# Row your boat or walk your boat: A literary study on the hydrological issue of the water level difference between the rivers, Rhine and Meuse, at the construction of the canal of Corbulonis in the first century AD and its subsequent permanent solution.

Taal, Kim

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# Introduction

What is a canal? According to the Cambridge dictionary the definition for a canal is:

> "a long, thin stretch of water that is artificially made either for boats to travel along or for taking water from one area to another" (Cambridge dictionary).

The Romans are known for their ingenuity and capabilities in revamping, inventing and designing hydrological and infrastructural structures. This of course is too broad for anything concrete for this thesis, as such one specific topic will be discussed, namely the process and permanent solutions of bridging water level differences between rivers which might occur at a canal.

The canal of Corbulo, also known as the *Fossa Corbulonis*, is the waterway which will be central in this thesis. Situated in the Netherlands, South-Holland, see figure 1, the canal was built around the year 47 AD by the Roman commander Corbulo who was stationed at the *limes* of the Roman province of *Germania Inferior*. To keep his soldiers busy and away from trouble, among other reasons, he ordered them to dig the canal, which connects the rivers Rhine and Meuse (Tacitus, *Annales* 11: 20).


Fig 1. General location of the Canal of Corbulo (De Kort & Raczynski-Henk 2014, 54).

Another reason as to why the canal may have been dug comes in the form of water management. As Jansma (2020) forms the theory that the felling dates of the wood used in the construction of the canal coincides with a flood that took place in the year 49 AD (Jansma 2020, 17). Jansma then concludes that the canal may have been used as a drainage basin for future floods and to further improve the dominance of the Romans in the area (Jansma 2020, 17). Jansma is not alone in this opinion as the Roman author Cassius Dio also mentions the canal functioning as a preventive method for flooding of the rivers (Cassius Dio *Historia Romana* 60, 30, 6).

The canal consisted of both man- made and natural parts, however it is possible to determine in large parts the path which the canal followed. This is done through connecting various locations at which excavations have proven the existence of the canal, thus the route of the waterway is interpreted (De Bruin 2017, 105). The canal connected Naaldwijk in the south with the *castellum Matilo* in the North, which was situated near the modern town of Leiden, see figure 2. *Forum Hadriani*, a small Roman city, also intersected with the canal, which was located at the modern-day town of Voorburg, see figure 2. In the south the path of the canal is a bit more difficult to determine as two possibilities exist. Namely the canal went down towards the east leading to Naaldwijk, near the estuary of the river *Helinium*, where evidence for a possible naval station in this area contributes to this theory (De Bruin 2017, 103). While the other path that is considered, flows into the Gantel river to connect with the estuary of the Meuse, located more northern than the first option, see figure 2 (De Kort & Raczynski-Henk 2014, 65).

The canal itself is still too broad of a subject as many different questions can be asked surrounding the topic: ‘Why does the canal of Corbulo have two different possible pathways in the south?’, ‘Why was the canal only used for a short amount of time?’ or ‘why was the canal superimposed on an older canal?’, just to name a few. However, for the topic of the thesis a narrower research topic is used, namely the water level difference between the rivers Rhine and Meuse and the subsequent hydrological solution that must have accompanied this issue.

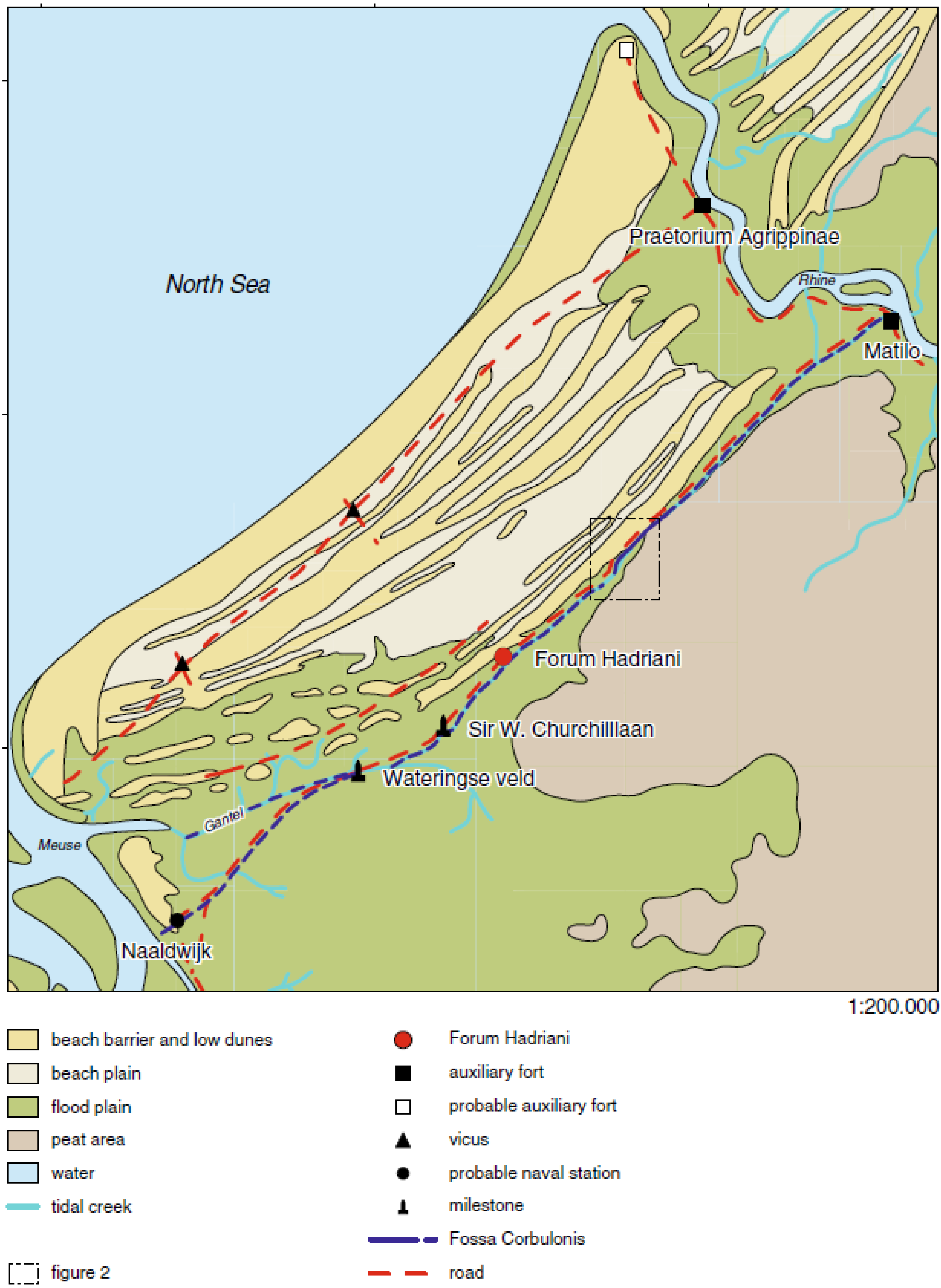


Fig 2. The general pathway of the canal of Corbulo (De Kort & Raczynski-Henk 2014, 66).

## 1.1 Previous Research

The canal of Corbulo has been excavated and has been subjected to other forms of archaeological researched multiple times during various excavations and other research related activities at different parts of the canal (De Kort & Raczynski-Henk 2014, 52). To give an indication, the canal was excavated in 1996 at the *castellum* of *Matilo* situated in Leiden but was also excavated more recently for example in 2006 at Leidschendam (Hazenberg & Polak 2000, 17; De Kort & Raczynski-Henk 2008). An overview of these locations can be seen in table 1, in which the locations, the depth and width of the canal of Corbulo are detailed. These are of course only a few examples as many other examples are available and some of those will be discussed in later chapters. Excavations on the canal itself are not the only research that has been done. As there is quite a variety of authors who have written on various topics about the canal of *Corbulonis* itself. Other works related to the canal are also very common: harbours associated with the canal, for example towns like the Roman city of *Forum Hadriani* (De Kort 2014; Driessen 2014;2018). However, for the topic of this thesis the canal of Corbulo itself is central, as stated previously.

| Number | Location | Depth | Width | Source |
|---|---|---|---|---|
| 1 | Leiden- Roomburg | 5-7m | 40 | Hazenberg 2000, 35 |
| 2 | Leidschendam-Versestraat 118 | 2 | 14,5 | Vos et al. 2007b, Appendix 1 |
| 3 | Leidschendam-Rietvink put 9 | Unknown | 13 | Hessing 1990, 342-343 |
| 4 | Leidschendam-Rietvinklaan 5 | 1,5 | 10 | De Kort & Raczynski-Henk 2008, 23 |
| 5 | Leidschendam-Rietvinklaan put 4 | 1,3 | 12 | Hessing 1990, 342-343 |
| 6 | Leidschendam-Rietvink proefsleuf | 0,8 | >2,75 | Hessing 1993B, 336-338 |
| 7 | Leidschendam-Rietvink put 10 | 1 | 4,6 | Hessing 1993B, 336-338 |
| 8 | Leidschendam-Rietvink put 11-II | 0,9 | >5,5 | Hessing 1993B, 336-338 |
| 9 | Leidschendam-Rietvink put 11-I | 1 | >5,8 | Hessing 1993B, 336-338 |
| 10 | Leidschendam-Rietvink put 7-I | 1,1 | 14 | Hessing 1992, 366-367 |
| 11 | Leidschendam-Rietvink put 7-II | 1,3 | 12,5 | Hessing 1992, 366-367 |
| 12 | Liedschendam-Rietvink put 5 | 1,2 | 12,5 | Hessing 1992, 366-367 |
| 13 | Leidschendam-Rietvink put 4 | 1,25 | >9,5 | Hessing 1992, 366-367 |
| 14 | Rijswijk-Churchilllaan | 1,3 | >4 | Dorenbos et al. 2009A, 23 |
| 15 | Kwintsheul | 1,5 | 1,5 | Klooster & Dorenbos 2002, image 6.1 |

Table 1 Table on the locations, depth and width of the canal of Corbulo at the know locations. After De Bruin 2017, table 3.10.

The aim of this thesis is to further expand the research on the topic of the canal of Corbulo, more specifically on the topic of the hydraulic component within the canal of Corbulo. To achieve this aim, this thesis will discuss various methods and techniques that are of use in answering the research questions. While also drawing upon ancient and modern texts and to provide an elaborate dataset from which information can be drawn. The techniques and datasets will be used to substantiate each other in order to answer the research questions. Other than that, this thesis will also aim to provide a comprehensive suggestion in the usability of the techniques discussed in this thesis for future research.

## 1.2 Thesis Outline

After this introductory chapter, the thesis will follow an outline in which the subsequent chapters will answer the sub-questions, as well as provide needed background information. The concluding chapter will focus on answering the main research question.

In the second chapter the research problems as well as the research questions will be outlined and explained. Other than that, the rivers Rhine and Meuse will be discussed in terms of their properties and their subsequent influence on the building and maintaining of the canal of Corbulo

The third chapter will discuss the methodological framework, a brief outline will be given on the literary background which will be discussed in later chapters and their usefulness. This chapter will also briefly discuss the theoretical chapter which follows this chapter and what this theoretical chapter is used for.

In the fourth chapter the theoretical framework will be discussed, this will focus on techniques that can be used to test the literary dataset that was created. This chapter will also give suggestions as to how these techniques might be of use for future research.

In the fifth chapter a literary background will provide much needed explanation to underline the previous chapters. While also providing a framework on which the subsequent chapters can built. At the start of this chapter ancient and modern authors are discussed to lay the groundwork of knowledge on canals. After which previous research surrounding on the canal of Corbulo will be discussed. The next part of the chapter will review different types of boats used in the general area. Lastly this chapter discuss different hydrological components which are known to have been used as a solution for water level differences within a canal.

In the sixth chapter a brief background on the previous excavations and the historical background of the canal is discussed. This will be reviewed in order to expand upon the previously discussed literary study of the research.

The seventh chapter will consist of a discussion based on the information gathered in the previous chapters. After which an outline of different possible solutions will be given.

Chapter eight gives a general guideline and suggestion for future research in regard to the canal of Corbulo and more specifically possible techniques that may be of use for examining the hydraulic mechanism.

In the last chapter, chapter nine, a conclusion will be drawn on the basis of the discussion from the previous chapter. At the same time suggestions for future research related to the research questions will be provided.

# Chapter 2: Research

## 2.1 Research Problems

Large parts of the canal remain unexcavated or undefined along its assumed route, this causes a lot of guess work and assumptions. While the parts that were excavated are of a very small scale and as such can only be used to interpret information at the local level (De Kort & Raczynski-Henk 2014, 52). De Kort and Raczynski-Henk (2014) mention the fact that the canal is only partially artificially made, as the canal also follows parts of natural waterways along its course, which also causes issues on data collection as this makes the canal even more difficult to identify (De Kort & Raczynski-Henk 2014, 52).

Although during previous excavations parts of the canal of Corbulo have been excavated from which data can be drawn, there is a noteworthy issue that remains underrepresented in the published papers. Namely the two rivers, Rhine and Meuse, have a different water level, how the hydrological issue of the difference in water level was resolved remains unknown. The presumed area in which the hydrological solution is assumed to be situated remains unexcavated (De Kort & Raczynski-Henk, 2014, 55). This area remains unexplored as local circumstances have in the past prevented excavation work to be done at the location of the presumed hydraulic element (De Kort & Raczynski-Henk 2014, 55). This causes some problems with the research, as circumstantial evidence is available, but no concrete evidence has yet been found to solve the issue at hand.

As such it is important to make a comprehensive outline of the available archaeological data in regards to the canal of Corbulo. More specifically with the focus on the data surrounding the location of the assumed hydrological structure. A good tool to substantiate this is by looking at other canals to gain a broader perspective, as this will give a good comparison tool to juxtapose technical aspects of hydrological engineering between the different canals. Through which a better understanding of the possibilities for the canal of Corbulo itself can be created.  Lastly it is also important to look at what types of boats have been found during excavations in the Roman province of *Germania Inferior*. A boat's size and weight would have had a direct impact on the types of hydraulic constructions that were built at a canal. As certain types of boats would not be suitable for specific hydraulic construction, a portage for example, would have made it difficult to transfer a flat-bottomed boat over the surface without the boat sustaining damage according to de Kort and Raczynski-Henk (De Kort & Raczynski-Henk 2014, 55).

## 2.2 The Rivers Rhine and Meuse

The rivers that connect the canal of Corbulo, the Rhine and the Meuse, are two different kinds of rivers in terms of their properties. The Rhine finds its origin in the Swiss Alps and ends its path in the

North Sea (Pfister *et al.* 2004, 230). Whereas the Meuse starts its course in France, more specifically the Ardennes, the Meuse ends its journey in the North Sea just as the Rhine does as previously stated (Pfister *et al*. 2004, 232). Both rivers have their delta flow through The Netherlands. In terms of property, the Rhine is a smelting and rainwater river, while on the other hand the Meuse is a rainwater river (Pfister *et al.* 2004, 230, 232). This means that the water level difference between the two different rivers differs throughout the year, seasonal changes play a big part in this. Rain falls throughout the year and as such the Meuse is much more balanced in terms of water volume that passes through the river's channels at any given point throughout the year (Pfister *et al.* 2004, 232). However, the Rhine has different peaks in its volume during the seasons, these peaks can vary in both location and season, smelting water is a key component of these fluctuations in water levels. For example, the upper Rhine is more likely to flood during the spring as smelting snow is a major driving factor in the increase of water levels during this season (Pfister *et al.* 2004, 230). Whereas the middle Rhine is more frequent to flood during the winter season (Pfister *et al.* 2004, 230). This means that the Rhine can vary in its water levels at different locations along its basin. The variation in seasonal flooding per region along the course of the Rhine is greatly influenced by local weather and precipitation (Pfister *et al.* 2004, 230). As such the fluctuating imbalance that this creates in the water levels between the two rivers, would have been one of the key components to pay attention to. Not only when building the canal of Corbulo, but also in its permanent bridging of the water level difference within the canal of Corbulo to maintain a steady water level within the canal itself. To bridge this discrepancy between the two water levels a hydraulic component must have existed, what this was however remains undetermined.

## 2.3 Research Questions

As there is an underrepresentation in research on the hydrological solution that bridges the water level difference between the two rivers that the canal of Corbulo connects, research questions are needed to answer this unsolved question. Through this a better understanding of the Roman capabilities in canal building in general can be generated. However, this thesis will solely focus on answer the research question:

> What kind of hydrological structure did the Romans incorporate in the construction of the canal of Corbulo in South-Holland, to permanently resolve the difference in water levels between the two rivers, Rhine and Meuse, in the first century AD?

To better answer this research question some more specific questions are needed to better answer the main research question. Three of these sub-questions will be used to underpin the main research question as well as provide a comprehensive dataset, with which the main research question can be best answered:

- What archaeological evidence is available for any kind of hydrological engineering to solve the difference in water levels between the rivers Rhine and Meuse in the canal of Corbulo?
- What type of hydrological solutions are known from other canals in an archaeological setting, both from earlier, contemporary and later canals?
- What kind of boats are known to have been used in the Roman province of *Germania Inferior*?
- What kind of techniques can be used during future research to help resolve the main research question?

The first sub question tries to get a better grasp on whether there is truly evidence for any kind of hydraulic component available concerning the canal of Corbulo. As a hydraulic component can be many different things, a portage, an artificial pond, a lock or a cofferdam are a few of the options just to name a few. As these possibilities each come with their own set of mechanisms it is important to outline the archaeological evidence from which hypothesises can be drawn.

The second sub question takes a closer look at other canals which used hydraulic elements to take care of water level differences. By outlining these solutions, a comparative framework can be made to draw information from to juxtapose the canal of Corbulo with the other canals. With this information a better overview of hydraulic element and their uses is created.

The third sub question tries to understand the variety of boats that were used in the Roman province of *Germania Inferior*. The types of boats that were used in this area are of importance to gain a better understanding of the scope of different types of boats with which the hydraulic element might have come in contact with and as such had to have been taken into account when building said hydraulic component. As previously stated, specific boat types would have been ill suited to for example be dragged over a portage as they would most likely have sustained damage to their bodies (De Kort & Raczynski-Henk 2014, 55). Of course, certain boat types don’t have to be looked at, as their dimensions are too big in comparison to the proportions of the canal of Corbulo and as such they will not be discussed at all.

Lastly the fourth sub question is aimed at future research and as such is not of any use to answer the main research question that is central in this thesis. However, it is still important to touch upon this subject as it will help to gain a better understanding of the possibilities in research techniques. As well as contribute to providing a frame of reference for future studies.

To answer the research question and sub questions this thesis will first look at specific archaeological methods that are best used to help answer these questions. After this more theoretical based research follows which will focus on various topics, which may be used to formulate new data in regard to the canal of Corbulo. Next a literary study will be done in which topics such as ancient authors, previous research and different canals are discussed. From this dataset an answer will be formulated to solve the research question and sub-questions. In addition to this a suggestion for future research will be added with the fourth sub research question at its core.

# Chapter 3: Methodology

This thesis is a desk-based research that aims to find an answer to the research question and sub questions through qualitative research. Within these studies the sub questions will also be answered which will be of usage to substantiate the main research question. Thus, by combining the data generated from both the theoretical and literary research a comprehensive dataset will be created which will be utilised to answer the research question.

## 3.1 Literature Study

Through a literary study a coherent assemblage of the known knowledge on the subject of the canal of Corbulo should become clear. This will substantiate an answer to the research question and sub questions. This will be done through the study of literary sources on the canal itself and on the general concept of canal building as well as on the more general topic of architecture during the Roman period, written by ancient authors. Through which a better understanding on the capabilities and knowledge of the Roman architecture can be achieved. At the same time information from modern authors who researched the architectural capabilities of ancient canal building projects are needed to gain better insights into the possibilities that may have been used for the canal of Corbulo. This will not only consist of data surrounding the canal of Corbulo itself but also on a broader scale with explanations on how the background research helps solve the research questions. It is however also of importance to analyse other data in addition to the aforementioned in regard to other canals. As a comparative dataset between different canals and their hydraulic components can be generated through this research. Which in turn will facilitate a better frame of reference to substantiate the answers that might be reached to conclude the research questions. It is of course impossible to answer the research question without first knowing various hydrological solutions that exist to bridge the difference in water levels in canals. Therefore, it is of importance to provide an outline on various different hydrological solutions, both from ancient and modern times. Furthermore it is worthwhile to look at the different types of boats that were used within the Roman province of *Germania Inferior* to create a general dataset, from which can be drawn to compare if the boat type that were known to be used within the general region would have been able to operate in accordance with the possible hydrological element of the canal. The dimensions of the boats also would put a limiting factor on what is viable in terms on hydraulic constructions as they would have had to fit through the said construction.

## 3.2 Testing the Literary Solutions Through a Theoretical Framework

The solutions offered in the literary chapters need to be tested for compatibility with the location of the canal and the canal itself. Besides that, it also needs to be tested whether the knowledge was already available to build the solutions provided in the literary study. To test these provided solutions a theoretical framework is needed, through which the provided data can be tested. The theoretical framework will provide possible tools to test the proposed hydrological solutions. This will be done by explain the Network Frame Model and dendrohydrological research. As this thesis is not broad enough to actually use these methods, they will only be described and explained as to how and why these techniques are of use in the evaluation of the dataset provided by the literary research. As such these techniques are suggestions which may be of use during future research.

# Chapter 4: Theoretical Framework

## 4.1 Network Friction Model

The network friction model, NFM, is a program based on GIS, Geographic Information System, created by Van Lanen (Van Lanen 2017). Van Lanen created the Network Friction Model to provide a new system that uses both archaeological data and environmental data to generate potential routes that might have been used during the late-Roman period (Van Lanen 2017, 30). As a lot of former roads, river channels and artificial water ways have become lost through time by means such as sedimentation and other natural and man-made phenomena it is often times difficult to identify such features as they are covered in modern sedimentation or have been deconstructed (Van Lanen 2017, 23). The Network Friction Model creates a means of identifying possible locations for these lost features. Van Lanen (2017) describes the use of the network friction model as follows:

"Network friction can be used to reconstruct possible routes from landscape factors, based on the assumption that routes in a large part are defined by the wish to evade major landscape obstacles (push factors)" (Van Lanen 2017, 40).

It is however important to note that the Network Friction Model is only a suggestion mentioned within this thesis, as the technical expertise required to operate and adjust this system to work for the canal of Corublo is not within the scope of this thesis. At the same time the operating systems and the exact settings used by van Lanen (2017) might need adjusting to fit the research question of this thesis, as such it is currently impossible to actually use the Network Friction Model and therefore merely remains a suggestion for future research. A MA-thesis might be more appropriate to conduct this specific research.

### *4.1.1 How is the Network Friction Model used*

As stated previously the Network Friction Model is based on a program called GIS. The Geographical information System is used in creating, manipulating and analysing all sorts of data by transferring the data to a map and thus creating a visual representation of the data (Conolly & Lake 2006, 11). Through these maps a better understanding of the data can be generated as the visualisation might bring to light relationships and patterns that might have been missed without said visualisation (Conolly & Lake 2006, 11). The Network Friction Model uses this basic concept of the program and further improves on it for its own purposes. Through the use of both spatial modelling and palaeogeographical environmental data the system evaluates the path of least resistance for possible movement corridors, see figure 3 (Van Lanen 2017, 29). The application of this program can be used for both terrestrial and aquatic movements (Van Lanen 2017, 29). Van Lanen (2017) explains that other research mostly focusses on the difference in elevation levels to generate possible traveling routes (Van Lanen 2017, 29). Van Lanen also explains about the limited usefulness of these programs when applied to The Netherlands, as very little difference in elevation levels occurs in the low-lying country (Van Lanen 2017, 30). Instead, the Network Model takes different things into account, when calibrating possible routes, such as rivers, mires and other factors that might influence the landscape, see figure 3 (Van Lanen 2017, 30). These are also factors that might have been of influence in the decisions making process of creating a road or canal in one location and not at another location. Besides landscape factors van Lanen also uses known and proven archaeological sites as input data to improve the accuracy of the probable routes generated by the NFM (Van Lanen 2017, 40). This however is only done after the landscape factors have already developed the most likely paths taken within the terrain, see figure 3 (Van Lanen 2017, 40).

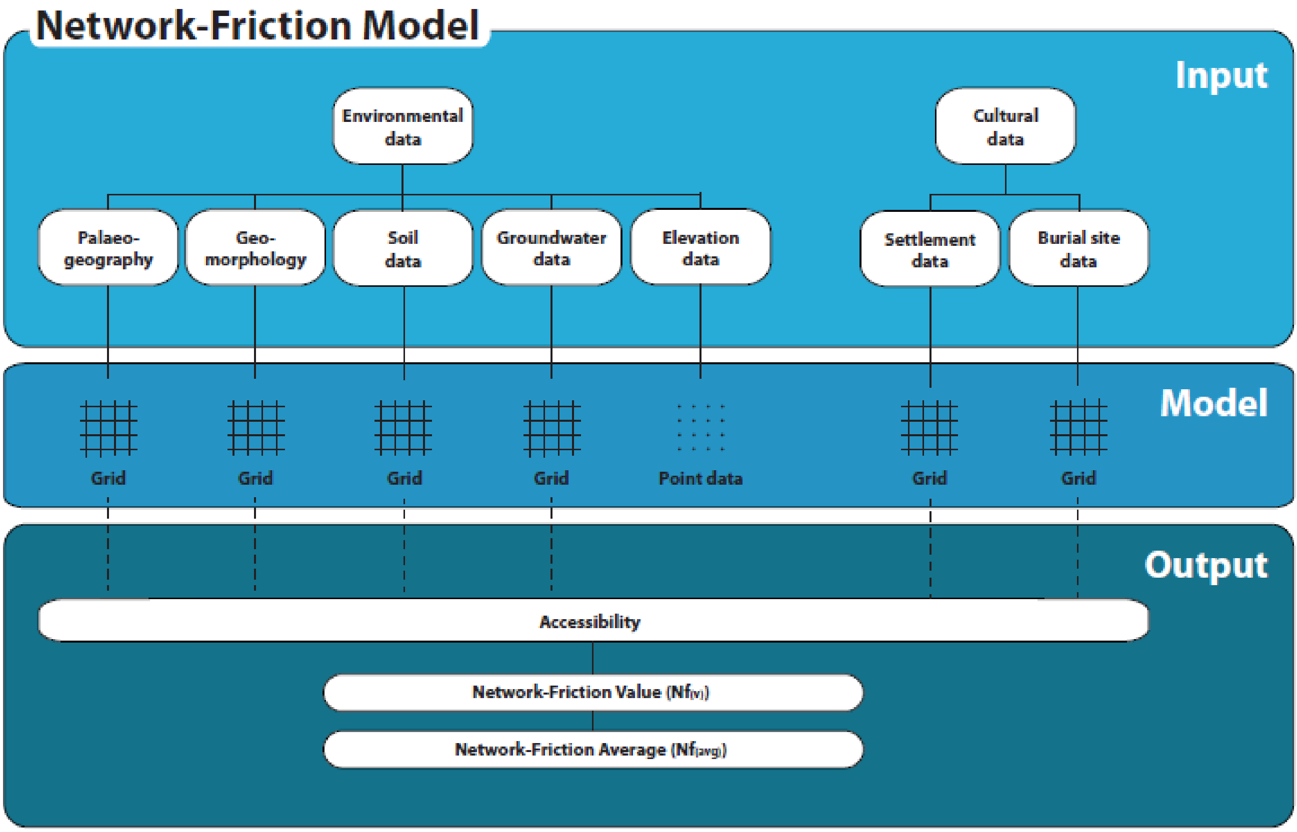


Fig 3. Structural outline of the NFM (van Lanen 2017, 37).

In other words, the archaeological data only enhances the landscape data, with which possible routes are then more accurately generated within the said landscape. What makes this model useful for this thesis is that the NFM can not only generate possible travel routes on land but also possible routes for water travels, see figure 4 and 5 (Van Lanen 2017, 39). These water maps also take into account hydraulic specific data, such as archaeological finds related to water, shipwrecks and settlements at the water frontier for example, see figures 4 and 5 (Van Lanen 2017, 65). It is however important to note that the data for the maps used in creating the NFM maps for water travel are derived from information on the situation of the waterways from 100 AD (Van Lanen 2017, 65). As such of the NFM water transport map is of a somewhat later time than the assumed date of construction for the canal of Corbulo, which is at around 47 AD. This is however a very small difference in terms of a time frame in which major changes within the landscape would be less likely to occur. These maps are highly useful since the canal of Corbulo remained in use until between 100 AD and 150 AD (De Kort 2013, 237). The NFM therefore can be a useful tool to use in a predictive framework to see how the waterway for the canal of Corbulo flowed and what natural channels they might have used.

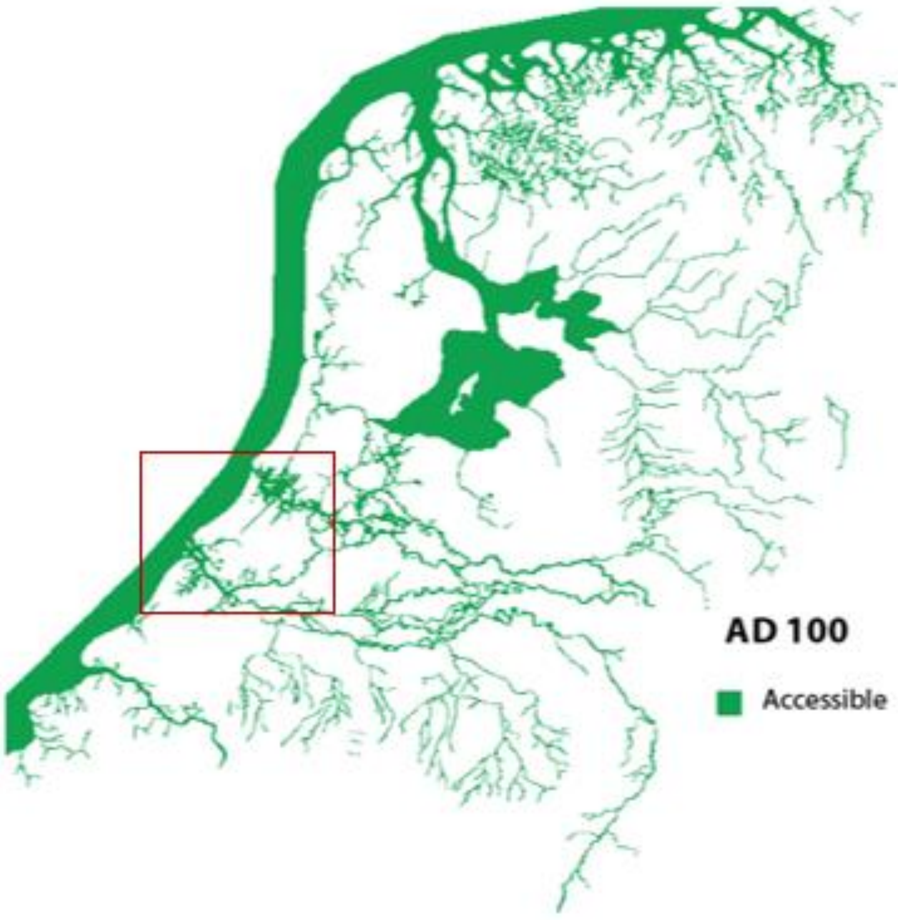


Fig 4. Map of the NFM for accessible water transport ways at 100 AD, with general location of the canal of Corbulo (van Lanen 2017, 44).

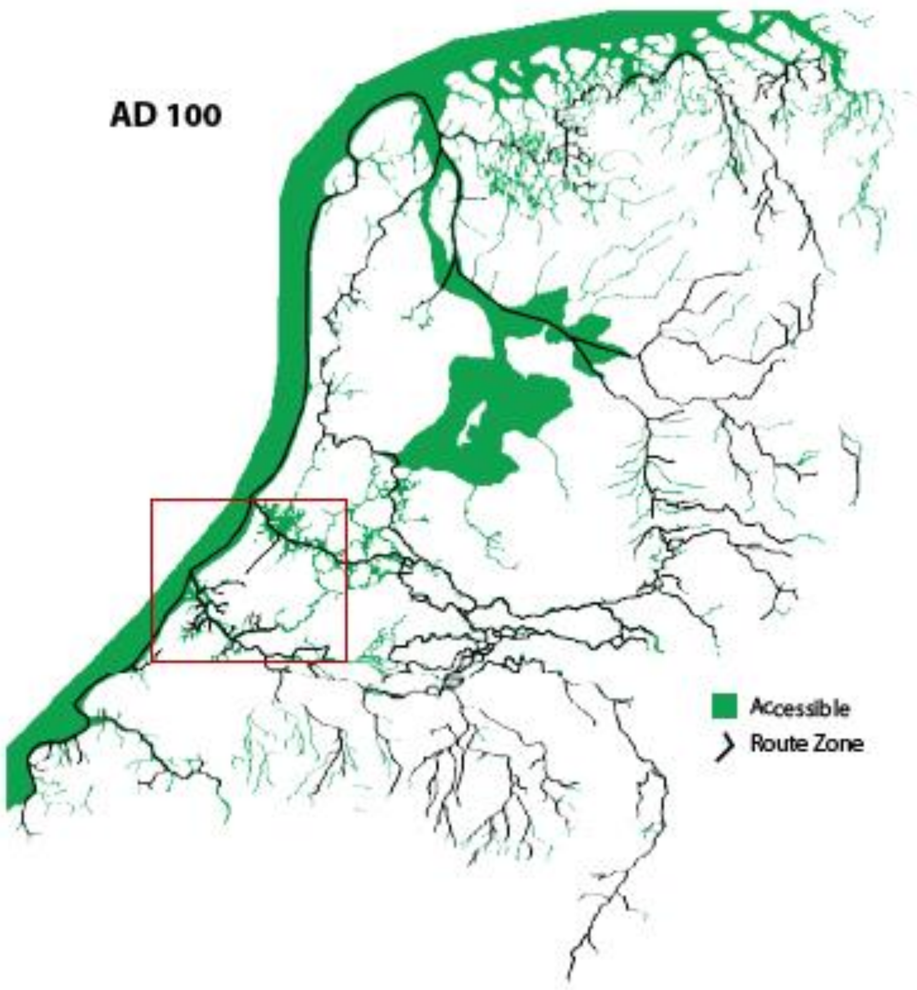


Fig 5. Map of the NFM for accessible water transport ways and routes at 100 AD, with general location of the canal of Corbulo (van Lanen 2017, 44).

### *4.1.2 Application of the Network friction model*

To apply the Network Friction Model to the canal of Corbulo, first a detailed map is needed of the natural water ways within the general area of the canal of Corbulo. Furthermore, the knowledge of the stratigraphy of the sediment is also needed. This as some sediments naturally repel water whereas others let water seep through, these water repelling properties are known to have played a role during the construction of the canal of Corbulo as they did not dig through the peat layer (De Kort 2013, 239). These landscape factors can be factored in when the Network Friction Model calculates possible routes on a regional level. After a calibrated route is created, known archaeological data that is associated with the canal of Corbulo can also be used as input data to further enhance the accuracy of the possible route.

As stated previously the Network Friction Model can be a good tool to help generate a possible route for the canal of Corbulo. As this predictive map may also highlight areas in which the hydraulic element of the canal might be located that human research might not have thought of. At the same time, it might indicate for example possible locations which were missed by human error which would have solved the issue of the water difference between the two rivers Rhine and Meuse through different means than for instance a portage, a cofferdam or an artificial lake. This however is to broad an application for this thesis and as such only remains as a possible means of research for future research. It is however still of importance to mention this method as the application of this model is very broad in terms of data generation with regards to the canal of Corbulo.

## 4.2 Dendrohydrological research

One way to look closer at the seasonal changes of the water levels in the surrounding landscape during the time period in which the canal of Corbulo was in use, is through dendrochronology. Jansma (2020) explains the analysis of water level differences through the usage of dendrochronology. By looking at the growth width of the year rings Jansma aims to showcase that flooding of the area has a direct impact in the growth of a tree which can be seen through the smaller growth in year rings of a tree (Jansma 2020, 3). The direct impact is caused through the fact that flooding bereaves the tree roots from gaining enough oxygen, destroys the soil structures and causes the built up of toxic gasses within trees (Jansma 2020, 3). All of these factors negatively impact the growth of a tree. Which can then be seen in the year rings of a tree, as the year rings are narrower, and can be seen on a cellular level as well, where the impacts of a flood can influence the early wood development and its vessels (Jansma 2020, 3). Jansma further explains that these negative impacts on the growth of the trees are not caused through local rainfalls, but by the higher situated basins of the Rhine and the Meuse (Jansma 2020, 13). It is however important to mention that this actually remains out of the scope of Jansma's article. As she goes on to explain that the actual event of a flood could have taken place at various points before or after the start of the growth phase of the tree rings and thus seasonal changes can currently not be derived from the dataset used by Jansma in her article (Jansma 2020, 15). Jansma (2020) however does give further instructions on how to improve the dataset so that the readings of the dendrohydrological database can be more accurate and can even be refined to seasonal analysis (Jansma 2020, 15).

This however remains an important tool that can be further developed to help analyse the difference in water levels between the rivers Rhine and Meuse. As precipitation and/ or smelt water levels of the Rhine and Meuse have to be taken into account while looking at the water level difference at the canal of Corbulo. By looking at the dendrochronology of the year rings of the trees from the surrounding landscape a dataset can be created through which an overview can be designed to track the seasonal general water levels of the surrounding landscape, both in terms of ground water levels and floods. This in turn can help in creating a better understanding of what a hydraulic component of the canal of Corbulo had to have been able to accommodate in terms of varying water levels throughout the seasons and year. By using this generated data an elimination of hydraulic components that do not fit the criteria can take place and thus further narrowing the research in terms of possibilities.

# Chapter 5: Literature Study

In this chapter ancient authors related to the topic of canal building or certain hydrological components connected to canals will be discussed. At the same time both ancient and modern authors who researched the canal of Corbulo or those topics directly related to the canal of Corbulo will be discussed as well. Other than these texts directly related to canal building, other ancient canals will be discussed as well to gain a broader perspective on canals and more specifically various solutions used in bridging water level differences within a canal. After which different types of boats will be touched upon to gain a better understanding on the types of boats that were used in the Roman province of *Germania Inferior.* Lastly different hydrological structures are discussed that are known to have been used in bridging water level differences in canals. This chapter aims to provide a methodological perspective on the literary sources to gain a better understanding of the research material.

## 5.1 Historical Background

### *5.1.1 Ancient Authors*

Of the many Roman authors only four will be discussed below, first of is the most widely known Roman author in regard to architecture, Vitruvius. He wrote the "The Ten Books on Architecture". While this book mentions all kinds of aspects within the broad subject of architecture, the focus within this thesis will be on the topic of water within the writing of Vitruvius. An interesting part to touch upon within the book is the process of creating cofferdams within waterways from which larger dry areas can be achieved (Vitruvius *De Architectura* 5, 12). Vitruvius gives two different detailed explanations on how to build a cofferdam in his book, the first focusses on a direct building of a cofferdam, whereas the second possibility takes into account a current that is too strong to build a direct cofferdam and thus first makes use of a platform from which the cofferdam is build (Vitruvius *De Architectura* 5, 12). Vitruvius goes on to mention that when the cofferdams floor must be dry or made dry "in order to make a strong foundation on which ultimately even a tower can be build" (Vitruvius *De Architectura* 5, 12). In the writing of Vitruvius, a cofferdam is mentioned in relation to a shipyard, however perhaps other uses for a cofferdam were also a possibility, which will be further discussed in the next chapter.

Another author who is well known for his writings on the architectural topics in the Roman world is Sextus Julius Frontinus, or more commonly referred to as Frontinus. A general under the emperor Domitian, but also a civil engineer and author of a few texts, he wrote the "*De Aquis Urbis Romae*" a text on the aqueducts of Rome, which also includes the topic of channels, which in turn have detailed descriptions, including the architectural components (Frontinus *De Aquis Urbis Romae*).

The problem however with these architectural components is that it is mostly a summary of the channels themselves, their location and the amount of water they discharge (Frontinus *De Aquis Urbis Romae* 1). These descriptions are unfortunately impossible to use as a point of reference for the building of the canal of Corbulo itself, however these descriptions still remain useful as they can give insights in more general hydraulic methods and techniques known and used by Roman engineers. On the subject of hydraulic architectural constructions itself Frontinus mentions very little and if anything is mentioned it is mostly in a historical and or juridical context. On the topic of canal building itself very little to no mention is made by either Vitruvius or Frontinus, owing to this very little can be said about the knowledge on canal building by literary accounts of the Roman writers discussed above. However due to the other topics that can be related to canal building assumptions can still be made.

Publius Cornelius Tacitus or Tacitus for short, is one of the two only authors who wrote on the topic of general Corbulo and his canal, however even this text is very limited in regard to the information. As Tacitus mostly writes about the general circumstances on how the canal came to be and the historical events surrounding the occupation of the area (Tacitus *Annales* 11, 18-20). The text of Tacitus is however significant in that it mentions where the canal is located: between the rivers Rhine and Meuse, and he also mentions how long the canal is 34,5 kilometres (Tacitus *Annales* 11, 20). Unfortunately, this means that although the text itself is informative, it is not informative on the hydrological components of the canal and cannot be used to further the research.

Lucius Cassius Dio is the other author who mentions Corbulo in his writing, however like Tacitus he is more focussed on the historical aspects of Corbulo than on the canal itself. The texts are quite similar on the theme of the canal and its surrounding story, despite that there is a significant difference between the texts as Casius Dio mentions that the canal was built:

> "in order to keep the rivers from flowing back and causing flooding due to tidal activities of the sea" (Cassius Dio, *Historia Romana* 60, 30,6).

Whereas Tacitus mentions:

> "thus making it possible to evade the hazards of the North Sea" (Tacitus *Annales* 11: 20).

Which of the two texts is correct is impossible to judge, or perhaps both are right, however that would be speculation, the importance of these texts lies within their similarity which strengthens the overall credibility of both texts.

Lastly a brief overview of the Greek writer Herodotus, he wrote the histories, in it he mentions the building of a canal by the Persian king Xerxes (Herodotus *Historíai* 7: 23-24).

The most interesting part about his description of the building of this canal however is that he partly describes how this canal was dug, which can be used as an indicator on the knowledge of canal building itself (Herodotus *Historíai* 7: 23). Although the information in this book is much older than the Roman writers it is still something that can be used as a benchmark of knowledge in hydraulic engineering. In this text a dry-dock which could separate the dock from the water and keep it dry while having a mechanism to open it up to the water when needed is also mentioned (Herodotus *Historíai* 7: 22). There is also a mention of a mechanism of pumping the water out when so desirable (Herodotus Historíai 7: 22). This does make the possible to hypothesise that the knowledge for a pound-lock was within their capabilities, although no physical archaeological evidence is currently at hand.

### *5.1.2 Modern Authors on Roman Hydraulic Engineering*

An author who also outlines the history or lack thereof, of several canals, both those of the Roman world and beyond is Wikander (2000). The author highlights the fact that very little ancient texts touch upon the notion of canal building besides a brief mention of the canal itself (Wikander 2000, 330). This however is an issue not only ancient authors partook in, but modern authors also seem to be of the same mind, which makes the research of canals and the hydraulic structures surrounding canals limited (Wikander 2000, 321). Despite this the outline on the canals that Wikander mentions in her article are of great use in a referential framework. Throughout her article Wikander refers to several canals that were built by the Romans and even some canals that predate the Roman Empire, such as the Athos canal, which is also mentioned in an ancient text by Herodotus (Herodotus *Historíai* 7: 22; Wikander 2000, 328-329). Especially the discussion on this text helped with researching the ancient author Herodotus, who has previously been discussed.

## 5.2 Previous Archaeological Research Surrounding the Canal of Corbulo

As previously stated, the Roman city of *Forum Hadriani*, located in modern day Voorburg, is connected to the canal of Corbulo. However how this connection between the harbour and the canal exactly functioned remains unclear as limitations in the size and location of the excavation trenches plus the position of current buildings prevented to uncover this (Driessen 2018, 444). This connection is through the harbour at the Roman town, the harbour however is significantly younger than the canal itself, as the age for the oldest part of the harbour is from a post with a dendrochronological date of circa 160 AD (Driessen 2018, 446). Whether this is also the oldest date of usage is more difficult to ascertain, as the building phase around 160 AD of the harbour would most likely have destroyed any evidence for an older phase during this process (Driessen 2018, 446). This is further emphasised, as proof for dredging within the harbour during this building phase has been established, through the dredging evidence for older layers could have been removed, making it impossible to know for certain (Driessen 2014, 99).

Which means that it cannot be excluded that an older phase of the harbour might have existed. But if we stick to the date of 160 AD, it makes the canal over a hundred years older, the canal was built around the year 47 AD (De Kort & Raczynski-Henk 2014, 63). It is interesting to note that parts of the canal of Corublo were already out of use by 100 – 150 AD (De Kort 2013, 237). The Roman city of *Forum Hadriani* was first excavated in the 19th century by Caspar Reuvens and has since been excavated on multiple times by others (Driessen 2018 ,444). What makes the relation between the harbour of the Roman city of *Forum Hadriani* and the canal of Corbulo of importance to note on separately is the difference in water level depth between the two. As the harbour has a depth of between 1.80 m and 2.10 m below NAP (Normaal Amsterdams Peil), whereas the canal of Corbulo has an average depth that is deeper than that of the harbour at the Roman city of *Forum Hadriani* (Driessen 2018, 447; De Kort & Raczynski-Henk 2014, 61). The depth of the northern part of the canal of Corbulo is between 2.2 m and 3.5 m below NAP (De Kort & Raczynski-Henk 2014, 61). While in contrast when looking at the more southern part of the canal of Corbulo, the water levels seem to lessen in depth, see table 1 (De Bruin 2017, 106). Which would then be closer to the water levels at the harbour of Voorburg, which is between 1,8m and 2,10m below NAP (Driessen 2014, 99). However, there is still a slight difference in water levels as the NAP at the excavation at Leidschendam trench 4 and 5 are respectively 2,2m and 2,3m below NAP, whereas the harbour at Voorburg at its deepest level is at 2,1m below NAP (Driessen 2014, 99). Because of the discrepancy between the NAP levels between the harbour and the canal a hydrological solution must have been used to make up for this difference in water level. Or perhaps something else was done to solve this issue, nevertheless this problem remains unsolved because of the unexcavated part of the harbour that connected to the canal of Corbulo (Driessen 2018, 444). It is however also a possibility that the canal of Corbulo had a branch through which the harbour at Voorburg could be reached or it may have been a completely different canal altogether which was linked to the harbour. The possibility for a branch is further emphasised as de Bruin talks about a man-made trench in his PhD thesis (De Bruin 2017, 102). This trench finds its origin in a branch of the Gantel river in which the harbour of the Roman city of the *Forum Hadriani* is located, however this connection is dated to the construction phase at approximately 160 AD (De Bruin 2017, 102; Driessen 2014, 125). As the canal of Corbulo finds its origin at around 47AD, it is impossible to just assume that these circumstances also apply to the older connection between the harbour at Voorburg and the canal of Corbulo. As such it is important to keep a hydrological solution in mind for the water level difference between the harbour and the canal. There is a large amount of data that substantiates the usage of the harbour at the Roman city of *Forum Hadriani* as a transhipment harbour (Driessen 2018, 451). What this entails can be various things, it could mean that the shipments were transferred to smaller boats for inland navigation along the rivers, or larger boats to continue on their journey across for example the North Sea to *Britannia*, or the shipments could have continued their travels by land. One thing can be deduced through the connection between the harbour and the canal, the canal was used to transport good across the region but also the wider area. This is also supported by archaeological evidence found during excavations of the harbour as pottery has been found that connects both the local area and the Roman province of *Britannia* (Driessen 2018, 451). All of this data combined makes the harbour at Voorburg a good point of reference to take into account when thinking about the hydrological issue of the difference in water levels within the canal of Corbulo itself as the issues are somewhat alike.

## 5.3 Other Canals

While the use of literary sources is a great start, it fails to create a large enough data set to work with in order to answer the research question:

> "What kind of hydrological structure did the Romans incorporate in the construction of the canal of Corbulo in South-Holland, to permanently resolve the difference in water levels between the two rivers, Rhine and Meuse, in the first century AD?"

As such as mentioned before a comparative framework with other canals will be discussed below in order for a large enough data set to be created from which answers can be derived.

### *5.3.1 Fossa Carolina*

The *fossa Carolina* is a younger canal compared to the canal of Corbulo, as it was built in 792-793 AD by the orders of king Charlemagne and is located in Germany (Werther *et al*. 2020, 464). The canal was an attempt to connect the rivers Swabian Rezat and the Altmühl, which are catchments of the rivers Rhine and Danube, whether this succeeded or not is a contested issue, see figure 6 (Kirchner *et al*. 2018, 3-4). For this thesis however, the hydrological engineering component of the canal is of importance. As the two rivers also had a water level difference, just like the canal of Corbulo, a hydrological solution to solve this issue was needed, several options are put forward by various authors. However, the two most important options: a continuous canal or a canal that is interrupted at various points along its course by artificial ponds (Leitholdt *et al*. 2012, 93). This however would mean that the boats would have had to have been transferred to the next pond or in other words be removed from each pond and moved to the next one by land (Leitholdt *et al*. 2012, 93). This would have been a physically intensive process and would have required a lot of resources to do (Leitholdt *et al*. 2012, 93). It is the latter for which evidence is available, in the research of Zielhofer *et al*. (2014). In very broad terms they used grain-size analysis and stratigraphy analysis to determine the disturbances in the stratigraphical layers, which in turn proves the construction of ponds, watersheds, during the Carolingian and in later periods (Zielhofer *et al.* 2014, 16).

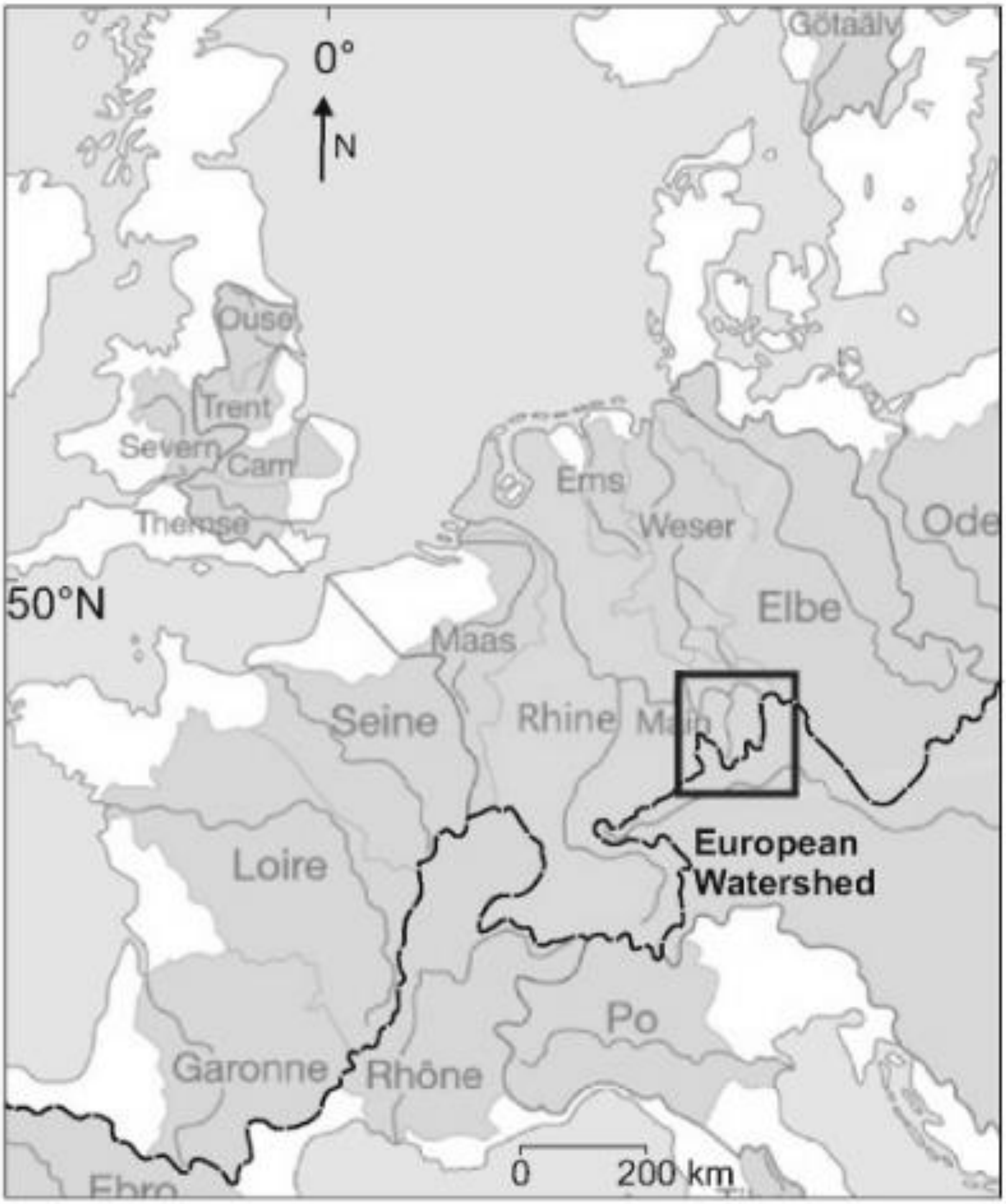


Fig. 6 General location of the *Fossa Carolina* (Zielhofer *et al*. 2014, 2).

## 5.4 Boats

As the canal had specific dimensions, it is important to spend a small part of this thesis to mention some the known boats used in the general area, as this will give indications on different possibility of what is and is not possible in regards to the hydrological possibilities as the dimensions of the canal and boats create limiting factors on the hydraulic element that could have been used for the canal of Corbulo.

#### *5.4.1. River Barges: Flatboats*

Flatboats were designed to navigate the relatively quiet rivers and not suitable for open sea faring (Moeyes 2007, 152). They were constructed to be long and fairly flat in depth and flexible which made them ideal boats for usage along the rivers in the province of Germania Inferior, for which they were most like specifically built (Moeyes 2007, 152). As the water levels change a lot during the different seasons along the rivers the boats with their shallow depth were ideal modes of transport (Moeyes 2007,152-153). A great example of river barges comes from the excavations at Utrecht they're called De Meern 1 and De Meern 4 (Jansma *et al*. 2014, 484). De Meern 1 has a length of about 24.6 metres and its width is 2.7 m at its widest point, see figure 7 (Morel *et al*. 2007, 101).

Fig. 7 General depiction of De Meern 1 in situ (Morel *et al*. 2007, 123).

Through dendrochronolgy a felling data of circa 148 AD was produced for the wood used in De Meern 1, De Meern 4 had a felling date of around 100 AD (Jansma *et al*. 2014, 484). This puts all of the barges within the time frame of when the canal of Corbulo was in use. Another piece of evidence for this is the fact that these barges were not suited for seafaring, this because the ships do not posses a keel and as such would have had to travel through inland water ways, and their construction and dimensions do not allow to venture the interwave lenghts of the North Sea (Jansma *et al*. 2014, 493; Driessen 2014, 452 ). The De Meern 1 barge, and perhaps the other two barges as well, was most likely specifically built just for the transport within the Rhine area (Moeyes 2007, 152). De Meern 4 is quite similar to the barge of the De Meern 1 barge and only differs in certain building techniques (Jansma *et al*. 2014, 484). These are of course not the only barges found, the research on the flatboats for example, first started with Zwammerdamsee figure 8, De Weerd (1988) discusses the barges type Zwammerdam in his PhD and their differences with other types of barges that existed before and contemporary to the type Zwammerdam (de Weerd 1988). De Weerd (1988) is the primary source from which all other subsequent research on barges within the region is based. Driessen (2018) gives a great overview of the different location at which Roman boats have been discovered within the Rhine-Meuse delta, see figure 8 (Driessen 2018, 438).

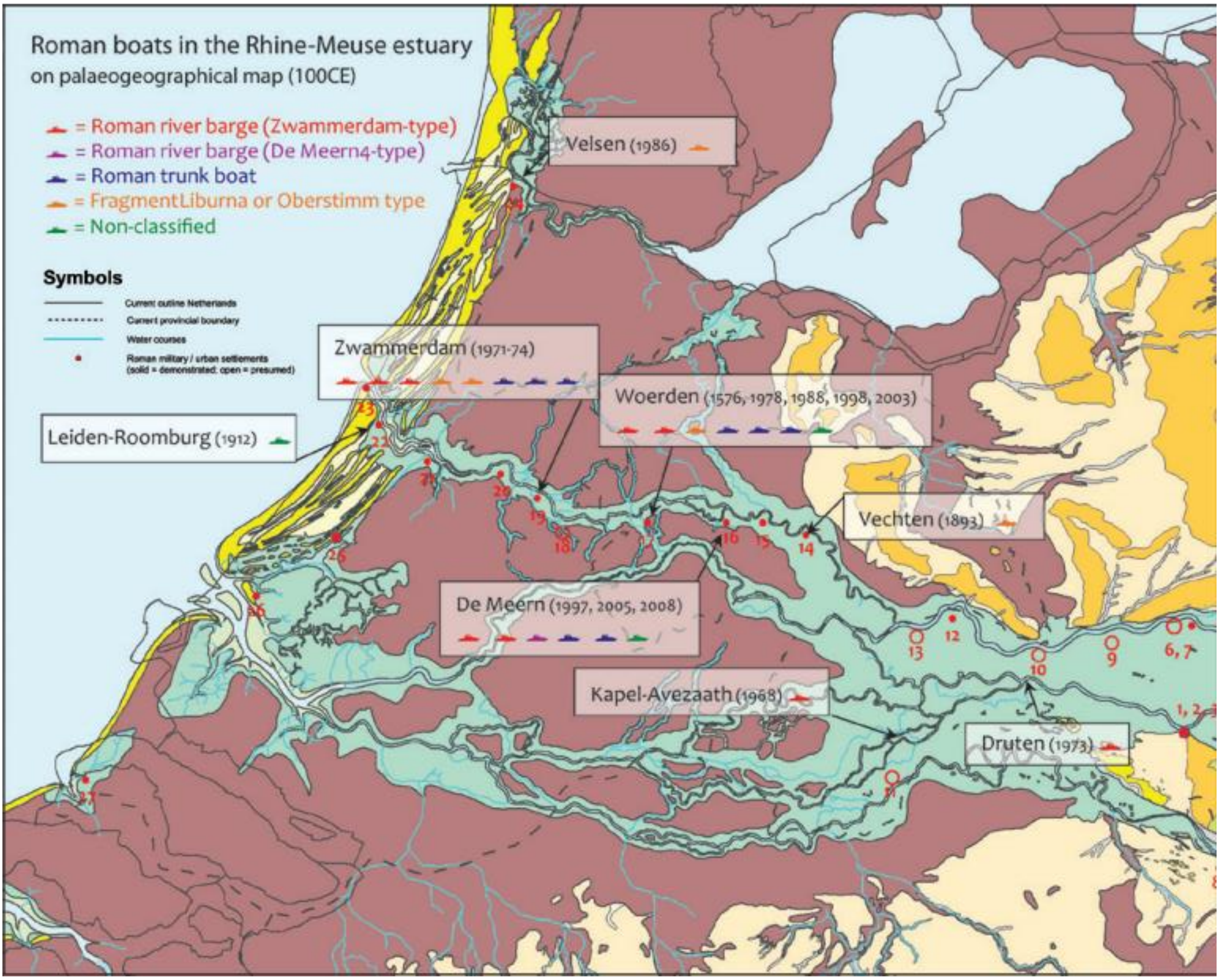


Fig. 8 Overview of archaeological finds related to Roman boats (Driessen 2018, 440).

### *5.4.2 Punts*

While the De Meern 6, is also from the direct area of Utrecht, the ship itself is of a different typology (Jansma *et al*. 2014, 484). Athough not much wood remains for this ship that can be used for dendrochronology one piece of wood did qualify, it had a felling date of later than 158 AD (Jansma *et al*. 2014, 484-485). Whereas the flatboats are known to be of specific use within the Roman province of Germania Inferior, punts are known to have been used in the Mediterranean world itself and as such are not only of local usage (Dallmeijer & Morel 2012, 10). Through reconstructions it is estimated that the De Meern 6 was about 9.25 metres long and is as such a lot smaller than the flatboat barches (Dallmejier & Morel 2012 ,224; de Weerd 1988).

### *5.4.3 Seafaring Ships*

Besides river barges and punts, that were specifically constructed for the meandering and anatomising rivers, seafaring ships were also in use within the region of *Germania Inferior*. An example of this are galleys, evidence for the usage of these types of ships was found at the excavation of Velsen (Driessen 2014, 214; 2018, 442). Driessen (2014) also mentions the coaster Blackfriars, which was excavated in city of London, in its Roman harbour, Driessen goes on to explain that the dimensions of this harbour are comparable to those of Velsen (Driessen 2014, 224). This then leads to the theory that the same type of dimensions on a ship that can enter in the Roman harbour of London, could fit into the harbour of Velsen. The Blackfriars was reconstructed with the following dimensions as a suggestion; 18.5 metres in length, a width of 6.5 metres and a depth of about 1 metre (Marsden 1994 ,76; Driessen 2018, 452).

## 5.5 Hydrological Elements

As there are many different solutions in regard to the bridging of the difference in water level between the rivers Rhine and Meuse in the canal of Corbulo a brief outline of several possible solutions is given below. This is done in order to make sure all technological aspects are understood. These possible solutions will be drawn from both ancient authors who described ancient techniques and modern techniques used today.

### *5.5.1 A Portage*

A portage is a piece of land between two bodies of water over which one can carry a boat and or goods to reach the other body of water after which they can continue their travels via water. Portages can be man-made or naturally occurring, however it is known that the man-made versions were already in use during the Roman period and prior to that in the Greek world, a good example for this is the portage in Corinth (Pettegrew 2014, 127). The portage in Corinth, or the *diolkos* of Corinth is a good example of this from ancient times. The portage was used to either transfer ships themselves or their wares across its path (Pettegrew 2014, 128). This portage was located in ancient Greece and runs across the strait of the Isthmus (Pettegrew 2014, 127). The earliest known texts that refer to this portage date from the fifth century BC (Pettegrew 2011, 549). Portages can be made through different means, for example the portage in Corinth is made of a limestone pavement (Pettegrew 2014, 127). The Network Friction model would be a good technique to test a possible location for a portage. By using the known archaeological locations of the canal of Corbulo and combining these with the landscape data of the region the most probable location for such a structure might be achieved.

### *5.5.2 An (Artificial) Pond*

Ponds can be both natural and men made, in the case of the canal of Corbulo this could be an artificial pond or a natural pond as the canal was surrounded by a lot of natural water ways. In the case of an artificial pond this entails that at the end of part of the canal an artificial pond would have been created to prevent the clash of different water levels. A possible example is the *fossa* Caroline, which is discussed in paragraph 5.3.1 (Leitholdt *et al*. 2012, 93). If this solution was like that of the *fossa* Carline it can be associated with a portage as in practise the solution to bridge the water level difference ends up doing the same thing, that is transporting the vessel from one body of water to the other body of water by land, which is the description of a portage as it defined in the previous heading. However, if the pond whether artificial or natural connected the two water ways directly no such need would have been needed of transferring the vessel from one body of water to the other by land. The Network Friction Model would be a great way of testing possible locations for such a possible pond. As all of the natural water ways can be taken into account through this model a calibration can be done on the suitability of all the known natural ponds, lakes and other such water bodies directly or closely linked to the canal of Corbulo. At the same time if an artificial pond was created the Network Friction Model can take into account possible locations through environmental data and the known archaeological finds to determine the most likely location (Van Lanen 2017, 40).

### *5.5.3 A Cofferdam*

A cofferdam is a watertight space built within a body of water which has been pumped dry, this is usually used during constructions like building sites in and surrounding the water. The concept of building a cofferdam is mentioned in the texts of Vitruvius as previously mentioned in paragraph 5.1.1 he gives details and advice on two different techniques on building a cofferdam.

The first technique as Vitruvius describes begins with the area in question first being quartered of with wooden beams tied together after which the area is levelled and drained of its water (Vitruvius *De Architectura* 5, 12). Once all of this is done a mixture of concrete is used to fill up the drained space to create a reinforced space (Vitruvius *De Architectura* 5, 12). The other technique has a similar approach but differs in the aspect of the cofferdam beginning at the edge of the water and step by step encroaching further into the water, this second technique Vitruvius recommends for water that is too rough for direct building (Vitruvius *De Architectura* 5, 12). However, if a cofferdam was used this would mean that it was probably constructed in an already existing body of water and as such might be in a location that has as of yet not been thought of. As if it was not built within a body of water this would in essence be a portage and as such is less likely. Once again, the Network

Friction Model might offer a solution in terms of finding a suitable location for this structure and whether this structure was even suitable for the canal of Corbulo.

#### *5.5.4 A Barrage or Dam*

A dam can be both natural or artificial way of preventing water from flowing its natural course and is usually stored in a manmade lake, a dam in essence controls the amount of water being allowed to flow through at any given time. A natural example of a dam is for example a beaver dam. However, for this thesis the focus will be on man-made dams. Quite a few dams are known from around the Roman world, one of those is the dam of Drusus, which is also located within the Roman province of *Germania Inferior* (Verhagen 2022, 40). Although no archaeological evidence remains of this dam, it has been described by multiple authors (Verhagen 2022, 40). However, some evidence does remain in the form of an epigraph on a tombstone as this tombstone mentions *Carvium ad molem,* this also substantiates the fact that a dam must have exited (Heeren & Driessen 2022, 29-30). Tacitus is an ancient author who mentions the dam of Drusus in his works (Tacitus, *Annales* 13, 53; Tacitus *Historiae* 5, 19). Verhagen (2022) explains that two different words are used within the texts of Tacitus for the dam of Drusus, namely agger in the *Annales* and moles in the *Historiae*, which creates a subtle difference in meaning of the sort of dam (Verhagen 2022, 40-41). Verhagen (2022) goes on to explain that however most modern researchers have come to the general consensus that these two words refer to the same dam (Verhagen 2022, 41). De Kort & Raczynski-Henk (2014) also discuss to possibility of one or more dams within the canal of Corbulo as this would have solved the difference in water levels and also would have maintained the water levels throughout the seasons (De Kort & Raczynski-Henk 2014, 63). If a dam was used this might also be visible in the dendrohydrological archive of the year rings surrounding trees from this period as the dams would have helped to maintain an even water level as such flooding would not be present near the canal whereas it might be seen in the dendrohydrological record of the year rings closer to the unobstructed Rhine River. At the same time the Network Friction Model could once again provide a model generated from both environmental data and archaeological data on the most likely location (Van Lanen 2017, 40). The environmental data could be enhanced with the data generated from excavations more specific the sediment data (De Kort & Raczynski-Henk 2014, 63).

#### *5.5.5 Jetties or Wave breakers*

Jetties and wave breakers are means to disrupt and alter the flow of the water and change the location of deposition of sediment or to stop the accumulation of sediments entirely at a specific location (Christopherson & Birkeland 2015, 474). Which are known to have been used during the Roman period. Evidence from a little later than the construction of the canal of Corbulo exists in the form of the canal Traiana which is located in Italy near the Roman town of Ostia that connected to the Tiber River (Giraudi *et al*. 2009, 371, 376). This canal connected the Tiber River to an artificially made harbour from the first century AD (Giraudi *et al*. 2009, 371). Jetties dating to before or contemporary to the construction of the canal of Corbulo exist as well, the jetty at the port of Alexandria is a great example of this, Flaux *et al*. (2017) dates this jetty to the beginning of the imperial period (Flaux *et al*. 2017, 677).

### *5.5.6 A Pound Lock*

A pound lock is a mechanism that controls the water levels within a lock by having gates on each side of the lock, these locks which prevents the water from entering or leaving can be opened and closed. The lock bridges the water level difference between the two sides of the mechanism, one side usually has a lower and the other a higher water level. Within the pound lock a boat or ship can be lowered or raised to the water level on each side of the lock. This is done by slowly letting water either flow in or out of the lock. Although there is no archaeological evidence for the usage or knowledge of pound locks the possibility however unlikely still remains that the Romans actually did have the technical knowledge to build such a mechanism.

# Chapter 6: Archaeological and Historical Background

The research question of this thesis:

> "What kind of hydrological structure did the Romans incorporate in the construction of the canal of Corbulo in South-Holland, to permanently resolve the difference in water levels between the two rivers, Rhine and Meuse, in the first century AD?"

is quite a narrow research question within the broader general topic of the canal of Corbulo. It is important to give a more general overview of the background of the canal to gain a better understanding of the importance of such a specific research question. As part of the canal of Corbulo has been excavated, researched and discussed in a variety of ways. This chapter aims to give a brief overview of the background of the canal, both on the historical and on the archaeological aspects, as well as providing a basic understand of the geographical landscape in which the canal is situated. All of this together should provide enough information to place the research question of this thesis in a wider scope.

## 6.1 The Canal of Corbulo

### *6.1.1 Historical Background*

Although it was known that the canal of Corbulo was situated somewhere between the rivers Rhine and Meuse the exact location of the canal was contested for quite some time (De Kort & Raczynski-Henk 2014, 53). Finally, it was accepted in the 20th century that the canal had to be situated somewhere where two tidal creeks became connected through this canal (De Kort 2013, 235). One of these tidal creeks was connect to the Rhine while the other tidal creek was connected to the Meuse, this southern tidal creek was assumed to be the natural waterway named, the Gantel (De Kort 2013, 235). Through these tidal creeks and the associated canal of Corbulo the Rhine and Meuse were connected to each other.

The canal of Corbulo was not the first canal built in the area, there is archaeological evidence for another canal, while no accurate dating can be produced due to the lack of sufficient archaeological evidence which can be used to accurately date the canal (De Kort & Raczynski-Henk 2014, 55). Nonetheless it is possible to at least determine that the other canal is older than the canal of Corbulo, as the canal of Corbulo is in parts superimposed on the other, older canal, see figure 9 (De Kort 2013, 237). For the canal of Corbulo dating however is possible, through dendrochronology Jansma (1995) dated some of the wood used to line the canal, this wood was dated with a felling date of 50 AD, see appendix 1 (Jansma 1995, 129). Jansma is not alone in gaining a felling date for the wood used in the canal of Corbulo, as others have used dendrochronology on other parts of the canal. Which also let to a felling data of 50 AD (De Kort & Raczynski-Henk 2014, 60). The canal itself remained operational for various amounts of time, as not all parts of the canal were closed off by fluvial deposits at the same time, however the general consensus approximates the end of the lifespan of the canal to be somewhere between 100 – 150 AD (De Kort 2013, 237).

At least the Southern part of the canal near the Roman city of *Forum Hadriani* was still accessible around AD 160, which can be deducted from wood discovered at the site of the harbour at the Roman city of *Forum Hadriani* (Domínguez -Delmás *et al*. 2014).

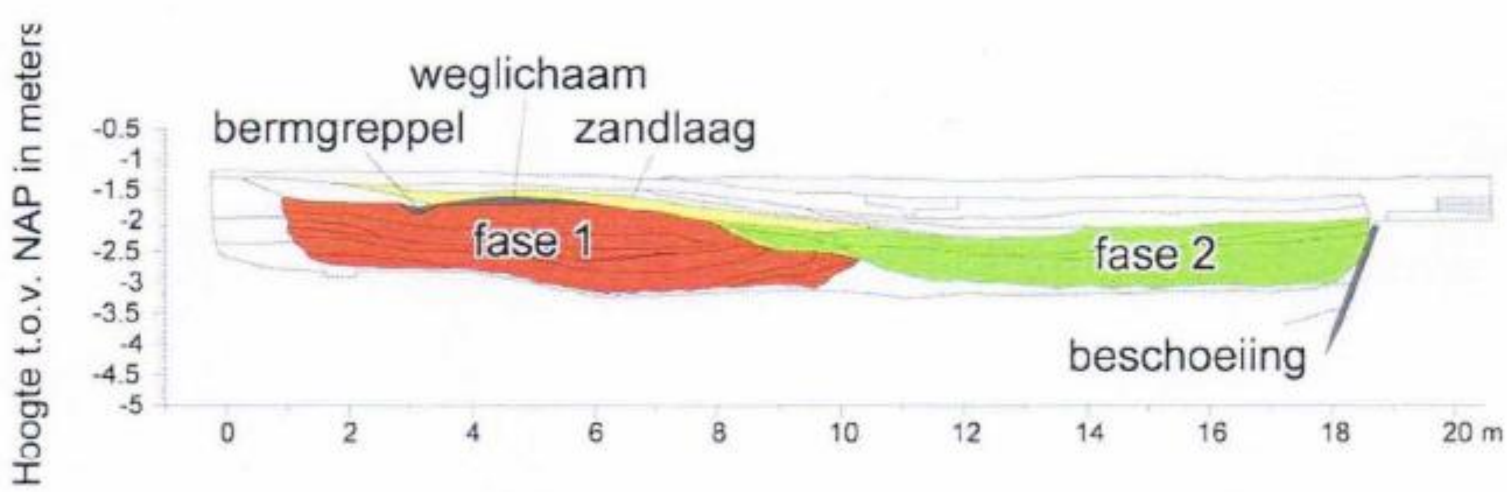


Fig 9. Section of the superimposition of the canal of Corbulo on the older canal. (De Kort 2013, 237 ).

### *6.1.2 Archaeological Background*

The canal of Corbulo has been excavated multiple times by different excavation teams and at different times, however it is the excavations in 1992 by the Cultural Heritage Agency, RCE, at Leidschendam that will be discussed in more detail. It is this excavation of the canal of Corbulo that De Kort, and Raczynski-Henk (2014) discuss, that is of special importance to this thesis. More specifically they discuss the possibility of a portage or a dam in their article, which as discussed in the previous chapter are one of the potential solutions for the hydrological issue of the difference in water levels in the canal (De Kort & Raczynski-Henk 2014, 55). Two of the test trenches that were dug during this excavation, trenches 10 and 11, both show physical evidence of the canal becoming narrower (De Kort & Raczynski-Henk 2014, 55). It is generally accepted that the canal of Corbulo had a width of something between 12 – 15 m, with a depth of approximately 1.4 m (De Kort 2013, 235; De Kort & Raczynski-Henk 2014, 61). It is with these general dimensions in mind that the narrowing of the canal, identified in trenches 10 and 11 of the excavation of the RCE in 1992, is noteworthy and in need of further elaboration. The specific dimensions of the narrowing of the canal are a width of only 4.5 m in both trench 10 and 11, however in trench 11 when moving away from the portion of the canal that is reduced in width, the canal becomes wider once more namely a width of 6.5 m or even more, see figure 10 (De Kort & Raczynski-Henk 2014, 55). When it comes to the depth of the canal there is a clear difference between the measurements of trench 10 and 11 (De Kort & Raczynski-Henk 2014, 63). In trench 11 a depth of 2.81 m below NAP was gauged, this is immediately south of the supposed location of the indicated hydraulic element (De Kort & Raczynski-Henk 2014, 63). While on the other hand directly north of the supposed location of the indicated hydraulic solution the depth of the canal is at 2.5m below NAP (De Kort & Raczynski-Henk 2014, 63). In the northern most trench, trench 4, the depth increases even more to 3.5 m below NAP (De Kort & Raczynski-Henk 2014, 63). This also coincides with what De Bruin (2017) mentions in terms of the dimensions of the canal of Corbulo. De Bruin (2017) refers to the depth of the canal of Corbulo around Leidschendam as being around the 1,5m as well as the depth of the canal south of Voorburg being the same (De Bruin 2017, 106). Further south near the location of the proposed hydraulic element by De Kort & Raczynski-Henk (2014), De Bruin also discusses the narrowing of canal to about a width of 6m, see figure 10 (De Bruin 2017, 106). As can be seen in table 1, numbers 6,7 and 8 show a narrower width of the canal whereas the canals width, broadens both before after these numbers.

In the opposite direction further south of the assumed location of the hydraulic structure the depth of the canal decreases even further to 2.2 m below NAP, see appendix 2 (De Kort & Raczynski-Henk 2014, 63). This clearly indicates a discrepancy between the two parts of the canal in terms of water levels that only becomes more apparent the further away from the location of the possible hydraulic solution the canal is situated, see table 1. De Bruin (2017) also mentions this decrease in canal depth the more south the canal travels (De Bruin 2017, 106).

The canal at the location of trench 10 and 11 of the excavation by RCE in 1992, is also reinforced with wooden beams, specifically along the narrowing of the canal, whereas once the canal widens once again, the said reinforcement of the wood disappears once more, see figure 10 (De Kort & Raczynski-Henk 2014, 55). These could have been used to reinforce the structure of the canal and its hydraulic component. So that for example no boats that bumped against the sides of the canal would damage its structural integrity. At the same time these wooden beams could have been used to reinforce the sides of the canal so that no structural collapse would take place. The actual location of the supposed hydraulic element nonetheless remains unexcavated, this De Kort and Raczynski-Henk (2014) attribute to local circumstances that prevented the location from being excavated (De Kort & Raczynski-Henk 2014, 55).

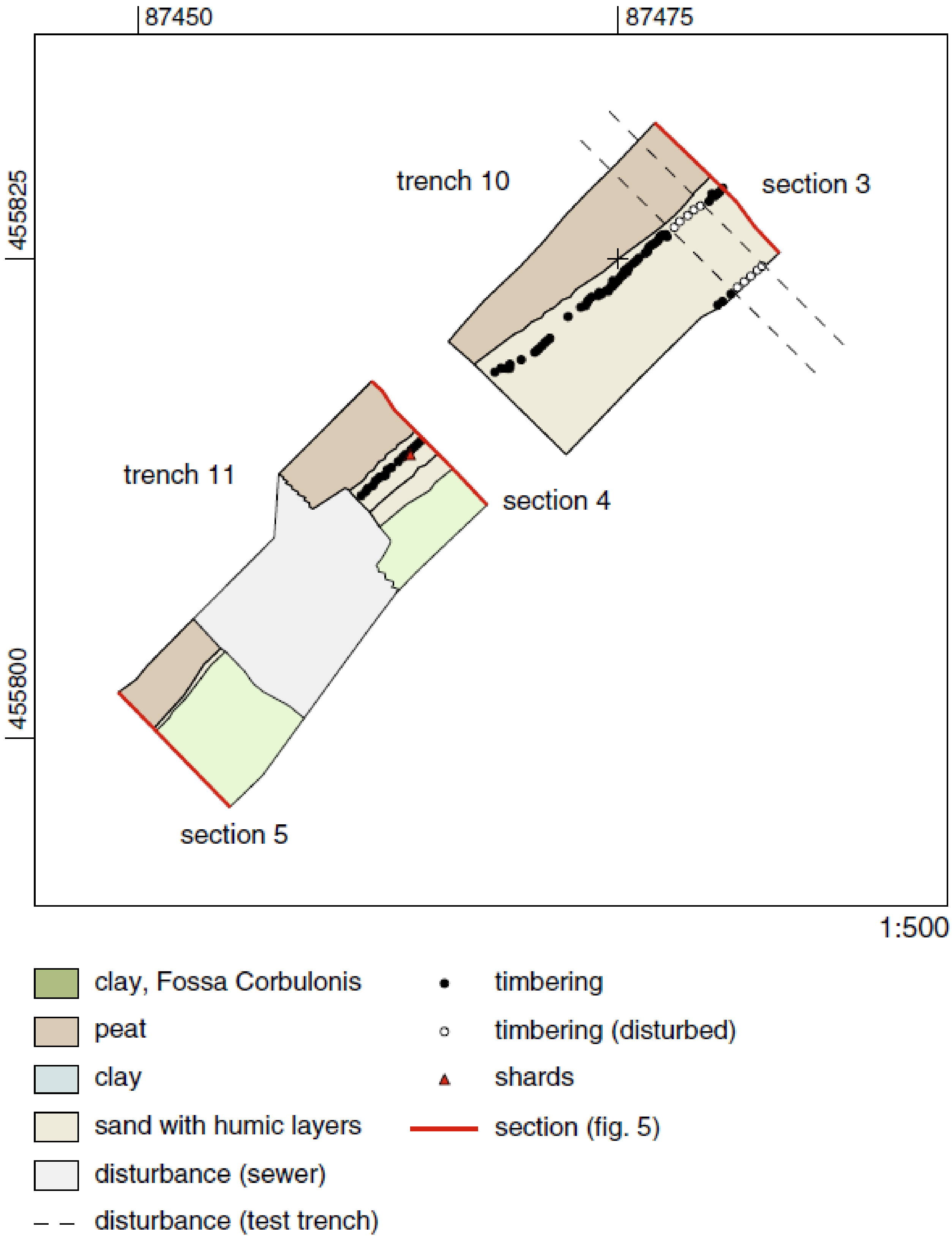


Fig 10. Plan view of trenches 10 and 11 (De Kort & Raczynski-Henk 2014, 57).

## 6.2 Geographical Frame of the Canal

To better understand how the canal is situated within the landscape as well as how the canal itself is built within the land a brief overview of this is needed. This overview will be given with references to figure 11 to create a better visual image.

The canal itself was located near a beach barrier, yellow in figure 11, and as such was cut off from the sea, which as Tacitus mentions in his *Annales* might have been one of the reasons to build the canal in the first place (De Kort 2013, 238; Tacitus *Annales* 11, 20). To expand on this, the North- Sea was a dangerous and difficult sea to traverse, with the building of the canal of Corbulo the Romans could hence forth evade the dangers of the sea and use the canal instead for transport (Tacitus *Annales* 11, 20). The canal itself, dark blue in figure 11, is dug out within a soil composed of peat, dark brown in figure 11, with a sandy layer beneath the peat, the canal however does not reach the sandy layer, this was probably done to stop water from seeping through from below, so as to keep working conditions within the canal dry (De Kort 2013, 239). Over the course of its lifespan the canal began to close due to fill in of sediments, this was caused by the connection with natural waterways, light blue in figure 11, that the canal had on various fronts (De Kort and Raczynski-Henk 2014, 58). As the canal is also connected to two tidal creeks, which are connected to the Rhine and Meuse on either side of the canal, it is no surprise that a lot of sediment entered the canal (Hazenberg 2000, 34).

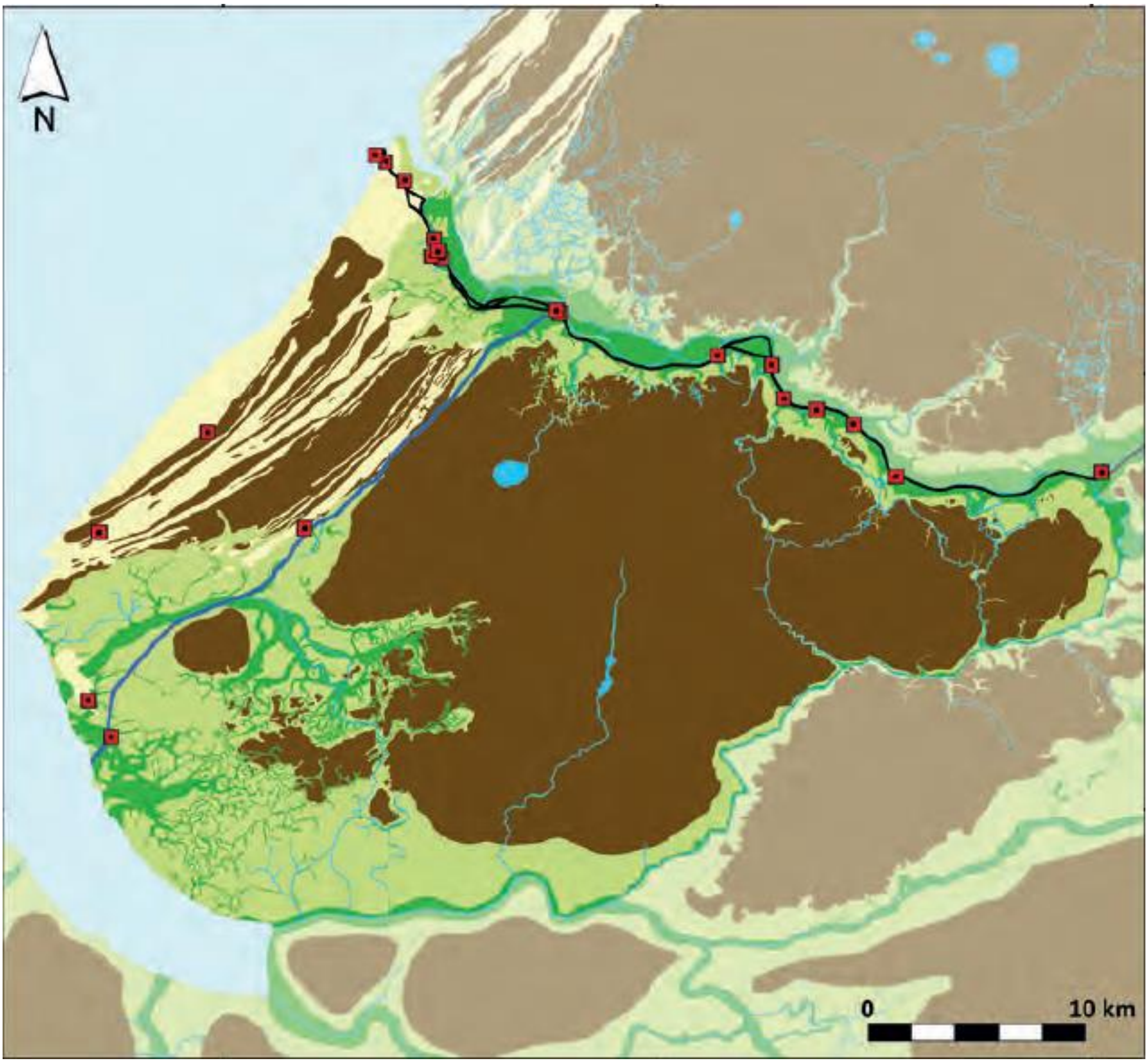


Fig 11. General geographical situation in the landscape surrounding the canal of Corbulo (De Bruin 2017, 101).

# Chapter 7: Discussion

An issue during this research was the limited availability of ancient texts which directly state the canal of Corbulo, only two ancient sources do so namely Tacitus and Cassius Dio, this is however not the only limited data set. As the canal of Corbulo has also only been archaeologically researched at only a few segments. These issues cause the data to be drawn from contemporary literature to be extremely little and of relatively poor quality as neither of the ancient sources mention anything in regard to the technological processes that went into building the canal. Which restricts the information to a more historical nature. The same can be said for the archaeological research devoted to the canal of Corbulo, as such limited research on the topic itself also limits the amount of generated data.

## 7.1 Comparing the Canals

Although the fossa Carolina is significantly younger than the canal of Corbulo, the hydraulic issue that both canals have is quite similar that is to say they both have a difference in water levels significant enough that it needs human interference to prevent issues. As previously discussed, the archaeological evidence at the fossa Carolina points to a canal interrupted by multiple ponds to solve this issue (Leitholdt *et al*. 2012, 93). This in turn would result in the removal of the transport from the body of water to be moved to the next body of water, which could be seen as a form of a portage. For the canal of Corbulo a portage has also been suggested to counter the hydraulic issue of the difference in water levels (De Kort and Raczynski-Henk 2014, 55). However no artificial ponds are known to have been constructed along the pathway of the canal from the archaeological research conducted in regard to the canal of Corbulo, although this might be due to the limited excavations that took place along the canal. A natural lake or pond would seem like a more likely candidate. The Network Friction Model could play an important role to test this theory. A portage however seems like a more viable option that could have been constructed during the building of the canal of Corbulo. The issue however remains whether the boats used within the province of *Germania Inferior* would have survived such a transferal. At the same time depending on the type of boat, it would have been a significant weight to pull out of the water and transfer overland. Of course, beast of burden might have been used to help pull said boats from the water, but it would still have been quite the undertaking. Another solution to this problem might have come in the form of a crane, which could have lifted the boat out of the water all together without compromising the boats' structure. The ship construction of the Zwammerdam- like river barges- with a width of around 3 metres, a length of sometimes more than 20 metres and a draft of around 0,5 metres- makes this an unlikely solution. Again, the Network Friction Model could prove useful to test these theories, at least in regard to likelihood of a portage being a viable option.

## 7.2 The Dimensions of the Ships Compared With the Canal

The flatboat barges discussed previously are also a great indication for the different possibilities of what is and is not feasible. Because of the dimensions of the barges, it can be assumed that they were useable in the canal of Corbulo as well. The barge from the site of De Meern 1 has a length of about 24,6 metres and its width is 2.7 metres at its widest point (Morel *et al*. 2007, 101). While the depth of the barge was at 0.4 metres means that they were able to navigate very shallow waters (Moeyes 2007, 154). The dimensions of the canal are in comparison much larger, with the width of the canal on average between 12-15 metres and a water level of around 1.4 metres (De Kort 2013, 235; De Kort & Raczynski-Henk 2014, 61). While at the narrowest part near the assumed hydraulic construction the width goes as narrow 4.5 metres (De Kort & Raczynski-Henk 2014, 55). When these dimensions are compared with each other this leaves great conditions for the travel with the flatboat barges on the canal of Corbulo. Despite this it should be taken into account that the barge of De Meern 1 itself had an estimated weight of somewhere between 8000 and 9000 kg, if for example the ship had to be dragged over a portage this would have been an extremely difficult and physically demanding undertaking (Moeyes 2007, 155). Whereas the barge of De Meern 4 is quite similar to De Meern 1, the barge excavated at De Meern 6 is of a different typology (Jansma *et al*. 2014, 484). But despite the differences the punt type ship is also a good example for other types of ships that could have been used to travel across the canal of Corbulo and small enough to be transported over a portage.

Whereas the seafaring Blackfriars have an estimated dimension of 18.5 metres in length, a width of 6.5 metres and a depth of about 1 metre and as such still fit comfortably within the dimensions of the canal with the width of the canal on average between 12-15 metres and a water level of around 1.4 metres as mentioned before. The only point of contention is with the narrowing of the canal near the proposed location of the hydraulic element namely 4.5 metres. This would suggest they could only partially travel the canal.

## 7.3 The Different Hydraulic Solutions

Of the different hydraulic constructions that were discussed in paragraph 4.5 the artificial pond which is most likely used in the Fossa Carolina seems the least feasible solution for the canal of Corbulo. Simply because of the dimensions of the canal as the canal becomes narrower towards the perceived hydraulic structure it seems unlikely that a pond was created at this part of the canal in either trench 10 or trench 11 that were excavated by the RCE in 1992. However, by using the Network Friction Model, perhaps a different location might be indicated where an artificial pond might have existed as the NFM analyses the most likely travel route with the least resistance from nature (Van Lanen 2017, 40). As such it may be so that it was overlooked by human eyes.

While there are some similarities between the canal and a cofferdam surrounding trenches 10 and 11 this also seems like an unlikely candidate. As Vitruvius details the need for wooden fixtures to strengthen the dam and separate the water and these details of wooden beams are situated on both sides of the unexcavated part of the canal (Vitruvius *De Architectura* 5, 12). But despite these similarities there is one glaring issue that remains, this part of the canal is artificially made and as such would not have needed the process of building a cofferdam. There is however a slight possibility of there being a natural channel of the Gantel system at the location between trench 10 and 11 (De Kort & Raczynski 2014, 55).

-In that case a cofferdam would have been a feasible solution to bridge the water level difference. The easiest way to prove this hypothesis would be to use the Network Friction Model to gather further information on whether a nearby natural channel could have been actively used in connection to the canal of Corbulo as the most probable accessible route. If so, a cofferdam would not be a strange solution at all. On the other hand, if it was just a canal and no natural channels were active at the time of construction, the soldiers could have just left a part of the land as it was, while digging out the canal in order to create an automatic portage. This of course is just an assumption and cannot currently be proven.

As just mentioned, a portage also seems like a likely solution as it would have entailed the least amount of human interference to create this. The wooden beams in both trench 10 and 11 that were dug by the RCE in 1992, can be explained through the existence of a portage as well. If a portage was indeed used to bridge the water level difference between the two parts of the canal the wooden beams could have functioned as a strengthening tool to reinforce to portage itself as well. Especially because the ships were extremely heavy, for example the barge excavated at De Meern 1, which weighed approximately between 8000 and 9000 kg, as stated before in this chapter. This would have created quite some pressure on the portage itself if not damage from having the ships dragged over it repeatedly. It is also known that portages were a commonly used structure in the coastal areas of The Netherlands and remained in use up until the 19$^{th}$ century (De Kort & Raczynski-Henk 2014, 55).

A barrage or dam also seems like a likely solution as this would immediately solve the issue of the water level difference. The only issue with this remains how did they transfer the cargo from one level of the dam to the other? A crane seems like a likely option to solve this issue; however, no such evidence is currently available that a crane was ever present. Evidence however does exist for a possible dam as De Kort & Raczynski-Henk (2014) mention sandy deposits at the top of the sediment fillings of the canal, which might indicate the breaking of a dam as the deposits in other parts of the canal or of a finer grained and clayey deposition (De Kort & Raczynski-Henk 2014, 63). Another possibility for an explanation of these sandy sediments might come in the form of a natural side channel of the Gantel system (De Kort & Raczynski 2014, 55). The Network Friction Model could be a useful tool in testing these possibilities as they NFM takes into account the path of least resistance from nature (Van Lanen 2017, 40).

Jetties or wave breakers seem like a less likely solution, they might have been used at the beginning of either side of the canal to prevent the silting up of the canal of Corbulo itself. However, in terms of bridging the difference in water levels between the rivers Rhine and Meuse these structures would not have made a difference in terms of solving the water level difference issue.

As mentioned before there is no archaeological evidence for the existence or knowledge of a pound lock (Wikander 2000 ,323). Although this mechanism would have solved the bridging of the water level difference quite easily it is difficult to associate this hydraulic construction with the canal of Corbulo. Simply because of the fact that there is no evidence for the knowledge of pound locks available from the Roman period. As such it seems like an unlikely candidate for the hydraulic component within the canal of Corbulo. However, it cannot fully be discarded either.

Despite the proposed possible solutions in this thesis there are of course other options as well, for example the canal could have ended and diverged into a new canal all together or another hydraulic solution may have been used that this thesis did not touch upon (De Kort & Raczynski-Henk 2014, 55).

## Chapter 8: Future Suggestions

By using a combination of the Network Friction Model and a dendrohydrological analysis, as discussed in chapter 4, any of the discussed hydraulic components would gain more credibility. The NFM could draw up different scenarios of waterway courses. It would be good to look at natural channels within the nearby area with which the canal of Corbulo could have been connected. As these channels could have functioned as a separate passage between two parts of the canal. Meaning that the canal itself might not have been attached to the other part of the canal. If so there might be two separate canals which are located right next to each other. To prove this hypothesis more research is needed. Besides more research also more data is needed to implement this within the NFM with regards to the canal of Corbulo. More detailed information on the local aquatic dimensions is needed for this type of research. A geomorphological map with the details of the area between 0 and 100AD would be a needed for this.

Besides this extra research in the direct location of the supposed hydraulic solution should also be done. If indeed a portage was used in this location a coring campaign should provide extra information, this is also recommended by de Kort (De Kort 2013, 240). Coring would be useful to obtain extra information because if there truly is a portage this would mean that the Roman soldiers never dug into the ground at that location. This is of importance because it would indicate that a peat layer would still be in situ at the location of the perceived hydraulic structure, the peat layer would be much thicker in the location that was not dug at. As previously stated in chapter 4 the Roman soldiers left a small layer of peat on the bottom of the canal to prevent the water from leaking through (De Kort 2013, 23). At the same time if a non-invasive is preferable, ground penetrating radar techniques would also be highly useful as if there is indeed a portage the soil should not show any unnatural features. However, if there are features it is also immediately known that something was constructed at the location. Both of these suggestions would also lend themselves to further substantiate the archaeological input data for the Network Friction Model.

It would also be useful for any future archaeological campaigns in regard to the canal of Corbulo to incorporate some of this into their programme of requirements and plan of action. By including the suggested research, especially the geomorphological information, a better dataset for the Network Friction Model might come into existence from which subsequently a better and more accurate suggestion can be created by the Network Friction Model.

## Chapter 9: Conclusion

Articles, books and journals related to canal of Corbulo and more specifically any hydraulic engineering is very limited to come by, both from ancient and from modern sources. It also does not help that there are relatively few known canals from ancient times that have been excavated, and or have been written about, this significantly limits the dataset from which conclusions can be drawn. When taking into account that the fossa Carolina also has fairly limited evidence for the artificial ponds and the subsequent transport of ships from one water body to the next, it becomes difficult to draw any conclusive answers. Other known canals, for example the canal of Drusus remain lost to modern times (Verhagen *et al*. 2022).

This thesis attempted to answer the research question: *"What kind of hydrological structure did the Romans incorporate in the construction of the canal of Corbulo in South-Holland, to permanently resolve the difference in water levels between the two rivers, Rhine and Meuse, in the first century AD?*'

To underpin this research question four sub-questions were also created:

- What archaeological evidence is available for any kind of hydrological engineering to solve the difference in water levels between the rivers Rhine and Meuse in the canal of Corbulo?
- What type of hydrological solutions are known from other canals in an archaeological setting, both from earlier, contemporary and later canals?
- What kind of boats are known to have been used in the Roman province of *Germania Inferior*?
- What kind of techniques can be used during future research to help resolve the main research question?

While there were quite a few articles related to the topic of the canal of Corbulo most of these focussed on the harbours and towns associated with the canal (Domínguez-Delmás *et al*. 2014; Driessen 2014, 2018; Hazenberg 2000). Articles related to the canal itself were far more limited and those that were available had a lot of recurrent information in them and were partly written by the same author (De Kort 2008, 2013; De Kort & Raczynski-Henk 2014). To further the difficulty of the research, the research question is limited to a very specific part of the canal and thus this limits the available data as well. The excavations that were carried out on the area surrounding the location of the suspected hydraulic structure were done in 1992, which is also quite some time ago (De Kort & Raczynski-Henk 2014, 55). All of this together creates a fairly limited data set to gather information from.

Possible solutions to test theories as discussed in chapter 4 are just theoretical. The techniques and equipment needed to test these hypotheses are not readily available either and as such remain untested hypotheses.

As such the research question remains unanswerable, despite all the circumstantial evidence that is available, it is difficult to draw a concrete answer, as the specific location related to the perceived hydrological solution remains unexcavated. While the sub questions were answered throughout the thesis the dataset remains too small to draw a concrete answer from for the main research question.

To summarise, more research is needed at the location of the assumed hydraulic solution, techniques such as coring and non-invasive methods, for example ground penetrating radar, could be a useful tool for this to avoid a full-scale excavation. Results from these campaigns could lend themselves to the Network Friction Model to calculate possibilities and probabilities in regard to the hydraulic solution.

## Abstract

At the beginning of the first century AD the canal of Corbulo was dug to connect the rivers Rhine and Meuse in the Roman province of *Germania Inferior*, in the modern day country of The Netherlands. The rivers Rhine and Meuse however have a difference in water levels as they have different properties, The Rhine is a smelting water and rainwater river, whereas the Meuse is rainwater river. To bridge this difference in water levels a hydraulic component would have had to have been incorporated within the canal to permanently bridge the difference in water levels. What this hydraulic structure was, however remains unknown. This thesis aims to answer that questions. To better answer this, a theoretical framework in regards to the Network Friction Model and dendrohydrological research is given, from which a suggestion for future research is drawn. By analysing both ancient sources and modern texts, as well as giving a comparative framework of hydraulic components, both those known in ancient and modern times a dataset is created to help answer the research question as well. At the same time a general overview of the boats in use within the Roman province of *Germania Inferior*. This data set is created to compare the dimensions of the boats and the canal itself but also with different hydraulic constructions so as to analyse whether they were compatible. After this an archaeological and historical background is given on the canal of Corbulo itself to outline the known data on the canal of Corbulo itself to gain a better understanding of the research itself. The geographical situation within the surrounding landscape in which the canal of Corbulo is situated is given for the same reason. Lastly suggestions for future research are given after which the thesis finishes with its concluding chapter. In this last chapter it is concluded that no specific answer can be generated to answer the research question as to little data is currently in existence.

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## Figures



## Tables



## Appendices

## Appendix 1. Dendrochronology Canal of Corbulo

The dendrchronology information on the Leidschendam excavation of the canal of Corbulo (Jansma 1995, 129)

| LEIDSCHENDAM | Canal of Corbulo (ROB) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Object** | **Filename** | **Dendro-code** | **No.** | **Date** | **Reference** | ***St*** | ***PV*** | **NL** | **Remarks** |
| RH01 | LRC00017 | NLR17001 | 89 | 49 | *NLRom_R* | 4.2 | 67.3 | *NLRom_W1* | Date through avg. chronology |
| RH06 | LRC00061 | NLR17003 | 101 | 49 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH09 | LRC00092 | NLR17004 | 119 | 49 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH03 | LRC00135 | NLR17007 | 94 | 49 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH14 | LRC00145 | NLR17008 | 114 | 49 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH17 | LRC00175 | NLR17009 | 99 | 50 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH18 | LRC00186 | not coded yet | 93 | 46 | *NLRom_R* | idem | idem | *NLRom_W1* | |
| RH21 | LRC00210 | not coded yet | 132 | 48 | *NLRom_R* | idem | idem | *NLRom_W1* | |

## Appendix 2. Information on the properties of the canal of Corbulo

Information on the properties of the canal of Corbulo from multiple sites (De Kort & Raczynski- Henk 2014, 62)

| Site nr. (in Fig. 2) | Fig. 5 section nr. | Trench | Section | Minimal width (m) | Base of canal (m. below NAP) | minimal depth (m) | Timbering | Roman surface intact | Source |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | N | 14.5 | −3.5 | 2 | East | Yes | Vos et al. (2007) |
| 2 | – | 9 | – | 13 | – | – | East | Yes | Hessing (1990) |
| 3 | – | 1 | N | 10 | −3.17/−3.08 | 1.5 | East | Yes | de and Raczynski-Henk (2008) |
| 4 | 2 | 4 | N | 12 | −2.5 | 1.3 | None | Yes | Hessing (1990) |
| 5 | 3 | 10 | N | >2.75 | – | 0.8 | Both | No | Hessing (1993) |
| 5 | – | X | S | 4.6 | −3.2 | 1 | Both | No | Hessing (1993) |
| 6 | 4 | 11-II | N | >5.50 | – | 0.9 | Both | No | Hessing (1993) |
| 6 | 5 | 11-I | S | >5.80 | −2.81 | 1 | None | No | Hessing (1993) |
| 7 | 6 | 7-I | N | 14 | −2.65 | 1.1 | None | No | Hessing (1992) |
| 7 | 7 | 7-II | N | 12.5 | −2.9 | 1.3 | None | No | Hessing (1992) |
| 9 | 8 | 5 | N | 12.5 | −2.3 | 1.2 | None | No | Hessing (1992) |
| 9 | 9 | 4 | N | >9.50 | −2.2 | 1.25 | None | No | Hessing (1992) |
| 10 | – | – | – | – | – | – | – | – | observation at Schoorwijck |
| 11 | 10 | 3 | N | 8 | −4.88 | 2.1 | None | Probable | Griffioen and Hoogendijk (2011) |
| 11 | 11 | 4 | S | 8 | −4.88 | 2.1 | None | Probable | Griffioen and Hoogendijk (2011) |
| 12 | 12 | 1 | N | 18 | −3 | 0.75 | None | No | van Heeringen (1997) |