Portus, most shipping for Rome would have arrived at Ostia, but in this case, the port moved. In some cases, such as the creation of the new capital of Constantinople (Reynolds, 2010:74), which caused a major change in the Annona shipments, instead of ships being sent to Rome in the western Mediterranean, they were redirected towards the eastern Mediterranean. Similar events may have forced changes in other trade routes.
2.13.1 **Eastern Mediterranean Basin Routes**

Rogue’s map of major sea links (1966) see Figure 32 and Arnaud’s map (2007) see Figure 33, indicate a trading relationship between the Black Sea area and the eastern Mediterranean ports. The Black Sea is described as a major source of Garum products (Casson, 1994a), which suggests that Garum was a return product for a ship navigating to the Black Sea in exchange for goods from the eastern and possibly the western basin. Both maps suggest that Rhodes was acting as a focal point of trade within the area.

Reynolds states that, with the *refounding of the city of Constantinople*, *Constantine sought to secure the food supply for his ‘New Rome’ with the introduction in 332 of an Annona civica that provided free distributions of bread similar to the system established at Rome. For this purpose, Alexandria's regular contribution was redirected from Rome to Constantinople* (Reynolds, 2010:74). This suggests that there was a regular trade route from Alexandria as per Arnaud and Rougé to Constantinople, and that in late 332 a major reorganisation of the existing trade routes occurred.

McGrail suggests the possibility of a *counter-clockwise voyage (Mc Grail, 2014:59)* around the eastern Mediterranean, from Crete to Libya, Libya to the
Nile, northwards to the Levant, west towards and along the Turkish coast, then to Rhodes and then from Rhodes to Crete, this being confirmed by Fulford (1989).

2.13.2 Western Mediterranean Basin Routes

Monte Testaccio in Rome (Claridge, 1998:367) is built from approximately 55 million amphorae which had a Spanish origin, dating from between the middle 1st century to the mid-3rd century. If a ship has an average carrying capacity of 1,500 amphorae, it would suggest approximately 37,000 cargos during a 150 year period. If the amphorae originated on the Spanish Mediterranean coastline it suggests that there were two trade routes coming from the area of Spain, either coast-hugging along the southern French coast, or via an open sea route through the Straits of Bonifacio as (Figure 32). Either of these routes could also include parts of the southern coast of France. Muckelroy reaches a similar conclusion based on evidence from shipwrecks (1980:56). Reynolds suggests the existence of a rival oil industry in Africa, with Proconsularis as a rival to Baetica (2010:138), the analysis (chapter 5) indicates that geographically this area is closer to Rome with a faster route, as confirmed by McCann and Free (1994). This route also avoids the difficult passage through the straits of Messina, which may explain the economic growth in Africa Proconsularis, (Hobson, 2015).

Rougé describes Africa as providing most of Rome’s grain supply (1981:190) with trade routes starting from the area north of the province of Africa (the area around Carthage) and went up to the eastern coast of Sardinia and along its shores, after which the ships sailed before the wind into the Italian ports (Rougé, 1981:190).

Alternatively, McGrail described a route from Sicily to Tunisia (2014:59) which seems to suggest a different route to Rougé’s suggestion.
2.13.3 **Inter-Basin Routes**

Reynolds, when describing the distribution of Baetican oil, states that it was *largely a western phenomenon that had and continued to be only rarely exported to the east* (Reynolds, 2010:70). It may have only been exported rarely, but it does indicate that a valid trade route existed between the western and eastern basins of the Mediterranean.

There are three major ways of crossing between the different basins of the Mediterranean: either starting in the centre, north or south or crossing via Sicily into the other basin. The selection of which trade routes may have been used is difficult to identify. McGrail suggests the use of a northern and southern route, with the northern route being relatively more developed, both agriculturally and commercially (2014:85).

Rougé (Parker, 2008) study of the Price Edict (see Figure 32), indicates two possible ways of making a voyage from Alexandria to Portus, either along the northern coast of Africa, following the route under Sicily, turning around the western side and heading towards Portus, or taking a route that crosses the Mediterranean south of Crete and navigating around the eastern side of Sicily to Portus. This route is investigated in chapter 7. If the existence of a trade route is defined by the nature of goods being exchanged, then any changes to
the location of the supply of goods might result in changes to the nature of trade routes.

2.14 Summary

This chapter has explored the available evidence about the physical and spatial environment of the Mediterranean and the nature of Roman shipping. From the available evidence, it allows some general patterns to be identified.

The winter sea conditions are worse than summer ones, and the spring and autumn serve as a transition phase to summer, with the effect that sailing in the winter would be localised and confined to short and essential journeys only.

There is evidence to suggest that Roman ships could have sailed up to 90 degrees into an oncoming wind and that sailors would have known the differences between a short route and a long route for the purposes of travel.

The evidence from natural factors, shipwrecks, port locations, and patterns of trading is ambiguous, with no single source being able to provide an effective answer to the nature of Roman travel patterns.

It is possible for one or more ports to function as a localised trading network, with an interface to long-distance trade being supplied by one or more specialist ports where any such port would not normally have expected to be near another specialist port. Any locations in such a network could have a symbiotic relationship between large inland towns or could function as a gateway to a river system.

Port network relationships are not static. As technology and skills develop, any port network will adapt, with the result that some locations may become more developed and other locations would be abandoned. The pattern of movement between such locations may also change, which would result in changes to shipping densities. The evidence presented in Figure 26 to Figure 29 suggests the possibility of several different trading models which could co-exist together, or that any single individual trading model could be the dominant
system, but it is the ratio of long to short distance voyages that define which system would be used.
Chapter 3

Measuring Maritime Movement: a review of the literature and previous research
3. Measuring Maritime Movement: a review of the literature and previous research

3.1 Introduction

This chapter describes an overview of previous attempts to research maritime networks and to explain the current research and understanding. Recent research methods in archaeology have focused on the concept of network analysis for explaining or understanding the concept of movement (Llobera et al., 2011), (Graham, 2006) the distribution of resources (Knappett et al., 2008) and interconnection between settlements (Brookes and Huynh, 2018), (Matson, 1974), (Guimil-Farina and Parcero-Oubina, 2015). These methods have long been employed in other fields of research to examine similar concepts (Carter, 1969), (Hattie, 2002), (Haggett and Chorley, 1972) and are considered proven.

This review considers current solutions and the application of data algorithms to identify gaps in previous and current research.

As explained in chapter two, maritime journeys are subject to the wind and wave patterns, the metrics of travelling between different locations are different and are subject to seasonal influences. The effect of the differences is cumulative, small errors in local travel patterns can be ignored but may be significant when dealing with wider travel patterns. Consideration must also apply to the area being navigated, some travel patterns may only permit coastal travel patterns to be considered.

Unlike journeys along road systems where travel is constrained to move through a given set of roads through towns linking those roads, in maritime movement, a ship is free to bypass any individual port by simply sailing past it, to a different destination. This results in most maritime networks being formed as a network of bypasses instead of a network of direct connections, with the result that maritime networks are often more complex than road networks.

As identified in section 2.2 the Mediterranean basin includes many different types of coastal landscape features, any successful modelling method must be
capable of measure progress travelling around these features instead of jumping across a landscape feature such as a peninsula. The scale of detail must be accurate enough so that all possible travel patterns may be considered.

At the same time, any results generated must be comparable between the different types of landscape feature. Consider Figure 36 where a passage in the Aegean between the different islands and coastline consists of short journeys compared against the Levant coastline where the only possible journey is along the coastline.

![Figure 36 Mediterranean coastline landscape sections](image)

The project goals described in chapter one and issues identified in chapter two suggest that the following subject areas need to be reviewed.

### 3.1.1 Areas of influence

An alternative solution to the previous suggestion is to consider the influence of different areas. Travel can occur for many different reasons a well-connected network with no areas of influence would generate a smooth flow of travel, but a network subject to different areas of influence would generate totally different travel flow, see sections 2.11 and 3.3.
3.1.2 Network approaches to travel networks

The issues of cabotage and long-distance travel represent totally different movement model concepts, where the next travel location may be in either the local area or as long distance journey. As such, the concept of which destination is best connected for these different travel goals needs to be considered, see sections 2.11 and 2.12.

3.1.3 Approaches to understanding port hierarchies

The thesis port database material identifies over 3000 different possible locations. Some, due to the physical characteristics of the Mediterranean basin, may be a more important location for travel than others. A classification of port locations by their available infrastructure (see sections 2.10) may suggest reasons for travel near these locations.

3.1.4 Parsing a network

The previous methods have focused on network concepts of how different locations may be connected to each other, but a different method is to consider the physical cost of travelling between different locations instead of how well a location is connected. An extortionate travel cost may be a significant reason to avoid travelling between locations no matter how well connected they are, see section 2.11 and 3.6.

3.2 The Orbis Platform

During the development of this thesis the Stanford geospatial network model of the Roman world, the Orbis system (Scheidel et al., 2012) was released. It is a simulation tool which is designed to estimate the journey time between two different known points. It calculates an estimated journey time between two different points from a choice of 751 known points (268 are listed as Roman seaports). Options include a choice of routes either by land, river or sea, the effects of the different seasons and different types of transport models. The site can be accessed via either a web site interface or via the programmer’s interface.
An initial investigation suggested that the tool could satisfy some of the travel requirements of this thesis, but a closer look suggests that there are some important issues.

The wind data mesh is limited to only 20 different values for the entire Mediterranean and Black Sea basins which constrains the data accuracy when processing movement patterns. The detailed studies of this thesis require a more accurate data source, it is proposed to use data from the Wind and Wave atlas (Athanassoulis et al., 2004).

This includes 129 different data points which will allow for the generation of more accurate data results, it should be noted that this data source is limited to the Mediterranean basin only.

The ORBIS site only used a predefined mesh of routes across the Mediterranean basin, see Figure 37. The green routes indicate routes that cross the Mediterranean and blue routes that cover coastal areas.

Figure 37 The route transport grid used by the Orbis platform indicating all possible routes known to the Orbis system, which shows some gaps in the southern Mediterranean coastline and entrance to the Adriatic (Scheidel et al., 2012)
As can be seen in Figure 37 some coastal areas such as the Gulf of Sidra are ignored, making it impossible to calculate a coastal journey along the entire African coastline.

There is limited coverage of the central Mediterranean, which results in all possible traffic from Egypt being routed via Cyprus or Crete and then along the northern Mediterranean coastline.

These restrictions cause problems when attempting to model previous research such as routes suggested by Bonifay (see Figure 38) because the routing mesh (see Figure 37) does not include a direct link between Alexandria and the straits of Messina.

Figure 38 Theoretical pottery distribution routes within the Mediterranean basin during the period of the Roman empire (Bonifay and Tchernia, 2013).

The case studies of this thesis are designed to consider every point within the Mediterranean basin instead of the limited subset offered by Orbis, so that suggested routes by Bonifay and other sources may be evaluated.

The ORBIS platform includes an external computer interface, which allows the generation of data without having to use a web site, but this option does not include all the choices present in the website version.

A requirement of some of the thesis studies is to investigate the choice of sailing areas. The original Orbis platform did not offer features to say: avoid
this area’, ‘traverse this area’ or only journeys to be made within the sight of the coastline when making a route calculation. A recent upgrade now allows these features but by the time they had been provided another method had already been devised for this thesis.

The Orbis platform only offers a choice of 268 known port locations for the starting and end points of a journey, some calculations in this thesis will require the selection of user-defined arbitrary points along a coastline or possibly in the middle of the Mediterranean basin.

The Orbis platform offers many useful features in predicting general patterns of movement across the Roman empire, but for the reasons stated it does not provide the amount of detailed data required to satisfy the geospatial requirements of this thesis.

### 3.3 Areas of Influence

An area of influence defines the projection relationship possible between different locations. The relationship can be any significant factor such as political control, trade treaty, travel potential between different groups of ports, attraction and buying power measure in the size market, or port features such as warehouses, lighthouse ship sheds etc.

An example of such an analysis model is presented by Huff (1979) when a list of Irish population centres is factored into bands by considering variables such as population size, commodity output, sales etc. A sphere of influence is then generated by calculating a line of equilibrium based on the linear distance between selected population centres.
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Figure 39 Sphere of Influence of 2nd order Centres (Huff, 1979).

Figure 40 Sphere of Influence of 3rd order centres (Huff, 1979).

This type of presentation shows which town locations are most influential in each area. For example, in Figure 39 both Dublin and Dun Laoghaire are considered as level 2nd order centres but Dublin has much more influence. Similar results were discovered by Re Velle (1986) when studying the effects of a new ice cream vendor on an existing group of vendors.

A sphere of Influence is a useful metric to indicate which areas are most influential, within a system of interconnected areas, such as the different models of port systems described in section 2.11. Some port systems/areas may be more influential or better connected than others, the size of areas may vary. Such an analysis requires a metric to determine local or global influence, which may often be missing when considering the ancient world due to lack of data or partial data sets.
3.4 Network approaches to travel networks

By studying the properties of transport networks, it may be possible to identify some locations or routes which may be more significant than others for reasons which are not immediately obvious. For example, the rail transport network for southern London includes two mainline stations, Victoria and Waterloo, where most trains start and terminate. This would suggest that they should be regarded as the two most important locations for the supply of resources or services, but since the traffic flow for both locations is routed via Clapham junction, it suggests that for the supply of resources or services Clapham junction might be a more important location. Similar network analysis suggestions may identify possible primary and secondary travel patterns, centres of control etc.

Connectivity has been studied by Rivers (2009), (2015), (Rivers et al., 2016) to determine the possible relationships between different locations when only the location information and the distance to travel is considered (see Figure 41 to Figure 43).
In the early Bronze Age, the sailing technology is limited to short distance journeys of 20 KM to 50 KM sufficient to only allow travel connections within local island groups.

In some cases, it can be shown that travel is possible between some locations such as Syros and Paros if a long-distance route is followed but is not possible between Paros and Ios even though the distance between Syros to Paros looks to be a similar distance.
Figure 42 Network map for possible exchange of goods in the bronze age in the Aegean sea (Rivers et al., 2016).

Using an increased distance of 100 KM and a population size metric, Rivers et al (2016) generates an exchange network for the southern Aegean, which indicates that Knossos (site 1) is a major hub site with satellite sites at Malia (site 2), Gournia (site 8), Thera (site 10), Naxos (site 13), Rethymnon (site 22) and Myndus (site 32).
Figure 43 Network map for possible exchange of goods in the late Bronze Age in the eastern Mediterranean basin (Rivers et al., 2016).

Rivers applied the methods to model a wider area trade network in the late Bronze Age which allowed for a sailing distance of 400 KM, but discovered that provide difficult to connect the more far-flung sites like Sicily (Rivers et al., 2016). The map does show that to make connections between the Aegean and the rest of the Mediterranean, either a direct route via Marsa Matruh (site 1) or long coastal journey along the Levant was necessary which still required a long-distance journey between Kouklia (site 29) and Rhodes (site 18).

River’s research does identify possible travel patterns, but it ignores the asymmetrical nature of maritime travel and the differences between seasonal movement patterns and uses the Euclidean distance to measure the length of travel instead of the actual distance. These issues may be overlooked in small scale maps but may introduce significant distortions in large scale movements.

Preiser-Kapeller(2015) also studies the Aegean using a combination of a Delaunay triangulation to identify all possible travelling connections (see Figure 44) and an application of Newman’s clustering algorithm on any travel routes that are shorter than a single days sailing and did not cross a land bridge (see Figure 45).
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Figure 44 A Delaunay triangulation of the Aegean sea (Preiser-Kapeller, 2015).

The generated map results in a series of regional clusters of ports, see Figure 45. Each of these clusters could act as an isolated small world within the larger travel map or a sphere of influence.

Figure 45 Map of a possible series of regional clusters of ports within the Aegean sea (Preiser-Kapeller, 2015).
The same problems that affect Rivers research into long-distance sailing connections (Rivers et al., 2016) also applies to this method, it works when considering highly connected network areas, but breaks down when processing long coastlines.

Dicks (1972) when studying Roman Roads in England, used the concept of polar networks with different roads subdivided into different classes, using the nature of the connecting town to determine the importance of the connecting road. The roads are classified by considering their ordering from nodes, and then sub-divided in first, second, third or fourth order roads, see Figure 46. Level one roads feed into level two roads, level two roads feed into level three roads etc. In such a network, a major centre would be expected to have more major roads feeding into it. This illustrates that London dominates the road network.

This type of network analysis is subjective: Hutchinson (1972) described it as a fine example of a misused technique, the problem being what is considered to be the focus on the network and the nature of the interconnection between different location. By picking another location Hutchinson managed to prove
that other locations could be regarded as a polar node. The flaw is not in the method, but in just using one method to assess a travel network.

Dick’s method was reworked by Brooks and Huynh to compare the different measures of centrality and an application of the Page Rank method (Brooks, 1998), (see Appendix 7 and Figure 47).

The “betweenness” centrality identifies those nodes that control the flow of resources from a public town, i.e. bottlenecks in the network.

The “closeness” calculation returns those locations which either compare a public town’s independence from other towns or its ability to communicate with other locations. The results returned from Brookes and Huynh (2018) suggest that the Roman public towns to the north of London are significant and have a better quality of transportation road then might be expected in this area. The degree results should return those locations which have a controlling function across the network, the returned results do identify London as an important controlling centre.

It is important to understand that measures of centrality require a certain density of nodes in order to return a valid result, Brooks (2018:487) discovered that measures underestimate the importance of nodes in the outer parts the network and was only suitable for identifying nodes near the centre of the network.

Brooks (2018) also applied a PageRank method of classification, originally used by Google to classify the relationships between different web pages, classifying the way that road junctions interconnect to other road junctions and locations in a similar method.

Brooks (2018) concluded that PageRank has potential in archaeological applications examining physical networks. Jenkins (2001) also used the same measures of centrality to study the Inca road network and did not discover any problems with the centrality measures and suggested that these methods were sufficient to calculate
“the favourable network positions of administrative centres, production enclaves, and storage sites related to both production and administration” (Jenkins, 2001:678).

Figure 47 The different measures of centrality within Roman Britain (Brookes and Huynh, 2018).

Carter (1969) applied a similar methodology to calculate Interconnectivity in 13th – 14th century Serbia (Carter, 1969), see Figure 48. Where a road network is shown against a distribution of node connectivity, the outline areas have better connectivity and better access to resources.
Figure 48 The Interconnectivity in 13th – 14th century Serbia (Carter 1969).

The results from these calculations show that the majority of network travel could be expected to occur in the centre and some areas of the north, with little travel in the southern area. Similar methods have also been applied by Sanders and Whitbread(1990) to study the nature of road systems and place locations in the Peloponnese.

Fouriner(2016) applied the alternative strategy of plotting all known valid Incanto trading routes to construct a representation of the Venetians Incanto trade system (see Figure 49).
which indicates the principle trade flows towards Venice in the Incanto network, with some locations providing major trade flows and other locations being ignored.

The concepts of the relative neighbourhood graphs have been used by Badillo(2011) to explore spatial analysis in a network space. This method uses a ‘rest of region emptiness’ to assert if there is a relationship between different points. This test works well enough if the network space has a uniformed nature, but in a maritime network with the network space being affected by coastal geography, the asymmetrical nature of maritime travel and the grossly different land and sea transport rates (see section 2.2) these methods fail to work correctly.

In all network studies it is important to remember that placement of a location is normally decided by the physical geography of the landscape and the limitations of available transport infrastructure which can sometimes force connections to exist.
3.5 Approaches to understanding port hierarchies

To model the hierarchies of ports as discussed in sections 2.10 and 2.11, it is necessary to model hierarchies formally in some way. There are various approaches to this problem.

3.5.1 Classification and regression trees

The other methods described so far have focused on a theoretical analysis of possible connections between different geographical data constructs. In this method, a profile is created that defines the concept of the port type that is being searched for.

This algorithm is normally employed to classify the nature of a data sample, to look for patterns within the information flow. A typical example of the use of this method is Mathieu’s (1999) analysis of the features of a castle, to discover the purpose of a room (Mathieu, 1999). Mathieu’s implementation is a simple binary style classifier, where an analysis starts at the top of the tree and navigates to bottom by answering yes/no at each node. The value of the lowest node describes the purpose of the room.
Figure 50 Decision tree classification of the different room types of a medieval castle (Mathieu, 1999).

More complex machine learning forms (classification and regression trees) (Murphy, 2012:547) are available. These take a sample data set used to train the method of navigating the decision nodes of a tree, by measuring the number of data samples which can be used to process a choice at a node.

There are some problems:

- The inability to reapply the same question on the same data sample. This problem normally leads to the same question being asked several times in different ways. In Mathieu’s research, the request about ‘Connected Visually to a Chapel’ is repeated twice but leads to different conclusions.

- An incorrect set of questions can cause “overfitting” issues in the design of the tree, where the tree design closely matches the design of the data set instead of the nature of the data being processed. In Mathieu’s research, the data source is about four castles which were all
designed by the same builder for the same king in the same period. Use
the same “castle classifier” on another group of castles, such as the
Henry VIII artillery platforms at Deal, Pendennis, Walmer etc and the
software would fail. The fault is not in the sample data, the castles were
all designed by the same builder, for the same king in the same period
as with the previous groups, it is the just that “castle classifier” is
overfitting the data.

In this thesis questions such as:

- Does the pattern of features present at a given port location match the
  pattern of features found at a known hub port?
- Is the known location of this port similar to any other known port
  locations?

3.5.2 Cluster density Analysis

An alternative method of establishing which port is significant within a group
of ports using sphere of influence (see section 3.3) is to use a cluster density
analysis of the port locations (described sections 2.5 and 2.9) but using a
method that correctly differentiates between areas of high and low clustering
and using a distance travelled metric instead of the Euclidean distance between
points.

There are many different clustering methods available each of which offers
different results; Frankel used hierarchical and close-proximity cluster analyses
when studying Inter-Site relations in the middle Bronze Age and noted it was
better to run more than one method to obtain a valid result set a result as

There are many different algorithms available in the subject area, but because
the concept of a cluster is not well defined it is subject area specific. The
subject area of this thesis is the geospatial locations of ports into possible port
hierarchies, which suggests that centroid K-means (Wong, 1983) or density
models (Raschka, 2015) should be considered instead of object distribution
models or graph models.
3.6 Parsing the network

The methods and studies presented so far have all considered methods and studies that seek to extract information about the structure of a network by considering some aspect of the network.

A different strategy is to consider the different aspects of crossing the network instead of analysing its structure. The city of Rome is known to be one of the key consumer centres and areas such as Egypt (Tchernia, 2016:188) Sardinia (Semple, 1921:73) and Western Africa (Swanson, 1975) are known to be production centres. By considering how travel might occur between these different locations it may be possible to construct a general solution to the entire Mediterranean basin. There are several possible strategies:

3.6.1 Agent-based modelling

Agent-based modelling (ABM) is a mechanism designed for simulating the interaction between groups of different software constructs (an agent), which behave autonomously following a given set of predefined rules. The collective action of the total system may provide an insight into possible behaviour patterns which are not normally obvious. ABM solutions are sufficiently flexible that they may be used to simulate virtually any system such as the behaviour of traffic in piracy-affected waters in the Gulf of Aden (Vaněk et al., 2013), the behaviour of customers at a supermarket (Casti, 1997), traffic and pedestrian modelling (Helbing and Balietti, 2011), or improving Southwest Airlines cargo (Seibel and Thomas, 2000) etc.

These methods could be applied to the concepts of maritime movement where an agent could simulate the different movement patterns of ships which might be engaged in cabotage or long-distance sailing, the effects of different size fleets of ships, the different effects of sailing in the winter avoiding hazards or not avoiding hazards etc.

This assumes that enough rules can be established that correctly reflect the known information about the size and nature of the Roman fleet and the behaviour of Roman travellers.
3.6.2 Raster Methods

The methods described so far take a consideration of a mathematical model of locations and infer different possible properties about relationships. An alternative solution is to create a model based on physical movement. In modelling the movement patterns of Roman ships, the surface is a representation of the Mediterranean basin, with the land masses forming blocking features and the sea the movement area. There are two possible methods of implementing such a model: a friction model, or a diffusion model, see section 3.6.2.1 and 3.6.2.2.

3.6.2.1 Friction Models

In a friction model, a raster planer surface is created, where each cell of the raster reflects the cost of moving over the surface, a cell which represents a blocking feature such as a land mass is encoded as an impossibly high value. The other cells are encoded to represent the ‘friction value’ of passage, i.e. an area which is difficult to cross will have high value (such as a tidal intersection), an area which is easy to cross (such as an area with a high current value) will have a low value. A journey across the surface is measured by the accumulated values of the different regions crossed.

3.6.2.2 Diffusion Models

In a diffusion model, a series of expanding rings is generated from tessellating a polygon that represents a unit movement of a ship. The magnitude and orientation of the polygon are controlled by the wind direction at the location being processed. The centroid of the first polygon is the starting point of the journey. The number of points used to draw the polygon must be sufficient to accurately reflect the nature of the landscape being processed, too few and the generated results will look like an angular sawtooth, too many will result in a large computing overhead required to process the more detailed polygon interaction.

Passage through a barrier feature such as a water channel is calculated by drawing only a fraction of the polygon. The resulting pattern is like the effect of a diffraction grating on multiple energy sources. Some areas merge together
to form a larger surface, others cancel out. For example, when using this method when navigating through a narrow area such as the Straits of Messina, the resulting pattern will expand after the passage is made.

Friction and diffusion methods have their benefits. The diffusion model deals with passages through navigation channels and avoids linear barrier breaching issues, (see (Conolly and Lake, 2006) for a description of this problem), which may cause issues when navigating some complex shorelines found in areas such as the Aegean.

Other problems are caused by the octagonal navigation model supported by the friction model; expansion is limited to the eight principal points of a compass. The limited movement pattern may more accurately represent the required movement model. A friction model with a very small cell size could be used to overcome this issue, but this will cause an increase in the required processing power.

The diffusion method requires many defined points on a polygon to define the movement pattern and to deal with complex shorelines. There needs be a polygon point in the sea area being modelled, to enable the polygon to expand. This issue requires a significant amount of computer processing power. Due to the limited movement model and linear barrier breaching issues, the diffusion model has been used to model the movement pattern.

Liedwanger (2013) have used these methods to construct a valid representation of travel in the ancient Mediterranean. Being a raster solution, it is possible to calculate a value for any given area of the Mediterranean for which data is available, unlike the Orbis project which only uses a series of predefined routes to model a passage across the Mediterranean, see section 3.2.

This type of modelling also resolves the ‘network of bypass’ issues as the generated raster just measures the time take to reach a location without constructing a direct route between the two locations. But since the direct path is an unknown value it is impossible to identify any port hierarchy issues
3.6.3 Walking the network

Preiser-Kapeller (2015) suggests that by applying the nearest neighbour model and eliminating any route longer than a single day’s travel, and applying the Newman algorithm to the remaining network, it is possible to identify region clusters. This method was designed to be employed in the Aegean, which is densely populated by islands forming well connected localised networks between the coastline and islands.

Some solutions to the problem of walking across a network assume that the nature of the network is known to the traveller and the traveller must visit a given number of locations such that they never visit the same location twice and end up at the location from which they started from. This solution is known as the travelling salesman problem. There many different implementations which add an extra feature such as Yang et al., (2008) ant colony model, where other travellers leave information about how to travel the network at secondary locations, or the travelling politician problem where the politician must visit only a single city in one or more individual voting areas (Noon, 1993).

Other researchers have considered a combination method where the network topography is built from an application of Dykstra shortest route calculation, and network analysis methods are used to query the name of the generated network graph. Verhagen used this method to considering the nature of travel in the Zuid-Limburg area in the Netherlands (Verhagen et al., 2012); White used similar methods to consider a pedestrian network in Oaxaca, Mexico (White, 2012).

Other researchers have used the concept of the least cost path to provide the network metric, i.e. the ease of the journey is considered instead of the speed of passage, such as Güimil-Farinna and Parcero-Oubinna (2015) reconstruction of Roman roads in the Iberian Peninsula.

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8 Also known as the generalized traveling salesman problem.
3.7 Summary

Looking at each of the different methods presented in this review, no one single method or algorithm examined can provide a definitive answer to any of the issues identified in chapter one. In some methods, a network must exist before its structure can be studied. In others, the important centres of travel must be similarity identified in advance. This suggests that a combined solution of interconnectivity, networking and port classification is required.

The port data set includes 3000 different locations, too many to be manageable. Filtering the port data on key features (see section 2.10) still results in 500 ports. Using this number of ports would render any network analysis to be too detailed for any general patterns of travel obtained. Carter (1969) used 42 points when studying medieval Serbian movement networks, Huff (1979) used 39 points when studying Ireland’s urban geography. This suggests that using about 40 different points is enough to identify key centres.

Using this number of ports would allow for the seasonal variations in travel to be studied, as required by chapter 5. By comparing the differences in navigating between these key centres and other ports, the goals outlined in case studies two and three can be completed.

As already described in chapter two, the scale of traffic/voyage profile is being considered which suggests that it is necessary to determine if the Mediterranean can be split into several different economic areas or zones.

The properties of key features (described in section 2.10) could be used to factor the list of ports into a manageable number by the application of cart tree analysis. (see section 3.5.1). This assumes that the list of key points is correct. This selection method would allow the different properties of ports to be the determining factor. A hierarchical clustering analysis of the same port data set may also generate possible information about likely centres of travel, but this analysis would be determined by spatial information alone, in areas where there are only a sparse number of ports no results would be generated, in densely packed areas the key points would be identified.
As identified in chapters one and two, the total amount of information about the Mediterranean basin in the Roman period is limited. The existing evidence based on distribution maps of the scatter patterns of objects suggests the possible origins and nature of travel potential, but not the path or choices used to define individual travel patterns.

The raster solutions presented in section 3.6.2 can generate data about how long it takes to travel between two different points without suffering from any of the issues produced by the network of bypasses, but this approach suffers from the slow time taken to generate results and does not allow factors such as lee shore winds etc, to be considered. This suggests that a raster solution would allow general patterns of interaction to be examined, but not the detailed results required for case studies two and three.

The combination of fastest or least cost path methods to create a network, rather than employing methods based on the proximity of individual port locations, offers an opportunity to consider the effects of avoidance of maritime hazards, such as lee shore winds, which suggest methods like this would be applicable for the requirements of case studies two and three.

The travelling salesman problem (see section 3.6.3) requires a detailed knowledge of which ports might be travelled to; as suggested by chapter 2 the level of information about maritime networks and the actions of Roman travels is limited and is insufficient for application of this type of algorithm in all but the most limited circumstances.

Preiser Kapeller (2015) maritime analysis was limited to the Aegean, where there is a well-defined group of islands; outside of the area this method would only generate an effective interconnection network in those few areas of the Mediterranean where there is a coastal island structure. In all other locations, a chain network along the coastline would be generated. It suggests that this method may be of limited use when constructing some of the detailed networking structures required for chapter 6.

The transportation networks identified are a mixture of road, airline and marine networks, it important to under that that there are important differences between these network types. Marine and aeroplane networks are
free to choose their path between locations whereas road networks are fixed. A road network includes crossing points that may interact with other routes, but these intersections do not occur in airline or marine networks.

The concepts of the relative neighbourhood graphs, as applied by Jiménez-Badillo (2011), require a spatial reordering of the data space to ensure correct operation which is virtually impossible considering the two speed systems that have to be employed in covering land distances as well as sea spaces.
Chapter 4

Modelling methodology
4. Modelling methodology

4.1 Introduction

This chapter describes the data sources, methods and applications of theoretical models used to construct an efficient system to simulate the Roman era Mediterranean basin, with the objective of exploring the possible relationships between the different concepts of port hierarchies, as outlined in chapter 2. It is proposed that some of the methods described in chapter 3 should be used to provide input data for the individual case studies, (see sections 5 to 7).

Most transport simulation systems developed in the past (see chapter 3) have tended to focus on road networks where the paths between locations are fixed and routes across the road networks are constant. This differs for maritime networks, these being, by nature, less defined. In a maritime network, the traffic flow is subject to seasonal changes in weather patterns, and if the start and end points can be defined, then a range of virtual routes may be proposed.

Historical evidence about the precise nature of which routes or travel patterns may have been followed in the Roman era is ambiguous. This is described in sections 2.12 and 2.13. Data is available about how some parts of the Mediterranean may have been navigated, however, it is not a comprehensive data set, and there are some omissions. These gaps may have been caused by a loss of information over time, or alternatively may be because these areas were avoided by sea traffic in the Roman period. This incomplete data set makes it difficult to meet the requirements of the different case studies with a complete degree of certainty.

One possible solution to these issues is to construct a software model which can be used to generate a travel pattern between one or more input locations to one or more output locations, and which can deal with the different weather

9 Ducruet (2016) simple online search of different types of networks returned 10,000 answers for road networks, 261 for airline networks, between 1000 and 4000 for river and railway systems and 100 results for maritime networks.
conditions and geographic features encountered within the Mediterranean basin. Other solutions would be to attempt to extract details from the known historical sources (as identified in sections 2.4, 2.5, 2.12 and 2.13) and to postulate theories based on these sources, the issue being that existing historical sources are incomplete and may be subjectively interpreted to reach different possible conclusions.

In the context of geography, a model is defined by Chorley and Haggett (1967) as *a simplified structuring of reality which presents supposedly significant features or relationships in a generalised form and as they are valuable in obscuring incidental detail and in allowing fundamental aspects to appear*. This suggests that a model should seek to identify the important factors to model and should discard trivial or other non-contributory factors.

In this thesis, any developed model would attempt to represent the possible ways in which a Roman ship may have navigated across the Mediterranean basin. As with the analysis of historical sources issues such as:

- How representative is the model of the Roman travel systems?
- How accurate are the generated results?
- Is the quality of a generated data set representative of the quality of the source data?
- Is there an existing proven system model that could be used without having to create another instance of a modelled solution?
- Is a modelled system the correct solution to the problem of simulating Roman travel in the Mediterranean basin?

It is a known property of the Roman empire that ships did cross the Mediterranean, but often only their start and stop points are known, unless something of note happened during the voyage, for example, if the vessel was wrecked during a storm, thus generating a literary reference to the event, for example, if the ship was transporting a person of significance (e.g. Pliny during the Pompeii disaster), setting a new transport record, being becalmed for an unusually long period, etc. If the model provides a generated route between locations it can be regarded for research purposes as being representative of
Roman travel systems, because insufficient data is available to prove otherwise.

As already stated, not enough factual evidence is available to address the accuracy of the results. One possible method is to compare the results of a voyage generated by this model with an actual voyage recorded in an accurate representation of a Roman-era ship, this might provide an indication that the modelled results were accurate. A replica of a 4\textsuperscript{th} BC Greek vessel (Kyrenia 2) was recently made, which then made the return voyage between Crete and Greece (Katzev, 2008). Comparing the course of the route taken on this experimental voyage against a result generated by the model used in this thesis, with the possible issues described in section 4.7, could verify if the model was generating accurate results, see section 4.2.7.

As described in section 3.2 in the review of the Orbis system, the Orbis system is a complete modelling system, but there are issues with the size of the mesh used to generate results, as well as with the quality of the data sources, these factors make it necessary to construct a new model, instead of using the existing Orbis system.

As already stated, the quality of historical data sources does not address every possible combination of factors that could influence the construction of a voyage between different fixed points. A modelled solution would address this issue if the input datasets cover the locations of interest.

It is the conclusion that a modelled solution to the possibilities of how the Romans may have travelled the Mediterranean basin provides a more effective solution than an in-depth analysis of historical sources, because of the coverage of the data issues. In addition, a modelled solution offers the ability to apply a greater number of factors and to test more complex and richer solutions to issues than those which are simply available from historical sources.
4.1.1 Model overview

There are many potential factors that need to be taken into consideration when constructing such a data processing system.

The possible Input considerations are:

- The carrying capacity of a ship: just how much cargo or passengers would it be possible for a ship to carry? These capacity factors could limit or define any travel pattern. For example, a ship with a large carrying capacity could not dock at some locations due to the draft of the ship.
- The design of the ship’s rigging: the rigging is designed to capture the maximum amount of wind energy available within a given area.
- The physical strength, design and construction of the ship. A poorly constructed ship would be incapable of executing some of the suggested manoeuvres described in section 2.9.
- The design of the ship’s hull profile, or streamlining, which defines its ability to make a passage without being subject to drag factors of the water patterns as suggested by Figure 14.
- The possible available choices to the Roman captain when navigating the Mediterranean basin, based on either historical evidence or determined from data derived from known modern routes (see section 2.12 and 2.13).
- The wind and wave forces acting in a given area, as described in section 2.3.
- Information about known Mediterranean resources, such as the locations of ports, safe harbours from extreme weather systems, lighthouses, ship sheds or other shore-based infrastructure, etc.

The accuracy of any result generated by a model is subject to the quality of the input data and the complexity of the design of the simulator. Many of the listed factors are unknown, are poorly documented, or may need to be experimentally determined.
To manage the complexity of the simulation to a level that is both manageable and computable, certain assumptions have been made. The design of the simulator presented in this thesis assumes the following principles.

- Where possible, keep the design as simple as possible, the more complex the design, the greater the difficulty in generating a correct solution.
- Wherever possible, minimise the number of variable parameters used, to minimise the number of generated data sets.

4.1.2 Carrying capacity

The carrying capacity of a ship is defined by its design, which will, in turn, be influenced by its intended purpose. A larger ship will obviously include a greater ability to carry larger cargos or cargoes of greater volume and would presumably be capable of travelling further without stopping than would a smaller ship. This thesis addresses general travel issues, but it does not cover issues such as cargo distributions, compositions, size, etc, all of which could affect the performance due to the resting mass or handling. Due to the lack of information about the nature of, or the size of cargos, this thesis assumes that modelling a general purpose ship is sufficient to investigate the nature of travel in the Mediterranean in the stated period unless specific information is known about a given port.

It could be assumed that if a large ship was attempting to deposit a cargo at a port which could not accommodate a ship due to its size, a lighter would have been used to load and offload cargo, such as at Puteoli (Bennett, 2000:142), where lighters were used to unload grain cargos from ships that could not enter the port.
4.1.3 Rigging design

As previously stated, the precise nature of a ship’s rigging design is unknown; from the available evidence (mosaic images, etc), ship design (see Figure 14) could use one or more masts, could use a bowsprit etc. This thesis assumes that the design of a Roman ship is sufficient to capture enough available wind energy to enable it to be successfully navigated between different locations. As such, any model employed does not have to consider the design of rigging structures.

4.1.4 Design of ship

As with the rigging and carrying capacity of a ship, this thesis assumes that the design of a Roman ship was sufficient that it could endure moderate storms. The assumption is also made that it would have an effective steering mechanism that would allow it the ability to perform the type of manoeuvre suggested in section 2.9, to enable tacking/gybing into the wind. The experimental Kyrenia ship (Cariolou, 1997) broke several steering oars during its initial voyage. It is not known if this was due to a fault in the design, or if it was the results of an inexperienced crew, but the experimental Kyrenia ship did survive the experience of the voyage and managed to eventually complete its training voyages by sailing into the wind. Similarly, the pre-Roman design of the Phoenician ship (Beale and Taylor, 2013) managed a complete circumnavigation of Africa.

4.1.5 Design of ship’s hull profile.

The design of a ship hull can introduce drag factors to the water resistance encountered when a ship moves through the water. Travel by a merchant boat would be significantly slower than travel by a military vessel as the merchant ship hull profile is optimised to carry the largest quantity of goods possible as measured by Froude’s number \(^{10}\) (Stecher, 2001:92). Unfortunately, there is insufficient evidence available to supply the information required to calculate the Froude’s number for the different types of possible Roman boats (see _______.

\(^{10}\) Froude’s number is used to define the resistance of a semi submerged object through a water body.
Figure 14). It is assumed that the different types of Roman boats performed well enough to enable voyages to be made and any changes in data processing input caused using different values of Froude number would be insignificant when compared to the other problems already described.

4.1.6 Historical evidence and navigation choices

Some ancient data sources do quote how long it may have taken to sail between different points, but not every factor necessary to establish detailed voyage profiles is always included. For example, Pliny the Elder describes several different voyages.

*Is there a greater miracle than the flat plan which brings Egypt so close to Italy that of two governors of Egypt Galerius reached Alexandria from the Straits of Messina in seven days and Balbillus in six, and that in the summer [AD 55] 15 years later the praetorian senator Valerius Marianus made Alexandria from Pozzuoli in nine days with a very gentle breeze? That there is a plant that brings Cadiz within seven days' sail from the Straits of Gibraltar to Ostia, and Hither Spain within four days, and the Province of Narbonne within three, and Africa within two? The last record was made by Gaius Flavius, deputy of the proconsul Vibius Crispus, even with a very gentle wind blowing.* (Pliny the Elder Book XIX Chapter 1 in Rackham et al, eds, 1949)

In some cases, even where the ultimate destinations are known, neither the starting point nor any intermediary points of voyages are provided. It could be suggested that, in these cases, Rome might be assumed to be the starting point and the destination would be the nearest large port to Rome within the named province.

The wind speed is described as ‘gentle’; other than suggesting that it was low power wind, its velocity and direction are unknown. The wind might have blown in the right direction for the entire voyage, but this is highly doubtful. A gentle wind is described in the Beaufort scale (see Appendix 6) as level 3, a wind blowing up to 5 meters/second.
Modelling methodology

In ancient texts, the length of the many voyages is only described in terms of days. It is impossible to determine if the part of the journey in question required a whole or a partial amount of a day. Given that the number of daylight hours varies according to the season, a day used as a measurement of distance could produce a widely varied result. This makes measurements according to such historical data more imprecise.

Other ancient data sources describe different voyages using the same type of terms, but it is impossible to know if the different authors are using the same frame of reference in respect of distance, time, and wind strength, etc.

The available ancient data sources only offer a partial coverage of the Mediterranean basin whereas the scope of this project is the entire Mediterranean basin, and for the purposes of generating an accurate model, such historical references can be ignored due to the differences in descriptions, unless factors such as Pliny’s description of a direct sailing route are considered.

The length of the voyage is the distance that can be sailed between two different ports, constrained by the available resources of the ship. It has been suggested by Preiser-Kapeller (2015) that the maximum daily travel of a ship of the Roman period is 100 KM, with no upper bound being suggested for the maximum length that could be made. It is quite possible for a Roman-era ship to be sailed at night without a break just using constellations, as described by Pliny’s references to starlight on the yards and other parts of the ship (Pliny the Elder Book II Chapter XXXVII in Rackham et al, eds, 1949).

It is suggested that the limiting factor in the total length of a journey may be the ability to provide provisions for the crew, or the requirement to avoid a possible sea storm, etc. However, as previously described by Pliny, a possible maximum distance is the journey described between Alexandria and Pozzuoli (1600 KM) without describing any stopping off points, so unless otherwise stated this distance is used as a maximum possible distance that could be covered in a single part of a journey without the requirement to resupply the ship.
The figures of 100 KM to 1600 KM, therefore, represent the concept of a maximum length ideal voyage. They do not allow for local influences of the weather, such as the hazard of being blown off course by gale conditions, which would increase the journey time or the probable increase in time taken to complete the voyage if the vessel is becalmed.

4.1.7 Mediterranean wave circulation

The wave model described in chapter 2 refers to the general circulation of water through the entire Mediterranean basin. This circulation has been described by McElderry (1963:12) as being *tideless, or that is tides are so small that they are not worth considering*. This statement describes the general pattern of water circulation, it does not address areas of water flow exchange between tidal areas (the discharge from the Black Sea or Atlantic Ocean), water flows from the discharge of river systems, such as the Nile, Po, Rhone etc, into the Mediterranean. In these areas, there is an increase of tidal activity, but these effects are limited to their specific localised areas and may be ignored in the general context as only having a marginal overall effect unless a direct passage is being made through the affected area.

4.1.8 Mediterranean wind system

In this thesis, a Roman-era ship is assumed to be using the wind as a power source. As stated in section 2.9, the movement profile of a ship is different when travelling into a foul wind, or when travelling with a favourable wind behind it. As such, the general tendency on a voyage is for movement to follow an asymmetrical pattern, which would greatly affect the possible movement patterns or the relationship between different port groupings.

As illustrated in section 2.3, the wind patterns are not constant, they are subject to seasonal change which may affect the ability of a vessel to travel at either the same speed or to follow the same route throughout the different seasons. In some cases, it may be even impossible to make the same trip in two different seasons due to the influence of the weather patterns.
Modelling methodology

The generalised wind force in the Mediterranean basin is derived from the physical shape of its topography. Since there have been no significant area-wide geological changes within the last 2000 years (see section 2.2), it is assumed that, as per Murray (1987:159) research that there have been no major changes in the wind patterns in the Mediterranean in the last 2000 years, and that therefore modern data values may be used to simulate the Roman maritime environment.

Data about the behaviour of the Mediterranean is taken from the Wind and Wave Atlas (Athanassoulis et al., 2004) sponsored by the French, Italian and Greek Navies. The information covers the Mediterranean Basin from 5 west to 36 east and from 46 north to 30 south measured by from ERSI2 and Topex satellites (Cavaleri, 2005), see Figure 51.

![Figure 51 Location of Topex satellite buoys within the Mediterranean basin, centres of data readings (Athanassoulis et al., 2004)).](image)

This data set was selected because it covers the entire Mediterranean basin and was constructed by a single authority. Other datasets from many other sources such as the Instituto Nacional de Meteorologia, the Greek National Meteorological service, etc, are available for individual coastal areas, but these datasets used different metrics and origins offsets, issues which would make the merging of multiple datasets a complex problem. Other sources such as
the US Navy marine climatic atlas (USA Navy, 1995) only includes 28 data points, which would provide less granularity in the data set. The Wind and Wave Atlas data set provides information at 129 different buoy points (see Figure 51). Values are provided for the four seasons, for significant wave height, wind frequency and strength at 15-degree directional intervals for each data point, which makes approximately 192 differences per point. This needs to be processed to provide a single known wind value and direction at each buoy point on the map. It should be noted that, as extensive as this data set is, it does not cover the entire Mediterranean basin, and in some areas, the data areas overlap. In these specific cases, data can be sourced from the nearest buoy to the area of interest.

4.1.9 Port data sources

Details about the location of Roman ports, their features and structures are taken from the Geodatabase of ancient ports (de Graauw, 2013) which only includes maritime harbours and river ports that could be reached by deep-sea ships, information is based on the writings of 82 ancient authors and hundreds of modern authors (de Graauw, 2013)

Some ports have the extra infrastructure which suggests that they may have been more developed, possibly a centre of trade and travel, given that the construction of quays, moorings, lighthouses, number of road junctions etc, did not come without investment. see Table 2 and Figure 52 to Figure 54.

<table>
<thead>
<tr>
<th></th>
<th>Ports in the set</th>
<th>de Graauw (2013)</th>
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</thead>
<tbody>
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<tr>
<td>295</td>
<td>Ports with breakwater</td>
<td></td>
</tr>
<tr>
<td>234</td>
<td>Ports with quays</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>Ports with lighthouse</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Ports with ship sheds</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ports with breakwaters, lighthouse and ship sheds</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Ports by infrastructure type de Graauw (2013)
Figure 52 Ancient Ports with moles or quays (author’s interpretation of data from de Graauw(2013)).

Figure 53 Ancient ports with Slipways or Ship sheds (author’s interpretation of data from de Graauw(2013)).

A slipway, ship shed, and moles or quays are important infrastructure features of a port. They all contribute to make a port a more desirable location, given the alternatives of beaching, cost of lighters, breakages etc.
Figure 54 Ancient ports with Lighthouses (author’s interpretation of data from de Graauw(2013)).

Lighthouses may exist to help ships locate a given port, or to warn about specific hazards, which suggests that the location of a lighthouse can be used as a marker of travel.

Although larger ports may have provided useful infrastructure, the adaptability of merchants and sailors should not be underestimated. During the experimental voyage of Kyrenia II, attempts were made to load and unload the ship by hand, with the resulting in some breakage of cargo, and a lot of time spent manually lifting the goods to be transported. An alternative method of attaching a "mast derrick" to the main mast resulted in a greatly increased speed of unloading (Katzev, 2008:78).

Considering the density of Roman settlements in the Mediterranean basin, see Figure 55, this indicates significant amounts of Roman activity in Carthage, the Levant and the Aegean Sea, with the hot spots at Alexandria and Rome.
Modelling methodology

Figure 55 Areas of high and low-density Roman Settlement regions within the Mediterranean basin (author’s interpretation of data from (AWMC, 2014)).

These findings are also confirmed by Russell (1985) research, on the population of Roman cities, see Figure 56.

Figure 56 Cities by population size within the Mediterranean basin during the period of the Roman empire (author’s interpretation of data from Russell (1985).
<table>
<thead>
<tr>
<th>Key</th>
<th>Name</th>
<th>Population (1,000)</th>
<th>Key</th>
<th>Name</th>
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<td>HippoRegis</td>
<td>10</td>
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</tbody>
</table>

Figure 57 Roman cities by population (Russell, 1985).

A densely populated area may either function as a producer or a consumer of resources, suggesting a requirement for travel to those areas, or may also suggest that those areas may be acting as a centre of localised travel.

The inland cities near the coastline could have been served by localised ports such as Athens and Piraeus, or Rome and Portus etc.

The state of the local road system near a port can be used to indicate if a port is well connected to any hinterland. Figure 58 indicates road junctions where four or more Roman roads meet, suggesting that these locations may indicate major crossing points in a supply network.
Figure 58 Roman roads with four or more connections showing possible centres of distributions (author’s interpretation of data from (AWMC, 2014)).

Several data clusters can be identified in Figure 58, which align with the data generated from processing settlement densities, see Figure 55.

4.2 Modelling the travel space

As identified in the previous section, virtually the only important input parameter that needs to be considered when modelling potential journey time and viability is the wind factor. Other factors may influence the voyage but are normally insignificant when compared to the effects of the wind.

This thesis uses an implementation of the Dijkstra algorithm to calculate the shortest paths across a graph representation of a geographical space, see Appendix 5.

The pgrouting PostGIS extension package (PG Routing Community, 2015) implementation has been used because of its ability to calculate the one to one, one to many, the multiple different routes between different locations, and the driving distance calculations required for implementation of the individual study chapters (5 - 8 ); other packages such as boost library (Boost
Community, 2017) require the construction of a specific program to implement
a solution.

The pgrouting package, along with all other implementations of the Dijkstra
algorithm (see Appendix 6), requires a description of the travel space, a
mathematical description (the cost) of how difficult it is to travel between
different locations. This section describes how this model may be generated
from the available wind data sources.

4.2.1 Modelling the wind data

This thesis develops the concept of a prevailing wind model to describe the
possible strength and direction of the wind at any given point on the map,
where, at every point, only a singular dominant wind value is recorded. This
concept overlooks the fact that the wind may, at times, change direction or
strength in a totally unpredictable manner.

It is assumed that to overcome the resting inertia of a stationary ship, a strong
wind is required. To allow time for a crew to set the sails to capture a wind, the
wind must blow in a known direction for a fixed period, hence any insignificant
winds may be ignored as they may be assumed to be incapable of supplying
enough energy to move the ship. As described in section 4.1.7, the effects of
the water circulation are insignificant unless the ship is crossing a specific area
in winter or autumn.

The Wind and Wave Atlas (Athanassoulis et al., 2004) defines a significant or
dominant wind, as any wind which has a speed of greater than 6 m/s and a
frequency greater than 10 per cent, see Figure 59, and where all the
insignificant wind values have been removed.
Figure 59 Dominant winds in summer season within the Mediterranean basin (author’s interpretation of data from (Athanassoulis et al., 2004)).

To achieve the goal of having only a single wind value at a given point, it is possible to select the modal value in strength and to use this to find the direction of the most common wind. However, this concept overlooks the fact that the most frequent wind may blow at several different values or in a directional range. To ensure the correct wind value is selected the following process is used.

For each point:

- If a single wind value remains use it.
- If two wind values remain to select the most frequent value, not the strongest.
- If three or more wind values occur, select only those values that form a range and then pick the most frequent value within that range.

For example, at point N7 82E six different wind values occur, comparison of two ranges and a single outlier, see Figure 60.
Figure 60 Wind direction and speed (meter/second) at point N7 82E (author’s interpretation of data from (Athanassoulis et al., 2004)).

Removing all insignificant wind values results in Figure 61, where the wind values that blow to the west are treated as an outlier and are eliminated.
Figure 61 Wind direction and speed (meters/second) at point N7 82E after removal of minor wind values (author’s interpretation of data from (Athanassoulis et al., 2004)).

The prevailing wind is assumed to be part of the spread between the values of 90 and 135 degrees. The wind direction which includes the most frequent wind speed is assumed to be the dominant wind direction for this point. This calculation gives the wind direction.

The physical wind strength is assumed to be the wind that blows most often i.e. the most frequent value for this direction.
Modelling methodology

This method generates a prevailing wind data set, see Figure 59, where at each buoy point the strength and direction of the prevailing wind is a known value. This result has eliminated some of the exceptional wind values displayed in Figure 59 for more commonly occurring values.

Alternative wind data models based on the average wind speed were considered, but single exceptional wind values generated distorted data sets, i.e. a single wind value blowing at 18 m/s has a greater effect in the resultant data set than a wind blowing at 6 m/s for three times as long.

Maximum and minimum models were also considered but were subsequently abandoned, as this thesis is considering the normal expected time to sail between two different locations, as opposed to considering singular or exceptional journeys, where the wind blew in the right direction all the time.

4.2.2 Voyage Characteristics

As described by Casson, Roman ships could move at a sailing speed of between 4.5 and 6 knots (2-3 m/s) if a favourable wind was blowing, and between 2 and 2.5 knots if they were affected by a foul wind. (Casson, 1995).

These speeds are derived from capturing as much wind energy as possible. Consider the 2011 Phoenicia Circumnavigation of Africa project (Kendall, 2012), which described a square sailed rig as being inefficient in practice. This implies that at least a moderate wind was required to move a loaded Roman ship for any significant distance. Pliny describes that gentle wind blowing. (Pliny the Elder Book XIX Chapter I in Rackham et al., eds, 1949) was required to move a ship (possibly without a cargo) over a long distance. These facts suggest that a wind strength of at least 5 m/s was required to supply enough energy to move a ship of that era.

The difference in Casson’s figures is a result of the extra amount of tacking and manoeuvring required over the course of a voyage when sailing into a foul wind. Casson’s analysis was based on several singular voyages between several different data points, where a ship was fortunate enough to be always subject to constant favourable winds or was,
unfortunately, subject to a constant foul wind. It is more probable that these measurements represent the best and worst cases possible, and that ships moved slightly faster and slower than the supplied figures.

4.2.3 Modelling the sailing angle

The previous section described a method for calculating the prevailing wind speed and direction at any given point. As described in section 2.9, it is possible that a ship can tack to ensure that movement can be made in any direction, the amount of tacking required being dependent on the amount of offset required from the direction of the current wind.

When sailing into a favourable wind no tacking will be required, whereas when sailing into a foul wind 100% tacking will be required as shown in Figure 62, with the blue sine wave (arrow A) denoting the pattern of movement when sailing against a foul wind, and the red line (Arrow B) the same movement when sailing with a favourable wind.

Figure 62 Comparison between movement against a foul wind (length A) compared to the movement against sailing with the wind (length B). The total distance moved along either line is identical, but in terms of physical displacement from the centre, there is a large difference.

These different distances represent the best and worst cases for movement in a straight line. By mapping the ratio of these values at different angles, it is possible to obtain a measure of distance a ship could have moved in any given direction, see Table 3.
Table 3 Distances sailed per angle.

<table>
<thead>
<tr>
<th>Angle</th>
<th>% Blue distance (A)</th>
<th>% Red distance(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>45</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>135</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>180</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>225</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>270</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>315</td>
<td>75</td>
<td>25</td>
</tr>
</tbody>
</table>

As described in section 4.2.2, it has been suggested that a sailing speed of between 4 and 6 knots could be achieved when sailing with a favourable wind, and a speed of between 2 and 2½ knots when sailing against a foul wind, (see Figure 63 for a comparison of the possible sailing distances).

Figure 63 Comparison between the minimum and maximum possible sailing distances, where the minimum value indicates sailing against a foul wind and the maximum represents sailing with a favourable wind.

Using figures for the worst and best sailing speeds, for the values of the length of A and B, as per the values in Table 3, see Figure 64, using the top of drawing as the angle location of 0 degrees. The right-hand value of 90 degrees represents the maximum distance it would be possible to sail with a favourable wind (length B).

The left-hand value (270 degrees) represents the maximum possible distance to sail with a foul wind (length A). The values of 0 and 180 degrees represent values when taking the balance of sailing with a foul and favourable wind, a ratio of length A and B.
Figure 64 Possible ship movements using the best and worst possible sailing methods.

- The ‘ship’ represents the starting position of the vessel.
- The ‘Minimum Sailing Area’ represents the area that could be covered from the starting point, if the best possible wind was used to cover a distance.
- The ‘Maximum Sailing Area’ represents the area that could be covered from the starting point if the best wind blew constantly in all directions.

As would be expected with the ship following the wind the maximum distance would be covered, whereas when sailing with a foul wind, it would be expected to travel the minimum distance.

By tessellating this cardioid shape in a single direction, using the centroid as the point of intersection, it is possible to calculate the performance of ship movement. If the wind is blowing in a northeast direction, Figure 65 shows movement for all principal directions for the same period.
Figure 65 Comparison of travel in different directions using ninety degrees directions.

As shown, a ship sailing in a north-west direction will move much further than a ship attempting to sailing in a south-west direction.

4.2.4 Mesh Resolution

As explained in the previous section, by using a mesh, it is possible to determine how long it may take to make a journey, provided that the journey is made along the lines of the mesh, as the scale and the design of the mesh effect the accuracy of the result.

A high scale resolution mesh of length 17.32 KM allows the accurate plotting of data through the many island groups of the Mediterranean. For example, in Figure 66, the data mesh allows for plotting a course between the islands of Sardinia and Corsica, or for plotting a course near to the coastline.
Figure 66 Possible sailing routes using a fine scale mesh between Corsica and Sardinia in the western Mediterranean, which may cause oversampling due to the size of the network.

The use of a lower resolution mesh of lengths 99.98 KM (diagonals) and 70.70 KM (sides), see Figure 67, forces a more inaccurate result, where attempts to navigate close to an island which, in the modelled journey data, result in the projected course crossing a land bridge, or where circumstances mean that the model is unable to get an accurate result for sailing in the vicinity of a navigational hazard such as a lee shore wind. But the coarse scale used requires less data processing, as there is a smaller set of data to process.
Modelling methodology

Figure 67 Possible sailing routes using a coarse scale mesh between Corsica and Sardinia in the western Mediterranean, which may result in possible inaccuracies in data processing due to the gaps in the mesh.

The choice and scale of the mesh selected for use in the project is an important consideration, although the square based mesh (see Figure 67) allows a choice of eight directions at every mesh intersection, it does not scale to the profile of a coastline. The different length segments of the mesh could also cause problems by not allowing a direct comparison between some extended route profiles. A hexagonal solution allows for a better fit to the shoreline, even though it is only limited to six different directions at a mesh node intersection, this solution uses the same unit segment length which allows every link on a computed route to be compared to another.

Having decided to use a hexagonal mesh, the scale and offset were decided by ensuring that as many mesh nodes as possible intersected with the different coastal features, such as the Gulf of Sidra, the Gulf of Gabes, the Sea of Marmara, the Straits of Otranto, etc. Possible issues of oversampling of the
data were avoided by ensuring that the size of the mesh links were as large as possible, while still allowing the majority of the coastal features of the Mediterranean to be processed.

4.2.5 Calculating the cost

As described in the previous section, a predefined fixed mesh is used to define the pattern of the possible movement. The software package used to calculate a route (see section 4.2.6) requires a defined value which reflects the amount of effort it takes to cross a link in the mesh in a given direction (see section 4.2.4). A smaller value indicates a faster passage, a higher value a slower passage.

In this model, the grid resolution defines the physical area which must be crossed and is a constant fixed value. The speed of the ship is a variable value which measures how long it takes to cross a given distance, by calculating the amount of time it takes to cross a fixed distance at a known angle it is possible to provide a cost `value' for crossing any part of the mesh. The previously developed cardioid calculation can be used to generate speed calculation for any direction, see Table 4 and Figure 68, provided that the wind direction and speed are known.

![Figure 68 Different journey offsets using a hexagonal mesh](image-url)
The length of the radius is given
\[ \alpha = |1 \ldots 360| \]

Then the radius is
\[ \text{abs}((\alpha \times 5)/9+100) \]

where X is the maximum length of the radius (17.32 KM in this example).

<table>
<thead>
<tr>
<th>Line</th>
<th>Distance(KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.73</td>
</tr>
<tr>
<td>B</td>
<td>8.56</td>
</tr>
<tr>
<td>C</td>
<td>10.18</td>
</tr>
<tr>
<td>D</td>
<td>14.94</td>
</tr>
<tr>
<td>E</td>
<td>13.31</td>
</tr>
<tr>
<td>F</td>
<td>16.48</td>
</tr>
</tbody>
</table>

Table 4 Length of radius for cardioid.

By scaling the cardioid used to perform the calculation such that the `line'' is the same resolution as the size of the mesh, it possible to provide a time value for how long it would take to sailing a given distance, see Figure 69, where the size of the cardioid has been expanded to the size of the grid segment.

![Figure 69 Line segments per sailing distance mesh extended by mesh length](image)

The original sailing area defined by the wind value is defined as ‘Sailing Area’ A ship attempting to sail in a northerly direction (direction D in Figure 68 would
sail 14.94 KM whereas a ship sailing in the direction of the wind flow would sail 17.32 KM.

Adjusting the values so that the distance covered sailing north is the same distance as the mesh size of 17.32KM gives a value of

\[ \frac{17.32}{14.94} \times 17.32 = 20.079 \]

for sailing in the direction of the wind.

Assuming the wind is blowing at 5KM/hour i.e. it takes one hour to cover 5 KM, 20 minutes to cover 1KM, then it takes

20.079\times20 \text{ minutes} \text{ to cover the required distance i.e. } 6.693 \text{ decimal hours}

Applying the same calculations to contents of Table 4 and assuming a wind strength of 5KM gives the following cost values, see Table 5

<table>
<thead>
<tr>
<th>Line</th>
<th>Distance(KM)</th>
<th>Cost values</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.73</td>
<td>8.524</td>
</tr>
<tr>
<td>B</td>
<td>8.56</td>
<td>11.681</td>
</tr>
<tr>
<td>C</td>
<td>10.18</td>
<td>9.822</td>
</tr>
<tr>
<td>D</td>
<td>14.94</td>
<td>6.693</td>
</tr>
<tr>
<td>E</td>
<td>13.31</td>
<td>7.512</td>
</tr>
<tr>
<td>F</td>
<td>16.48</td>
<td>6.067</td>
</tr>
</tbody>
</table>

Table 5 Distance and cost values for a single cardioid.

As may be expected the cost values for the longer distances are greater than the cost values for the shorter distances given that the sailing into the wind takes longer than sailing with it.

The costs for the entire mesh need to be calculated for every intersection and for each season due to the different values per season.

Although the cost calculations reflect the amount of time taken to make a voyage, they cannot be taken as an accurate measure of the time taken to make a voyage, they only serve as a general means of comparing the ease of movement across a network, see section 4.7.
4.2.6 Generating Routing Paths

The previous section describes how the simulation methodology populates a mesh/network of defined resolution in which the edges of the mesh represent the sailing velocity between each of the nodes. This section describes the second step of the simulation, in which movement through the generated grid is modelled.

The majority of the methods presented in chapter 3 require a method for generating a route between two different ports, it has been assumed that the majority of Roman travellers would have preferred to take the fastest route where possible, subject to it being possible to make such voyage. If a slower voyage was required, the same route would have been selected but only a fraction of the sail canvas used. If a trip via a specific location was required, a voyage by that location would have been selected. This thesis uses the Dijkstra algorithm (see Appendix 7) to calculate the fastest route between locations using a mesh to represent all possible locations to define all possible segments of a voyage where each segment is denoted by a unique start and target number.

An example Dijkstra route calculation is shown in Figure 70 showing the journey from ports Agrigento to Rhegium using the cost calculations from section 4.2.5 and the mesh described in section 4.2.4.
Modelling methodology

Figure 70 Example of Dijkstra route calculation from Agrigento to Rhegium in Sicily illustrating the different routes used when sailing from west to east and making the return voyage.

A variant of Dijkstra, K-Dijkstra, returns the K number of routes between the stop and starting points such that all generated routes are different. Using this method, it is possible to identify not only the fastest route between points but also the general spread of fast routes, by plotting a number of different trade routes simultaneous using different scales of transport meshes, see Figure 71 and Figure 72. The wider the trade profile in a given area, the better conditions for travelling in that area.
Modelling methodology

Figure 71 Fastest 300 summer routes between Alexandra and Portus using a fine mesh.

Figure 72 Fastest 300 summer routes between Alexandra and Portus using a coarse mesh.
These two different results show the effects of using different meshes, the coarse mesh returns a quick result, but the resolution did not allow for all the values of cost to be considered with a very different result being generated.

Dijkstra algorithm is not known to suffer from any issues other than it takes progressively longer to calculate a result the longer the required voyage is. The algorithm can handle a weighted mesh with the result that the asymmetric nature of maritime travel is fully addressed unlike methods based on connectivity methods only.

An alternative to plotting the K routes between two locations is to calculate the single fastest route between two locations and then apply a constant buffer to that route, the suggestion being that given the available technology of the Roman Mediterranean era the perfect course could not be navigated, and the course used must be somewhere within the data boundary. Plotting the top K routes does show areas where speed increases could expect to be found because varying the route would include the include quicker access areas whereas a constant buffer would return no such extra information, see Figure 73 for a contrast between the two methods.

![Figure 73 Comparison between buffering a direct route to top 300 routes between Portus to Alexandra](image-url)
The top 300 route area shows a great degree variation near the Portus area than along the rest of the route suggesting that passage through this area would be faster than elsewhere along the route.

Dijkstra’s algorithm can also be used to measure the sailing distance from a location, by calculating the individual sailing times to all the local nodes in the mesh and by grouping by the total cost value for making that voyage gives the sailing distance for any given source point, see Figure 74, where the cost values from sailing from Portus have been calculated by group by common values.

Figure 74 Dijkstra’s algorithm used to map individual sailing distance from Portus.
4.2.7 **Accuracy of results**

It is difficult to prove the accuracy of the method given the sparse nature of the input data and problems encountered during the processing of data (see section 4.7). A voyage of the Kyrenia ship between Pathos and Alexandria (see Figure 17) was used to compare the difference between the theoretical model and singular documented route made by the Bronze Age ship Kyrenia 2, see Figure 75.

![Map of Eastern Mediterranean with routes](image)

**Figure 75** Voyage of the experimental Bronze Age ship Kyrenia 2 compared against computer generated results in the eastern Mediterranean.

The results were disappointing. The computer-generated route showed a marked difference from the route used by a human crew. But it was noticed that the computer route followed a route near the start and end points, picking out that there were more favourable winds encountered by sailing towards the north when making the western voyage, but the route towards the west was vastly different, until it was noticed that the human crew had selected to make a trip between an island and the coast; the reason for such a selection was not
given in the paper report. Altering the computer model to make the same passage resulted in a more accurate result, see Figure 76.

Figure 76 Voyage of the experimental ship Kyrenia 2 sailing via island strait compared against computer generated results in the eastern Mediterranean.

The Dijkstra algorithm will always return the quickest route which does not always respect some of the choices that have to be made in the real world and this must be considered when interpreting any results calculated from this theoretical model of assessment.

4.3 Modelling Mediterranean Port Systems

Using the data provided by Russell(1985) and de Graauw(2013) it is possible to factorise the data to create a prototype model of a set of port data to be used in the different case studies (see chapters 5 to 6 ).
It is assumed that Rome and Constantinople are the most important cites for the study period. As such the locations are classed as the largest and most important port locations i.e. the only 1st degree ports.

The cities identified by Russell are the most populated cities in the Roman empire, and are assumed to be important locations for trade and travel due to their resources and possible markets. These locations are classed as 2nd-degree ports.

Any location in the de Graauw data set which has any port facilities such as lighthouses, moles, ship shed or quays, which is not already classed as a 2nd-degree port is taken to be a 3rd-degree port as it is important enough to justify the type of investment, suggesting that this port location is important enough to justify this type of investment in its infrastructure.

Any port that is near at least two road connections is taken to be an important location but not as significant as any of the other ports.

Figure 77 Major Roman port locations, roads and settlement densities in the Mediterranean basin during the period of the Roman empire.
The generated map (see Figure 77) is similar to the settlement density map (see Figure 55), with the location of 1st and 2nd-degree ports matching the density of settlements.

4.3.1 Selection of starting locations for simulations (Ports)

As described in chapter 3, the majority of transport models use a set of locations and analysed routes between those locations. The prototype map was developed in section 4.3 from the locations identified by Russell(1985) and de Graauw,(see Figure 77). This result set includes a list of 3437 possible ports and may include port outliers as described in section 2.10; applying a distance algorithm to remove these locations reduces the amount of positional data locations. A decision tree, (see section 3.5.1) could be used to filter the available port locations in terms of port properties (see Table 6) but this problem is a spatial problem, so a method based on spatial abstraction is more applicable in this case.

There are two principle methods:

4.3.1.1 DBScan

The DBScan algorithm (Raschka, 2015) is designed to work with the metrics of a physical distance between each point and a minimum number of locations required to form a data cluster. This method compares the distance between its input locations and as result tends to generate an accurate result with spatial data.

4.3.1.2 K-means

This method (Raschka, 2015) groups a given number of values into k clusters, it is not an ideal choice for spatial position data because it is designed to minimise variance in the data instead of distances The way that the algorithm works tends to favour small densely grouped points, increasing the value of K to avoid this issue tends to generate a result set with small groups in sparsely populated regions.
Using the prototype map created in section 4.3 from the locations identified by Russell(1985) and de Graauw(2013) dataset results in Figure 77, with 704 port locations. Applying the DBScan method and using a distance of 50 KM, half the maximum possible sailing distance of a ship engaged in tramp style travelling, so that a return trip can be made in a single day and a minimum number of two locations that could form a port clusters, reduces the number of port locations to 98, see Figure 78.

Figure 78 Filtered Roman port locations, roads and settlement densities in the Mediterranean basin during the period of the Roman empire.

The different types of port are defined as follows:

4.3.2 **Class 1 Ports**

A class one port is a major location, its presence has a global effect on all possible movement patterns, there are two possible such locations Constantinople and Portus, one is a capital location and the other the supplier port to Rome.
4.3.3 **Class 2 Ports**

A class two port is a supplier port or location that has a large population as defined by Russell (1985), see section 4.1.9. The concept of an Atlantic and Black Sea gateways are included so that it's possible to examine external travel into the Mediterranean basin.

4.3.4 **Class 3 Ports**

Any port location that has some type of infrastructure, a lighthouse, mole, ship shed etc is assumed to be an important place of travel, but not as important as a class 2 port.

4.4 **Algorithms and Applications**

The previous selections have described a method for calculating the distance between two points, and how this function could be applied to map out the pattern of travelling between different points. This function could be applied to many of the methods described in section 3, but suggested movement patterns described in section 2 cause issues.
The principal issue is caused by the possible movement pattern of a ship.

A ship is free to select any course between two locations subject to a maximum sailing distance, whereas the road and river transports assume that movement pattern is subject to a fixed regulated network pattern of movement.

Consider Figure 79: passage along a road network from point A to D would require a journey by points B and C

In a maritime network a direct journey can be made from points A to D (Route3) using any combination of routes without having to travel by points B and C or the same trip could be made A to D via B or C etc. This results in most maritime networks being formed as a network of bypasses instead of a network of direct connections.

The journey from Rome to Alexandria is asymmetrical because it has a favourable wind most of the way, but the return trip from Alexandria to Rome is subject to a constant foul wind, with a much higher cost in terms of effort in making the journey, see Figure 71 and Figure 72.
Modelling methodology

Unlike travel in the Red Sea in the Roman era as described in Casson (1989), information about which courses were sailed in the Mediterranean is limited; suggestions which can be inferred from sources such as the Edict on Maximum Prices (Arnaud, 2007) or the spread of artefacts (Rice, 2011), (Bonifay and Tchernia, 2013), (Reynolds, 1995), (Reynolds, 2017). But since the price edict has been described principally as a taxation device (Arnaud, 2007) instead of a price control device, conclusions drawn from it can be difficult to accurately interpret.

Similarly, the artefact spread patterns are difficult to interpret. They could be the result of a single cargo, multiple cargos, a voyage blown off course, secondary trading of containers etc.

The selected algorithms used in this thesis are designed to discover what it is possible to infer from the limited available evidence.

4.4.1 Decision trees classifier

The methods presented so far have only examined the spatial characteristics of individual locations; the decision tree classification method presented in section 3.5.1 allows for an analysis based on a location’s properties, (see Table 6 for a list of properties) instead of its spatial position. The properties are designed to focus on the interrelationship between ports and the spatial environment. Which properties are selected for use depends on the type of analysis being performed, see chapters 5 to 7.

The decision tree classifier is an implementation of CART, where the Gini impurity of the properties from a known set of values is used to construct the leaf and nodes of the tree structure. This tree can then be used to classify if another other location matches the same type of locations as listed in the learning data set, (see (Raschka, 2015:80)) for a description of the algorithm and worked example.
Once correctly configured, this method allows for the fast comparison of different groups of ports or sections of coastline in terms of port locations.

<table>
<thead>
<tr>
<th>Property name</th>
<th>Property Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub Port</td>
<td>Set to true if this location is known to be a 1st, 2nd or 3rd-degree port site.</td>
</tr>
<tr>
<td>Distance to a hub port</td>
<td>The distance in KM to the nearest hub port</td>
</tr>
<tr>
<td>Near lee shore</td>
<td>The distance in KM from any lee shore winds to the location being studied with a maximum value of 10 KM. The presence of a lee shore wind in close proximity to this location are assumed to indicate a local navigation hazard which may cause some ships to avoid this area</td>
</tr>
<tr>
<td>Number of hub ports</td>
<td>The number of hub ports within a 20 KM distance of this location, as described in section 4.3.</td>
</tr>
<tr>
<td>Number of shipwrecks</td>
<td>The number of shipwrecks within 5KM of the port location. The presence of a wreck could suggest that there is a navigation hazard in the local area to this location</td>
</tr>
<tr>
<td>In low populated area</td>
<td>Set to true if this location is within 5KM of a low population area.</td>
</tr>
<tr>
<td>In a highly populated area</td>
<td>Set to true if this location is within 5KM of a highly populated area.</td>
</tr>
<tr>
<td>Port 50 count</td>
<td>The number of ports within 50 KM journey from this location.</td>
</tr>
<tr>
<td>Port 100 count</td>
<td>The number of ports within 100 KM voyage from this location.</td>
</tr>
<tr>
<td>Port 200 count</td>
<td>The number of ports within 200 KM voyage from this location.</td>
</tr>
<tr>
<td>Port 300 count</td>
<td>The number of ports within 300 KM voyage from this location.</td>
</tr>
<tr>
<td>Port 400 count</td>
<td>The number of ports within 400 KM voyage from this location.</td>
</tr>
</tbody>
</table>

Table 6 Location properties

This method allows for the comparison of different groups of ports or sections of coastline in terms of port locations.

There are problems associated with this data coverage, some properties, such as a lee shore wind, only address very specific issues within localised areas in the Mediterranean, while other properties such as the port proximity counts apply across the entire basin. see Table 7.
This suggests that either this method can only be applied in the very specific area, or only Mediterranean wide features such as the port counts should be used on a global scale.

<table>
<thead>
<tr>
<th>Property name</th>
<th>Number of occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub Port</td>
<td>true</td>
</tr>
<tr>
<td>Distance to the nearest hub port</td>
<td>N/A</td>
</tr>
<tr>
<td>Near lee shore</td>
<td>16</td>
</tr>
<tr>
<td>Number of hub ports</td>
<td>505</td>
</tr>
<tr>
<td>Number of shipwrecks</td>
<td>73 (within 4KM)</td>
</tr>
<tr>
<td>In a low populated area</td>
<td>59 (within 2KM)</td>
</tr>
<tr>
<td>In a highly populated area</td>
<td>40 (within 2KM)</td>
</tr>
<tr>
<td>Port 50 count</td>
<td>3078</td>
</tr>
<tr>
<td>Port 100 count</td>
<td>3078</td>
</tr>
<tr>
<td>Port 200 count</td>
<td>3078</td>
</tr>
<tr>
<td>Port 300 count</td>
<td>3078</td>
</tr>
<tr>
<td>Port 400 count</td>
<td>3078</td>
</tr>
</tbody>
</table>

Table 7 Percentage coverage by property

4.4.1.1 Application

Several locations on the Spanish coastline have been classified as hub ports due to their population size and port features, see section 4.1.9. By using the port properties of those locations as training data, it is possible to classify any other location as a possible hub port using the Decision tree in Figure 80; where the number of ports that can be reached with a sailing distance of 100, 200 and 300 KM is used to decide if a location could be described as hub location.
In Figure 80 the first box 13 samples are analysed; using the value 300_port property three samples are classed as Hub ports, all other values are sent further down the tree for additional classification. The results of this classification can be seen in Figure 81.
where four existing hub ports are known and all ‘Predict Ports’ match the same requirements to be classified as a hub port, and the ‘Known Ports’ do not. See Figure 81.

### 4.4.2 Sphere of Influence/Sailing distance/Catchment areas

An extension of the applications Dijkstra’s algorithm explained in section 4.2.6 can be used to map out how long it is possible to sail from/to a single port, see Figure 74. This method may also be used to calculate a zone of shared interest between two different ports; the space that could be accessed from both ports, see Figure 82, where the individual catchment areas can be identified by Port one (Blue) and Port two (Green) are mapped with the different coloured bands denoting areas that are further away.

Mapping the intersections between the two ports (the red area) shows the area of possible interaction with each other in the context of a small world or as a localised network.

Figure 81 Classified hub ports.
A similar process may be used to model a larger port hierarchy by merging individual ‘zones of catchment’ to form a larger sphere of influence. This type of mapping technology is useful in discovering possible isolated communities or clusters as described in 2.10.

4.4.3 Port connectivity

The network analysis methods described in section 3.4 all assume that travel within a network, where movement is constrained to traverse a given set of roads through towns and voyages, are symmetrical in nature. But as described in section 4.4 this is not the case in maritime transportation networks. This has implications with the majority of network processing methods.

Port connectivity methods such as the measures of centrality or Eigenvector analysis are measures of node interrelations without considering the real problems and issues, such as: -

Figure 82 Zones of catchment
• It may take much longer to traverse a network going from vertex A to B instead of B to A when completing a long journey

• Some sections of the network may be subject to adverse weather conditions which make traversing some network connections much harder.

This implies these methods may only be applicable to short distance journeys in areas of stable weather conditions. An application of Dicks (1972) polar network research (see Figure 46) could run into the same issues as raised by Hutchinson (1972) on Dick’s research; the different nature of possible port structures (see section 2.11) makes this analysis method very subjective as an initial method of investigation. The method may be applicable, but only to consider a completed or well-defined network.

Preiser-Kapeller’s (2015) examination of inter-port relationships only considered voyages of less than 100 KM using a Euclidean distance. This worked efficiently in the densely populated Aegean, but extending this method outside of this area may run into issues of voyage length.

Rivers (2009 and 2015), resolve their results by only considering short distance voyages under 100 KM, the limit of a single days sailing (Preiser-Kapeller, 2015). Applying Rivers (2016) long-distance methods requires the assumption that the cost of traversing a bidirectional route is identical. For example, in Figure 43, two possible routes are suggested for getting from Italy to Egypt; Rivers uses the distance to measure the traffic flow, but the wind patterns may make the route via Crete a more obvious choice with a return by the Levant.
4.4.4 Isochron curves

The methods described so far have all used some variant of measuring travel across a mesh. An alternative method is to calculate a result set by using a method derived from generating an expanding series of isochron curves from an origin point. The following methodology is used.

1. Select a point as an origin, normally a port value.
2. Draw a cardioid of radius X and calculate the arc of the cardioid that intersects with any part of the Mediterranean basin.
3. Subdivide that arc in a series of point segments of sufficient size that represents the form of the curve.
4. At each point segment draw another cardioid shape of radius X scaled to the local wind direction and strength
5. Merge the out circumference of the cardioid generated in phase 4, this becomes an isochron band.
6. Repeat stages 3-5 until there is no sea space left or enough isochron bands have been generated.

Figure 83 Movement patterns from Portus.
This process can be seen in see Figure 83. where 1st generation represents the initial cardioid, the 2nd generation cardioids represent the first iteration of the process, the 3rd generation the 2nd iteration etc. Merging the cardioids generates a series of bands which represent different stages of a journey, see Figure 84. The movement bands of different width are due to the different wind profiles, with some sections being traversed much faster than others.

Figure 84 Isotropic map for the port of Portus for the summer season showing the possible ship movements ranges.

For comparisons between the different seasons, see Figure 143, Figure 144 and Figure 145. These maps have a significant advantage over the maps using a mesh table, in that they respect the true angle of wind direction when the cardioid is being generated whereas the mesh table can only use one of six cardinal points of the mesh with the possible result of a loss of accuracy.
These isochron maps are useful for illustrating the general movement metrics within the Mediterranean basin, but they do not supply port specific information, such as how individual ports may interact with each other.

4.5 Time distorted Maps

The results shown so far have all used distance as a metric, but by changing the metric to how long it takes to get somewhere instead, it is possible to see alternative patterns in the data results. The results are calculated by selecting a centre point of interest, and then assigning a cumulative sailing time to every node in the network (see section 4.2.4) The generated maps show which points can be reached from the central point in the same amount of time.

![Figure 85 Time distortion map from Portus](image)

The end results have to be measured from the centre point selected; Figure 85 suggests that sailing from Portus to the far end of the Adriatic will take about the same amount of time to reach Gaza or sailing to the Atlantic gateway will take the same amount of time as sailing towards Syria.
4.6 Route Calculator

Chapter 7, is designed to consider the possible travel patterns along a specific route between two ports subject to known hazards. This process is similar in nature to Rivers et al., (2016) research in concept, that a join the dots process is used build a complete multi-segment route between different locations with the exception that this process includes the concept of building a route that

1. Must pass through a given area if requested.
2. Must avoid a given area if requested.
3. Must not call at given port.
4. The length of the route between two ports must be no longer than a given distance.

The process is designed to build a list of probable routes.

The process starts off from a known location and repeatedly select another port location that is near the final destination until the only port that can be selected is the destination, subject to the following rules.

1. The next destination to be selected must not be a location that has already been visited.
2. The next destination port must not be on a predefined list of ports to avoid, this list may be zero in length.
3. The next destination must be geographically nearer to the final destination.
4. The route to the next destination must not lie in a restricted area.
5. In the event of two locations being discovered, the location that is nearest the destination and furthest from the starting point will be selected.

This methodology allows for the generation of multi-segment routes which meet the requirements of chapters 6 and 7. It is possible for the software simulator to fail to generate a requested route, this is normally caused by an impossible set of user constraints.
4.7 Problems

This simulation uses the most frequent statistics to derive a result, but there are always exceptions in any model. Strabo (1917 book 3 chapter 2 section 5) describes winds which “blew at a fixed time each year” and how, in an exceptional voyage, it took three months to reach Italy from the Gulf of Sardinia. As such it is possible for some voyages to take much longer or shorter times than any derived information from the sailing model might suggest.

Roman era ships are depicted as having single and multiple masts, with single or multiple sails of varying size (Casson, 1995:277). The model assumes that whatever sailing system was used, it captured a fixed percentage of the available wind. It is unknown if this is an accurate model. With the available evidence, it is only possible to state that whatever sailing technology was employed, it was sufficient to move a ship between two fixed points. If a ship tacks, it is still being affected by the same wind that it would face if it was being manoeuvred in the same direction as the wind, so it is assumed that this model may be applied with equal accuracy to a ship tacking or to one sailing normally. The model does not address the time taken to load/unload, or the amount of time entering/leaving a port; it is restricted only to the actual sailing period.

There are some problems when attempting to consider ancient sources. They do not tend to describe the nature of the journey, which time of the year the journey was taken, or for how much of the journey was the ship anchored/beached. Cariolou (1997:96) discovered that it was possible to shelter overnight on the open sea while undertaking long-distance journeys in the Kyrenia replica ship.

The simulation considers the starting point of a journey to be the nearest point on the coastline to the port’s stated location; it is assumed that the approach from the port to the open sea would be unique for every port, and therefore could not be accurately modelled by a generalised simulation. Similarly, the termination point of a journey is affected by the same issue.
The data is measured using a coordinate projection system that assumes that the Mediterranean basin is part of a perfect sphere that represents the entire planet; there may be some localised distortions in some of the measurements as the real shape of the earth is an oblate spheroid.

Some of the methods outlined in section 3.4 consider connectivity issues using a distance matrix (see Appendix 7) and apply matrix multiplication to derive a result. But these methods expect a singular distance to be supplied, however in maritime models the cost of getting to and making the return trip to a port are different; a possible solution to this issue is to use either a mean of the two distances or to calculate two possible solutions to each connectivity problem which represent the best and worst case solutions.

During the development of some of the software used in the project, some invalid direction data was generated. On closer inspection, it was discovered that the value of -0 was being generated. Mathematically this value does not exist, the value means a negative number so small that it cannot be displayed, but it was sufficient that the >= operators used to process the directional data generated failed. The issue was addressed by defining an approximately equals function that resolved the issue.

Some GIS processing operations generated a point cloud, an attempt was made to generate a bounding polygon. Sometimes the software miscalculated the shape of the bounding polygon. If asked to process something that looks like a letter ‘C’ the resultant object would look like a large ‘O’ instead of the expected large ‘C’.

The cardioid processing procedure proved difficult to generate correctly, mainly because it had to generate a vast number of points to ensure that whenever an island feature was covered, a processing point was always present. The calculation also exposed several bugs in the open source geoprocessing software that were only fixed in later versions of the software library.
4.8 Data processing issues

The method used to calculate the direction and speed of the wind is not perfect. As illustrated in Figure 59, peak winds may occur at any time whose value may greatly exceed the value of the most frequent wind strength used by this project. It is possible for the wind to blow in any direction for any period during freak weather conditions. Since this thesis addresses the subject of general travel within the Mediterranean, these unusual weather events may be ignored.

The known values for wind are limited to individual squares as shown in Figure 51; when crossing a boundary, the value of the centroid of the mesh section is used to select a wind value, which may result in some areas returning an unexpected value near the border of the mesh square.

Some areas are difficult to process due to the nature of the geography such as the straits of Messina or straits of Bonifacio are different in nature of the open sea style areas addressed by the project supplied data from (Athanassoulis et al., 2004). These problems were ignored due to the limit length of the straits in comparison to the length of the journey being calculated any distortions introduced would minimal. This could have been a problem if only short distance journeys were being considered.

In some areas data is not available, in these cases the wind data from the nearest square is used, see Figure 51.

Some data is available about some historical journeys, (Arnaud, 2007), (Casson, 1951), (Whitewright, 2017) but these sources only tend to quote the number of days taken and if there were any general exceptions to normal sailing. Details about the course taken, stopovers made along the route, the ability of crew, etc, are not normally recorded unless an exceptional event or journey time was made.

Some ships may have dropped anchor at night, visited ports during the voyage, others may not. Consider the recent voyage of experimental ship Kyrenia2 (see Figure 17), the voyage was supposed to use a direct route between Greece and
western Cyprus, but the ship was blown off course several times before recovering and moving back towards the desired route.

Bearing these factors in mind, it follows that any generated sailing times from whatever simulator used are always going to return an approximate figure for the total sailing time between points. But the design listed in sections 4.2.1 to 4.2.4 will allow for the comparisons of different journeys between different points, using different seasonal data, voyage profiles etc. It is impossible to imply or suggest a time for completion of any given voyage unless the seasonal and route metrics are already known.

### 4.9 Summary

The sailing model provides as accurate a model of the movement of a ship within the currently known data of the Roman period as possible if its limitations are accepted. However, a model is just that – a model, and not the real world. In addition to the variables already noted, there would have been many other possibilities that would affect the duration of a voyage. For example, individual traders or captains may have their own preferences for the selection of a route.
Chapter 5

Travel in the Roman Mediterranean environment
5. Travel in the Roman Mediterranean environment

5.1 Introduction

This chapter explores some different aspects of maritime movement and travel, given what we understand to be the characteristics of the Mediterranean itself, and the potentialities of Roman vessels of the period. Using the modelling approach developed above, it attempts to explore whether the combination of environment and available technology in this period may have favoured different approaches to maritime movement such as summer versus winter sailing, day versus night passages and coast-hopping versus longer distance movements.

The modelling approach ignores issues such as the size of the ship, the purpose of the voyage, locations of ports, and shipwrecks, but will only consider factors such as the wind strength and directions in individual locations, the ability to sail in some areas etc.

This method is different from methods employed by previous studies (Arnaud, 2005), (Reynolds, 1995), (Rougé, 1966) which have all used the focus of quickest route between several identified ports to map the possible travel patterns.
5.2 Sailing at Day and Night

It has been suggested that travel in the ancient world was reserved for daylight only and that the maximum daily sailing distance was approximately 100 KM only (Preiser-Kapeller, 2015) this would have restricted all daily sailing to within the buffer display in Figure 3, the implications being that at night time it was impossible for ships to navigate due to lack of access to reference points on the shoreline or the presence of another ship in the immediate area.

Pliny, (Pliny the Elder Book II Chapter LXXIII in Rackham et al, eds, 1949) while describing ‘What regulates the daylight on the earth' states

*For this reason ships sailing westward beat even in the shortest day the distances they sail in the nights, because they are going with the actual sun.*

This quote suggests that sailing at night was a known method, but the suggestion is that it is harder than sailing during the day. This suggests that some ships did sail at night time. Under an open sky, it was possible to navigate by presence of constellations on a clear night. Other ships would just have anchored inshore or docked at a port location.

A ship docking at a port might have been expected to engage in local trade, the travel plans or policies of local merchants, subject to whatever charges that port may have raised for the use of its service, possible customs inspections etc as described by (Arnaud, 2015). All such options are possibly expensive and would have been avoided where possible.

Although no evidence has been found on the type of ship lamps used in the post-Roman period, it is perfectly possible to make a loud noise to indicate the presence of the ship such as blowing a horn/trumpet or ringing a bell etc.

Sailing at night offers the opportunity to make a much faster journey across the Mediterranean; if sailing is constrained only to the visible coasts in sections of the Mediterranean basin, much slower voyages may be expected, see Figure 5. Another factor affecting the choice of sailing during day and night may be the length of a voyage, it may be possible to make a short distance voyage
during a single day hence avoiding at night problems. A longer distance voyage would last much longer than a single day and would have required the possibility of a significant amount of night time sailing.

Both Rouge (Parker, 2008), see Figure 32 and (Arnaud, 2005) see Figure 34 do not seem to consider this to be an issue, so it can be assumed that as per Pliny’s statement, sailing at night time did occur on at least long distance routes.

5.3 The seasonal effect of wind and wave patterns on general trading zones

Historical sources indicate that seas were probably closed during the winter months, as described in section 2.6, due to bad weather, which acts as a break to the travel potential. If the historical reports are correct, then these should be supported by the available data. The polygons identified in section 2.6 and displayed in Figure 19 and Figure 20 represent a 10% chance of encountering a significant wind wave event during the autumn or winter seasons. A journey navigated through several of these boxes results in an increased cumulative probability of a possible disaster, see Table 8 and Table 9.

With careful navigation, or just ensuring that no trading is done in the north-western Mediterranean, the hazards of autumn sailing can be ignored.
Travel in the Roman Mediterranean environment

<table>
<thead>
<tr>
<th>Event</th>
<th>Probability of disaster</th>
</tr>
</thead>
<tbody>
<tr>
<td>The probability of having an accident in the first rectangle</td>
<td>10%</td>
</tr>
<tr>
<td>The probability of having an accident in the 2nd rectangle</td>
<td>19%</td>
</tr>
<tr>
<td>The probability of having an accident in the 3rd rectangle</td>
<td>27%</td>
</tr>
<tr>
<td>The probability of having an accident in the 4th rectangle</td>
<td>34%</td>
</tr>
<tr>
<td>The probability of having an accident in the 5th rectangle</td>
<td>41%</td>
</tr>
<tr>
<td>The probability of having an accident in the 6th rectangle</td>
<td>47%</td>
</tr>
<tr>
<td>The probability of having an accident in the 7th rectangle</td>
<td>52%</td>
</tr>
</tbody>
</table>

Table 8 Percent cumulative probability of a disaster by sailing across repeated rectangles, see Figure 86.

![% Cumulative probability of a disaster](image_url)

Table 9 Cumulative probability of a disaster by sailing across repeated rectangles, see Figure 86.
But the hazards of winter sailing cannot be ignored; the cumulative effects of a disaster and issues of sailing outside of sight of a coastline suggest that journeys in the winter period were of limited duration, undertaken with caution and that the longer time is spent in stormy areas, the greater the chance of a disaster, see Figure 86.

![Map of Mediterranean showing winter hazards areas](image)

**Figure 86** Marine hazards in the winter months.

### 5.4 Wind Strength Patterns

The Roman sailors had the ability to navigate across the Mediterranean using either foul or favourable winds. But there is always a choice about which route to navigate around an area, see Figure 87.

The significant wind systems in both basins tend to blow in a south easterly direction making voyages from the northern coastlines easier than the reverse trip, suggesting transporting anything from the southern Mediterranean was always going to be harder and more expensive in terms of time and effort.

A faster voyage can be made in the eastern Mediterranean basin by navigating across the Sea of Crete (see Figure 4) instead of sailing to the south of Crete. Although the winds encountered are stronger they do not reach dangerous speeds encountered elsewhere (see section 5.3). But the passage is much harder to navigate. A similar issue occurs in the western basin, the passage
Travel in the Roman Mediterranean environment

from the Gulf of Lion is much faster through the straits of Bonifacio than navigating via the Ligurian and Tyrrhenian sea.

The western basin is subject to two different main wind systems: the Mistral blowing from France and in the spring and summer a wind systems blowing from Gibraltar west across the Alboran and Balearic sea making a passage towards the Atlantic gateway difficult (see Figure 146 and Figure 87). In the autumn and winter months, this wind systems reverse (see Figure 147 and Figure 148).

![Wind Map](image)

**Figure 87 Wind strengths in the summer sailing season.**

The wind speeds for the summer season only suggest that Mistral is a dangerous wind blowing between high 5 and low 6 of the Beaufort wind scale where the advice would be to seek safety (see Appendix 6).

In the eastern basin the prevailing wind blows a in south easterly direction with the island of Crete forming a blocking feature to the strong wind systems blowing from the Aegean. As noted in section 5.3, these wind speeds greatly increase in the winter, see Figure 148. Although only some sections of the winter wind systems are considered dangerous, the increase in wind value affects the entire Mediterranean basin.
5.5 Lee shore Winds

A lee shore wind is a wind that blows in the direction of a coastline, such locations are normally avoided by mariners as sailing in this area could result in a ship being blown on to a coastline if reasonable care is not taken with navigation, or if an unusually strong wind is encountered. Normally such strong lee shore wind systems are avoided where possible.

![Map of Mediterranean showing lee shore winds](image)

**Figure 88 Lee shore winds in the summer sailing season**

As can be seen from Figure 88 there are several lee shore winds that occur during the summer sailing season, with only the straits of Bonifacio being subject to a particularly strong winds. This might suggest that this area would be avoided as ships have to navigate a narrow passage as well as encounter a strong lee wind. The straits of Bonifacio give access from Rome to shorelines of Spain and southern France, to avoid the straits, it suggests that traffic may have preferred to navigate by the north of Corsica, but such a choice would subject any ships to the effects of the Mistral wind system, see sections 2.3, 5.3 and 5.4.

The same problems also occurs in the other seasons, see Figure 149, Figure 150 and Figure 151 except that during the autumn and winter seasons the entire area to the north-west of Corsica (see section 5.3) is considered to be impassable suggesting that traffic might have considered taking a passage.
through the straits or take a significate detour around the southern coast of Sardinia to access the southern coast of Spain.

Several lee winds blow in the Gulf of Sidra; the issue is not the strength of the wind system but rather its size. It suggests that cautious sailors may have chosen to avoid the entire region if possible. As already noted in section 5.4 wind becomes much stronger in the winter season, see Figure 148.

Another lee shore wind does occur to the west of Sicily which is insignificant during the summer season but significant in the winter. The proximity of the Battle of Aegates in March 241 BC suggests that this location is navigable in the spring season when no lee shore wind blows in this area.

Lee shore winds also occur towards the east Cyprus through all four seasons suggesting that this area might be avoided if possible, even through it allows access to the silk road at Antioch via its port city of Seleuceia.

5.6 Coastal/Cabotage/Tramping trading

It has been suggested by Arnaud (2008:62) that some patterns of travel around the Mediterranean were achieved by sailing along the coastline and stopping after a single day’s travel. Using such a method of sailing would require physical locations in which to either dock a ship overnight or to find a safe anchorage and the ability to be able to navigate along a coastline without difficulty. The interaction between these different patterns of movement might indicate a possible pattern of travel, movement or a small world interconnected trade system (see section 2.11). Preiser-Kapeller (2015) identified such systems by assuming the maximum voyage that would be made as 100 KM and generating an interaction diagram. Any clusters within the diagram could be taken as a possible small world network. This interaction diagram was generating a Delaunay triangulation between all port vertices within the Aegean. Impossible voyages which are longer than 100 KM or which crossed a land boundary were eliminated. Preiser-Kapeller then applied Newman’s clustering algorithm to classify any clusters that could be interpreted as small world trade systems.
Applying the same Delaunay triangulation method to the entire Mediterranean basin generates Figure 89.

Figure 89 Delaunay triangulation in the Mediterranean basin.

Removing the long-distance links results in Figure 90, where the remaining links indicate areas where there is a high of area possible interchange, due to the proximity of sites.

Figure 90 Delaunay triangulation in the Mediterranean basin after the removal of long-distance links.
Applying Newman’s clustering algorithm generates several clusters as per Preiser-Kapeller’s research, see Figure 91. Unlike Preiser-Kapeller’s research in the densely packed Aegean Sea, the results for the entire Mediterranean basin are inconclusive.

Figure 91 Small world communities identified by Newman’s algorithm.

It was expected that some localised networks might have been generated and a coastal trading pattern extracted. The lack of results is due to the nature of the coastline which, unlike the Aegean, occurs in the form of a straight line. A small world feature is only formed from a tight cluster of locations which can occur in areas such as a peninsula, a gulf, island etc. A straight coastline can only generate a ‘sausage’ style feature which does not conform to the small world pattern, except where three or more locations occur in close proximity. Using a longer voyage distance might have generated a different set of results, but the increased distance required would void the concept of a small world trading network. It may be assumed that any cabotage style trading must have occurred in the form of pass along style pattern along the coastline and any trading clusters are in the form of a ‘sausage’ except where a coastal feature occurs.

Having identified a possible pattern of movement along a coastline based only on the location of ports, it is necessary to consider the movement metrics by
checking the localised weather patterns to see if it was possible to make such a journey.

This can be done by subdividing a circumnavigation of the Mediterranean coastline into a series of segments (see Figure 92) and calculating the journey times along the different segments in both directions. Any segments that take a marked increased time to navigate along indicates a possible blockage to travel (see Figure 93 and Figure 94).

Figure 92 Factorisation of Mediterranean coastline.
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Figure 93 Resistance to coastal sailing east to west.

Figure 94 Resistance to coastal sailing west to east.
The vast majority of the results indicate that it is possible to navigate along the Mediterranean coastline except for a section of the Aegean, Cap Bon and the tip of Italy. Because the nature of the Aegean is different to the rest of the Mediterranean it is suggested that a pattern of movement based on island hopping instead of coastal sailing may be the preferred choice for travelling within the Aegean.

5.7 Analysis of possible travel routes

The results of the different geographic analysis have suggested many different solutions on how to travel around the Mediterranean basin, depending on what the requirements of a journey may be. The general results suggest that sailing towards a south-easterly direction is much easier than making the return trip (see section 5.4, Figure 94).

5.7.1 North-South Navigation Routes

If a movement strategy prefers the minimum of time spent away from a coastline and only simple navigation instruments are available, it suggests a route along a north-south axis or a direct transport route would be used by preference to cross the open Mediterranean, as a ship making a passage in this direction can determine its position by measuring the height of the stars or direction of the sun.

There are five such possible 'north-south crossings and transport in the Mediterranean (see Figure 95).
Figure 95 Shortest north-south crossing points in the Mediterranean.

Such routes are much longer than the single day sailing distance of 100 KM suggested by Preiser-Kapeller(2015), see Table 10. Even using an island so that some navigation by coastline is possible (B1 & B2) instead of using R1 takes longer. But using a crossing route is faster than making a coastal journey even within the 100 KM buffer (see Figure 95).

<table>
<thead>
<tr>
<th>Route name</th>
<th>Route length (KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>314</td>
</tr>
<tr>
<td>B2</td>
<td>548</td>
</tr>
<tr>
<td>B3</td>
<td>189</td>
</tr>
<tr>
<td>R1</td>
<td>663</td>
</tr>
<tr>
<td>R2</td>
<td>494</td>
</tr>
<tr>
<td>R3</td>
<td>258</td>
</tr>
<tr>
<td>R4</td>
<td>207</td>
</tr>
<tr>
<td>R5</td>
<td>264</td>
</tr>
<tr>
<td>R6</td>
<td>357</td>
</tr>
<tr>
<td>R7</td>
<td>212</td>
</tr>
</tbody>
</table>

Table 10 Crossing points sailing distances

As suggested by the wind strength patterns in section 5.4, a north south voyage does not follow the directions of dominant wind systems and the cost of the making the voyage is asymmetrical. The use of such routes cannot be proven, but Arnaud's analysis of ship routes includes all these routes plus several others, see Figure 34.
5.7.2 **Sailing East West**

There are several areas in the Mediterranean basin (e.g. Gulf of Lion, Gulf of Sidra etc) where the total journey length and time may be greatly reduced if a course is navigated along a horizontal direction instead of along the coastline,

An experience steersman would have knowledge of such areas and would have assumed that the decrease in distance travel would have out weighted the risks in making the passage across an open sea, missing possible ports, safe anchorages etc. If a storm was encountered it may have been possible to steer back into the coastal feature being avoided.
5.8 Conclusions

This chapter has considered some of the different aspects of maritime movement and travel, given what we understand to be the characteristics of the Mediterranean itself, and the potentialities of Roman vessels of the period.

The information presented has suggested that sailing at night on long distance journeys was a regular occurrence and that short distance night time voyages may have been made as well.

It has also suggested that there are two distinct sailing periods of summer and winter with spring and autumn acting as a transfer period. It has confirmed that any extensive sailing during the winter period was extremely risky and would have been avoided when possible. Some local journeys may have been made.

Evidence has also been present about the possible use of cabotage to access any part of the entire Mediterranean basin. It is possible, but it is a very slow distribution method as all resources have to be distributed along the entire coastline from source instead of being able to supply from some nonlocal hub location.

The number of small world systems found within the Aegean basin suggests that the entire Aegean basin could be considered as a localised trading system within its self.
Chapter 6

The affordance of travel – likely patterns of movement
6. The affordance of travel – likely patterns of movement

6.1 Introduction

Having explored, through modelling, the implications of different types of voyages, this chapter attempts to model some more general patterns of movement over longer time, highlighting (for example) those areas that we may expect to have been 'natural' foci for maritime movement. It also explores how mapping (modelled) travel time from specified locations produces very different views of the Roman world which may inform us about how the different parts of the Mediterranean world may have been perceived to be closer or more distant than a conventional, Cartesian map would suggest.

In some studies Isaksen(2008), Sindbaek(2007), Heslin(2008) detailed information is known about the movement patterns, the type of cargoes carried, number of passengers transported, nature and location of production and consumer centres, reasons for travel etc. But this scope of this information is localised to the area of study and does not address the global nature of the entire Mediterranean basin. The information about the Roman Mediterranean is more limited. In some instances, possible production and consumer centres can be identified and some others inferred. Information about the possible movement of cargos can be inferred from pottery distributions Papaloannou(2011), Rice(2011), Oguz Alpozen et al., (1995), Peacock and Williams(1986) but these studies always suffer from issues with fragmentation, possible exception cargos, secondary cargo redistribution etc(see section 2.11).

The travel plans of individual people are virtually unknown unless the traveller was exceptionally important, in which case the travel patterns applicable to that person might be unique. This chapter defines a network as a set of known locations and considers connectivity issues without reference to object distributions because of the previously stated reasons; only the possible interactions with other locations are studied.
6.2 Network Model

As described in section 4.3.1 the network model is constructed from a subsection of the de Graauw (2013) list of ports. The original intention was to use a decision tree classifier (see section 4.4.1) to identify a subsection of ports using common factors, such as location, proximity to Roman road junctions, port infrastructure features such as lighthouses etc, and a clustering method to control the size of the generated network. This proved to be unworkable.

The decision tree algorithm selected needs to be trained using a selection of predefined data that provides a definition of what port concept is. This sample is then used as a template to process the rest of the data set. The problem is the different nature of the coastlines. For example, a training data set derived from sampling the Spanish coastline has a different profile (a sparsely populated coastline) to port’s infrastructure found within the Aegean Sea (a densely populated collection of islands, coastlines and external gateway), with the result that the algorithm generated a set of visibly impossible results.

The issue was resolved by using methods from section 4.3 to create a base map of locations.

The network was populated by choosing different classes of possible routes as defined in Table 11.

<table>
<thead>
<tr>
<th>Route class</th>
<th>Maximum Manhattan distance length</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Infinite</td>
<td>Any route between a class 1 port and another class 2 port.</td>
</tr>
<tr>
<td>2</td>
<td>800 KM</td>
<td>Any route between a class 2 port and any other class 3 port.</td>
</tr>
<tr>
<td>3</td>
<td>500 KM</td>
<td>Any route between a class 3 port and any other possible location subject to a maximum length.</td>
</tr>
</tbody>
</table>

Table 11 Different classes of a route.
This allows class 1 ports to have a global profile across the entire Mediterranean basin, class 2 ports to have a semi-global profile and class 3 ports a localised profile. The distances between class 2 and 3 ports were chosen to allow a complete circumnavigation of the Mediterranean basin via class 3 ports, see Figure 97.

Not all possible routes have been included; it is assumed that there is a physical limit to the distance that a ship may be sailed without a break, in section 4.1.6 a long distance journey between Portus and Egypt is described; this has been taken as the maximum possible distance as possible to sail between different locations. Any routes with a higher cost have been removed from the dataset\(^\text{11}\).

The resultant map allows for travel by tramping around the coastline or by taking a direct route, see Figure 96 for long, medium and short distance routes and Figure 97 for medium and short distance routes.

Figure 96 Mediterranean network route, all routes.

\(^{11}\) A 10 percent margin has been included to allow for errors in distance calculations by the original Roman authors.
From the known information it is difficult to state if the majority of the traffic was constrained to using long-distance routes or a sequence of shorter journeys between different locations. One method exploits the shortest travelling distance and the other allows a great travel diversity.

Figure 97 Mediterranean network route, class 2 and 3 routes.

As described in section 4.4, this map can be regarded as a network of bypasses as well as a direct connection network. Carter’s(1969) study of Serbian trade networks and River’s(2016) Mediterranean trade networks included similar constructs. As such this network is a possible representation of a combination of long and short distance travel patterns within the Roman Mediterranean.
6.3 Network Centrality

The network (see section 6.2) is represented as a series of vertices and transport links; by studying the linkage between the different vertexes, it’s possible to stress the importance of some vertices compared to others when considering the possible ways of navigating the network. As described in section 3.4, four different methods of network centrality are considered in this thesis, Betweenness, Closeness, Eigenvector and Page rank centrality. These values were calculated by using the Gelpi package (2016) using the transport cost (see section 4.2) between port locations as the edge cost. The description and implementation are defined in Batagelj(2005).

6.3.1 Betweenness Centrality

Betweenness centrality is a measure of the number of shortest paths that pass through a given vertex, in a transport network, and is described as

*not how easy it is to reach other nodes, but the likelihood of it being en route when taking the shortest path between other routes. Vertices with high betweenness need not necessarily have a high closeness centrality but they are classically associated with bottlenecks and focal points of systems* (Isaksen, 2008).

In Figure 98 only size sizable centrality points are displayed, with similar results being shown in Figure 152 to Figure 154 implying that there are either few bottlenecks or that the network is equally connected.

In all cases, the Straits of Messina is shown to be a constant bottleneck, which is consistent with it acting as a bridging point between the eastern and western sections of the Mediterranean basins. Corinth also behaves in a similar manner, it assumed that this behaviour is generated because access to Corinth is through a single passage with no other connections along the way.

The coastline of Tunisia is also shown to be an area which returns high values again suggest that it is acting as a bottleneck in the travel network.
It is important to note that the Balearic Islands, Corsica, Crete and Sardinia according to this metric do not function as bottlenecks, suggesting they do not perform any exceptional bridging points (as expected in section 5.7.1) and behave in a similar manner to the northern and southern Mediterranean coastlines.

The behaviour of Chytos to the south of Rome cannot be explained, there are no known issues with the travel network in this area, but in the summer season, this metric suggests that it functions as a bottleneck for travel to Rome.

The high values for Rome in the autumn and winter (see Figure 153 and Figure 154) making it a bottleneck is suggested by the change of autumn and winter winds, in that it is harder to reach the Rome area from the southern coastline of France, see section 5.4.
Closeness centrality is a measure of how easy it is to reach a given vertex from any other vertex within the network, in a transport network it can be assumed that such a network would have the largest number of direct connections from other vertices, a suggestion that such a port would be an important location.

As can be seen from Figure 99 virtually every port is considered to be well connected, only class 3 ports on the southern Mediterranean coastline being considered poorly connected with the exception on the Alexandria, Tunisian and some sections of the Adriatic coastline.

Similar results are recorded for the spring, autumn and winter results, see Figure 155 to Figure 157. This suggests that transport routes along the north eastern Mediterranean coastline would be more popular for making return trips from Egypt to Rome rather than passages by the southern alternative route.
6.3.3 **Eigenvector centrality**

Eigenvector centrality is a measure of how well connected a vertex is to other vertices that have a compatible high value of connectivity. In a transport network, this metric identifies high connected nodes or groups of highly connected nodes.

![Eigenvector centrality values](image)

**Figure 100 Summer Eigenvector centrality values.**

The results of the Eigenvector centrality analysis suggest that the Aegean basin is a highly connected subsystem with some additional areas found near Crete, Cyprus, the Levant, the Tunisian coast and the port of Alexandria; this suggests that these areas are easy to traverse using short distance boats as well as long-distance boats, and that there should be a higher distribution of objects in this area than elsewhere within the Mediterranean basin.

Unlike Rome, the Aegean and its immediate area are in an easier area to travel in and to supply resources to Constantinople. Similar results are recorded for spring and autumn (see Figure 158 and Figure 159) In winter high connectivity is recorded for the Levant coastline (see Figure 160).
6.3.4 Page Rank models

Page rank Centrality is a way of calculating centrality that considers the generosity of other vertices when measuring centrality. A high value of interconnectivity will only be indicated if the connected vertices are less generous with their return routes then the originating vertex. In a transport network it indicates that a vertex is important if it connects to many other vertices and few vertices make a return connection, i.e. the vertex is functioning as a distribution centre instead of an interchange centre.

Figure 101 Summer Page Rank Supply models.

In Figure 101, the majority of the vertices return similar answers with only the values of Rome and Neapolis, Elea, Ephesus, Smyrna, from the Aegean, Berytos, Sidon, Tyre from the Levant and Carthago, Hadrumte, Hippo Regius, Rusicade and Syllectum from the Tunisian coastline returning high values than some of the class 2 port locations, This suggest that all these ports are better connected hub locations.
6.3.5 Centrality Conclusions

The different results from the centrality calculations have all indicated that there is virtually no difference in centrality through the different seasons of the year. Where there are differences the effect is mild, suggesting that areas of high centrality only occur in areas not subject to extreme weather conditions.

There is a marked absence of bottle necks in the network except for the Strait of Messina, the eastern Aegean, Levant coastline and Tunisia coastline with a smaller contribution from the western Italian coastline.

Prior expectations of good results from nexus ports subject to long-distance shipping routes were unrealised with vertices such as Constantinople and Rome not behaving as expected.
6.4 Port Catchment areas

A port location functions as an exchange interface between different ports through the Mediterranean basin in terms of travel to and from its location by measuring the possible catchment area. In both contexts it may be possible to indicate the travel of a given global journey potential of a port location throughout the entire Mediterranean basin.

This analysis measures how many other locations may be travel to or from a single location. A location that can be reached from more locations than others has greater global travel potential than other locations. This methodology has been used by the UK Civil Aviation Authority (2011) to measure the market power of the major London Airports. The use of this type of method has been objected to by Gilmore (2010) due to concerns about the nature of the data used, given that only the port location and inter-port journey time is available makes alternative data models difficult to use.

There are subtle differences between the supply to (see Figure 155) and supply from (see Figure 103). In both cases, localised voyages between ports in close proximity are shown to carry the same travel potential i.e. the cost of the voyage is symmetrical; as the inter-port distance increases the journey time can become more asymmetrical. There are several clusters of higher localised interactions along the eastern Aegean, Levant, southern Sicilian and Tunisian coastlines. In both cases, areas such as the northern Adriatic and Gulf of Sidra appear to be ill connected to the rest of the Mediterranean network.

The central areas of the Mediterranean are not included in this analysis; this absence is caused by the maximum permitted voyage length. If a longer voyage time had been used, the northern and southern results would have overwritten each other.
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Figure 102 Support port catchment areas.

Note this metric is subjective in its response, it only generates data where there is a port located in areas such the western side of Corsica (and other similar locations); where there is no port location, then no data is generated.

The data patterns reflect the nature of the localised wind patterns; as such, the area activity on the northern coastline is more active than the southern coastline.
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The spring travel patterns are similar in nature to the results from the summer, see Figure 164 and Figure 165.

The results from the autumn (Figure 166 and Figure 167) show similar data patterns except for access to the north western Italian coastline which is restricted with access only being possible by access from Rome or from the southern side of Sardinia as already described in section 5.3.
6.5 Common Routes

It is unclear from the available evidence how travel patterns were made; for example, it is known that grain was exchanged between Alexander and Portus but there are many possible combinations of possible routes that may be selected. By randomly selecting the different routes between different port locations within the network defined in section 6.2 and by mapping the different route intersections, it may be possible to identify which areas of the Mediterranean would be commonly sailed in the different seasons.

This was done by generating random journeys between different ports; the journeys were plotted using 17.2 KM segments, the centroid of every segment was used to generate a data point, the results are displayed by plotting the number of times the data point was recorded.

Two different route profile representations were used, all possible routes (Class one, two and three), and data set generated by using long distance (Class one routes only, see section 6.2) this allows results to be generated for generic and long distance transport models.

The summer generic result (see Figure 104) indicates a preference for sailing within the eastern Aegean, the Levant and Tunisian coastlines, Sea of Sicily and the southern part of the Ionian Sea, and the Straits of Messina with a tail towards Cyprus and Apollonia/Darnis.

With virtually no results being displayed for the southern coastline or western Mediterranean basin, these results are caused by the distribution of route segments, in these areas the routes are more sparsely distribution over a great surface area as described in section 6.4.

The tail feature is suggestive of a possible N/S link between the northern and south coastline of the Mediterranean basin as suggested in section 5.7.1.
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The results for spring (Figure 170) autumn (Figure 171) show similar results, with the winter results (see Figure 172) show the compaction of the results towards a much more northern location and less of a tail feature towards Cyprus.

This suggests that spring, summer and autumn sailing routes are similar in nature with the exception of the Mistral wind area, see section 5.4. The previous analysis of catchment areas (section 6.4) only considered short distance routes (Classes 2 and 3).

Using the long-distance routes only results in Figure 105. This indicates that access to the western Mediterranean is included in the data results but obscured by the larger set of results for the shorter routes.
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Similar results are generated for spring, autumn and winter see Figure 173 to Figure 175.

6.6 Time Distorted Maps

An alternative way of considering information about the Mediterranean basin is map the time taken to reach a place instead of the distance that must be covered; this alternative presentation model shows how difficult it can be reach some parts of the Mediterranean from a fixed point, see section 4.5.

In Figure 106 the key points that must be crossed when making an inter basin journey are indicated.

For an explanation of the symbols used see Figure 83.
These points were selected because

- **Portus**: This is the central shipping point for the entire empire, the port city for Rome.
- **The Balearic Islands**: These islands dominate the western Mediterranean basin and can be used as a possible stopping/starting/refuelling point between the southern and northern coastlines.
- **Straits of Bonifacio**: This point controls access to the western Mediterranean from Italy: all voyages attempting to avoid the mistral wind and Ligurian sea may wish to travel by this point.
- **The island of Sicily**: Dominates the connections from the western Mediterranean basin to the eastern Mediterranean; all traffic must pass either side of the island, and the eastern and western points can be used to considering the generic access around Sicily.
- **For similar reasons**, the eastern and western ends of the island of Crete are also included.
- **Although not a fixed land mass eastern and southern Mediterranean is also included**, traffic taking the direction between Alexandria and Rome must pass this way, ditto the traffic flows around the eastern basin.
The majority of the different seasons gave a result, but in some cases the origin of the centre of distortion occurred in an area of high generation which resulted in either no results being generated, missing sections or a data collapse, see section 5.3 for a description of general patterns effects of the winter weather season.

6.6.1 **Balearic Islands**

![Time distance map for the Balearic islands.](image)

The Balearic Islands dominate the western Mediterranean basin, offering little or no connection with the eastern Mediterranean, it implies that traffic attempting to make a crossing between the northern and southern coastlines of the western Mediterranean basin would have navigated by these islands. Voyages to the eastern Mediterranean are possible, but the distances required
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to make a successful voyage are long. It indicates that traffic to the eastern Mediterranean would have stopped off at either Portus, the western part of Sicily or possibly through the sea of Sicily. Possible routes to Rome would have gone via either the Ligurian sea or the Straits of Bonifacio. Due to the difficulty of reaching either the Aegean of the Adriatic, it suggests that resources for these areas may be been exchanged at a port near the entrances to these areas depending on the nature of what was being transported.

6.6.2 Central Mediterranean

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No generated results</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td></td>
<td>Winter</td>
</tr>
</tbody>
</table>

Figure 108 Time distance map for the central Mediterranean.

As may be expected since this data point represents the centre of the Mediterranean basin, there is little or no distortion. It shows that unlike most of the maps the Adriatic is easily reached, suggesting that traffic originating
between the Gulf of Gabes to the Gulf of Sidra would have no issues reaching either the Tyrrhenian or Adriatic Seas. The Alboran and Levantine Sea are difficult to reach from this area. During the winter this region is in the middle of an area of high winds and as such would have been avoided.

6.6.3 Straits of Bonifacio

Figure 109 Time distance map for the straits of Bonifacio.

Given the physical topography of the landscape of the Straits of Bonifacio, it suggests a similar method of access to the Balearic Islands (see section 6.6.1) with the possibility that some voyages may consider a passage along the Tyrrhenian sea and through the Strait of Messina to access the eastern Mediterranean. The difficulty with this proposal is that Messina is known to be a difficult channel to navigate, but a passage via this channel avoids the
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possibility of being blown across the sea of Sicily towards the Gulf of Sidra which is also known to be a difficult area to successfully navigate.

6.6.4 The island of Crete

The island of Crete blocks the strong flow of winds from the Aegean into the rest of the Mediterranean basin, see Figure 177. Ships navigating this area could take the northern route, which would result in a faster passage due to the increased wind strength available in this part of the Mediterranean, but this also includes the possibility that a ship might be sunk due to excessive wind strength.

Taking the southern route around Crete could result in a much slower passage due to the much weaker wind patterns in this area, there is no way of telling which the route of choice would have been made, see Figure 176.

As with patterns associated with the centre of the Mediterranean (see section 6.6.2), there is little distortion in this area suggesting that voyages could easily be made to either the Adriatic or Tyrrhenian sea.
6.6.5 Eastern Mediterranean

The distance map for the eastern Mediterranean as expected shows the reverse picture to the Balearic Islands results (see section 6.6.1) with the Aegean, Adriatic and Tyrrhenian seas being easy to reach and the Alboran and Balearic sea being virtually impossible to reach; as with the other results it suggests that traffic would have made a direct connection to Portus.

Figure 110 Time distance map for the eastern Mediterranean basin.
6.6.6 Portus

As with other results from the western basin access to the Adriatic is shown as being difficult to reach, see Figure 178, suggesting that goods being transported or travel from Rome might have gone via road instead of being transported by ship.

6.6.7 The island of Sicily

<table>
<thead>
<tr>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No generated result</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
</table>

Figure 111 Time distance map for the western end of Sicily

As with navigating around Crete, there are two possible ways of navigating around the island of Sicily; the western tip is known to suffer from lee shore winds (see section 5.5), the eastern route requires a difficult passage through the straits of Messina, an area known to be difficult to navigate.
Which route was selected is difficult to resolve, either route has its different advantages,(see chapter 7 for a worked example). Travelling to western Africa would suggest a trip around the western side mainly due to issues of speed. Trips to eastern Africa would probably favour the eastern tip; this method of travel would allow navigation by the coastline whereas travelling via the western tip would require a trip across an open sea, which is normally avoided.

Figure 112 Time distance map for the eastern end of Sicily.
6.7 Conclusions

All the different methods used in this case section have shown, with the exception of the autumn Mistral wind and some minor differences, that access patterns for spring, summer and autumn are broadly similar, with winter being markedly different.

All methods in this chapter have shown the Aegean to be a well-connected subsystem within the larger Mediterranean basin.

Access to the central areas of the mid and eastern Mediterranean basin is limited and would only be undertaken if strictly necessary.

The results from the Aegean tend to create a localised distortion effect that can block out the results from the rest of the Mediterranean basin.

The majority of the results appear to indicate much greater level of activity along the northern Mediterranean coastline than along the southern coastline; an inspection of the raw data indicates that this result is due to a more densely packed result set in the northern area compared to that held for the southern coastline.

This chapter measures the number of common routes in a specific area; a widely distributed set of routes does not generate a ‘result’ in this context, but activity is still being undertaken.

There appear to be several localised areas of interconnectivity along the Levant and Tunisian coastlines.

The straits of Messina appear to be an important bridging point.

There is some evidence to suggest some possible north-south crossing points.
Chapter 7
Implications for Travel along a known axis of movement (between Alexandria and Portus)
7. Implications for travel along a known axis of movement (between Alexandria and Portus)

7.1 Introduction

To conclude the analytical work within the thesis, this chapter changes focus from the very general patterns and trends discussed in chapter 6, to consider how the modelling approach developed previously may inform us about much more specific movement patterns relating to one, well-documented, route within the Roman world.

The different routes selected by the Romans to transport goods between different known ports is subject to much speculation; many studies have focussed on the distribution of goods (Papaioannou, 2011), (Heslin, 2008) etc. The suggestion is that if common goods are found between different locations, then there must be a form of trading relationship between those locations, the number of goods indicating the strength of the relationship. These relations are supported by secondary factors such as the contents of shipwrecks (Parker, 1992).

This chapter considers travel potential between known points and examines the different possible factors which may affect the choice of travel route selected between two different ports.

The Roman state had to supply and warehouse a large supply of grain and other products to fulfil the Annona/dole requirements. Failure to supply had been known to lead to cases of rioting and general civil unrest. It has been estimated that some 200,000 tonnes were required under Emperor Augustus (Garnsey, 1989:231). The storage was run as a public enterprise, with independent merchants being used to manage the grain supply under contract. The grain was transported from Egypt, North Africa and Sicily, with Egypt providing the largest supply.
Implications for travel along a known axis of movement (between Alexandria and Portus)

This chapter examines the possible variations of a single travel route between Alexandria and Portus, Portus being the principle harbour for the city of Rome. This route is listed in the Diocletian price edict (Arnaud, 2007). This chapter investigates the different ways of navigating across the eastern Mediterranean basin. The wheat supply was transported from the Egyptian province in enough volume to allow most carriers to take a direct route, i.e. most ships working the route would not be required to stop off at additional ports on route to make up their cargos. It is also assumed that since the carriage of grain required a specialised design of the boat, issues about trading with mixed cargos do not have to be addressed in this chapter.

The traversal of this route is asymmetrical in nature; travel from Alexandria to Portus must be made against the prevailing wind (see section 2.3) Figure 113 and Figure 114 show different bands represent the same amount of travelling effort. It takes 13 cost bands to reach Alexandria from Portus and 21 to make the reverse trip.

Figure 113 Flow from Portus to Alexandria in the summer season

12 This could have been possible but would have resulted in the choice of return route being fixed.
Implications for travel along a known axis of movement (between Alexandria and Portus)

Several different possible trade routes were described in section 2.13. This chapter attempts to test the possible results of attempting to use these routes in the different seasons of the year.

A journey could have involved sailing along a coastline or sailing across the centre of the Mediterranean Sea; as suggested by Arnaud (2008:62) that some Romans may have sailed either along a coastal route or via a direct route (see section 7.4). The subject of Roman navigation has been addressed by Davis (2009), who suggests that detailed navigation was understood, which implies that it was possible to take a direct route (see section 2.13) without requiring any form of coastal navigation. It should be noted that due to some geographical constraints (Strait of Otranto, the sea of Sicily) (see Figure 4) unless sailing by the straits of Messina, some open sea sailing would always be required.

Both areas are within the area of known coastline visibility, see Figure 5, and as such present no issue for boats using a coastline as a navigation marker. Ships making these passages must cover either the 210 KM (sea of Sicily) or 140 KM (Strait of Otranto), which define a minimum sailing distance for models.
Implications for travel along a known axis of movement (between Alexandria and Portus)

If it was impossible to sail directly between Alexandria and Portus, a stop at an anchorage or a supply port would have been required to complete the passage. The maximum inter stop distance that could be covered in a single segment of a multi-segment journey will affect the selection of a course.

The avoidance of some areas of the Mediterranean basin to avoid well-known hazards is also a possible consideration when selecting a route to navigate. For example, a requirement to navigate a coastal route would require that the areas identified in Figure 5 were not traversed.

This chapter examines possible trade routes which attempt to:

- Follow a direct route to between Alexandria and Portus.
- Compares the routes which avoid the Gulf of Sidra$^{13}$, the north African coastline and the Levant area.
- Compares the northern and southern coastal route between Alexandria and Portus.

This chapter uses the process described in section 4.6 to calculate a route.

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$^{13}$ This area was selected because of the results discovered in chapter 6.
7.2 Direct routes between Alexandria and Portus

The supply routes described in section 2.13, all suggest a strategy of sailing along the coastline, either in part or for the entire journey, all of which are much longer than a direct route between Alexandria and Portus.

Assuming that it is possible to sail on a direct route, subject to sailing across the Mediterranean without stopping, and a standard of navigation suggested by Davis (2009), a direct route would be the preferable choice. But making such a trip does not allow for resupply of the ship, or the ability to make up for a short cargo.

The possible direct route varies per the seasonal winds. Except for the autumn route, all the generated routes will encounter the lee shore winds found off the western coast of Sicily in the summer and winter seasons (see section 7.3.1). The autumn route passes through the known hazard of the Straits of Messina.

This western coast of Sicily must have been considered navigable due to the location of the port of Lilybaeum in this location, and the battle in summer 218 BCE during the 2nd Punic war. The same area is a required passage point to Carthago which indicate any hazards would be well known to sailors.

Except for the circumnavigation of Sicily, the entire trip is made without reference to any landscape features. The spring and summer maps may appear
to support a coastal sailing pattern, but the coastline shore of north Africa is flat (see Figure 5 and Figure 7) and unobservable from ships in this area.

7.2.1 **Direct route via Agrigento**

As noted in the previous section, the autumn route preferred the eastern side of Sicily by requiring all traffic to navigate by the coastal city of Agrigento on the southern shore of Sicily, forcing all traffic to move by the south coast of Sicily.

All three routes are virtually identical, requiring passage through the Tyrrhenian Sea away from the coastline, some parts of which are not observable to a passing ship, see Figure 116.

The autumn journey (see Figure 116) does pass close enough to the north African coastline to allow for some coastal navigation which may have made a difference to the possible autumn direct trade route (see Figure 117) which allows no coastal navigation.
7.2.2 Direct route via Straits of Messina

This addresses the other possible choice of direct route and directs all traffic to navigate by the Strait of Messina. A passage through this area always seems to have been hazardous due to the location of strong tidal currents during the passage through the Straits. The Greek legends of Charybdis and Scylla (Roberts and Homer, 1976 book XII) indicate a known problem. As suggested in section 7.2.1, a passage is required across the Tyrrhenian Sea, but using a route which is much closer to the coastline would make it possible to navigate by fixed navigation points, see Figure 5.

Figure 117 Fastest direct route via Messina.

Comparing the distances travelled suggests that the route via the Straits of Messina is an average distance of 241 KM shorter (see Table 12).

<table>
<thead>
<tr>
<th>Season</th>
<th>Agrigento (KM)</th>
<th>Messina (KM)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>2994</td>
<td>2770</td>
<td>224</td>
</tr>
<tr>
<td>Summer</td>
<td>2890</td>
<td>2614</td>
<td>276</td>
</tr>
<tr>
<td>Autumn</td>
<td>2873</td>
<td>2648</td>
<td>225</td>
</tr>
</tbody>
</table>

Table 12 Sailing distance between Alexandria and Portus.

Sailing a Roman era ship is a complex and difficult task. The ability to navigate near a coastline, follow the shorter route through the Straits of Messina and avoid the lee shores of the western side of Sicily (see section 5.5) suggest that this route would have been the preferred choice for a direct route.
Implications for travel along a known axis of movement (between Alexandria and Portus)

7.3 Avoiding areas

There are several different areas of the Mediterranean that are known to be dangerous to navigate. By configuring the route simulator to avoid these areas, different suggested trade routes can be generated.

7.3.1 Gulf of Sidra

The Gulf of Sidra is an area of sea to the north of modern Libya (Roman provinces of western Cyrenaica and Africa Proconsularis). Strabo describes the hazards of shipping in the area as

> the difficulty with both the Greater and the Lesser Syrtisi is that in many places the water is shallow, and at the rise and fall of the tides ships sometimes fall into the shallows and settle there (Strabo 17.3.20).

Another author Pomponius Mela (1.35-7) describes the area as

> “having no ports and are alarming because of the frequent shallows and even more dangerous because of the reverse movements of the sea as it flows in and out”.

This is confirmed by Stone(2014), who lists major ports along the African coastline but does not include any from the Gulf of Sidra. The presence of lee shore winds throughout the four seasons of the year (see section 5.5) also suggests that this is an area to be avoided where possible. Avoiding the Gulf of Sidra as per Figure 179 would imply not using a southern Mediterranean coastal trade route (see section 2.13) i.e. shipping traffic would have to use the northern route or undertake a route across the middle of Mediterranean to navigate around the hazard.
Implications for travel along a known axis of movement (between Alexandria and Portus)

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Figure 118 Possible trade routes avoiding the Gulf of Sidra.

Where possible the longer segment routes attempt to generate a route across the Mediterranean towards Crete. As the maximum route segments become shorter, a route is generated across the void between Libya and Greece. Only when it becomes impossible to generate a route across the Mediterranean is a route generated that navigates along the Levant coastline. At no point is an attempt made to make a southern Mediterranean route above the Gulf of Sidra. This seems to be because the route across the mid-Mediterranean is regarded as a shorter route. It suggests that passages via the Levant coastline would have been avoided where possible, as they would have required a much longer passage to make that journey or would only have been made if the voyage was attempting trade along the Levant coastline itself. A route that allowed long-distance trading across the Mediterranean is the preferred choice. Given the number of calculated routes that attempt to avoid the Gulf of Sidra, it is suggested that the nearest major ports to the east (Leptis Magna) (see Figure 134) and west (Apollonia) (see Figure 134) of the Gulf may have operated as transaction points.
Implications for travel along a known axis of movement (between Alexandria and Portus)

7.3.2 Levant

In the previous route simulation, some generated passages suggest a route along the coast of the Levant. Blocking access to this area would be expected to generate routes along the southern Mediterranean coastline, as per Figure 180 where access to the northern Mediterranean coastline near Cyprus is blocked.

As per the section 7.3.1 most of the suggested routes (see Figure 119) are made across the Mediterranean at its narrowest point or using Crete as a transit point.

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Figure 119 Possible trade routes avoiding the eastern Mediterranean.

It is only when it becomes impossible to navigate across the Mediterranean basin that a route following along the southern Mediterranean coastline is generated. This suggests that the southern Mediterranean coastline was avoided where possible.
Implications for travel along a known axis of movement (between Alexandria and Portus)

7.3.3 North Africa

In this simulation, most of the north African coastline towards the west of Alexandria was removed as per Figure 181. The simulator was expected to generate suggested long-distance trade routes that traverse via the eastern end of Crete. The attempt to avoid the north African coastline does not result in a generated route across the Mediterranean basin (as per sections 7.3.1 and 7.3.2), but instead, routes along the Levant coastline are generated.

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Figure 120 Possible trade routes avoiding the north coast of Africa.

Comparing the results generated in this study (see Figure 120) and the results generated in section 7.3.2, it seems that beginning a journey along the north African coastline is an important factor when considering how to cross the Mediterranean, either along Levant coastline or across the Mediterranean basin. Some of the longer generated (900 KM & 800 KM) passages suggest a route directly in to the Aegean on to the shores of eastern Greece, although theoretically possible, the routes have been suggested because the selected algorithm is attempting to generate the longest segment possible. It seems
Implications for travel along a known axis of movement (between Alexandria and Portus)

more likely that a route avoiding the centre of the Aegean would have been selected.

7.4 Comparing the Northern and Southern routes

The case studies so far have all focused on allowing the possibility of generating routes that may cross the Mediterranean basin. This chapter considers trade routes which stay in sight of a coastline i.e. the southern and northern trade routes, as identified in section 2.13.

In all cases, a trade route is generated along the Levant coastline ignoring the bulk of the island of Cyprus towards Greece, see Figure 121.

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Figure 121 Possible trade routes navigating along a coastline.

At no point is any attempt made to follow a route along the southern Mediterranean coastline. It seems that in terms of efficiency of travel the northern coastal route is preferred. By configuring a requirement to visit the port of Leptis Magna, the simulator will generate a route along the southern Mediterranean coastline, see Figure 122.
Implications for travel along a known axis of movement (between Alexandria and Portus)

Given that the northern route is the more efficient of the two routes, it seems that there must have been a good reason for attempting a passage along the southern route. Both routes have lee shore winds (see section 5.5) which will cause issues whichever route is followed.

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Figure 122 Possible trade routes along the southern Mediterranean coastline.

It is known that the African coastline was a source of grain, a ship unable to pick up resources from Alexandria under a grain charter may have been forced to make a trip along the African coastline to fulfil that charter.
Implications for travel along a known axis of movement (between Alexandria and Portus)

7.5 Other coastline combinations

Different combinations were attempted, any attempt at mapping a coastal route that avoided the Gulf of Sidra resulted in routes being generated along the northern coastline because all other route combinations were blocked. Similarly, attempts to block access to the Levant coastline resulted in all route combinations being generated along the southern coastline.

The template used to enforce a coastal journey (see Figure 182), is at its narrowest point along an axis generated between the coastlines of Libya and Crete; it is plausible to assume that some boats with a preference for coastal sailing may have been tempted to cross the Mediterranean basin at this point. The resulting journey across an open sea is shorter than the journey that would have been necessary to make per Figure 183 which is a required crossing if a journey between Alexandria and Portus is to be completed.

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Figure 123 Suggest routes sailing across the Mediterranean.
Computing routes using the outline listed in Figure 183, results in a series of routes navigating along the north African coastline and bridging the Mediterranean along the suggested north/south axis. The differing values of the inter-port distances resulted in different stop off points in Greece or Crete. Applying a similar logic suggests that other borderline areas outlined in Figure 183 could be also ignored. There is a reference in the Odyssey (Roberts and Homer, 1976 book 14 line 300), which describes a passage made on a seafaring ship 'bound for Libya which makes passage to the windward of Crete', which suggests that a route across the Mediterranean was known to pre-Roman sailors.

## 7.6 Conclusions

The different journeys generated between two major ports suggest that, depending on the choices made, different voyage profiles could be created. The ship that is only prepared to make a small journey will be constrained to move along the coastline. Such a journey would allow for trade in other objects and cargo may not be restricted to grain only.

As indicated in section 5.4, the eastern Mediterranean is subject to stormy weather in the winter season. Most of the suggested winter routes intersect with the area of suggested storms, which suggest that these routes would have been undertaken only as required.

Apart from several outlying routes, the majority of the generated voyages avoid a journey across the central zones of the Mediterranean, which suggests that it is not often crossed.

The most efficient projected voyage profiles suggest a mixture of the use of southern and northern trade routes, unlike the suggested trade routes indicated in section 2.13. There is some evidence from shipwreck data (see section 2.5) to indicate coastal Roman sailing activity, but no wrecks have yet been discovered in the middle area of the Mediterranean basin possibly due to the depth of the Mediterranean basin.
Implications for travel along a known axis of movement (between Alexandria and Portus)

None of the analyses generated routes which made use of the southern Mediterranean coastline by choice, see section 2.13. The reasons for the preference for generating routes along the northern coastline is a matter of efficiency; the routes generated by the routing program are designed to be the 'most' efficient, which suggests that unless there was a good reason to assume otherwise, the northern trade route would be the default route when compared against making a lengthy passage along the southern trade route.

Some of the generated routes match some of the profiles as generated by Arnaud (2005), see Figure 34, other suggested routes also trace a similar route to the voyage of Kyrenia2, see Figure 17.

A trade route via Greece, as suggested by the results in section 7.5 could be based on historical precedent. Greece had been the former major maritime power in the eastern Mediterranean (Semple, 1921:60); grain could have been initially transported to Greece, because that's the way it had always been done, and then forwarded along the northern coastline to Portus.

The routes were generated by a route simulator which assumed preferred predetermined movement pattern for a ship, but a ship of the period was a slow-moving object which took time to respond to a movement change. As such, the generated routes should be taken as the best possible estimation of a movement pattern; reality would have been slightly different. Given this, it is possible to suggest that there are areas where more ship movement would be expected to occur.

Some of the routes follow the same patterns found between Venice and Alexandria during the period of the Republic of Venice (see Figure 49), with the eastern and western end of Crete being used as stopping off points.

Simple solutions to the issues of crossing the open voids in the Mediterranean are suggested by combination maps Figure 102 and Figure 103, i.e. sailing along the southern/northern coast of the Mediterranean, and then heading due north/south at a known landmark/navigation point. The presence of lighthouses at the Cyrenaica ports of Apollonia, Phycus, and Ptolemais (Stone, 2014:571) could suggest the presence of traffic at these ports during the hours of darkness. But the presence of lighthouses at Sabratha, Lepcis Magna
and Thapsu (Stone, 2014:570) could indicate passage along the southern trade route, or trading activity from the direction of Tunisia.

Navigating by the sun or using the position of a constellation above a given height can be used to ensure that a northern or southern path is navigated. A similar route has been suggested by Davis (2009), except that Davis has the crossing of the Mediterranean basin just to the west of Cyprus, with the route than following the northern trade route. Reynolds (2010) also suggests a crossing between Crete and Alexandria via Libya for the distribution of pottery instead of grain (see Figure 35).

As described by the Diocletian price edict (Arnaud, 2007), there was a trade route between Alexandria and Portus across the Mediterranean basin. The evidence in this chapter suggests that the crossing point was between Libya and Greece, but it could equally have occurred in other places.

However, given the design of Roman ships, despite the navigation methods suggested by Davis (2009), the direct route does not seem a practical proposition, as it does not offer any shelter in the event of a storm during the days spent on the open sea, whereas all other routes do.

Given the large number of routes generated for a journey made between two different ports, this suggests that the focus of route research should be the identification of common subsections of route network instead of the generation of all possible routes between all locations. The number of north-south crossings generated suggests the need for an exchange point on both sides of the Mediterranean basin, in the south, it is suggested that this location is Apollonia, the port connection to Cyrene.
Chapter 8

Discussions and Conclusions
8. Discussions and Conclusions

The principal aim of this research was to examine the patterns of travel within the Roman Empire, focussing on travel relationships between different areas and point locations within the Mediterranean basin, during the period 30 BC to 500 AD, and how these may have been affected by seasonal changes which would have impacted on the transportation corridors commonly used at that time. In order to better understand the nature of possible Roman travel patterns, GIS methods have been applied to the available information about the geospatial structure of the Mediterranean basin, incorporating known weather patterns, wind and wave data, and the locations of possible Roman ports. The inferred movement patterns, or trade route models, derived from this approach measured the ability of Roman shipping traffic to move from presumed fixed points around the Mediterranean basin. This chapter draws together the results of the individual case studies, with reference to the research questions set out at the beginning of this thesis.
8.1 The seasonal effect of wind and wave patterns on general travel Areas

As described in section 6.3, 6.4, 6.5, 6.6 and 7.2, there are subtle differences in all seasons through the Mediterranean basin. But apart from the Mistral wind blowing in the Gulf of Lion the general pattern of behaviour between Spring, summer and autumn are similar in nature.

During the winter period aggressive wind systems exist; there is a margin between the coastline and the suggested position of wind systems, that could be interpreted as a space to navigate around the storm system. The nature of storm systems is fluid; the long distance effects may change localised wind and wave patterns in such a way that experienced sailors would prefer to avoid the entire border area, when considering the effects of length of the day between winter and summer. These winter stormy areas subdivided the Mediterranean into three safe areas (extreme western, central Italian and general eastern) and two dangerous areas, see Figure 86.

The position of the strong wind areas in the western Mediterranean (see Figure 86) suggest that there is an effective barrier between the western provinces and sailing to the central Mediterranean area. It is highly unlikely that any travel would have attempted between the Atlantic and Mediterranean, the Atlantic not being an enclosed area any sea storms would have been significantly stronger than anything encountered within the Mediterranean.

Casson (1995) states that only the minimum amount of sailing was done in the autumn and winter seasons, but Beresford (2013:17) describes how it was possible to trade between Egypt and Rhodes in the winter months. These different viewpoints suggest that only parts of the Mediterranean basin were closed during the winter period and that within the safe areas trading continued, with goods being stockpiled at boundary locations such as the Balearic Islands, Rhodes etc. Rhodes (and Delos) have been described by Casson (1954) as being at the centre of the grain trade during the Hellenistic period. There is no reason to suggest why it should not still be an important stopping place during the Roman period.
When the spring season arrived, these stockpiled goods would then be traded onward, avoiding a long journey from their normal home location. It also suggests that the routes from the Carthage area via Sicily would be open throughout the entire year. The same logic suggests that during the winter period, Malta would stop being a gateway to Africa.

8.2 Analysis of possible travel routes and maritime provinces

The results of the different geographic analysis have suggested many different solutions on how to travel around the Mediterranean basin, depending on what the requirements of a journey may be. The general results suggest that sailing towards a south-easterly direction is much easier than making the return trip (see section 5.4, Figure 113 and Figure 114).

8.2.1 Supply Routes

The supply routes from the western to the eastern Mediterranean basin are, in general, easier than the return trip, which requires a constant struggle against the wind. It has been suggested by Tomber (1993) that the trading systems for the Mediterranean followed a twin basin system, with the east and west rarely meeting (see section 8.3). This viewpoint can be accepted if gaps between the Italian mainland, Sicily and Cap Bon are taken as a virtual land bridge along a north-south axis, blocking most access between the western and the eastern basins. But the Annonae grain supply to Rome voids this argument, which crosses this notional ‘bridge’ (Garnsey, 1989). A variety of different travel routes have been suggested, (see section 2.13) all of which are supported by relevant distorted map (see section 6.6).

8.2.2 Eastern Routes

Reynolds (2010) suggestion about Egypt being a major supplier of grain to Constantinople (see section 2.13.1) are confirmed, (see the diagrams for the eastern Mediterranean, see sections, 6.6.4 and 6.6.5), subject to issues about crossing into the Aegean Sea from the Mediterranean.
Discussions and Conclusions

McGrail’s (2014) suggestion of a counter clock wise route (see section 2.13.1) is confirmed, but the route through the Sea of Cyprus looks to be difficult and would generate many small route intervals in the winter. This suggests that instead of going around the island of Cyprus, this route would instead navigate along its southern and western tips to avoid some lee shore winds (see section 5.5). For similar reasons, the route around the north-eastern Egyptian coastline and southern Levant would be treated with caution due to the presence of lee shore winds (see section 5.5).

8.2.3 Western Routes

As described in sections 6.6.1 and 6.6.3 traffic attempting to travel towards the west in the western Mediterranean would have no problems, but travel to the eastern basin was difficult, particularly when attempting to access either the Adriatic or Aegean seas.

The results from sections 6.5, 6.6, 6.7, 8.4.2 and 8.4.3 conform to (Rougé, 1966) suggestion of mid-Africa providing some of Rome’s grain, as the flows show that this is possible, (see section 2.13.2).

8.2.4 Inter-Basin Routes

The inter basin routes suggested in section 2.13.3 are confirmed, subject to what has already been said about lee shore winds (see section 5.5). The Price Edict (Arnaud, 2007) lists passages from Sicily (Syracuse to the Levant) Caesarea, from Ostia to the Levant, Gades to the Levant, Alexandria to Syracuse etc. Most of these routes require an inter-basin journey, see section 6.6.7, which implies that these routes are possible, but suggest that when travelling to the Gades area, the faster route would be towards the south of Sicily and Sardinia towards Gibraltar. This route requires a great deal of travel out of sight of a coastline, so it is possible that a southern trade could have been followed, avoiding the Gulf of Sidra (see Figure 4). Making the same trip from the Levant to Carthage would follow most of the same route.

The edict also includes a route from the Levant to the south of France at Arles (see Figure 4). It is suggested that again a route along the southern
Mediterranean coastline towards Sicily would be the quickest, as after Sicily there is a choice, either navigating along the Italian coastline using Sardinia to block the effects of the Mistral and or through the straits of Bonifacio to Arles, a trip via northern side of Corsica (Cap Corse) or a trip along the entire Italian coastline with an exposure to lee shore wind (see section 5.5).

8.3 Connectivity from Constantinople and Rome

Historically Portus and Rome were the port and capital city of the Empire, but in 286 the Empire divided between Rome and Constantinople with the results that the travel networks may have changed. This section considers the individual travel metrics from Constantinople and Rome to the rest of the Mediterranean basin by using an isochron map, (see section 4.4.4).

Both Constantinople and Portus can be difficult to reach; in the case of Constantinople an archipelago of islands and complex deeply tidal channel has to be navigated, to reach Portus either the lee shores (see section 5.5 )/Straits of Messina of Sicily, the mistral wind or the straits of Bonifacio have to be successfully navigated before either location can be reached.

8.3.1 Constantinople

The Constantinople supply metrics from the Mediterranean (see Figure 124) indicates that anything west of Sicily was getting difficult to reach, suggesting that these areas would be unlikely destinations unless the demand for specific resources was considered exceptional.
Discussions and Conclusions

The same map indicates that travelling in the eastern Mediterranean was easy, not subject to issues with lee shore wind, see sections 5.5 and 13.5.

The Constantinople area may have been supplied from the Black Sea as well as the Mediterranean basin.

8.3.2 Rome

The Rome supply map (see Figure 125), presents a similar access pattern for Rome to Constantinople access except showing the focus of activity in the western Mediterranean. The map suggests that the access from Rome via the Tyrrenian sea happens at the same time, regardless of whichever access route is selected. Access to the eastern Mediterranean is controlled by passage through the Straits of Messina, it may be possible to sail to the eastern Mediterranean via sailing around the western side of Sicily but the access route is much longer and subject to lee shore winds, see sections 5.5 and 13.5.
Access via the Straits of Bonifacio and the Ligurian Sea takes about the same time.

Both Constantinople and Rome/Portus have a local supply network which is difficult to access from the other spatial locations suggesting that with two major centres the travel network could be considered to be a twin basin distribution solution see Figure 126, where areas such as the Adriatic and the Gulf of Sidra being considered shared common areas and the extreme eastern and western ends being localised to Constantinople or Rome.

It could be assumed that two ‘primary’ areas would rarely exchange resources unless special circumstances such as Indian/Chinese products were being exchanged, Pliny describes how this trade with India/China/Arabia was costing 50 million sesterce (Pliny the Elder Book VI Chapter XXVI in Rackham et al, eds, 1949) and elsewhere 100 million sesterce (Pliny the Elder Book XII Chapter XLI in Rackham et al, eds, 1949).
Discussions and Conclusions

Figure 126 intersections and common areas.
8.4 Port Systems analysis

8.4.1 Introduction

The analysis of port systems is a complex issue. Many different authors have suggested different solutions based on evidence such as pottery distributions (Oguz Alpozen et al., 1995) trading practices (Arnaud, 2007), profit and loss accounts (Warnking, 2016a) efficient use of boats (Warnking, 2016a) Roman law (Arnaud, 2015). Several different areas of based theories are suggested in section 2.11).

It has already been suggested that there is only one period of sailing (see section 8.1), the summer season, with spring and autumn being slightly different and the winter season being totally different, a period when most sailings were avoided where possible. The Adriatic and Aegean (see sections 8.5.1 and 8.5.2) have been identified as possible subsystems with possibly localised sailing hierarchies and connections to global sailing routes, see section 2.11.

It has been suggested in section 8.3 that in the later Roman period that the Roman Mediterranean was a twin basin system with Constantinople and Rome dominating possible trade systems.

At this point, it is possible to suggest at least another two port subsystems and a single interface point. Large river system such as the Nile, Rhone etc can be regarded as closed regional subsystems with Alexandria and Marseille function as interfaces given that a journey that needs to be made up river requires the use of a shallower draft boat with any cargo/passengers being swapped between boats.

The analysis in section 6.5, attempted to identify common sailing areas in the different seasons by considering models of all sailing routes and long distance sailing routes only. To ensure that the majority of theories are considered, the following sections considered other possible common access sailing models.
8.4.2 **Top 15 Return Routes between ports**

This alternative analysis model of pattern movement is based on the concept of a ship making a return trip between two different ports. As before a random number of journeys are considered. To ensure the maximum number of possible variances is considered, 15 different way of making the same return trip are considered, see Figure 127.

![Figure 127 Map 15 return trips between different ports.](image)

The majority of the areas are still shown to be along the northern eastern Mediterranean coastline, the Italian coastline and African coastline near Sicily.
8.4.3 Distortions in the data results

In virtually all routes, analysis of sections 5.6, 6.3, 6.6, 7.5 and 7.6 results from the Aegean area of the Mediterranean have dominated the result sets. Repeating the common routes analysis but removing all ports associated with the Aegean results in Figure 128.

![Figure 128 Common routes without the Aegean dataset.](image)

In this analysis the majority of the common travel area occurs around the southern end of Italy, Tunisian, the straits of Messina. The Levant forms a region subsystem with five north-south crossing points as described in section 5.7.1. being highlighted.
8.4.4 **Short Routes only**

In this variant of the common access method, only short and medium length routes are plotted.

![Figure 129 Shortest common routes](image)

As with the majority of other common areas activity is shown to be constrained to the mid-Mediterranean basin belt, the Aegean, Tunisian coastline and the Levant with the straits of Messina being shown as a common access point. These results look very similar to section 8.4.3, implying that part of the popularity of the Aegean is the number of short distance journeys made in that area, see Figure 87.
8.5 Different sailing area characterises

8.5.1 The Aegean

The time distorted maps for the eastern Mediterranean (see 6.6.5) shows the area to be well integrated within its local area and could function as a closed subsystem as per section 2.11.

The modelled cost flows for the connections coming from the Mediterranean to the Aegean is poor suggesting that it is easy to sail within the Aegean but to connect to other areas of the Mediterranean basin is more difficult. The localised winter wind systems have been described as *these winds have been known to make entry into the gulf very difficult* (NGIA, 2017) towards the island of Rhodes. This feature can be explained by the wind patterns (see Figure 87, Figure 146 and Figure 147) where the prevailing wind blows towards the Mediterranean away from the Aegean. The island of Rhodes does not seem to be affected due to the presence of the Turkish mainland. The journeys from the Aegean to the rest of the Mediterranean must have been made on a regular basis as the trip from Ephesus to Ostia is described in the price edict (Arnaud, 2007).

Casson’s suggestion of the Black Sea supplying Garum (Casson, 1994a) and Stecher (2001:46), a possible grain route from the Black Sea via the Aegean in section 2.13.1 is supported by the Modelled cost flows. This and the Edict route from Ephesus, suggest that the Aegean not only acted as a local subsystem but also as a major route between the Black Sea and the Mediterranean basin.

8.5.2 The Adriatic

The Adriatic basin is a prisoner of its geography, with mountain ranges to the west and east (see Figure 7), its only connection to the sea being at its southern border. The wind strength map (see Figure 87) shows that it is a difficult place to reach compared to sailing to Rome from the rest of the empire. The same diagrams suggest that it is faster to transport goods from the west coast to the east coast via the road network rather making the long
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trip around the Italian coastline. Compared to the western side of Italy, the eastern side does not have the attractive lure of the large cities of Rome, the bay of Naples etc. The Adriatic acts as a connection to the Po Valley (see Figure 7) and its large delta, evidence of Roman sailing is shown by the many shipwrecks in the area (see Figure 18).

The same problem is shown in the majority of the time distorted maps (see Figure 107, Figure 109 and Figure 111). A different instance of the same type of problem is shown in section 8.3 where the Adriatic is shown as a possible shared area between Constantinople and Rome.

It was important enough to have its own naval fleet at Ravenna and outposts at Ancona, Brundisium, Salona etc (Pitassi, 2009:207). In later history, the Republic of Venice, located at the northern end of the Adriatic, had major trading connections with most of the Eastern Mediterranean basin (see Figure 49). An ancient Greek connection is described by Kirigin et al., (2009). Both Arnaud(2005) and Rouge(1966) analysis of Roman trade patterns (see Figure 33, Figure 34 and Figure 35) suggests that the Adriatic was deeply connected with the rest of the Roman network. Jurisic(2000) suggests the presence of a general eastern route supplying northern Italian wine. It is also possible that Brundisium acted like the end of the via Appia and Dyrarchio the start of via Traiana and these ports could have supplied goods along these routes as part of a larger national network.

The mouth of the Adriatic at the strait of Otranto (see Figure 7) forms a narrow section of the open Mediterranean which must be crossed by all traffic coming from the eastern Mediterranean basin. The local ports in this area (Brundisium and Dyrarchio), both have lighthouses (de Graauw, 2013) which infer that there was either a local marine hazard or either port wished to attract night traffic as well as day traffic. These facts suggest that the Adriatic functioned mainly as a localised maritime province. Most of the larger ships ignored the direct trade and possibly exchanged goods at Brundisium or Dyrarchio which acted as redistributive/exchange hubs by ships working the local network and wider area networks. Some direct long-distance trade was done, but it was limited in nature compared to the trade flows operating between the western Italian coastline and the rest of the Mediterranean basin.
8.5.3 **Proposed Port Hierarchy/System**

Evidence presented in chapters 5 to chapter 7 suggested that some areas of the Roman Mediterranean are much easier to navigate between proven localised trading systems. In this context a trading system is a small group of ports exchanging goods in a localised area, intergroup trading does take places but operates in a global context.

As already identified the Aegean (see section 8.5.1) and the Adriatic (see section 8.5.2) function as localised subsystems. The Rhone and Nile river valleys function as single track distribution systems. The river headwaters and sea junctions form an interface with the global travel potential of the Mediterranean basin which requires a change of ship size or type due to the different maritime environments (see Figure 131).

The common route analysis (see section 6.5) indicates that some areas of the Mediterranean basin are accessed more often. Extracting any areas that match the same route destiny criteria present within the Aegean (already identified as a subsystem, see section 8.5.1) for the spring to summer months (see Figure 130).

![Figure 130 High density common routes](image-url)
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This analysis suggests that the Levant coastline operated as two distinct subsystems (north east and north east central, see Figure 131) with a shared common interface between them as explained in Figure 28. It also possible to suggest that both subsystems could have functioned as a single larger system.

The Tunisian coastline operates in a similar manner to the Levant coastline but with Malta and Patelleria acting as bridging points to Sicily.

The amount of activity shown in the Sea of Sicily (the suggested Mediterranean region system, see Figure 131) towards the Tyrrenian Sea suggests that all access to Rome was by this access area. There is an issue of a lee shore wind on the western side of Sicily, see section 5.5 and Figure 88, Figure 151 and Figure 152. The lack of noted activity in the western end of the Mediterranean in Figure 130 does not imply not that there is a total absence of activity, but the pattern may be more widely distributed, so that it does not generate the peak activity found elsewhere as per Figure 104, Figure 129, Figure 170, Figure 171 and Figure 172. Also, the method used does not factor in any traffic entering the Mediterranean from the Atlantic gateway.
8.6 Questions and Answers

The first aim of this thesis was to provide a new understanding of potential travel relations between the different areas of the Roman Empire. The original questions can now be readdressed.

1. Do the patterns of wind create any zones of travel within a given seasonal period, and if so, how might these affect the general trade potential throughout the entire Mediterranean basin?

As has been described in section 8.1 there are two main phases of current activity in the Mediterranean, the winter and the rest of the year. Both spring and autumn operate as transitory phases between the two extreme values of summer and winter, there are some areas of the Mediterranean where travel in winter is ill-advised (see section 5.3) and some areas where passage is still possible but taken under advisement only. Pliny notes

\textit{not even the fury of the storms closes the sea pirates first compelled men by the threat of death to rush into death and venture on the winter seas, but now avarice exercises the same compulsion.} (Pliny the Elder Book II Chapter XLVII in Rackham et al, eds, 1949).

The arrangement of port hierarchy (see section 8.5.3) does suggest that it was possible to store cargos on the route if that was desirable. This may have been deliberately done to take advantage of possible movements in prices but there is not the evidence to suggest if it was common practice or not. There is a discussion by Cicero (1994 Book 3 chapter 12) about the moral ethics of taking advantage of famine, and the knowledge of other merchants being en route, which suggests that some merchants might have attempted to take advantage of famine situations.
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2. Are there identifiable regional travel subsystems within the Mediterranean basin, where the patterns of travel might be different from other areas?

As described in section 8.5.3 there are six different distinct travel subsystems, see Figure 130. Just how much interaction there was between different areas is extremely difficult to quantify.

Two of the subsystems are the Nile and Rhone) which require a change of transport. The enclosed basins (Adriatic and Aegean) while not requiring a change of transport are isolated from the rest of the Mediterranean to the extent that different sailing environments exist with totally different weather dynamics function as intendant subsystems. The remaining trading areas are sections of open coastline (Levant, Tunisia). Natural due to different geographic factors sailing conditions are all different within each subsystem.

The maps generated in section 6.5 (Figure 105, Figure 170 and Figure 171) do indicate a globalised trading system, but how much was actually sent between different areas is not known. The facts that some routes were only one way most have affected the distribution systems between the different subsystems. It is also important to understand that some of these trading areas offered unique or multiple supplies resources. The silk road acted as an input to the Roman Mediterranean system (Pliny the Elder Book XII Chapter XLI in Rackham et al, eds, 1949) and monetary sink; its resources were available through either the Levant coastline or the Aegean basin, but these resources were luxury products unlikely to have been widely distributed outside of the top levels of society, suggesting only limited exchange or voyages.

It is suggested by Tchernia (2016:188) that the grain supply for Rome is unclear, and only documented by four textual references (Tchernia, 2016:188), with the suggestion that only one third of the grain supply for Rome was supplied from Egypt via Alexandria.
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Semple (1921:73) agrees with this analysis and states that another third would have been provided by Sicily and Sardinia, with the rest provided by Carthaginian and Numidia Africa. Rickman (1980), Mattingly (1995) and Swanson (1975) all list western Africa as a supplier of grain and other goods. It is the relationships between supplier and consumer that define the nature of the transport model. It is most unlikely that grains from one area would be transported directly to another, so it suggests that the major relationship between Tunisia and Alexandria is in the form of a star network with Rome acting as the nexus. The different return route possibilities are described in depth in section 7.1.

3. Are there any trade hot or low spots where the wind patterns may cause an excessive change in the localised travel potential?

It has already been described in section 2.6 and 5.4 that the Mistral wind dominates the profile of the western basin: there is an increase in the number of shipwrecks in the local area, (see Figure 18) suggesting that this area was traversed on a regular basis but must have been noted for its gale force wind hazards.

As suggested by the common route area in (Figure 127, Figure 128, Figure 129, Figure 170, Figure 171, Figure 173 and Figure 174), there is a marked difference in the amount of activity along the northern and southern coastlines with the central areas of the Mediterranean basin being totally avoided. It is suggested that the northern route is the more popular option because of the greater density of ports along the route which allows the use of fleets of smaller ships as well as the possibility of using larger ships and, as such, acts as a magnet for increased travel potential. It also avoids having to pass near a semi-desert coastline, (see Figure 55) where there would be few resources.

The prevailing wind systems in the eastern Mediterranean basin blow towards the south east enabling rapid voyages to be made as described in section 4.1.6 but a return journey along the same route would require
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a constant battle against a foul wind, which suggests that a different route would have been selected for a return journey.

The second aim of this thesis was concerned with building an understanding of how local travel locations could interact with each other, and if any organisation existed between different locations. This section of the research was focused on a further set of questions:

4. Do changes in the season affect the position of a port within the travelling hierarchy?

Not all possible port locations are equal when considering the different effects of the localised weather systems. Some study port locations are within or close to a no sailing zone, see section 5.3. The difference between the long and short common area analysis see (Figure 105, Figure 173 and Figure 174) and (Figure 104, Figure 170 and Figure 171) does indicate that areas such as the Gulf of Sidra are ignored when the focus on travel is based on a long distance travel model.

It has been suggested that either a cabotage model or a hub port system (see section 5.6 ) may have been used to distribute goods. Whatever mechanism is defined, an important consideration that needs to be considered is the ease of transport and navigation for the transport and distribution of goods. It is possible that the choice of navigation path to follow may have been affected by the factors such as harbour duty, the time entering port or may even have been a requirement of the party paying for the cost of the voyage (Arnaud, 2008).

For such cabotage system to work efficiently, there needs to be a series of hub locations to serve as resource centres, assuming that the daily travelling distance is near 100 KM as suggested by Preiser-Kapeller (2015). The port hierarchy identified in section 8.5.3 only identifies major locations. An issue could be the granularity of the filter being applied to identify redistribution locations. The population density maps, Figure 55 indicate where the major population centres may be
found, suggesting that long distance cabotage distribution systems may be found in these areas and localised cabotage distribution systems may operate on the periphery of the possible port hierarchies described in section 8.5.3.

5. Was travel throughout the Mediterranean constant, or was it subject to any form of regional organisation?

As described in section 8.5.3 the evidence suggests that several regional subsystems do exist. All of which, as previously described in question one, are different unlike the homogenous port system models presented in section 2.11.

It is suggested the Roman Mediterranean is a combination of several different aspects of the port system models all of which suggest a regional organisation.

The Levant coastline may be either a single larger subsystem or two smaller systems sharing a common interface as shown in Figure 28. The rest of the subsystems Aegean, Adriatic etc, are linked together as Figure 26, with the rest of the western basin being an instance of Figure 29. This solution incorporates different aspects of the answers previously presented in the current chapter. Such a system is regionally organised with different models allowing for different structures for the distribution of goods and travel metrics.
8.7 **Strategic access corridors of Travel**

As described in previous sections an organisation model has been suggested, which implies that the Romans transport model only used see parts of the Mediterranean basin, see Figure 132.

The following evidence is presented to prove this verify this hypothesis.

As identified in section 5.6 cabotage trading can take place on any coastline within the Mediterranean so it reasonable to assume that every possible coastline represents a trading surface. These features represent the northern and southern trading routes described in section 2.13.

This narrow coastal travel strip is enhanced where there is an increase in the density of the local Roman settlements, see section 4.1.9.

The density packed nature of the Aegean basin( see section 8.5.1), strongly implies that this entire region should be included.

The sparse and separate nature of the Adriatic (see section 8.5.2) suggests that it should not be included other than the narrow coastal previously identified.

The common area used to identify a possible port hierarchy in section 8.5.3 is used to define possible access patterns to the central and eastern Mediterranean basin. This area also includes the islands referenced by Gambin(2012) as way-points, shelter and hazards.

As inferred in section 5.7.2 a direct route along the coastline of gulf of Sidra is a complex undertaking and would have been avoided where possible, hence a direct route which avoids this area and the associated lee shore winds has been added.

The Balearic Islands function as described in section 5.7.1 acting as a potential bridging point or possible pass through port, enabling traffic to move between the north and south Mediterranean coastline.

For similar reasons routes bridging points have also been made between southern Greece and northern Libya and between Sicily southern Greece.
The one way diagonal routes which representing the most likely connections between the Straits of Messina and Alexandria.

Figure 132 Most likely position for a sailing boating in the Roman Mediterranean

The map Figure 132, represents the most likely locations for finding a Roman era ship within the Mediterranean basin. With the exception of the suggested route along south western coastline this map matches Arnaud(2007) research (see Figure 33).

Similarly with the exception of routes portrayed in the Adriatic and the east west nature of the connections to the Balearic islands the generated map Figure 132 matches the results of Arnaud(2005) research (see Figure 34).

The map also matches some aspects of Reynolds(2010) research about the distribution of Baetican oil, it should be noted that Reynolds research did not
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cover the entire Mediterranean basin and only focused on the western basin. The east–west routes displayed in Figure 132 represent a possible problem with Roman navigation, it is easy enough to sail along a north south route by using solar or stellar navigation but navigating an east west route across an open sea represents a problem. Without a fixed landmark its impossible to ensure that true horizontal course is being kept.

The courses labelled ‘Route option’ in Figure 132 do represent a great saving in time and effort but it cannot be proven if they were used. But comparing the one way route with a map of marine hazards (Figure 86) shows that a large segment of this journey lies with a ‘Non coastal zone’, Pliny describes this journey as being made( see section 4.1.6) so it suggests that these ‘Route options’ were viable routes.
8.8 Conclusions

The major struggle with travel within the Mediterranean basin has always been the relationship between the origin and destination of the amount of travel and the season. The majority of travel issues can be overcome depending on travellers’ choices and actions.

The essential problem can be summarised as how to cross the Mediterranean basin if origin and destination occur on different coastlines, it is the difference between making a long coastal journey or making a voyage across an open sea. If the traveller is prepared to undergo a voyage across an open sea, risk sea storms, etc the passage will be swift. If the coastal journey is preferred the number of crossing points is limited to either island hopping across the sea of Sicily or much longer voyage along the Levant or across the Alboran Sea.

Navigation and travel within the Roman Mediterranean depend on the size of boat available, the nature of what is being transported, the amount of money available, and skill/choices of the master and crew.

Through the period of the Roman Empire travel was successfully made, the travel patterns function on both a local and global context with some individual areas functioning as localised sub system each interacting with each other (see section 8.5.3).

The option of sailing along the northern Mediterranean coastline was more popular than sailing along the southern coastline. The eastern basin of the Mediterranean seems to have been more developed than the western basin. Where ever possible routes across the open sea was avoided.

Access to the Mediterranean was seasonal, in some areas travel occurred throughout the year, but large areas were considered closed during the winter months. Travel occurred through the spring, summer and autumn, but spring and autumn functioned as gradual transition phases to and from the limited winter sailing period.
8.9  Closing remarks

This research is based on an inductive interpretation of the available evidence. There are many areas where the original data set is weak or ambiguous, where assumptions have had to be made and generalisations applied.
9. Considerations for further research work

The research present in this thesis has not considered the following subject areas:

- Localised weather systems.
- The potential shipping tonnage restrictions on some routes.
- The position of main Roman fleets.

9.1 Localised weather systems

This thesis has considered the general weather patterns in the Mediterranean basin, but it has not considered the effects of the consistent daily variance on shipping during this period which may be of interest to other researchers in this field. Warnking (2016b) suggests that the effects of localised wind systems may be overcome by using a better resolution of wind data that than was available when this project was undertaken, using a resolution of one degree instead of five degrees. This may overcome the effects of unknown localised wind systems found near the coastlines. Issues such as Diurnal winds have not been considered which may have affected any ship making a coastal journey.

9.2 The potential effect of shipping tonnage restrictions

No research has been carried out on any of the factors affecting the size of ship’s hold. A larger ship (see section 2.4) was capable of carrying a larger load and may have been able to navigate over longer distances without calling in at other ports on a route. These issues could be resolved by an application of Ford-Fulkerson or Edmonds-Karp methods (see section 3), assuming that the larger ship kept to the longer transfer route and avoided any ports without deep water access.

The same type of metric and models can be used to examine if the model presented in section 8.7 is valid.
9.3 Roman Fleet

There several different fleets described in the Mediterranean basin, (Pitassi, 2009) with the Praetorian fleets based at Misenum in the bay of Naples, at Ravenna in the Adriatic sea, and several provincial fleets distributed throughout the Mediterranean basin. The ships that made up these fleets followed a design principle focused on speed, instead of a merchant fleet designed to support bulk cargo transport at a slower rate of transport. Plotting the possible movement of both fleets from their main base should indicate the 'time to engage threat' of both fleets, an essential requirement when attempting to deal with an external hostile military threat. This assumes that both fleets included the same type of ship.

![Figure 133 Possible Roman Praetorian fleet deployment sailing distances.](image)

As shown in Figure 133 the Misenum fleet travelling towards the Ionian Sea would reach it in the same amount of time that it would take for the Ravenna to arrive. Given that there are no common signal systems to relay messages
between both fleets at the same time, it is open to speculation what the true purpose of the Ravenna fleet was. The extensive system of lighthouses along the coastline of Adriatic coastline could be used for signalling purposes to bring the fleet to deployment outside of the Adriatic Sea.

An alternative interpretation is that the Ravenna fleet was designed to operate in the Adriatic Sea for most of the time, ensuring that the area was kept clear of threats such as pirate activity. It may have been deployed outside of the Adriatic as and when required, but its principal function was localised control of the Adriatic Sea.

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14 Possibly to deal with Piracy
Bibliography


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University of Southampton

Faculty of Humanities

Department of Archaeology

Travelling in the Roman Mediterranean a GIS approach

Volume II Appendices and supplementary documents

by

David Potts

Thesis for the degree of Doctor of Philosophy

February 2019
# Appendix 1 External Resources

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Appendix 2 Project ports

The following sub selection ports from the (de Graauw, 2013) is used to model the Roman Mediterranean basin.

![Map of the Mediterranean with ports]

**Figure 134 Ports identified by case studies.**

### Class 1 Ports

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**Table 13 Class one ports**
## Class 2 Ports

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Table 14 Class two ports
## Class 3 Ports

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</tr>
<tr>
<td>52</td>
<td>Caucana Portus</td>
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<td>Cercenna</td>
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<td>Gergis</td>
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<td>Gigthis</td>
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<td>Hippo_Diarrhytos</td>
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<td>Icosium</td>
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<td>75</td>
<td>Indike</td>
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<tr>
<td>86</td>
<td>Leptis Minor</td>
</tr>
<tr>
<td>87</td>
<td>Lune</td>
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<td>88</td>
<td>Macomades Minores</td>
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<td>Mallorca</td>
</tr>
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<td>Metapontum</td>
</tr>
<tr>
<td>95</td>
<td>Mykenai</td>
</tr>
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<td>96</td>
<td>Na Guardis</td>
</tr>
<tr>
<td>97</td>
<td>Naxos</td>
</tr>
<tr>
<td>98</td>
<td>Narbo Martius</td>
</tr>
<tr>
<td>99</td>
<td>Oea</td>
</tr>
<tr>
<td>100</td>
<td>Oiniiade</td>
</tr>
<tr>
<td>101</td>
<td>Olblianus</td>
</tr>
<tr>
<td>102</td>
<td>Orea</td>
</tr>
<tr>
<td>103</td>
<td>Orikon</td>
</tr>
<tr>
<td>104</td>
<td>Palaia Knidos</td>
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<tr>
<td>105</td>
<td>Palmeria</td>
</tr>
<tr>
<td>106</td>
<td>Paretonius</td>
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<tr>
<td>107</td>
<td>Paestum</td>
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<td>108</td>
<td>Patara</td>
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<td>109</td>
<td>Pelousion</td>
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<tr>
<td>111</td>
<td>Perinthus</td>
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<tr>
<td>112</td>
<td>Phora</td>
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<td>113</td>
<td>Port Hercules</td>
</tr>
<tr>
<td>114</td>
<td>Port of Altimum</td>
</tr>
<tr>
<td>115</td>
<td>Port of Hatria</td>
</tr>
<tr>
<td></td>
<td>Description</td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>116</td>
<td>port_of Stentor</td>
</tr>
<tr>
<td>117</td>
<td>Port of the Acanthiens</td>
</tr>
<tr>
<td>118</td>
<td>Portus Illicitanus</td>
</tr>
<tr>
<td>119</td>
<td>Portus Magnus</td>
</tr>
<tr>
<td>120</td>
<td>Poseidion</td>
</tr>
<tr>
<td>121</td>
<td>Psyrie</td>
</tr>
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<td>122</td>
<td>Ptolemais</td>
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<tr>
<td>123</td>
<td>Pyrgoi</td>
</tr>
<tr>
<td>124</td>
<td>Rethymno</td>
</tr>
<tr>
<td>125</td>
<td>Rhygmanis</td>
</tr>
<tr>
<td>126</td>
<td>Rusaddir</td>
</tr>
<tr>
<td>127</td>
<td>Rusippisir</td>
</tr>
<tr>
<td>128</td>
<td>Sabratha</td>
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<td>129</td>
<td>Saguntum</td>
</tr>
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<td>130</td>
<td>Saralapis</td>
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<tr>
<td>131</td>
<td>Scidrus</td>
</tr>
<tr>
<td>132</td>
<td>Sida</td>
</tr>
<tr>
<td>133</td>
<td>Silvoa</td>
</tr>
<tr>
<td>134</td>
<td>Soloi/Pompeiopolis</td>
</tr>
<tr>
<td>135</td>
<td>Startonos Pyrgos</td>
</tr>
<tr>
<td>136</td>
<td>Styra</td>
</tr>
<tr>
<td>137</td>
<td>Syracusae</td>
</tr>
<tr>
<td>138</td>
<td>Tarrai</td>
</tr>
<tr>
<td>139</td>
<td>Telone Martio</td>
</tr>
<tr>
<td>140</td>
<td>Thabraca</td>
</tr>
<tr>
<td>141</td>
<td>Thasos</td>
</tr>
<tr>
<td>142</td>
<td>Thermai</td>
</tr>
<tr>
<td>143</td>
<td>Tripoli</td>
</tr>
<tr>
<td>144</td>
<td>Turris_Libyssonis</td>
</tr>
<tr>
<td>145</td>
<td>Vadis_Savadis</td>
</tr>
</tbody>
</table>

Table 15 Class three ports
The following major cities listed by (Russell, 1985) as defined in section 4.1.9 are served by the following port locations listed in Table 16.

<table>
<thead>
<tr>
<th>Major City</th>
<th>Port City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexandria</td>
<td>Alexandria</td>
</tr>
<tr>
<td>Antiochia</td>
<td>Seleukeia</td>
</tr>
<tr>
<td>Apamea</td>
<td>Laodicea</td>
</tr>
<tr>
<td>Athens</td>
<td>Piaeneus</td>
</tr>
<tr>
<td>Baalbek</td>
<td>Berytos</td>
</tr>
<tr>
<td>Cadiz</td>
<td>Atlantic-gateway</td>
</tr>
<tr>
<td>Cartagena</td>
<td>Carthago Nova</td>
</tr>
<tr>
<td>Carthage</td>
<td>Carthago</td>
</tr>
<tr>
<td>Catania</td>
<td>Catina</td>
</tr>
<tr>
<td>Corinth</td>
<td>Corinthe</td>
</tr>
<tr>
<td>Cyzicus</td>
<td>Chytos</td>
</tr>
<tr>
<td>Ephesus</td>
<td>Ephesus</td>
</tr>
<tr>
<td>Hadrumetum</td>
<td>Hadrumete</td>
</tr>
<tr>
<td>Hippo Regis</td>
<td>Hippo Regis</td>
</tr>
<tr>
<td>Isaura</td>
<td>Coryco</td>
</tr>
<tr>
<td>Jerusalem</td>
<td>Ascalon</td>
</tr>
<tr>
<td>Miletus</td>
<td>Miletos</td>
</tr>
<tr>
<td>Mytilene</td>
<td>Mytilene</td>
</tr>
<tr>
<td>Naples</td>
<td>Neapolis</td>
</tr>
<tr>
<td>Nicomedia</td>
<td>Nicomedia</td>
</tr>
<tr>
<td>Nicea</td>
<td>Praenetus</td>
</tr>
<tr>
<td>Pergamum</td>
<td>Elea</td>
</tr>
<tr>
<td>Pisa</td>
<td>Pisa</td>
</tr>
<tr>
<td>Rome</td>
<td>Portus</td>
</tr>
<tr>
<td>Rusicade</td>
<td>Rusicade</td>
</tr>
<tr>
<td>Sidon</td>
<td>Sidon</td>
</tr>
<tr>
<td>Smyrna</td>
<td>Smyrna</td>
</tr>
<tr>
<td>Tarragona</td>
<td>Taracce</td>
</tr>
<tr>
<td>Thysdrus</td>
<td>Syllectum</td>
</tr>
<tr>
<td>Tyre</td>
<td>Tyre</td>
</tr>
</tbody>
</table>

Table 16 (Russell, 1985) Major towns to project port
The following town locations identify by (Russell, 1985) were not include due reasons of being reachable on another highway/river systems(see Table 17) or being too far inland (see Table 18).

<table>
<thead>
<tr>
<th>Arsinoe</th>
<th>Capua</th>
<th>Cirta</th>
<th>Memphis</th>
</tr>
</thead>
</table>

Table 17 (Russell, 1985) Major towns reachable by another highway/river system.

<table>
<thead>
<tr>
<th>Ancyra</th>
<th>Antinoe</th>
<th>Bologna</th>
<th>Cordoba</th>
<th>Damascus</th>
<th>Heliopolis</th>
<th>Lambrasis</th>
<th>Merida</th>
<th>Oxyrhymcus</th>
<th>Pamplona</th>
<th>SiccaV</th>
<th>Thugga</th>
<th>Trebizond</th>
</tr>
</thead>
</table>

Table 18(Russell, 1985) Major towns too far inland to be included in this thesis.
Appendix 3 Provinces of the Roman Empire

Figure 135 Provinces of the Roman Empire.

<table>
<thead>
<tr>
<th>Name</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achaia</td>
<td>5.23</td>
</tr>
<tr>
<td>Aegyptus</td>
<td>1.93</td>
</tr>
<tr>
<td>Africa Proconsularis</td>
<td>2.43</td>
</tr>
<tr>
<td>Alpes Maritimae</td>
<td>0.05</td>
</tr>
<tr>
<td>Arabia</td>
<td>0.03</td>
</tr>
<tr>
<td>Asia</td>
<td>3.48</td>
</tr>
<tr>
<td>Baetica</td>
<td>0.32</td>
</tr>
<tr>
<td>Bithynia et Pontus</td>
<td>0.34</td>
</tr>
<tr>
<td>Cilicia</td>
<td>0.60</td>
</tr>
<tr>
<td>Creta et Cyrene</td>
<td>2.10</td>
</tr>
<tr>
<td>Cyprus</td>
<td>1.24</td>
</tr>
<tr>
<td>Dalmatia</td>
<td>1.83</td>
</tr>
<tr>
<td>Iudaea</td>
<td>0.16</td>
</tr>
<tr>
<td>Lycia et Pamphylia</td>
<td>0.48</td>
</tr>
<tr>
<td>Macedonia</td>
<td>0.98</td>
</tr>
<tr>
<td>Mauretania</td>
<td>0.82</td>
</tr>
<tr>
<td>Mauretania Caesariensis</td>
<td></td>
</tr>
<tr>
<td>Mauretania Tingitana</td>
<td>0.42</td>
</tr>
<tr>
<td>Narbonensis</td>
<td>0.75</td>
</tr>
<tr>
<td>Numidia</td>
<td>0.38</td>
</tr>
<tr>
<td>Sardinia et Corsica</td>
<td>4.36</td>
</tr>
<tr>
<td>Sicilia</td>
<td>3.39</td>
</tr>
<tr>
<td>Syria</td>
<td>0.61</td>
</tr>
<tr>
<td>Tarracconensis</td>
<td>2.19</td>
</tr>
<tr>
<td>Thracia</td>
<td>0.71</td>
</tr>
<tr>
<td>I</td>
<td>0.49</td>
</tr>
<tr>
<td>II</td>
<td>0.81</td>
</tr>
<tr>
<td>III</td>
<td>0.90</td>
</tr>
<tr>
<td>Roman Numeral</td>
<td>Value</td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
</tr>
<tr>
<td>IV</td>
<td>0.13</td>
</tr>
<tr>
<td>V</td>
<td>0.18</td>
</tr>
<tr>
<td>VI</td>
<td>0.07</td>
</tr>
<tr>
<td>VII</td>
<td>0.56</td>
</tr>
<tr>
<td>VIII</td>
<td>0.18</td>
</tr>
<tr>
<td>IX</td>
<td>0.27</td>
</tr>
<tr>
<td>X</td>
<td>0.47</td>
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</table>
Appendix 4 Divisions of the Roman Mediterranean

Figure 136 Divisions of the Roman Mediterranean (Hohlfelder, 2008:193).

<table>
<thead>
<tr>
<th>Sea no</th>
<th>Roman name</th>
<th>Sea no</th>
<th>Roman name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mare Ibericum</td>
<td>12</td>
<td>Mare Aegeum</td>
</tr>
<tr>
<td>2</td>
<td>Mare Balearicum</td>
<td>13</td>
<td>Mare Myrtoum</td>
</tr>
<tr>
<td>3</td>
<td>Mare Gallicum</td>
<td>14</td>
<td>Mare Icarium</td>
</tr>
<tr>
<td>4</td>
<td>Mare Ligusticum</td>
<td>15</td>
<td>Mare Creticum</td>
</tr>
<tr>
<td>5</td>
<td>Mare Sardoum</td>
<td>16</td>
<td>Mare Carpathicum</td>
</tr>
<tr>
<td>6</td>
<td>Mare Infernum</td>
<td>17</td>
<td>Mare Libycum</td>
</tr>
<tr>
<td>7</td>
<td>Mare Africum</td>
<td>18</td>
<td>Mare Aegyptiacum</td>
</tr>
<tr>
<td>8</td>
<td>Mare Adriticum</td>
<td>19</td>
<td>Mare Phoenicium</td>
</tr>
<tr>
<td>9</td>
<td>Mare Ionium</td>
<td>20</td>
<td>Mare Cyprium</td>
</tr>
<tr>
<td>10</td>
<td>Syrtae</td>
<td>21</td>
<td>Mare Pamphylum</td>
</tr>
<tr>
<td>11</td>
<td>Mare Thracicum</td>
<td>22</td>
<td>Pontus Euxinus</td>
</tr>
</tbody>
</table>
Appendix 5 Introduction to graph theory

Graph theory is a mathematical method for representing networks of objects. What the network represents depends on what is being modelled. In this thesis, it is used to represent different properties of transportation models, see Figure 137 and Figure 138.

Each dot represents a location, the presence of a line between two locations represents part of a journey. By analysing the properties of the network, it is possible to suggest the nature of a journey across the graph depending on what is being measured or identify controlling locations.

The following terms are used throughout this thesis.

Adjacency matrix: A representation of a graph as a matrix, with the columns/row pairs of the matrix indicating a connection between different vertexes.

Asymmetric edge: An edge where the cost of traversal is different according to which direction is taken.

Asymmetric network: A network populated with asymmetric connections.

Betweenness centrality: Is the fraction of shortest paths between all pairs of nodes in the graph. A node with a high value indicates a node which controls flow to other nodes (Freeman, 1978).

Centrality: A concept used to define how well a node is connected to other nodes in the same network.

Clique: A subgraph of a graph where every pair of nodes is connected by a connection; there may be 0 or more clique in a graph depending on the nature of the graph.

Closed path: A path in a directed network where the starting and end nodes are identical.
Closeness centrality: Is the inverse sum of the number of shortest paths between the node and every other connected node. It is a measure of how close a node is to all other nodes in the same graph.

Connect component: A subgraph of an undirected network where all nodes are linked together by one or more connections.

Connection: A linkage between a pair of nodes, the connect defines the nature of the relationship, see Figure 137 or Figure 138, where the links between the nodes represent connections.

Degree: Is the number of connections associated with a given node.

Degree centrality: is the total number of connections to a node compared to other nodes in the same network. This value normally reflects the ability of a node to access what concept is flowing through the graph., this would suggest that a node might be an administrative or storage centre (Freeman, 1978).

Dykstra path: The shortest tour between two supplied nodes.

Directed edge: An edge which implements one-way relationship: A Tour can only cross the connection in the direction of the relationship.

Directed network: A network populated with weighted connections see Figure 138, where all connections are single direction connections except the connection between nodes c and d.

Edge: See Connection.

Eigenvector centrality: Is a measure of how well a node is connected to other nodes with a high eigenvector connection value.

Graph: A set of nodes linked by 0 or more connections.

In degree: The total number of incoming connections associated with a given node in a directed graph.

Link: See the for a connection.

Isolated: A node which is not connected to any other node with a network, see Figure 137 or Figure 138 where node F is isolated.
K Dykstra path: A set of k paths, shortest tours through a network.

Network: See the entry for a graph.

Node: A defined point with a network, it may be connected to zero or other nodes.

Page Rank centrality: how many other nodes are connected to the current node in a directed graph, the higher the value indicates that other nodes consider this to be a well-connected node.

Path: A set of one or more linked connections.

Path length: The number of connections within a path.

Out-degree: The total number of outgoing connections associated with a given node in a directed graph.

Small world network: A graph where the shortest path between the different nodes increases slowly towards the total number of nodes in a network, see Easley and Kleinberg (2010:537)

Tour: A navigation across a network by crossing the individual connections between pairs of nodes, the tour may contain 1-n different connections. In Figure 138 the navigation between nodes a-d-c-e would be considered a tour.

Unconnected: See isolated.

Unweighted edge: A edge without an associated value.

Unweighted network: A graph constructed from unweighted edges.

Vertex: Also known as a node, see node.

Walk: See tour.

Weighted edge: An edge associated with a numerical value, its value is defined by the type of network.

Weighted network: A network constructed from a set of weighted edges.
Figure 137 Unweighted graph

Figure 138 Weighted graph
Figure 139 Comparison between spatial networks and Concept networks.
Appendix 6 The Beaufort wind scale

<table>
<thead>
<tr>
<th>Wind scale no</th>
<th>Wind speed (meters/second)</th>
<th>Sea action</th>
<th>Advice to Yachts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt;0.5</td>
<td>Calm</td>
<td>Smoke rises vertically. Sea like a mirror. You will need a paddle to get home.</td>
</tr>
<tr>
<td>1</td>
<td>0.5 - 1.5</td>
<td>Light air</td>
<td>The direction of wind shown by smoke drift, but not by wind vanes. Ripples like fish scales form on the sea. Just enough wind to fill the sails and get the boat moving.</td>
</tr>
<tr>
<td>2</td>
<td>1.6 - 3.3</td>
<td>Light breeze</td>
<td>Wind felt on face. Leaves rustle. Ordinary vane moved by wind. Small wavelets, still short but more pronounced. The start of pleasant sailing conditions. Excellent for novices</td>
</tr>
<tr>
<td>3</td>
<td>3.4 - 5.5</td>
<td>Gentle breeze</td>
<td>Leaves and small twigs in constant motion. Wind extends light flags. Large wavelets. Crests beginning to break. The crew should be able to sit up on the windward side.</td>
</tr>
<tr>
<td>4</td>
<td>5.5 - 7.9</td>
<td>Moderate breeze</td>
<td>Raises dust and loose paper. Small branches are moved. Small waves become longer. Fairly frequent white horses. The crew will need to sit right out to keep the boat upright. Capsizes possible. Novices should start heading back to the shore.</td>
</tr>
<tr>
<td>5</td>
<td>8 - 10.7</td>
<td>Fresh breeze</td>
<td>Small trees in leaf begin to sway. Crest wavelets form on inland waters. Moderate waves taking more</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind Speed (knots)</th>
<th>Conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8 - 13.8</td>
<td>Strong breeze</td>
<td>Large branches in motion. Umbrellas used with difficulty! Large waves begin to form. White foam crests are more extensive. Probably some spray. The very top levels of dinghy sailing ability become necessary as the wind approaches 25 knots. Many will be unable to handle the conditions and should stay on shore. Safety cover is vital.</td>
</tr>
<tr>
<td>13.9 - 17.1</td>
<td>Near gale</td>
<td>Whole trees in motion. Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. Absolute survival conditions for top-level dinghy sailors. Head straight for shore with rescue boat escort!</td>
</tr>
<tr>
<td>&gt;=17.2</td>
<td>Gales, storms and hurricanes</td>
<td>Winds of Force 8 and beyond are highly dangerous to dinghy sailors. Boats should not venture out in these conditions.</td>
</tr>
</tbody>
</table>
Appendix 7 Dijkstra’s Routing Algorithm

- \text{source} = \cup \text{source}_i,
- \text{target} = \cup \text{target}_i.

The weight direct graph, \( G_d(V, E) \), is defined by:

- the set of vertices \( V \)
  - \( V = \text{source} \cup \text{target} \cup \text{start}_i \cup \text{end}_i \)
- the set of edges \( E \)
  - \( E = \{(\text{source}_i, \text{target}_i, \text{cost}_i) \text{ when cost} > 0\} \)
  - \( E = \{(\text{source}_i, \text{target}_i, \text{cost}_i) \text{ when cost} > 0\} \cup \{(\text{target}_i, \text{source}_i, \text{reverse}_i, \text{cost}_i) \text{ when cost} > 0\} \text{ if reverse} \neq \text{cost} \)

Given:

- \( \text{start}_i \in V \) a starting vertex
- \( \text{end}_i \in V \) an ending vertex
- \( G(V, E) = (G_d(V, E) \}

Then:

- \( \pi = \{(\text{path}_i, \text{node}_i, \text{edge}_i, \text{cost}_i, \text{agg_cost}_i)\} \)

Where:

- \( \text{path}_i = i \)
- \( \text{path}_i = i \)
- \( \text{node}_i = \text{\text{node}_i} \in V \)
- \( \text{node}_i = \text{\text{start}_i} \)
- \( \text{node}_i = \text{\text{end}_i} \)
- \( \forall i \leq |\pi|, (\text{node}_i, \text{node}_{i-1}, \text{cost}_i) \in E \)
- \( \text{edge}_i = \text{min}(\text{\text{node}_i}, \text{\text{node}_{i-1}}, \text{\text{cost}_i}) \text{ when } i \neq |\pi| \)
- \( \text{edge}_i = -1 \text{ when } i = |\pi| \)
- \( \text{cost}_i = \text{\text{cost}_i}(\text{\text{node}_i}, \text{\text{node}_{i-1}}) \text{ when } i \leq |\pi| \)
- \( \text{agg_cost}_i = \sum_{j=1}^{i} \text{\text{cost}_j}(\text{\text{node}_j}, \text{\text{node}_{j-1}}) \text{ when } i \neq 1 \)

The algorithm returns the shortest path between \( \text{\text{start}_i} \) and \( \text{\text{end}_i} \) if it exists in terms of a list of paths.

- \( \text{path}_i \) indicates the position in the path of the node or edge.
- \( \text{cost} \) is the cost of the edge to be used to go to the next node.
- \( \text{agg\_cost} \) is the cost from the \( \text{\text{start}_i} \) up to the node.
- Where lower costs indicate faster travel.
Appendix 8 Problems encountered

The placement of the mesh used to calculate the distance factors proved most difficult to place; it had to be small enough to allow navigation around the day and night maps yet wide enough to void an excessive amount of machine calculation when generating the results. Normally a square mesh is used; this project used a triangular mesh to allow a better representation of routes and a lower value for the Manhattan distance between the mesh and the port location.

The naming conventions used in de Graauw (2013) provide difficult to read in some of the computer software packages used in the project, not all applications are 8bit clean yet in the end, the character set was reduced to 7 bit Ascii characters.

A large amount of time was invested in a vain attempt to create a machine learning CART tree model for classifying the ports against the known characterises of the ports identified (Arnaud, 2005); it was ultimately unsuccessful.

Several problems where encountered during the printing of this project, namely what appears to be a readable map image of a computer screen look different when printed, which has resulted in some difficult choices being made with colour ramps.
9. Introduction

This document includes maps and data sets that were not included in volume due to reasons of space and size.

The empty sections are present to ensure that the section numbers match the same headings found in volume 1

10. Supporting maps: Chapter 2

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11. Supporting maps: Chapter 3

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12. Supporting maps: Chapter 4

Figure 140 Prevailing wind systems for spring (author’s interpretation of data from MedAtlas).

Figure 141 Prevailing wind systems for autumn (author’s interpretation of data from MedAtlas).
Figure 142 Prevailing wind systems for winter (author’s interpretation of data from MedAtlas).
Figure 143 Portus spring Isotropic map.
Figure 144 Portus autumn Isotropic map.
Figure 145 Portus winter Isotropic map.
13. Support maps: Travel in the Roman Mediterranean environment

13.1 Introduction
This space intentionally left blank

13.2 Sailing at day and night
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13.3 The seasonal effect of wind and wave patterns on general trading zones
This section is blank
13.4 Wind strength patterns

Figure 146 Wind strengths in the spring sailing season

Figure 147 Wind strengths in the autumn sailing season
Support maps: Travel in the Roman Mediterranean environment

![Map of wind strengths in the winter sailing season.](image1)

**Figure 148** Wind strengths in the winter sailing season

13.5 Lee shore Winds

![Map of lee shore wind in the spring sailing season.](image2)

**Figure 149** Lee shore wind in the spring sailing season.
Figure 150 Lee shore winds in the autumn sailing season

Figure 151 Lee shore winds in the winter sailing season

13.6 Coastal/Tramping trading

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14. The affordance of travel – likely patterns of movement Supporting Maps

14.1 Introduction

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14.2 Network Model

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14.3 Port Centrality

14.3.1 Betweenness centrality

Figure 152 Spring betweenness centrality
The affordance of travel – likely patterns of movement Supporting Maps

Figure 153 Autumn betweenness centrality

Figure 154 Winter betweenness centrality
14.3.2 **Closeness centrality**

![Map showing Closeness Centrality](image)

**Figure 155 Spring closeness centrality**
Figure 156 Autumn closeness centrality
The affordance of travel – likely patterns of movement Supporting Maps

Figure 157 Winter closeness centrality
14.3.3 Eigenvector centrality

Figure 158 Page Spring eigenvector centrality
Figure 159 Autumn eigenvector centrality
Figure 160 Winter eigenvector centrality
14.3.4 Page Rank models

Figure 161 spring page rank centrality
Figure 162 Autumn Page Rank centrality
The affordance of travel – likely patterns of movement Supporting Maps

Figure 163 Winter page rank centrality
14.4 Port Catchment areas

Figure 164 Spring catchment areas
Figure 165 Spring reverse catchment areas
Figure 166 Autumn catchment area
The affordance of travel – likely patterns of movement Supporting Maps

Figure 167 Autumn reverse catchment areas
The affordance of travel – likely patterns of movement Supporting Maps

Figure 168 Winter catchment areas
The affordance of travel – likely patterns of movement Supporting Maps

Figure 169 Winter reverse catchment areas
14.5 Common Routes

Figure 170 Generic spring common sailing areas

Figure 171 Generic autumn common sailing areas
The affordance of travel – likely patterns of movement Supporting Maps

Figure 172 Generic winter common sailing areas

Figure 173 Long distance only spring common sailing areas
The affordance of travel – likely patterns of movement Supporting Maps

Figure 174 Long distance only autumn common sailing areas

Figure 175 Long distance only winter common sailing areas
14.6 Time Distorted Maps

Figure 176 Time distance map for the western end of Crete.
<table>
<thead>
<tr>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autumn</td>
<td>Winter</td>
</tr>
</tbody>
</table>

Figure 177 Time distance map for the eastern end of Crete
<table>
<thead>
<tr>
<th>Season</th>
<th>Map Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>Time distance map for the port of Portus</td>
</tr>
<tr>
<td>Summer</td>
<td>No generated results</td>
</tr>
<tr>
<td>Autumn</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td></td>
</tr>
</tbody>
</table>

Figure 178: Time distance map for the port of Portus
15. Implications for travel along a known axis of movement (between Alexandria and Portus)

Supporting Maps

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15.1 Introduction

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15.2 Direct routes between Alexandria and Portus

15.3 Avoiding areas

Figure 179 Area outline avoiding the Gulf of Sidra (shown as purple).
Implications for travel along a known axis of movement (between Alexandria and Portus) Supporting Maps
Implications for travel along a known axis of movement (between Alexandria and Portus) Supporting Maps

Figure 180 Area outline areas to avoid the Levant (shown in purple).

Figure 181 Outline area for avoiding the north coast of Africa (shown as purple).
Implications for travel along a known axis of movement (between Alexandria and Portus) Supporting Maps

Figure 182 Areas of the central Mediterranean to be avoided (shown in purple).

Figure 183 Areas of the central Mediterranean with a gap to be avoided (shown in purple).
16. Support maps: Chapter 8

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17. Project Software

The vast majority of the maps used in this thesis were generated by specific used of the pgRouting library, within a given context. For example, the catchment area figures were generated by calls to driving distance method and as such are undocumented. Several larger scale program were created and are included on the project cd along with an instance of the project database.

17.1 Mesh table generator

This program builds the data mesh used to calculate the individual wind angles at different points which is required by the pgRouting library.

The program has the following structure.

- Purge the existing route mesh database
- For every entry in the mesh table
  - For every season
    - Calculate the current position in the mesh table
      - Look up the current position in the wind tables and calculate cardioid as per section 4.2.6
    - Check wind angle and value to ensure it does not exceed the maximum values.
    - Write value to route table
  - End of season loop
- End of entry loop
17.2 Isochron generator

The Isochron generator program is used to calculate the isochron curves drawings and is coded as GUI application.

- Collect all parameter from the GUI(port location, number of generation, season etc).
- Check that the port and season values are valid.
- Calculate the initial location of the port.
- Generate the cardioid value as per section 4.2.6 and store as the initial shape value.
- For every requested Isochron generation
  - Create an empty list.
  - For every point on the current shape which is a sea location.
    - Generate a cardioid for the current point.
    - Add the cardioid to the list.
  - End point loop.
  - Merge the list in to the next generation of isochron shape.
  - Clip the shape to current sea areas.
  - Store the current shape as the current generation.
  - Reset the current shape to the stored shape.
- End isochron generation loop.
17.3 Route generator

The route generator program generates the routes in chapter 7.

This program is implemented as a finite state machine. A finite state machine is a software construct which can have a given number of different states. A change between different states results in an action occurring. An example of a finite state machine is a traffic light sequence used to control traffic at junction, the more complex the junction, the more elaborate the design of the state machine. The machine is always in a known state and may change state in accordance with its external inputs.

The machine has five different internal states to simulate possible ship movements, see Figure 184

The machine starts in state 'Init', the only message that can be accepted is 'select start port' which causes a state transaction to change to state 'Start',

The machine then accepts a message 'Another Port need', which forces a state transaction to 'visit port'.

The state 'Visit Port' can accept two messages, which either cause a transaction to the state 'End' or back to 'Visit Port'.

![Diagram of the state machine](image)

Figure 184 Internal states of the state machine
To process the message ‘Another Port needed’, any new location selected must be subject to the following rules.

6. It must not be a location that has already been visited
7. It must not appear on a list of ports to avoid.
8. Its location must be geographically nearer to the end location
9. The location must not lie in a restricted area.
10. In the event of two locations being discovered, the location that is nearest the destination and furthest from the starting point will be selected.

The software model starts with predefined start and end points; it calculates a series of route segments from a selection of known geographical locations. The software model navigates from the starting point and selects the next location which is furthest point away from the current point and is geographically nearest to the end. The selection of which point to use is calculated by an application of Dijkstra's shortest path algorithm,(see section 7). This location is subject to the following constraints:

- It must not be on the list of locations to avoid.
- The software model must not have calculated a route that passes through this location.
- The location must not be in a restricted area.
- If the location is the required ending point then the software model will terminate.

This methodology allows for the generation of multi segment routes which meet the requirements of this case study. It is possible for the software model to fail to generate a requested route, this is normally caused by an impossible set of user constraints.

A typical machine sequence would be
<table>
<thead>
<tr>
<th>Machine state</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>Init</td>
<td>Select start port</td>
</tr>
<tr>
<td>start</td>
<td>Another port needed</td>
</tr>
<tr>
<td>Visit port</td>
<td>Another port needed</td>
</tr>
<tr>
<td>Visit port</td>
<td>Another port needed</td>
</tr>
<tr>
<td>Stop</td>
<td>Reached end port</td>
</tr>
<tr>
<td>End</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

This sequence starts, visits two ports before reaching an end port.

The attached disk includes a full data dump of system database and program used in the construction of this thesis.
18. Project DVD

18.1 shape files

The included DVD includes two shape files that present a list of the project ports and copy of the route mesh data that was used with pgRouting toolkit.

18.1.1 Route.shp

This file includes details of route table required for pgRouting software in the following format.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>Length of this link</td>
</tr>
<tr>
<td>source</td>
<td>Source vertex</td>
</tr>
<tr>
<td>target</td>
<td>Target vertex</td>
</tr>
<tr>
<td>season_id</td>
<td>Season of this node</td>
</tr>
<tr>
<td></td>
<td>1=winter, 2=spring, 3=summer, 4=autumn</td>
</tr>
<tr>
<td>night_mode</td>
<td>Set if this link refers to a night mode</td>
</tr>
<tr>
<td>X1</td>
<td>x coordinate of source vertex</td>
</tr>
<tr>
<td>Y1</td>
<td>y coordinate of the source vertex</td>
</tr>
<tr>
<td>X2</td>
<td>x coordinate of target vertex</td>
</tr>
<tr>
<td>Y2</td>
<td>y coordinate of target vertex</td>
</tr>
<tr>
<td>to_cost</td>
<td>Cost of moving from source to target</td>
</tr>
<tr>
<td>reverse_cost</td>
<td>Cost of moving from target to source</td>
</tr>
<tr>
<td>end_node</td>
<td>Set if this a port node</td>
</tr>
<tr>
<td>Parent_port_id</td>
<td>Id off port if this is a source or target</td>
</tr>
<tr>
<td></td>
<td>refers to a port location</td>
</tr>
</tbody>
</table>

18.1.2 Ports.shp

This file includes location details for all of the port locations used in this thesis.

<table>
<thead>
<tr>
<th>field name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>port_type</td>
<td>Set to port if this a port of island if</td>
</tr>
<tr>
<td></td>
<td>this is an island</td>
</tr>
<tr>
<td>name</td>
<td>The name of the port</td>
</tr>
</tbody>
</table>