Applying GIS to the Logistics of Material Transportation for Constructing the Baths of Caracalla in Rome

by

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in the Department of Art, Art History & Visual Studies in the Graduate School of Duke University

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ABSTRACT

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Abstract

The purpose of this thesis is to visualize the economic system (supply, production, and transportation) and the logistics of the movement of marble in the Roman Empire in an effort to better understand the larger system of material movement in Imperial Rome. This will be accomplished through a digital case study on the largest surviving bath complex in Rome, the Baths of Caracalla, for which we have evidence of the types of materials used in its construction and speculative observations on the quarries from which this material was procured. In order to effectively demonstrate this system and to accurately locate the Baths of Caracalla within the imperial trade network, a detailed visualization of the marble quarries and the web of transportation routes using ArcGIS Pro mapping software was created. Using ArcGIS Pro as a heuristic tool, this map will show the quarry sites and reconstruct the transportation routes by which marble was moved over long distances for the Baths of Caracalla in Rome. While the digital humanities have used the city of Rome as a site for experimental mapping projects on various subjects, this map on the stone quarries in the Roman Empire in relation to the Baths of Caracalla will be the first digital humanities mapping project of its type.
To Nicholas Hudson, Vibeke Olson, Edward Triplett, and Sheila Dillon, to whom I am eternally grateful for your continuous support and guidance throughout my academic career. You all have inspired me to pursue and fulfill my dreams, and opened doors to opportunities that I could not have imagined were possible.

I would also like to dedicate this work to my mother, who has always supported me in all my endeavors.
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1. Introduction

An integral part of any large-scale public building project undertaken in imperial Rome was the transportation of material to the building site. The larger economy of trade within the Roman Empire relied on a network of quarries and trade routes for efficiency and a successful import and export industry. The economics of monumental building projects in Rome also involved this trade and transportation network, particularly for the construction of imperial thermae. In order to better understand this advanced network during the third century CE, I analyze the Baths of Caracalla as a site-specific case study, since it is the largest and most well-preserved bathing complex in Rome. Because of the level of preservation and its enormous scale, the Baths of Caracalla offer the opportunity to understand how imperial builders commanded a vast amount of resources and employed multiple trade routes for maximum efficiency. In addition, the entire construction process has been well researched and documented in an extensive study by Janet DeLaine, which is the primary scholarship used in this thesis.¹

Focusing on a single site also offers insight that has broader implications for the imperial Roman transportation network, and allows us to understand the integration of the site and the network. By exploring in-depth the material evidence surviving from this structure, as well as the current scholarship, my research offers a new way of understanding the broader industry of bath construction, the trade and transportation network, and the vast material supply that went into the production of this massive

complex. The elements of production and distribution can perhaps be better understood through visualization. Thus, in addition to my analysis of the material transportation, I have created a visualization of the quarry and transportation road network using ArcGIS Pro and its interactive component ESRI Story Map.

The structure of my thesis involves three general sections on 1) The General History of Roman Baths, 2) The Trade and Transportation Routes and 3) The Spatial Analysis of Marble Movement Using GIS. The first chapter begins with a review of the recent scholarship on this building type. I then provide an overview of the historical development of Roman baths, discuss the economic production of imperial bath construction and the current gaps in research on this topic, and the methodology I have used to fill this gap. I lay out my research questions at the end of this chapter. The second chapter addresses the building materials and the logistics of the material production, labor, and transportation. In this section, I explore a review of recent scholarship on material trade and DeLaine’s analysis of the material supply, production, and transportation methods. I focus on the transportation routes utilized in constructing the baths and how this particular site fits into the larger trade network of imperial Rome. The third section discusses the design and creation process of the GIS map in ArcGIS Pro, how I came to the decision to use this particular software, an analysis of the map in its final version in Story Map, and the contribution this project makes to the fields of digital humanities and art history. The final chapter presents my conclusions and revisits my research questions.
1.1 Baths of Caracalla

The Thermae Antoninianae, more commonly known as the Baths of Caracalla, were constructed from 212-216 CE under the imperial building program of the emperor Marcus Aurelius Severus Antoninus Pius Felix Augustus (Caracalla). They are located at the foot of the Aventine Hill (in Regio XII) west of the Via Appia. The complex serves as the only surviving monument associated with emperor Caracalla in Rome, and is also the most well-preserved bathing complex of the 3rd century CE. These large-scale baths are one of the greatest examples of Roman architectural engineering and design of the imperial period, serving as a benchmark for Roman imperial bath construction. Only imperial patronage could have supported such rapid construction and financed such luxurious decoration, which necessitated command of a vast network of resources and the ability to transport these materials over long distances. With this project, Caracalla was continuing the vast program of public works initiated by his father Septimius Severus, the complex serving as a gift to the Roman people. The project also served as a massive employment opportunity for the urban poor, as thousands of workers were required to complete the project within the short span of five years. Based on archaeological evidence of brickstamps and later renovations, the baths remained in use throughout late antiquity, until the severing of the aqueducts that provided water to the facility by the Goths in 537 CE.

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3 DeLaine 1997, 10-13, 37.
DeLaine considers the Severan period the apex of imperial Roman construction and engineering; this assessment is based on the structural sophistication, advanced heating and construction techniques, vast array of building materials used, and the sheer size of the complex of the Baths of Caracalla.\textsuperscript{4} The Severan period was an era of heightened large-scale building projects and urban renewal in Rome. Most public expenditures for urban projects were funded by the emperor, which allowed for a highly efficient, costly, and extensive building process.\textsuperscript{5} Although this complex is the only extant example of Caracalla’s urban planning agenda, it serves as one of the most profoundly advanced structures of its time.

The Baths of Caracalla were modelled after the central block type, with a complete exterior precinct surrounding the central block and enlarging the entire complex. The baths were equipped with two libraries, two large palaestrae flanking the central block, a richly decorated frigidarium, natatio, and caldarium, and apodyteriae. In addition to this vast visible structure, the baths also had an underground network system consisting of two levels: the upper level had service passageways for repairs, fuel transportation, and basic functions, and the lower level comprised a sophisticated drainage system that led from the frigidarium to the aqueducts. Similar to the Baths of Agrippa, Caracalla had a new aqueduct, the Aqua Marcia, built as an additional source of incoming water branching from the Antoniniana Nova, that fed directly to the baths.\textsuperscript{6} The Baths of

\begin{itemize}
\item \textsuperscript{4} DeLaine 1997, 10.
\item \textsuperscript{6} Platner 1929, 523. For a more recent discussion, cf. DeLaine 1997, 15-17.
\end{itemize}
Caracalla dramatically transformed the standard model of imperial bath construction in the third century CE for future imperial baths in terms of its colossal architectural forms and luxurious building materials.\(^7\) The vast size of the baths and its luxurious decoration suggests that their construction commanded the resources of most imperial-owned quarries, particularly marble quarries. Marble was the most luxurious building material used in the entire complex. Due to the imperial nature of the building project, marble was sourced from many conquered regions of the Roman Empire to demonstrate the wealth, command, and power that the emperor held. Polychrome marble was used as a way to represent the different areas of the empire from which it was procured, and the vast quantities contributed to the wealthy and opulent appeal of the baths.

\(^7\) The imperial ownership of quarries can be dated from the first to the third century CE. The imperial command of the material trade network was heavily implemented by Trajan and used by Caracalla, as the imperial ownership of material quarries and the road network was largely expanded in the second century CE. Hirt 2010, 1-3.
2. General History on Roman Baths

2.1 Review of Recent Scholarship

Roman public baths were an important architectural and social phenomenon throughout Roman history. Imperial bathing institutions in Rome were unique spaces in that they functioned as communal and social environments available to any social class and yet were designed with opulent building materials and architectural luxury often only seen in imperial buildings or private villas. The origins of Roman baths are attributed to the influential Greek prototype, the thermae-gymnasia hybrid, a combination which emerged during the Hellenistic period. For the purpose of my research on the Baths of Caracalla, I have omitted a discussion of private baths in favor of focusing on public baths for the monumental architecture and the social aspects.

The history of Roman baths and bathing has been extensively explored by scholars, particularly since the 1980’s. Scholars have traditionally debated on how to best classify bath types based on their architectural form and design. Since then, scholars have changed their approaches to the study of Roman baths, with a focus in particular on typology and social history. There has been an increased interest in the social aspects of bathing, including exploring the use of the space by the bathers and how bathers would have experienced the architecture and bathing environment. These two interests – architecture and social history – come together particularly in DeLaine’s work in the 1990’s, which sets the agenda for future research.

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Bath Scholarship in 1980’s

A main theme of scholarship in the 1980’s was an attempt to create a standard approach to the architectural and typological aspects of baths. The benchmark methodology was producing comprehensive reports on both regional studies and individual buildings in order to construct a general overview of the function and architecture of bath houses. A prominent source on the standard thought on Roman baths in the 1980’s was DeLaine’s 1988 article that summarized current scholarly approaches to the study of Roman baths and suggested areas that needed further research. DeLaine addressed the origins and development of the hypocaust heating system, the monumental architecture of imperial thermae and how they differ from balnea, bath ornament, and the social aspects on the relationship between the baths and the bathers. She argued that baths deserve much more of our scholarly attention because they were used on a daily basis by a large cross section of the population and therefore their study can reveal more about the everyday lives of Romans than other social gathering places, such as amphitheaters, a type of building that had attracted significant scholarly attention. She concluded with her own theories on the hypocaust and thermae

10 The first major attempt to classify bath types in the 20th century was Krencker, D. 1929. *Die Trier Kaiserthermen*. Augsburg.
11 Scholars tended to focus on the architectural and typological aspects of baths, often not providing further insight into the social aspects, regional bath differences and similarities, or their own interpretations of the archaeological evidence; for example, Nielsen 1985, Heinz 1983. For a more recent discussion on thermae/balnea terminology inconsistency, cf. Yegül 2010.
developments, and suggested future studies on the social aspects and bath ornament. Her article contributed valuable insights to the study of Roman baths and provided several key directions for further research that would enhance the general scholarship of Roman baths and bathing.

**Bath Scholarship in 1990’s**

In the 1990’s, three articles stand out: Nielsen (1990)\(^{14}\), Yegül (1992)\(^{15}\), and DeLaine (1999).\(^{16}\) These works suggest a growing interest in the study of Roman baths perhaps due to the publication of more excavations and regional studies during the period. A comparison of early and recent works illustrates the developments made in bath construction over the years, especially in the subject of the origin of baths in Italy and their development. A main theme of scholarship during this decade was the attribution of Greek baths and gymasia as the major source of influence for Roman baths. Nielsen’s work (1990) is a general introduction to Roman baths, providing additional information gained from recent important discoveries. She discussed the origins and developments of *thermae* and *balnea*, early examples of Greek and Italian forerunners, and the hypocaust heating system and water supply. She defined the terms *thermae* and *balnea*, two types of bathing establishments, more narrowly and consistently than had been the case in the past. Nielsen explored the chronological development of early baths to *thermae*-gymasia


combination baths, and eventually to baths influenced by bath-gymnasia hybrids. She attributed the large variation in bath types to the amount of early exposure each region had to bath building. Therefore, regions that had earlier exposure had more time to develop and experiment with bath types and sizes, and could adjust them as needed to fit their specific population. She concluded with an analysis of the economics and social functions of baths in different regions, focusing on such issues as opening/closing times and admission fees.

The second major work of the 1990’s was Yegül (1992). The main theme of his work was the influences of the Greek gymnasium and Greek bath on the development of Roman baths. He argued that the Romans were first to conceptualize the act of bathing as a luxurious ritual that combined hot bathing and exercise, and they were therefore the first to develop an architectural environment for this type of bathing. The chapter on origins and development highlights his emphasis on the theory that Roman baths were influenced by Greek originals, and the bath-gymnasium hybrid is a telling example of western and eastern Hellenistic styles. He does not address chronological development due to a lack of evidence, but he does illustrate the gradual fusion of the gymnasium and hot baths as bath building became a larger phenomenon in Italy. He starts with the baths of Campania, citing the baths in Pompeii and Herculaneum as examples, and then moves on to other provincial bath types. Overall, Yegül’s book is a major contribution to Roman bath scholarship, especially on the subject of origins and development of the building type.¹⁷

The final work that gives a good idea of where scholarship on Roman baths was in the 1990’s is DeLaine’s short article (1999) on the urban nature of bathing in Rome. The goal of her article was to provide a clear and direct introduction to some of the important issues in the scholarship on Roman baths, with the generalization of bath types in regional studies a main problem. She argued that it is more effective to study bath architecture and social aspects on an individual basis, as these matters vary according to the region so it is difficult to generalize.\(^\text{18}\) She also argued that a focus on the different design and construction processes found in Roman architecture would be more productive and helps us to understand the architectural decisions made by the patron, builder, and architect. DeLaine’s work underscores the sudden plethora of work on Roman baths in the 90’s, and the general increase of interest in the field since the 1960’s.

Janet DeLaine’s contribution to the scholarship on Roman baths has largely shaped and indeed transformed the modern approach to the topic. She has explored some of the most important areas related to bath buildings, including their architectural development, the economics of their construction and their place within the larger Roman economy, and the social aspects of their use. Her early research focused on Roman bath development, and the origins of the heating element of baths. DeLaine’s article on the transitions from Greek to Roman baths (1989) discussed important themes of scholarship during the 1980’s on the Greek origins of bath houses, the hypocaust heating element,

and the attribution of baths as a Greek development, based on evidence from Pompeii.\textsuperscript{19} In a later more general study on Roman baths (1993), DeLaine addressed the key elements that made baths Roman, such as their architectural luxury, the social benefits of communal pools, and the elaborate, colorful decorations that covered almost every surface.\textsuperscript{20}

Perhaps her most important contribution to the field is her detailed study on the Baths of Caracalla (1997), which serves as the first systematic approach to understanding the bath building process from an economic perspective.\textsuperscript{21} The goal of this work was to better understand the architectural and economic processes involved in large-scale building projects in imperial Rome through a case study of the Baths of Caracalla, the most well-preserved bathing complex. Imperial thermae were one of the largest and most impressive civic benefaction and urban renewal projects undertaken by the emperors, and were largely constructed with the intentions of pacifying the public. Therefore, they were designed to be impressive, beautiful, and luxurious.\textsuperscript{22} DeLaine addresses material supply, production, and construction logistics involved in the building process, such as labor statistics, and production of the work force. She identifies a streamlined system of

\textsuperscript{21} DeLaine, J. 1997. \textit{The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome}. Portsmouth: Journal of Roman Archaeology. This scholarship was the first approach to the topic in the 1990’s. Since then, other scholars have contributed similar analyses, i.e. Manderscheid 2000 (on hydraulics); Taylor 2003; Wilson 2006; Lancaster 2008.
\textsuperscript{22} They are also among the most expensive buildings to construct and maintain, as once built, they require constant maintenance, a constant source of fuel for heating, and a constant and always flowing source of water. DeLaine 1997, 188.
construction: material supply, material production and man-power, and transportation to the site. Based on the archaeological evidence and her research, she suggests that this was the most effective and efficient system used for large-scale imperial building projects. She supplements her research with her own calculations on the cost of materials (based on literary evidence) and the cost of labor to indicate the economic significance of baths. She also addresses the social aspects of the Baths of Caracalla, and the reception by the bathers.

After her work on the Baths of Caracalla, DeLaine continued to study Roman bath building techniques, economics, and technology. A key example is her article on the intersection of costs, technology, and construction in the Roman Empire (2007).\textsuperscript{23} She discusses the technological aspects of construction in the Roman Empire, such as the transport of materials, the equipment of construction (for example, the scaffolding needed for vault construction), and the cost implications of utilizing the necessary technology and labor in building projects. In addition to her scholarship on bath studies, she has also explored brick production techniques, focusing on the port at Ostia which had one of the largest brick production and distribution centers of the Roman Empire. Her most recent contribution (2015) provides a brief but updated account of the supply, production, and distribution system for brick.\textsuperscript{24} DeLaine has been a vital contributor to the scholarship on


the internal systems of bath construction (economics, technology, etc.) and the role humans played in bathing institutions. DeLaine has transformed the field in many ways, from asking new questions about bath development to studying the economics of their construction, and her work is the major source on Roman bath development and construction.

Since DeLaine’s notable contributions to Roman bath scholarship, the field has experienced new approaches to the subject. New kinds of evidence and research methods allow us to better contextualize the baths and understand the environment in which they flourished. The first new approach is the theory that Greek bathing practices were similar to Roman practices. An important example of this current scholarship is Lucore and Trümper (2013), which is the most recent work written on Greek and Roman bath studies. Trümper documents that the number of known Greek baths has increased to 75 in total, which is a significant development from the past two decades.

Within this work is an article written by Yegül (2013), which focuses on the origins of Roman baths. Yegül argues that Italians were exposed to baths and bath culture early on when diverse people began immigrating to Italy from the Hellenistic East, bringing with them their own traditions of bathing. His evidence is based on the presence of Greek gymnasia-baths discovered in Sicily and other cities in Southern Italy. Yegül makes the distinction between Greek public baths and Italian public baths as building

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26 Public baths were common in Italy by 200 BCE, as seen from second century BCE evidence such as the Stabian Baths and the first century CE Baths of the Swimmers in Ostia. For more discussion, cf. Yegül 2010, 68-70.
types based on the early baths in Campania, concluding that the Greek and Roman baths were built upon similar traditions, but experienced regional stylistic changes. He maintains that the fundamental difference in baths lies in the architecture and decoration: Greek public baths served a simple cleansing purpose, which was reflected in their more modest architecture and smaller bath tubs, while Roman baths served a relaxing and luxurious purpose, and therefore were lavishly decorated and had larger communal pools with heating systems. Overall, Yegül’s work is the most recent comprehensive study on Greek and Roman baths, and his inclusion of recent discoveries and new theories emphasizes the continued interest in ancient bath studies.27

In terms of the materials used to construct the baths, scholars studying the Roman economy and the trade in material in the Roman Empire have become interested in the topic of Roman quarries.28 A key source for quarries is Hirt (2010),29 who discusses imperial and military mines and quarries in the Roman Empire from 27 BCE – 235 CE in terms of their geology, organization, and labor. The main goal of his work was to provide a broad overview of the organization of the quarry industry and to explain its place within the administrative structure of the Roman Empire. His use of detailed maps demonstrating the extent of the quarry network, as well as pictures of the archaeological

remains of quarries help us to identify and visualize the larger system of imperial quarries and material transport.

Recent scholarship on Roman baths has dealt primarily with the construction process of bath building within the framework of the Roman economy and the trade network of materials used in their construction. What is missing, however, from this scholarship is an analysis of the relationship between specific large-scale imperial building projects and the broader quarry system of the Roman Empire. That is the gap this thesis seeks to fill. However, a brief introduction to the historical development of Roman baths is first needed to understand fully the importance of the Baths of Caracalla.

### 2.2 Historical Development of Roman Baths

Understanding the major architectural and technological developments in Roman public baths from the late second century BCE to the construction of the Baths of Caracalla is necessary in order to place the Baths of Caracalla within the larger history of Roman bath building. The major developments from the second century BCE to the third century CE were the advancement of the hypocaust, an overall increase in the size of bath buildings, and the differences in the materials used in their construction; each is part of a broader movement towards an ever increasing luxury in public bath construction.

An increasing number of excavations, publications, and research conducted on both Greek and Roman baths has shed new light on the developments of the hypocaust system in Roman public baths. It is clear from the archaeology that central Italy played an important role in the early development of this heating system. One of the earliest heated baths that has long been known in Italy is the Stabian Baths at Pompeii, first built in the third century BCE. The development of the hypocaust can be seen in the transition of
the two building phases of the Stabian Baths, which are both the earliest example and evidence of the Roman hypocaust type. In the initial building phase, the baths did not have a hypocaust heating system and were smaller in size.\textsuperscript{30} During renovations in the second century BCE, a Roman type hypocaust system was built. This early Roman type had \textit{tubuli} that lined the interior of the walls of the caldarium or hot room, which effectively transferred heat throughout the entire room.\textsuperscript{31} This was a significant innovation that became part of the standard model for all future hypocaust construction. The standardization of the hypocaust was also introduced by the systematic use of baked brick material (which could withstand heat) and terracotta floor tiles, and a rejection of the traditional material of stone rubble. Based on archaeological evidence, this change is believed to have occurred towards the end of the second century BCE, which also coincides with the sudden growth of the Campanian terracotta industry probably for the production of hypocausts.\textsuperscript{32} The recent discovery of baths dating to the second century BCE in Fregellae (Latin settlement in Latium) shows that hypocaust-heated baths with shared facilities for men and women were also present outside of the Bay of Naples.\textsuperscript{33} Based on the evidence of these bath complexes, the consensus in recent scholarship is that heated baths developed in Italy in the early second century BCE.

An overall advancement in the size and material selection can be seen in bath construction from the Republican to the Imperial period. As DeLaine suggests in her

\textsuperscript{30} DeLaine 1989, 119. For further discussion, cf. Eschebach 1979, 45.
\textsuperscript{31} DeLaine 1989, 119-121.
\textsuperscript{32} DeLaine 1989, 124.
article on the transitions from Greek to Roman baths, there is a pattern of progression from smaller, individual baths to larger, more communal spaces and simpler, linear forms.\(^{34}\) A major element in this evolution was the development of Roman concrete, which led to an increased use of vaulting over larger spaces. Examples of this can be seen in the baths of central Italy during the second century BCE, such as the Forum baths at Pompeii.\(^ {35}\) After the evolution of the hypocaust in the second century BCE, baths began to expand in the late first century BCE, namely to larger and more grandiose spaces, luxurious decorations, and displays of imperial wealth. The first imperial public bath to be built was the Thermae Agrippae (Baths of Agrippa) in 25 BCE.\(^ {36}\) They were built in the Forum adjacent to the Pantheon, and were sourced from an aqueduct built by Marcus Agrippa solely for the baths, the Aqua Virgo.\(^ {37}\) The Thermae Agrippae were lavishly decorated with rich building materials, such as marble, and had exquisite mosaic and painted decorations.\(^ {38}\) The selection of material, particularly the marble, used in this bath demonstrates a significant development from earlier baths, as most earlier baths were constructed entirely of baked brick and rubble. Roman concrete (opus caementicium) was fully developed and widely used by the first century BCE, and transformed the entire construction industry.\(^ {39}\) The use of pozzolana-based lime mortar allowed for the

\(^{34}\) DeLaine 1989, 124.


\(^{36}\) Yegül 2010, 106. Agrippa was a statesman and the highest general to emperor Augustus. Literary evidence: Cassius Dio. *Historiae Romanae*. 53.27.1. and 54.29.4.

\(^{37}\) Yegül 2010, 105-107.

\(^{38}\) Pliny. *Naturae Historiae*.

hydraulic infrastructure to remain in-tact under water, which allowed for the large communal pools and supported the building’s massive foundations.

The Baths of Agrippa marked the beginning of the transition of bath decoration from utility to luxury. The social developments of Roman baths can be seen with the Baths of Agrippa as well. Upon completion, the baths were free to the public, which allowed for all social classes to enter the same bathing establishment. With the Baths of Agrippa begins the imperial tradition of large-scale civic building projects in Rome involving imperial thermae and aqueducts.

Roman imperial baths served an integral role in the experimental process for large-scale public building in Rome. The use of concrete made the structures more durable and more efficient (requiring less materials), and with this material builders were able to create some of the tallest and most impressive structures of the day. The vaulted ceilings allowed for loftier heights and more stability with an even-weight distribution that could extend across the largest rooms in the baths, especially the frigidarium. Imperial thermae were also architecturally designed to guide the bather through a systematic bathing process. The linear facilities channeled the bather through a set sequence of rooms, which became the traditional bathing ritual. This bathing ritual had been officially established by the early second century BCE.  

The architectural and social developments of baths were greatly expanded in the Thermae Traiani (Baths of Trajan), erected in 104 CE. The Baths of Trajan were the first

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fully-developed and monumental imperial thermae and the largest public bath complex of
their time. Occupying an area of 320 x 340 meters, the Baths of Trajan served as a major
architectural and decorative influence for the Baths of Caracalla.\(^{41}\) In terms of
architecture, the baths reflected an intermediary layout between the early linear style and
the later style of a central bathing block surrounded by palaestrae, libraries, and other
garden spaces. The Baths of Trajan were only partially surrounded by an exterior
complex on the western, eastern, and southern sides which contained libraries and
gymnasia.\(^{42}\) In addition to the grandiose size of the bathing complex, the materials used,
most notably imported marble, were an integral part of transforming the bath into a
luxurious environment. The central location of the Baths of Trajan on the Oppius Mons,
near the Flavian Amphitheater, was part of the social context, in that having the baths in
an easily-accessible and well-known location allowed for a larger sector of the general
population to attend them.\(^{43}\) Other social aspects of the baths included the shops,
libraries, and the large palaestra, where bathers could exercise athletics in the palaestra,
enjoy entertainment from reading in the libraries, converse about and enjoy the vivid
decoration, and engage in dining in some of the external shops.

Based on literary evidence, some of the activities that occurred in the baths included
athletics, entertainment, eating, and drinking.\(^{44}\) The imperial baths were furnished with

\(^{41}\) Yegül 2010, 108-110.
\(^{42}\) Anderson, J.C. 1985. “The Date of the Thermae Traiani and the Topography of the
Oppius Mons.” American Journal of Archaeology 89.3: 499-509. Also cf. Nielsen, I.
Companion to Roman Architecture.
\(^{43}\) Primary sources on the location of the Baths of Trajan: Martial, 2; Suetonius, Titus 7.
For general info on the Baths, cf. Cassius Dio 69.4.1; Pausanias 5.12.6; Anderson 1985.
\(^{44}\) Literary evidence on social activities in the baths: Martial, Epigrams 3.3, 4.8, 7.32,
7.76, 11.51, 12.5; Pliny, Epistulae 5.6, 9.36; Petronius, Satyricon 28.
libraries, often one Greek and one Latin, with adjacent reading rooms, providing an enriching as well as intellectual experience. The public thermae of Rome represented an egalitarian feature of life in Roman culture which only existed at the baths.\textsuperscript{45} The range of functions baths provided offer a precious insight into Roman social activity in an informal context.\textsuperscript{46} Unlike other public gathering spaces, the baths were a place where social stratifications did not play an active role in determining who attended or what kind of interactions took place there.\textsuperscript{47}

The pinnacle of bath construction was the Thermae Antoninianae (Baths of Caracalla), the largest surviving imperial bathing complex in Rome. The Baths of Caracalla were constructed from 212-216 CE, and were among the most impressive bathing complexes built in the Roman Empire during the third century. The major developments seen in the Baths of Caracalla are marked in the selection of materials and the overall size of the complex. The use of imported stones (polychrome marbles, alabaster, Numidian stone) and the glass mosaic windows transformed the space into a vividly bright and glowing atmosphere particularly during the peak and preferred afternoon bathing time.\textsuperscript{48} Although little of these materials survive today, the Baths of Caracalla were once extravagantly decorated with marble veneered walls, mosaic floors, and glass mosaic and painted stucco vaults. The interior was further embellished with

\textsuperscript{46} Fagan 2011, 360.
free-standing sculpture and colossal columnar orders.\textsuperscript{49} The overall size of the complex was larger than any imperial bath previously constructed, spanning an estimated 80,858 square meters.\textsuperscript{50} The amount of materials and labor needed to complete the Baths of Caracalla in five years surpassed any previous imperial building project. These baths, therefore, provide a good case study to analyze the economics of imperial construction.

\section*{2.3 Economic Production of Imperial Baths}

Baths were a part of placating the public through their presentation as a civic gift and also through their luxurious and expensive decoration. In the Roman economy, the baths were considered a source of consumption because they were consumed by the general public as a service provided by the government. As part of the economic system of bath construction, baths made use of the local trade network to import building materials such as stone, timber, and brick from quarries and distribution centers in Italy and beyond. To procure these materials, the architect or patron of the baths must have had access to the greater imperial quarry network. While imperial quarries and material sourcing have been extensively researched in scholarship, a visualization showing the broader economic system of material trade, specifically with the quarries, is needed. This visualization can provide us with an opportunity to look at baths as a way of understanding and analyzing a major economic system at play. This is where DeLaine’s 1997 and Hirt’s 2010 texts

\textsuperscript{50} For a breakdown of room measurements, cf. DeLaine 1997, 227-249. Area figures used to calculate square meters: 412m x 393m.
come into play. DeLaine’s text addresses the larger economic system of bath construction from material supply, production, and transportation to implementation at the construction site. Hirt discusses the imperial quarries and mines network in the Roman Empire, and a succinct breakdown of quarries largely by material type. The Baths of Caracalla can be used as a way to make these two texts speak to each other by using them as a case study in order to analyze the larger economic system of the network of quarries in the Roman Empire. They can also be used to ask questions of this system and where the baths fit into this system. One way to answer these questions is a map which depicts and analyzes the material network specific to this building and its place within the larger network of material trade.

2.4 Methodology

One way of thinking about economic systems in the Roman world is by focusing on stone quarries. Most of the archaeological evidence for the existence of quarries comes from analyzing stone. Therefore, my methodology for interrogating these two texts is to create a GIS map of the various stone quarries and the transportation routes specifically used by the Baths of Caracalla to visualize the larger trade network, and where the baths fit into this system. The next chapter of my thesis will discuss the materials used in the Baths of Caracalla. I will analyze how they were supplied, produced, and transported, with a particular emphasis on marble. This discussion will engage material covered by both DeLaine and Hirt, systematically uniting the two texts to understand the larger implications of the bath construction industry on the material goods industry, and how these industries relate to each other. The third chapter of my thesis discusses the process
and methodology used to create the GIS map, and describes its usefulness for answering
the questions I have posed. In this chapter I use the data provided by DeLaine and Hirt to
create a dataset of quarries and roads that will then be transformed into layers in the GIS
map. This map is augmented by other digital humanities projects that incorporated road
and water data, such as ORBIS and the Digital Atlas of Roman and Medieval
Civilizations. The creation of this map allowed me to ask questions of the system of the
marble network and how the Baths of Caracalla can provide us with a fundamental
understanding of the material transportation industry.

2.5 Research Questions

When analyzing the trade network of imperial Rome from a digital standpoint,
several important research questions can be explored, including what the industry looked
like during the third century CE, and what is the best way to visualize this evidence in a
digital environment. The research questions I hope to answer are the following: How can
a spatial process help us understand the breadth of materials that went into the
construction of monumental architecture in Rome, such as the Baths of Caracalla? What
is the relationship between the broad system of quarries in the Roman Empire and the
Baths of Caracalla? How do the Baths of Caracalla fit into this larger system and what
portion of this system do they represent? What was the larger transportation network of
Imperial Rome, and how was it utilized by the builders of the Baths of Caracalla? And
finally, what does the use of various transportation networks tell us about the economy
and organization of the building sector of the Roman Empire during the imperial period?
3. Trade and Transportation Routes

3.1 Introduction

The construction of Roman buildings during the imperial period has always been intertwined with economic or socio-political motivations. Looking at buildings in relationship to economic systems is a subject worth studying because the strength of the economic system in a building’s construction can provide a signal of the current state of the economy, specifically in relation to surpluses in labor and material acquisition. By economic system, I am specifically referring to the process of acquiring and handling materials for the building project: the source, labor, transport, and building processes on site. Current scholarship provides economic data about the system; as mentioned above, I am relying particularly on DeLaine (1997) and Hirt (2010). DeLaine clearly defines this economic system through her analysis of material sourcing, production and labor, and the costs of shipping and working the materials at the site. Hirt provides geographic data of the locations for material sources (quarries and mines) as well as road data (main roads used). The information about the roads, quarries, geographic locations, and the labor used in transporting these materials are, however, partial. We can infer from the available data assumptions about the cost of shipping materials from their primary source and about the roads most likely used for their transport from what is known of the main roads network. DeLaine provided labor and cost estimates for the Baths of Caracalla, which are quite helpful in grasping the scale of the building project. The vast size of the Baths of

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51 Current state refers to the contemporary state of the economy during the building’s construction dates.
Caracalla and its luxurious decoration suggests that their construction commanded the resources of most imperial-owned quarries.

In this section, I discuss the economic system (source, labor, transport, and building) of the Baths of Caracalla individually by material type, with a particular focus on the marble system. I will also address the transportation methods and roads utilized by the Baths of Caracalla to gain a better overview of the road network in Italy and the larger Roman Empire.

3.2 Material Supply

The key materials required in the construction of the Baths of Caracalla were concrete, brick, timber, and marble. These materials were mostly sourced from imperial mines and quarries located in Rome and its environs. Luxury materials such as marble and granite, and most other stones were imported from other parts of the Empire, namely Egypt and Asia Minor. The plethora of volcanic deposits near Rome, sourced from the Apennine Mountain range, provided Roman builders with ample raw material to make one of the most reliable and versatile construction materials, concrete. This section provides a general overview of the production methods of the various building materials used in the Baths of Caracalla, with emphasis on supply and sourcing.

3.2.1 Sources and Supply of Roman Concrete

Unlike its modern counterpart, Roman concrete, or *opus caementicium*, was a mortared rubble mixture used for the foundations, walls, and vaults of bath buildings, including the Baths of Caracalla. The ingredients used to make concrete, such as tufa,
selce, pumice, and pozzolana were supplied by the Latial volcanoes southeast of Rome, as well as regions in the vicinity of Rome (fig.1).\textsuperscript{53} Tufa (\textit{tufo lionato}), a porous volcanic rock, was sourced locally from Lunghezza– a site located along the Aniene (Anio) river, a major tributary of the Tiber. Tufa was transported to Rome by water, and the river Anio would have most likely been used to transport this material to the Baths of Caracalla.\textsuperscript{54} DeLaine confirms that this particular site provided the largest amount of tufa for the walls and vaults of the Baths, compared to other common sources of tufa for building.\textsuperscript{55} Selce (leucititic lava or \textit{lava di Capo di Bova})\textsuperscript{56}, a hard volcanic rock formed from hardened lava, was sourced from the Tor Carbone and Capo di Bove quarries in Rome.\textsuperscript{57} DeLaine suggests that due to the location of the quarry along the Via Appia, the material would have been transported to Rome, and thus the Baths of Caracalla, by road.\textsuperscript{58} Pumice, a light and roughly-textured volcanic rock consisting of vesicular volcanic glass, was the only non-decorative building material sourced outside of the environs of Rome.\textsuperscript{59} Pumice for the Baths of Caracalla was sourced from the ancient Peperino quarries located in Marino (Castrimoenium) in the Alban Hills, which were about 20 Roman miles (30km)

\begin{itemize}
\item \textsuperscript{53} DeLaine 1997, 85-86.
\item \textsuperscript{54} Russell, B. 2013. “Gazetteer of Stone Quarries in the Roman World.” \textit{Oxford Roman Economy Project}. www.romaneconomy.ox.ac.uk/databases/stone_quarries_database/
\item \textsuperscript{55} Other common sources for tufa were Grotta Oscura, Monteverde, and Anio. DeLaine 1997, 87.
\item \textsuperscript{57} Lancaster 2005, 16. Selce was produced from a volcanic event in the Alban Hills, southeast of Rome, which produced lava flow that extended north-west up to the Tomb of Caecilia Metella on the Via Appia. Cf. DeLaine 1997, 87.
\item \textsuperscript{58} DeLaine 1997, 87. For information on the Tor Carbone quarry, cf. Ashby, T. 1907. “The Classical Topography of the Roman Campagna, Part III.” \textit{PBR 4}: map I. Lancaster also confirms that selce would have been transported via road: Lancaster 2005, 16.
\item \textsuperscript{59} Lancaster 2005, 16 and DeLaine 1997, 87.
\end{itemize}
away from Rome. The direct route to Rome from these quarries was the Via Appia; thus, pumice was transported by road to Rome.\textsuperscript{60} Pozzolana is a volcanic ash that was used in mortar because of its hydraulic properties. There are three types of pozzolana that were used in Imperial Rome: \textit{pozzolana rossa} (red pozzolana), \textit{pozzolana nera} (black), and \textit{pozzolanella} (grayish-color). The type used in the Baths was \textit{pozzolana rossa}. DeLaine suggests that due to the pozzolana’s dark red color, it was most likely sourced from the earliest and largest volcanic formations that were easily accessible and close to the Tiber River, such as San Paolo fuori le Mura (fig.2). Other sources for red pozzolana procured for the Baths of Caracalla include Grotta Perfetta, Fosso delle Tre Fontane, which were about 4 Roman miles (6km) from Rome and accessible by the Via Laurentina, and Marrana della Caffarella, 2.7 Roman miles (4km) away and accessible by the Via Appia.\textsuperscript{61} Therefore, all pozzolana for the Baths was transported by road, except for the stone sourced from San Paolo, which used the Tiber.

\textsuperscript{60} DeLaine 1997, 87.
\textsuperscript{61} Figures from DeLaine 1997, 87.
Figure 1. Map of Central Italy showing the volcanic and limestone regions. After DeLaine, J. 1997.

Figure 2. Map of potential sources for building materials from volcanic deposits east of Rome. Source: DeLaine, J. 1997.
The Production of Roman Concrete

Roman concrete was made by mixing an aggregate (caementa), whether selce or pumice, with mortar to produce a strong hydraulic compound. The aggregate could be composed of rough-hewn stone rubble, which added strength and durability to the concrete. Mortar was traditionally made of water mixed with powdered slaked lime (burnt album saxum), which acted as a binding agent.62 One of the strongest ingredients of the lime mortar was pozzolana, a volcanic material that when added to mortar created a chemical reaction stronger than lime mortar.63 Pozzolana had hydraulic properties and therefore could set underwater, which was highly useful in the construction of baths, aqueducts, and ports.64 The process of setting ancient concrete differs from modern concrete by the size of the stones used and way it is put into place. Modern concrete is a mixture of cement mortar and an aggregate of small stones poured directly into place over a frame of steel bars (which act as reinforcement for the concrete). Ancient concrete was a separate form laid carefully by placing the aggregate of large stones into the mortar by hand and tamping them into place with a trowel. Some type of centering structure was most likely used to help contain and shape the mortar until it was firmly set. The caementa and mortar were laid separately in order to bind the materials, since the caementa had large chunks of aggregate and required more time to set.65

64 Lancaster 2005, 3-4. Pozzolana was discovered as early as the third century BCE.
In the Baths of Caracalla, concrete was used in the foundations, walls, and vaults, which reinforced the structure, allowing for thinner walls and wider vaults.\textsuperscript{66} The process for building walls is as follows: the wall faces are constructed of brick and concrete, then aggregate and abundant mortar is mixed in between the two faces. The wall is constructed in sections about 1-1.5 meters in height, and then is capped by a brick layer that goes through the entire wall (fig. 3). Once this section is set, the next one is built. The facing and core of the walls were built together and constructed as a single unit. All

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{wall.jpg}
\caption{Figure 3 (left). Photo of wall in natatio showing brick layering. Figure 4 (right). Photo of wall showing concrete rubble mixture faced with brick.}
\end{figure}

\textsuperscript{66} For more on concrete vaulting, cf. Lancaster 2005.
visible walls would have been revetted in marble using a thick coating of mortar and metal clamps to attach the marble to the wall (figs. 4-7).

Figure 5 (top). Photo of brick-faced wall covered with thick mortar layer. Figure 6 (middle). Photo of brick wall showing top mortar layer and metal clamps. Figure 7 (zoom-in). Photo of metal clamp protruding from mortar layer. Attached to the brick wall by additional layer of mortar.
3.2.2. Sources and Supply of Brick

Bricks for the Baths of Caracalla came from Rome and its vicinity; there was a thriving brick industry in the area due to the abundance of clay alluvial deposits in the region from the banks of the Tiber river.\textsuperscript{67} The clay supply for brickyards in Rome were sourced from clay deposits near the Vatican, Esquiline, and Caelian Hills, and from the Colli di Aquatraversa, which was located on the Via Cassia (fig.8). The brickfields that supplied imperial Rome came from these areas due to the ready availability of fuel and the proximity to the Tiber, which was used to transport finished bricks to Rome and other parts of the Empire. The bricks sourced from central Italy and distributed from Portus and Ostia are known as middle Tiber Valley bricks, and these were the most common in the Baths of Caracalla. DeLaine argues that bricks for the Baths of Caracalla were sourced from Sabina (Monti Sabini region), Portus Licini, and Ostia\textsuperscript{68} due to evidence of the \textit{figlinae} (brickstamps) showing Caracalla as \textit{dominus}. The \textit{dominus} on brickstamps was the official name (often the emperor or private owner) of the brickyard. Most brickyards were imperially owned, and bricks often bore the name of the emperor in power during the time of their production. The bricks bearing the name Caracalla were connected with the \textit{tegularium} (brickyard) of Portus Licini, which was operational until the 6\textsuperscript{th} century CE.\textsuperscript{69} The exact location of the Portus Licini is unknown, but it is possible to make assumptions about its location based on the types of bricks it produced and housed. The Portus Licini was probably the primary supplier of bricks for the Baths of Caracalla based

\textsuperscript{67} DeLaine 1997, 89-91.
\textsuperscript{69} DeLaine 1997, 90. Also Cassius Dio, \textit{Var.} 1.25.
on its speculative location in praedia Liciniana, which was closer to Rome and located along the Tiber river for transport. It is also thought to have been a major storage and distribution center for the many bricks arriving to Rome from other parts of Italy.\textsuperscript{70} Outside of Rome, evidence for brick production is scarce, which is why the scholarship relies so heavily on Roman evidence for understanding and reconstructing this particular industry.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{map}
\caption{Map of major clay deposits in Italy. Source: DeLaine, J. 1997.}
\end{figure}

The Production of Brick

The process of producing bricks in imperial Rome was complex and involved a series of time-sensitive steps. Brick-making was a seasonal industry, and bricks could only be made during the spring or autumn months as the weather during the summer and winter months would dry out the clay too quickly so that the bricks would not dry uniformly.\textsuperscript{71} The first step in brick production was selecting the source of clay and then preparing the clay for drying. The ideal clay which could be laid readily was red or white clay, as clay with sand or pebbles in it could not hold shape during the rain.\textsuperscript{72} The clay was procured from large open-cast pits located near the brickyards. It was dug during the summer, autumn, and winter months, and left to dry until the spring. After the clay was dug, it was transferred to an open area in the brickyard for weathering. The second stage was tempering the clay, in which the clay was worked by treading or hoeing to remove large impurities in order to form a paste.\textsuperscript{73} Sharp sand, pozzolana (in the case of Roman brick) or other fine volcanic stones were then mixed into the clay to prevent shrinkage and warping. Once the clay was prepared, the brick was moulded into shape by taking a flat slab of clay and placing it into a wet wooden frame. The clay was cut and shaped inside the frame to create a specific type of brick; the round \textit{tubuli} were formed by shaping the wet slab around a smooth, round object. Square \textit{tegulae} and other bricks for building were shaped by being cut inside the frame at a bench and sanded to prevent sticking. The more basic bricks that didn’t require too much shaping, such as the \textit{bessales}

\textsuperscript{71} This is based on literary evidence from Vitruvius, \textit{De Architectura}. 2.3.1-5.  
\textsuperscript{72} Vitruvius, \textit{De Architectura}. 2.3.1-2.  
\textsuperscript{73} The larger impurities were removed by hand. DeLaine 1997, 114.
were formed directly on the drying floor, which made the process faster.\textsuperscript{74} There were four different types of bricks produced for the Baths of Caracalla: bricks for facing on walls, vaults, arches and bonding courses (\textit{sesquipedales}), bricks for \textit{bessales} (heated floor tiles) and \textit{bipedales} for \textit{pilae} (small columns of brick supporting the suspended floor in the hypocaust), and bricks for the rectangular \textit{tubuli} used in heated walls.

DeLaine accounts for a total of 4,000 bricks (1,000 of each type) used in the construction of the Baths of Caracalla. The bricks were then carried inside the frames to the drying area, laid in rows of single layers, and then the frame was removed. The first stage of drying was the leather-hard stage, usually reached within one to six days. The bricks were then stacked in small piles to continue drying for another three to four weeks. Bricks were sun-dried in order to get the best quality and have uniform dryness.\textsuperscript{75} The whole production process took place from April to September, when it was least likely to rain in central Italy, based on evidence from graffiti on bricks dating between June and October, as well as footprints left by young sheep and goats on some tiles.\textsuperscript{76}

After the second stage of the drying period, bricks were ready to be fired in the kiln. The dried bricks were transported to the kilns in the brickyard and then fired according to their thickness and the kiln size. Kilns varied in height and width, which determined the amount of bricks that could be fired and the length of time for firing.\textsuperscript{77}

\textsuperscript{74} DeLaine 1997, 115.
\textsuperscript{75} DeLaine 2015, 227.
\textsuperscript{77} A key source for explaining the variation in kiln measurements, firing process, and fuel amounts is DeLaine 1997 114-118.
DeLaine estimates that an average Roman kiln measured 5x5x4m and had a firing capacity of 65m$^3$ of bricks. The firing would take about 60 hours, followed by a cooling period of 3-5 days.\textsuperscript{78} The firing season was a short season lasting from about five to six months, which created some variability in the final product depending on where the brick was placed in the kiln. Once the firing was complete, the finished bricks were sorted according to type, and either loaded onto carts for transport or put in storage for future construction projects.

### 3.2.3 Sources and Supply of Timber

Timber for the Baths of Caracalla was primarily sourced from the areas of Sabina, Etruria, and Umbria, all accessible via the Tiber and its tributaries (fig. 9).\textsuperscript{79} The Sabina was rich in oak, which was one of the strongest and most durable types of wood used in the baths. Oak was a native and dominant tree in central Italy, particularly in the forests of Western Italy. Other dominant tree types include the quercus ilex (evergreen holm-oak), elm, poplar, and cypress.\textsuperscript{80} Pine and fir trees were common in the mountains, although they grew at 1200m altitudes.\textsuperscript{81} Fir was sourced from the western side of the Apennines near Etruria and Campania because it was the best quality fir; the western side received more sun and therefore the wood was drier and harder.\textsuperscript{82} While we know that wood was definitely used in the construction of the baths, the evidence for timber usage

\textsuperscript{78} DeLaine 1997, 117.
\textsuperscript{79} DeLaine 1997, 91-93. Also cf. Strabo, Geographica. 222-228, 235.
\textsuperscript{80} Meiggs, R. 1982. Trees and Timber in the Ancient Mediterranean World. Oxford: Clarendon Press. 240. This is the primary source on timber from the ancient world.
\textsuperscript{81} DeLaine 1997, 92. Meiggs also mentions the popularity of the pine, oak, and cypress (p.218).
\textsuperscript{82} Meiggs 1982, 241.
as a building material and for scaffolding is not abundant: wood in Italy tends not to be preserved, and the literary sources do not mention the use of wood in bath construction. However, based on imprints of the wood in the clay from the walls and vaulting, as well as the putlog holes for the scaffolding, scholars have determined that wood was used at least as a temporary feature in the construction process for both scaffolding and as framework to support the concrete vaults until they set (fig. 10). Once the parts of the walls and vaults that relied on structural supports were finished, the scaffolding was removed. Timber and brushwood were used in increasing quantities as fuel for the furnaces in order to heat the rooms and walls through the *tubuli*. As the imperial public baths increased in size, the demand and consumption of wooden fuel also increased exponentially.

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**Figure 9. Map of Italian Regions and Timber Sources. Source: Boatwright, M.T. 2011. The Romans: From Village to Empire.**

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83 DeLaine 1997, 85, 92.
84 Meiggs 1982, 257-259.
The production of timber involved an economic system of acquisition, felling, extraction, transport, and implementation. The timber industry however is the least recorded among ancient sources. Vitruvius and Strabo provide decent accounts on the treatment of wood for urban development and domestic building, of which some descriptions can be applied to public baths. As with brick, the timber industry was seasonal. According to Meiggs, trees had to be felled when the year’s growth ended, usually in autumn, with the exception of the oak tree which had to be cut last because its leaves fell last. Columella suggests that January was the best month for cutting coppice, as well as felling and dressing timber for building (De Re Rustica, 11.2.11-13). Once the trees were felled, they were stripped of the branches using an axe and then taken to the

Figure 10. Examples of put-log holes from Baths of Caracalla.

The Production of Timber

The production of timber involved an economic system of acquisition, felling, extraction, transport, and implementation. The timber industry however is the least recorded among ancient sources. Vitruvius and Strabo provide decent accounts on the treatment of wood for urban development and domestic building, of which some descriptions can be applied to public baths. As with brick, the timber industry was seasonal. According to Meiggs, trees had to be felled when the year’s growth ended, usually in autumn, with the exception of the oak tree which had to be cut last because its leaves fell last. Columella suggests that January was the best month for cutting coppice, as well as felling and dressing timber for building (De Re Rustica, 11.2.11-13). Once the trees were felled, they were stripped of the branches using an axe and then taken to the
timber yard by ox-cart or wagon. At the timber yard, the wood was cut to meet the specific requirements for different building projects. Timbers that did not meet the length requirements were cut down on site. However, because of the vast scale of the Baths of Caracalla, particularly long timbers were required for the scaffolding and putlogs.\textsuperscript{85} Large square timbers were needed for the vault frameworks, as well as for supports, lifting device frames, and the posts of foundations.\textsuperscript{86} The timbers were then loaded onto oxcarts for road transport or the river for water transport, depending on the location of the timber yard.

### 3.2.4 Sources and Supply of Marble and Stone

The major stones used in the central bathing block of the Baths of Caracalla were white marble, granite, porphyry, and colored marble.\textsuperscript{87} They were sourced mainly from well-known quarries in Italy and the Empire, most of them imperially owned based on evidence from inscriptions on quarried blocks (fig.11).\textsuperscript{88} The main quarries supplying the Baths of Caracalla can be broken down by region (table 1): \textsuperscript{89}

\textsuperscript{85} DeLaine (1997: 91-93) discusses the length requirements for timber for the Baths of Caracalla.
\textsuperscript{86} DeLaine 1997, 91.
The types of building stones required for the Baths were sourced both locally as well as imported, especially with the expensive stones such as alabaster. More specifically, the column shafts required polychrome stones: Carystian, Yellow Numidian, Docimian, grey marble (Preconnesian), Egyptian Alabaster, red porphyry, red Assuan, grey granite from Mons Claudianus, and grey granite from Kozak Dag in the Asia Minor.90 The column fixtures (bases, capitals, entablatures) were constructed of white Luna marble from Carrara, Preconnesian marble from Asia Minor, and Pentelic marble from Athens.91 For the marble veneer on the walls, expensive marbles such as Thessalian, Red marble from Cape Taenarum, Chian, and Breccia Corallina were used (figs. 12-13). The breadth and variety of marbles, granites, and other stones suggests the luxurious and costly nature of the Baths of Caracalla, and the imperial command of a vast amount of natural resources.

91 DeLaine 1997, 94-95.
Marble was transported both by road on oxcart and by water (sea and river) on rafts and ships. Some interesting evidence for marble shipments to Rome were discovered in several shipwrecks bearing marble cargo found along the coasts of Sicily and Italy and dating to the early-mid third century CE. DeLaine suggests that these ships were probably headed to Rome and may have been carrying the exceptional amounts of material that were required for building the Baths of Caracalla. Based on this evidence, it is reasonable to assume that marble was transported via sea routes to Rome in large ships to support the width and weight of blocks of marble veneer, flooring, and decorative elements.

Figure 11. Map of the Roman Empire showing major marble quarries used in the central block of the Baths of Caracalla. Source: DeLaine, J. 1997.

Key:
1. Luna
2. Pentelic
3. Proconnesian
4. Red Porphyry
5. Mons Claudianus
6. Assuan
7. Kozak Dag
8. Green Porphyry
9. Numidian
10. Thessalian
11. Caryotian
12. Rosso Antico
13. Chian
14. Africano
15. Breccia Corallina

The Production of Marble

The process of producing marble for use in the buildings of Imperial Rome comprised a difficult procedure of extraction, initial working/shaping at the quarry, and then transportation to the building site. There were no standard methods of extraction for imperial quarries, as methods varied based on the geology and conditions of the quarry. These variations have made it difficult for scholars to generalize about the production methods used for different marbles. However, DeLaine believes that it is possible to assume there was a set of common extraction and production techniques in use at most Roman marble quarries. During the extraction process, a block was typically defined at
the quarry face through a series of trenches cut on the back and sides with a pick. The defined block was then separated from the bedrock by wedges or levers and moved away from the quarry face for shaping.\textsuperscript{94} Columns were not separated from the parent rock and were shaped while still attached to prevent breakage.\textsuperscript{95} Veneer blocks had to be shaped into rectangular blocks to remove defective spots, while other marbles used for architectural elements were left rough to be carved once on site. Marble was more difficult to work than timber or brick, as quarrying methods where highly technical and detailed work required skilled labor. Once the marble was procured and shaped, it was loaded on oxcarts and then ships for transport.

### 3.3 Material Logistics: Labor, Cost, and Transportation

A general economic picture of the supply, labor, and transportation of the building material as part of the economic system is necessary to understand the material transportation network used to supply the Baths of Caracalla. For cost, I focus on its importance relative to the luxurious aspect of imported goods, rather than an economic factor or indicator. By this, I mean that I am more interested in why the marble was expensive rather than how much it cost. The only known costs, most of which are speculative, are for the marble, and therefore these will be the only costs addressed.\textsuperscript{96}

\textsuperscript{95} DeLaine 1997, 119.  
\textsuperscript{96} DeLaine provides estimated costs for the bulk building materials, bricks, timber, and decorative materials based on the Price Edict. However, I am only focused on marble
Imperial Rome had a sophisticated road and nautical trade network that allowed for the efficient movement of stone, timber, and bricks from many areas of the Roman Empire. The most fluid part of the economic system for materials was the transportation component, of which two main options existed: land and water transport. Land transport was facilitated by the major road network of imperial Rome (fig.14). The main roads leading to and from Rome were the Via Appia, Via Ostiensis, Via Ardeatina, Via Latina, Via Laurentina, and the Via Portuense. The Via Nova was a new road constructed to be the main access line to the Baths of Caracalla; it ran parallel to the Via Appia on the northern side of the Baths. It was significantly wider (almost double in size) than the Via Appia in order to support the traffic of wide-loaded carts and wagons coming from the Tiber and south of Rome, thereby relieving the Via Appia of constant construction traffic. These main roads were also used to transport supplies from the local quarries in Rome and Luna, as well as imported materials that were shipped up the Tiber.

97 DeLaine 1997, 20, 100.
A comparative analysis on the various material productions can contribute to the discussion of the labor and transportation of building materials to the Baths of Caracalla. Timber was sourced from northern Italy, and its transportation to the Baths of Caracalla relied on shipping the logs down the Tiber until they reached the port closest to the site (Marmorata), from which they were carried to the site by oxcart. Much like timber, marble was shipped up the Tiber to the port closest to the Baths of Caracalla and then carried to the site by oxcart. Brickyards were much closer to Rome, and therefore relied on water transport to the major ports, such as Ostia, and then up the Tiber which led
directly into Rome. DeLaine calculates about 20 million total bricks\textsuperscript{98} were used in the Baths of Caracalla, mostly supplied from the distribution centers at Portus and Ostia. Because of the distances that imported marble had to travel and the significant weight of the material, the cost of transportation far exceeded that of the more local brick or wood.\textsuperscript{99}

A key factor in the economics of transportation was the labor component, both man power and ox or mule power. According to DeLaine, each man could carry a maximum load of about 50 kg over a short distance.\textsuperscript{100} For longer distances and larger loads transported on land, DeLaine argues that pack animals (oxen and mules) could bear loads ranging from \textasciitilde 55kg to 120-135kg, dependent upon the size of the animal. For an ox cart drawn by a pair of oxen or mules, she estimated the load bearing to be \textasciitilde 500kg travelling at a slower rate of 1.67km per hour with a heavy load (20 miles per day).\textsuperscript{101} Each pair of oxen required one attendant, which contributed to the cost of transport.

Water transport into Rome itself mainly involved the Tiber and its tributaries. For moving material over sea, the transportation loads could vary based on the vessel size. DeLaine suggests that smaller ships suitable for long distance could bear 70-80 tonnes,

\textsuperscript{98} DeLaine 1997, 124-130.
\textsuperscript{99} Timber that came from Pisa and further north of Rome was also difficult to transport due to the length and weight of the beams.
\textsuperscript{100} DeLaine 1997, 107. This figure is based on the old imperial hundredweight, which was the traditional standard maximum load in Britain. She opted for a slightly lower figure to account generally for all distances, resulting in potentially low err.
\textsuperscript{101} According to the Theodosian Code. 8.5.30., which states the figure as 1500 librae. She compared this with the standard cart load mentioned in the Price Edict, 14.8, 17.3., which gives 1200 librae, or about 400kg. (DeLaine 1997, 108.) Mileage based on 12 hour calculation. For 24 hours at 1.67km/hour, the total distance travelled per day would have been 85 miles.
while larger ships could carry up to 300-400 tonnes.\textsuperscript{102} Some cargo ships might even carry 1000-1200 tonnes, such as the \textit{Isis} mentioned by Lucian.\textsuperscript{103} For labor figures, she estimates that small to medium-sized vessels were operated by 4-10 men, and could travel up to 3-4 knots per day (75-95 miles/day), depending on the weather.\textsuperscript{104} Once the larger vessels reached the mouth of the Tiber, the materials were transferred to smaller rafts which then travelled up the Tiber to the docks at Marmorata or the Emporium areas.\textsuperscript{105} The materials were placed on carts and taken to the site, traveling a distance of 1.8 km (for the Baths of Caracalla).\textsuperscript{106}

Aside from the costs of labor and transportation, it is worth noting the larger economic benefits of bath construction. These large-scale building projects helped with unemployment in urban centers, especially in Rome. DeLaine provides some highly speculative figures for the building industry in Rome during the Severan period. I will use these figures to illustrate a general economic picture of the building industry in Rome during the construction of the Baths of Caracalla. DeLaine estimates that about 20,000 men were employed total – 14,000 skilled and unskilled laborers, 4,000-5,000 drivers and pairs of oxen, and 1,000 laborers in the countryside (farmers).\textsuperscript{107} The majority of workers employed for the Baths were located in Rome or the immediate environs, with a smaller

\begin{footnotes}
\item[102] DeLaine 1997, 108.
\item[103] Lucian, \textit{Navigium}. 5.
\item[107] DeLaine 1997, 197-200.
\end{footnotes}
amount employed in distant and rural areas. The mass production of brick and tile that took place from the 2nd century CE provided employment in private and imperial brickyards for the unskilled.\textsuperscript{108} According to DeLaine, the Baths of Caracalla costed an estimated 12 million KM of wheat (without the outer precinct).\textsuperscript{109} For a price conversion to Roman currency, DeLaine implies that 1KM = 10 sesterces, suggesting that the construction of the central bathing block cost 120 million sesterces.\textsuperscript{110} The outer precinct of the Baths of Caracalla was not constructed until the late third century CE. DeLaine argues that this might suggest a shortage of supplies on building materials, since imperial building projects were becoming less common in the early-mid third century CE due partially to imperial spending on wars.\textsuperscript{111}

3.4. Marble

For an economic analysis of the imperial construction industry, it is most useful to focus on marble, as this is the material for which we have the best and most extensive data. The marble veneer, columns, and sculptural displays were the key point of contact for bathers, in that the opulent polychrome and white marble fixtures were what people first saw upon entering the complex and what would have made the greatest impression on them. The final phase of the marble production process covered the different ways in which marble was worked, which varied from rough-cut to smooth textures, the play of the natural colors against white marble backgrounds, and the indication of luxury found

\textsuperscript{108} Meiggs 1982, 257-258.
\textsuperscript{109} Kastrensis Modii (KM) is a Roman dry measure of wheat, equaling 1/3 of an amphora. This has been converted to equal 8.5 liters $\rightarrow$ 550 in$^3$ $\rightarrow$ 2 gallons.
\textsuperscript{110} DeLaine 1997, 207-224.
\textsuperscript{111} DeLaine 1997, 207-224.
in the expense of imported marbles. Skilled experts that specialized in working specific types of marbles were brought on to building projects involving the specialized marble.\textsuperscript{112} There was a variable significance in marble cost, and marble can be looked at as a way to understand the priorities of building materials in relation to their face value and value in the bath building. The economic system of marble points to some significant parts of the structure, mainly the colossal columns of the frigidarium and the palaestra, and the marble revetment in most of the larger bathing rooms (fig. 15).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{granite_column_in_palaestra.png}
\caption{Photo of a Granite column in the Palaestra for a sense of the scale of the marble columns.}
\end{figure}

DeLaine provides the most detailed account of the costs of marble based on the price figures per square foot of marble slab in Diocletian’s Price Edict.\textsuperscript{113} Decorative marbles (capitals, architectural features) have too many factors to account for in terms of


\textsuperscript{113} DeLaine 1997, 213-215.
cost for the scope of this thesis. Therefore, I will only address the cost of marble veneer. I will use the values given by DeLaine and the Price Edict for veneer, expressed in denarii and KM. The Price Edict offers a list of the maximum prices for marbles charged per cubic foot, which range greatly.\textsuperscript{114} For example, Lacedaemonian and red porphyry cost 250 denarii, Docimian and Numidian marbles cost 200, Alabaster cost 75, and white marble from Proconnesus cost 40-50 (table 2).\textsuperscript{115}

Table 2. Prices of Polychrome Stones Listed in Diocletian’s \textit{Price Edict}. Source: Malacrino 2010. Unidentified stones were removed from this table.

<table>
<thead>
<tr>
<th>Stone Name (in Edict)</th>
<th>Modern Name</th>
<th>Price per cubic foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lapis Porphyrites</td>
<td>Porphyry Rosso Antico</td>
<td>250 denarii</td>
</tr>
<tr>
<td>Marmor Lacedaemonium</td>
<td>Serpentine, Porphyry Verde Antico</td>
<td>250 denarii</td>
</tr>
<tr>
<td>Marmor Numidium</td>
<td>Giallo Antico</td>
<td>200 denarii</td>
</tr>
<tr>
<td>Marmor Lucullaeum</td>
<td>Africano Marble</td>
<td>150 denarii</td>
</tr>
<tr>
<td>Lapis Pyyrhopoecilus</td>
<td>Syenite, Aswan red granite</td>
<td>100 denarii</td>
</tr>
<tr>
<td>Marmor Claudianum</td>
<td>Granito del Foro</td>
<td>100 denarii</td>
</tr>
<tr>
<td>Lapis Alabastrites</td>
<td>Alabaster, Alabastro Egiziano</td>
<td>75 denarii</td>
</tr>
<tr>
<td>Marmor Docimium</td>
<td>Pavonazzetto</td>
<td>200 denarii</td>
</tr>
<tr>
<td>Marmor Triponticum</td>
<td>Peacock’s Eye</td>
<td>75 denarii</td>
</tr>
<tr>
<td>Marmor Thessalicum</td>
<td>Verde Antico</td>
<td>150 denarii</td>
</tr>
<tr>
<td>Marmor Carystium</td>
<td>Cipollino Verde</td>
<td>100 denarii</td>
</tr>
</tbody>
</table>

\textsuperscript{114} In denarii. Cf. Malacrino 2010 p.30 for a list of the Edict’s prices on polychrome marble.

\textsuperscript{115} DeLaine 1997, 212-215.
### Marble Quarries and Transportation Costs

<table>
<thead>
<tr>
<th>Marble Quarring</th>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Marmor Scyrticum</strong></td>
<td>Skyros White Marble</td>
<td>40 denarii</td>
</tr>
<tr>
<td><strong>Herakleitotikos Lithos</strong></td>
<td>Marble from Herakleia at Latmos</td>
<td>75 denarii</td>
</tr>
<tr>
<td><strong>Marmor Lesbium</strong></td>
<td>Lesbos white marble</td>
<td>40 denarii</td>
</tr>
<tr>
<td><strong>Marmor Thasium</strong></td>
<td>Thasos white marble, Greek black marble</td>
<td>50 denarii</td>
</tr>
<tr>
<td><strong>Marmor Proconnesium</strong></td>
<td>Preconnesian, Marmo Cipolla</td>
<td>40 denarii</td>
</tr>
</tbody>
</table>

The transportation costs of marble depended upon the type and quality of marble. Duncan-Jones observed that the Edict’s prices for land transport were always higher than for shipment by sea due to frequent stops, animal feed and maintenance, and generic difficulties when travelling by road. He estimates the average freight charge for about 1200 *librae* (pounds) per wagon was 20 denarii per kilometer.\(^{116}\) Visualizing the system of marble quarries is both highly desirable and necessary for understanding the larger system of transporting materials in the Roman Empire.

4. Spatial Analysis of Marble Movement Using GIS

4.1 Methodology

Previous scholarship has extensively explored the construction and vast command of materials for monumental building projects in the Roman Empire. DeLaine provides a comprehensive and organized dataset of sources, production statistics, and methods of transportation of materials for monumental building projects in Rome, especially for the Baths of Caracalla. Several Digital Humanities projects, such as Stanford’s ORBIS and Harvard’s Digital Atlas of Roman and Medieval Civilizations (DARMC) incorporate GIS to explore the movement and broader network of cities and roads in the Roman Empire. ORBIS employs an excellent methodology of using GIS to perform cost-distance calculations for travel between cities in the Roman Empire according to the season and method of transportation (water or road). These projects are successful in using GIS to visualize spatial movement and places across the large expanse of the Roman Empire. Still, there is a lack of attention in scholarship to the visualization of the movement of materials in the Roman Empire. I believe that GIS has the ability to offer a more holistic and spatial sense of the wide reach of monumental construction in the Roman Empire, specifically for building projects in Rome. The question I want to answer with GIS is whether a spatial digital analysis can help us understand the organization of the breadth of materials that went into the construction of monumental architecture in Rome, such as the Baths of Caracalla?

Two projects in particular were critical to the research and methodology of my project. The first project that was critical to my research was DeLaine’s 1997 scholarship on the Baths of Caracalla. DeLaine provides structured datasets on the methods of
procurement, production, and transportation of building materials used in the Baths. I focused on her provisions for marble, for which she provided not only the quarry names and the procuring process, but went to great lengths to estimate the costs of labor and shipment of marble across the Empire based on Diocletian’s Price Edict. The second project critical to my research, but in a different way, was ORBIS. I was inspired by ORBIS’ approach, and found it to be useful to my project. The way that it is different is not about the data they were using, but the model they used (Agent-Based Modeling). Their data begins with settlements and the methods of movement between them. The approach becomes more complex when they used an ABM cost map that calculated travel time and distance based on variables such as weather, time of year, physical terrain, and mode of transport. They even included transportation technology constraints in their methodology, such as wind direction, to help them create accurate sea routes in real-time. This is an admirable project, and a lot of excellent research has gone into creating one of the most complex visualizations of travel in the Roman world ever made. As a whole, these are all extremely valuable contributions to fundamentally understanding travel in the ancient world. However, what is not relevant in the ORBIS project that is directly relevant to my analysis, is a constraint on settlements. In the context of my project, most of the quarries do not exist in settlements; rather they exist outside of cities and are often connected to main roads or waterways for transportation.

Therefore, my method is to combine open data from one project (DARMC), the methodology from another (ORBIS), and the topic and data of a non-digital project (DeLaine) in order to focus on marble quarries and the transportation of the materials from these quarries to the building site. My approach considers GIS as a method of
aggregating historical data by other scholars and applying the method of Agent-Based Modeling, specifically cost-distance and cost-path analysis. Using GIS, I created a map of all the known marble and stone quarries in the Roman Empire, with a focus on the quarries specifically used in the construction of the Baths of Caracalla, as well as the methods of transportation (road and waterways) that lead from these quarries to the building site. This map serves as a heuristic tool that combines data from several geographical resources and digital humanities projects to more fully investigate the transportation of marble in monumental construction.\(^{117}\) In this chapter, I discuss the process of designing the map in three phases: data collection, modeling, and analysis.

4.2 Pre-Process Layers

The design process in GIS generally occurs in three phases: data collection, approach, and process. The data I needed to collect for this project was:

- Quarry Locations – Russell Database
- Elevation Data – USGS Earth Explorer
- Road Data – DARMC
- Waterways Data (inland, open sea, rivers) – UNC-AWMC
- Ports and Harbors – DARMC
- Settlements Data – UNC-AWMC and Pleiades

The first phase of this project involved collecting data for the quarry locations. This data is the most essential as it is the main variable being measured. This data was sourced from an extensive gazetteer written by Ben Russell listing 792 stone quarries in the

\(^{117}\) I selected ESRI’s (Environmental Systems Research Institute) ArcGIS Pro and ESRI Story Map as the software for the synthesis and presentation of my research because it is the optimal software for Historical GIS projects, and has real-world applications for environmental and geological research. I considered open-source GIS tools, such as QGIS, but I thought there would be a performance loss for more advanced analyses like cost-distance.
Aside from the quarry data, the most vital data to collect was the elevation data because I needed this in order to perform analyses on historical data, such as ports and quarry locations, that account for terrain, like least-cost path or cost-distance. Therefore, the second step was adding the Digital Elevation Model (DEM), which is a raster file containing the height and surface data of a specified terrain. Because I had such a large dataset, I decided to use the elevation data provided by USGS Earth Explorer. The DEM is the foundation for my cost map, which is a calculated raster map based on elevation data that assigns cost to the slope of the elevation model. The cost map is required for the cost distance analysis. Cost distance uses the cost map to determine the shortest weighted distance from each cell to the nearest source. The analysis is based on the least cost (least cost path) over a cost surface, which is the cost map.

The third layer of data to collect was the roads. Roads were the next-fastest alternative to sea travel, and were the main means of transportation for bulk building materials sourced from Rome and the immediate environs, such as brick and tufa. The road data is a geodatabase of all the roads in the Roman Empire created by DARMC. The fourth layer was the water data, which includes inland water, open water (sea), and

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rivers in the Roman Empire. Waterways were the fastest method of transportation for building materials. This data was created by the UNC-Ancient World Mapping Center (AWMC). The fifth layer of data collection was the ports and harbors. This data is essential for pattern recognition of the proximity of quarries to water or road transportation routes, as well as distinguishing between coastal quarries and inland quarries. This data was also created by DARMC. The final data to collect was the settlements dataset, created by the UNC-AWMC, which combines data from Pelagios Commons and Pleiades digital projects. This dataset serves as a spatial indicator for the nearness table analysis which identifies the proximity of quarries to cities with ports or major road connections. These open source projects have a significant amount of research behind their data, and I find them to be accurate and valid sources of historic data.

The second phase is formatting the data to meet the file type requirements of the software. For the elevation data, each DEM file comes as a tile, which then had to be merged as a mosaic dataset. A mosaic is essentially a massive raster that combines all the elevation tiles into one seamless layer. The quarry data came as a .csv, for which I used the Display XY Data tool to plot the coordinates onto the map. The roads and water layers came as vector shapefiles, and the rivers came as polygons. The ports and settlements data also came as .csv files, and using the same tool for displaying the quarries, I plotted the points on the map. The projection system selected for the map is

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http://awmc.unc.edu/awmc/map_data/shapefiles/physical_data/inlandwater/ 
http://awmc.unc.edu/awmc/map_data/shapefiles/pleiades/data
ELD 1979 UTM Zone 33N. I chose this projection because my map is measured in kilometers, and the UTM projection uses an x y coordinate system based in meters rather than degrees. This type of projection was also necessary for the analyses I ran on the data. After the data collection phase, I was able to start aggregating the data and applying cost distance to the map, which is a form of Agent-Based Modeling.

4.3 Agent-Based Modeling and Cost-Distance

There are multiple definitions and applications of Agent-Based Modeling (ABM) in GIS and Digital Humanities projects.\textsuperscript{124} For the context of my project, I define ABM as a computational model for simulating the actions of an individual agent on its environment from the perspective of assessing the agent’s effect on the holistic system. The agent in my project is someone trying to move stone and the model is how difficult it is to move that stone. Within this ABM model, cost analyses are run to determine the least-cost path. ArcGIS Pro defines cost-distance analysis as the exploration of the movement of a traveler over a landscape. The analysis uses “cost tools” that create a least-cost path (LCP) between the source and the destination, which in my project is between the quarries (source) and the Baths of Caracalla site (destination).\textsuperscript{125} The entire model runs on an algorithm that essentially divides the map into a systematic grid of cells.


and assigns values to each cell based on the initial values set by the cost raster. During the cost analysis process, the model looks to the nearest neighbor of each cell, and based on the value of the cell, determines the least-cost path to take to get to the destination. The LCP is a single, one-cell wide path that leads from a specified source to a destination. ORBIS’ approach to cost distance was to determine the fastest, shortest, and cheapest routes based on the variables of time (month), season, weather, physical terrain (road, sea, river) and method (foot, oxcart, horse). Their measurements were based in kilometers, and they factored in environmental constraints such as wind and weather to more accurately determine travel time and distance.

For the scope of my project, I converted the roads and water data features into rasters with assigned values, essentially turning them into cells. The values are calculated in cost-kilometers, and the cell sizes are based on the height of the slope map. Based on the values I assigned to each raster pixel (or cell), when I run my cost analysis, the software will determine the least-cost path. Water travel is always preferable over roads because it is cheaper (less animal and man power involved, less elevation). Therefore, in order to make the software choose a sea route (path) when relevant based on quarry location (near a port/harbor), I assigned all sea-route pixels to be a lower value than roads. I assigned the sea rasters a value of 1 cost kilometer based on the slope map,

126 The roads were initially based on the slope map cell size, which is 31.3279. The slope map file size is 86 GB.
127 The slope map cell size is 31.3279130544396 or 31.33 for simplicity. My slope map ended up being 86 GB, due to the amount of elevation data it was mapping. The highest point reached in the terrain is 88.6401°. However, once the roads and water were converted to rasters, they took a cell size of 1 to equal the raster size of the DEM and slope rasters.
and roads a value of 4 cost km. However, to prevent the LCP from always choosing sea routes over roads (since this wasn’t the fastest route for all quarries and because stone can’t be loaded onto a ship just anywhere along the coast or river), I created a buffer “wall” around the coast that only allowed ports located within a 20km radius of the sea to connect to sea transport as the LCP. I also created a multi-ring buffer around the ports to connect them to the coastline. For the road routes, I used the extract by mask tool to make all the roads equal 4 cost km so the software would recognize the roads as lower cost in comparison to the general terrain (flat ground with no roads), which is valued at 8 cost kilometers. For rasters, the water (ocean) and general terrain adds to the cost km and roads, sea routes, and ports subtract from the cost km. This is configured in the slope map, which is the gradient/steepness from each cell of a raster file. The difficulty of moving stone in the ABM is reinterpreted as a cost map, based on elevation data in the slope map. In order to interpret the difficulty of moving stone in the ABM, I had to turn the slope map into a cost map based on DeLaine’s road and water distance calculations for a raw distance comparison. Therefore, the slope map is reclassified into a cost map, in which the slope values are calculated to represent the costs assigned to the different height levels of terrain (roads =4, flat ground =8, sea routes = 1, sea = 1000).

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128 Water should equal 1, because water travel is the easiest and most preferable. Roads should equal 4, because they are 4 times slower and more costly. I determined this number based on dividing DeLaine’s calculations for the mileage distance for water and road travel. 75 miles (sea) / 20 miles (land) = 3.75, which I rounded to 4 since cost distance calculations cannot be done in decimals.

129 I valued the entire sea as 1000 so the software would be limited to only using sea routes to get to the baths and not use the whole sea as one platform to reach them.
4.4 Cost-Map

In this section, I discuss how I built my cost map. A cost map is the elevation data from the slope map reinterpreted to represent cost in terms of distance measured in cost kilometers. I used the time and distance calculations provided by ORBIS and DeLaine for my experiment because I wanted to concentrate on building the cost map, collecting information for the quarries that supplied the Baths, and identifying any patterns in the data. I find the calculations provided by the Stanford ORBIS project and DeLaine to be perfectly suitable for my project and well-researched. The first step to build the cost map was to transform the elevation data into cost data by merging the roads, sea routes, the ports buffer, and the coastline buffer with the slope map. Then, I had to reclassify the slope map to account for cost. The process starts with taking the large DEM raster and converting it to a slope map. Then, I had to reclassify the slope map to different parameters in terms of cost:

- 0 – 10% slope = 1 cost km
- 10 – 20% slope = 2 cost km
- 20 – 30% slope = 3 cost km
- 30 – 35% slope = 4 cost km
- …continues until the maximum slope of 90% (90°)

Essentially, I used the slope map as a cost map but reclassified it according to how many units of cost each cell is worth. The best way to demonstrate the reasons for creating a cost map is through a sequence of maps illustrating the data layers on a scale of analysis from simple to complex. The first map is a single-point layer, which is a simple geometric map of plotted points on a grid (fig.16). The second is a multi-point layer, which has more than one data layer of point features (fig.17). The third is more complex, consisting of vector lines connecting points (fig 18). The fourth is a multi-point and
multi-line layer map created using ORBIS (fig 19). The fifth and final map is my map showing multiple layers focused on marble quarries (fig 20).

Figure 16. Single-Point Layer of Stone Quarries Colored by Stone Type.

Figure 17. Multi-Point Layer Showing Ports, Settlements, and Stone Quarries.
Figure 18. Vectors Connecting to Points Demonstration.

Figure 19. ORBIS Vector Map Showing Multi-point and Line Features.
The single-point map (fig. 16) is a simple geometric map of plotted points on a grid. The different colors represent different types of stone, with marble as the blue points. This map demonstrates clusters of quarries geologically based on stone type. The multi-point map (fig. 17) is more complex than the single-point map because it has multiple layers of points which implies a connection between points and quarries. The gray points represent settlements, the gold represent ports and harbors, and the multi-colored points represent the stone quarries. The vector lines map (fig. 18) shows stone quarries connected to a destination (the Baths of Caracalla) by straight lines “as the crow flies”. This map increases in complexity because it demonstrates a sense of movement and specific spatial relationship. Movement is displayed in terms of a network; showing a direct linear connection between the source (quarry) and the destination (Baths of Caracalla). However, the straight lines only get you so far. Physical terrain does not factor into the difficulty of travel. But as we know, simple distance “as the crow flies” is not a good indication of travel. Therefore, we need to add variables.

This brings us to the advanced vector map (fig. 19). This map was created using the ORBIS online mapping feature, and shows the fastest travel route from Carthage to Rome during autumn. ORBIS includes variables like wind, roads, and a system of travel, creating a realistic depiction of travel and environmental constraints. This map takes the representation of distance one step further by revealing how well-connected everything is. Working behind the scenes of this map is a cost map, determining how much each variable costs and giving it a spatial dimension.

The cost of transportation routes adds another layer of complexity to the map. You may wonder that since this visualization accomplishes my goal of giving a sense of
difficulty of travel, then why not use simply ORBIS? After all, it is the most comprehensive and complex mapping simulation of travel in the ancient world that exists today. The problem lies in the fact that it is a closed system. It is only capable of expressing travel times for their specific dataset of start and finish locations. In the context of my project, the marble quarries need to be processed in a separate system because they lie outside of the major Roman settlements that the ORBIS project is concerned with. This brings us to the most complex map, which is the one I created in ArcGIS Pro specifically to show the difficulty of transporting marble across the Roman Empire from the quarries to the Baths of Caracalla (fig. 20). This map shows the marble quarries in blue, the ports as grey, roads as green, and blue sea route lines showing the routes from the marble quarries to the Baths of Caracalla site in Rome.
The sea routes were based on the ones shown in the ORBIS map, but are different because they are rasterized with an assigned value for the purpose of cost-distance analysis. This map is also different from the ORBIS example in that it does not represent travel, for example, from Carthage to Rome, but the transportation of marble from the quarry in Carthage to the nearest port, from the port to the mouth of the Tiber at port Ostia, from Ostia to the port at Marmora, and from Marmora to the Baths of Caracalla. This involves multiple layers and routes all contained within one analysis.

The second step to build the cost map was to turn each layer into a raster using the Feature to Raster tool. The features had to be turned into rasters in order to be put into the Raster Calculator, which allowed me to add or subtract layers according to their function to produce the cost map. The following layers had to be rasterized:

- Roads
- Sea Routes
- Ports Buffer
- Quarries
- Sea
- Europe Shape (Europe Dissolve)
- Coastal Buffer

Once the layers were rasterized, I began the raster calculation process, which took place in five iterations. It required five steps because after each calculation was performed, I had to reclassify the values to remove any negative numbers resulting from the calculation. The negative numbers were from the Tiber river, which was not reading as a technical “sea route” since it was a river. In order to match the value of the Tiber with the values of the sea routes, I had to reclassify the negatives to make them equal to 1 (same as sea routes). After the raster calculation process, the cost map was created (fig. 21-23).
Figure 21. Cost Map with Value Breakdown.

Figure 22. Cost Map Elevation Detail.
4.5 Analysis

In this section, I discuss the various analyses I ran using the geospatial analyses tools in ArcGIS Pro, and the observations and results I gathered from performing these spatial analyses. The central goal of this analysis is to recognize patterns within data through a spatial query, especially how the quarries, roads, and waterways data correlate with the ports and harbors. Part of the analysis process is also filtering out data that is not relevant, such as smaller towns that are not located near major roads or waterways. Most imperial quarries would have been located near major roads or ports for accessibility and transportation. The analysis begins with the cost distance analysis. Cost distance is reflective of slope, which is why the slope map had to be reclassified as a cost map. I essentially simulated the cost distance model ORBIS used using elevation DEMs, water, sea routes, and road data to form the cost map. The DEMs had to be merged as a mosaic.
dataset (fig. 24).\textsuperscript{130} The layers of complexity that ORBIS has that my cost map lacks are wind direction, weather, and season variables. The scope of my project did not require extensive research in those areas because the research had already been completed by ORBIS and my primary focus was on constructing the cost map.

The water routes used in ORBIS were not available to download, so I drew vector lines for all sea travel using the routes, distance, and time generated in ORBIS (fig.25).

The water and road data had to be converted into raster files, for which the Feature to Raster tool was used.

\textsuperscript{130} The resolution of my elevation data is .43km per pixel, where each pixel represents a square km.
After I finished creating the cost map, I performed the Cost Distance Analysis (fig.26). The cost distance map shows the increasing range of cost by color for travel in the Roman Empire. The cost increases as it radiates away from the center and the colors get warmer. The grey area encompasses the entire Mediterranean, and even includes Egypt and Asia Minor as areas of cheaper travel because of their proximity by sea route to the Baths of Caracalla in Rome. Geographically, this map speaks to the validity of the travelable areas within the Roman Empire, as all of the grey areas represent conquered regions that were unified by the empire and play a major role in material trade. The map puts the spatial extent of the Roman Empire into a visual perspective, and provides a greater understanding of how the empire was navigated and interconnected in terms of travel and transporting building materials. It is clearly evident from this map that the sea routes ORBIS produced and the cost map that I have created accurately reflect the costs and methods of transporting materials within the Mediterranean basin.
Following the cost distance analysis was the cost path analysis. To create the cost path, I used the Cost Path tool which uses the cost map to create the lines of the least cost path (LCP) from the marble quarries (used by the Baths of Caracalla) to the Baths by both road and sea routes (fig. 27). A nearness table was used to identify which quarries were located near the water. After the cost path was created, I referred back to DeLaine’s sources for road travel estimates in regard to oxcart travel. DeLaine estimates that it would take 32 cost km per day for a horse to travel on flat ground. If this is the case, then how fast will oxcarts go when carrying marble on slope-based terrain (non-flat)? DeLaine estimates that an oxcart with a heavy load will go a maximum of 1.67km/hr. If we assume the average workday was 12 hours, an oxcart would be able to travel up to
20.04km per day. ORBIS provides the calculation that an oxcart travels 12km per day. Considering that ORBIS does not take into account material burden, and DeLaine specifically calculated for material burden for the Baths of Caracalla, I chose DeLaine’s calculation for oxcart travel. DeLaine estimates that they could travel more kilometers in a day despite a heavier burden because they would have had more resources (food, oxcarts, labor, and pack animals) and travelled on roads, especially in Rome, specifically designed for construction transportation to avoid causing more traffic on regular roads.

I agree with DeLaine that travelling with more resources and using certain roads would increase the amount of travel distance per day, despite having a heavier burden, and therefore these oxcarts could cover more distance than regular carts carrying passengers. For water travel, I relied on ORBIS’ calculations because they factored in environmental constraints such as weather, wind direction, and time of year.

Figure 27. Least Cost Path Analysis.

4.6 Challenges

In this section, I briefly address the challenges that I experienced in the making of this project. One of the biggest challenges in the creation of the quarry dataset came a realization that DeLaine’s identification of a place name for a quarry was not granular enough for mapping. Fortunately, I found a dataset from a white paper that included over 700 stone quarries in the Roman Empire with latitudes and longitudes and the provinces in which the quarries were located.\textsuperscript{132} I found the paper to be well-researched, and it produced a decent amount of data. Of course, as with almost all GIS projects, these advantages are followed by a quick disadvantage. A significant amount of data cleaning was necessary within this dataset, as the material type, color, and its uses were all dropped into a single description field. The descriptions were random and inconsistent, as some would mention details such as where the material was exported or what color variations the stone came in, while others would mention only one or two colors and no usage description. To remedy this, I had to bring the excel file into Open Refine and separate the field into three different fields categorized by type, color, and usage.

Following this, an important discovery I made was file formatting for uploading excel sheets into ArcGIS Pro. I realized that all excel files must be converted into .csv files in order to be read by the software and to perform analysis or geo-referencing tools such as Display XY Coordinates or XY to Line.

Another challenge of my project is that it, like ORBIS, assumes maximum efficiency in terms of traveling. While it would be ideal that transportation would have occurred according to the travel distances and times in modern mapping, it is still impossible to

\textsuperscript{132} Russell, 2013.
account for the variability in ancient travel, particularly in relation to weather, piracy, or other common issues faced in the ancient world that are less common today.

Perhaps the most difficult task was the process of creating the cost map. Building the cost map was an iterative process that required several phases of reclassifying. The map had to be reclassified four times in the attempt of calculating the correct raster values to use that would accurately represent the cost of travelling by road or sea route in my model. Each time I reclassified the map, I encountered different results, which had to be analyzed for accuracy before I could use the cost map to perform cost distance analysis.

The final challenge concerns the model itself. The biggest problem with using Agent-Based Modeling in GIS is accounting for human error. A perfect model can truly not exist because it is based on human behavior, which is not always rational or perfect. The alternative is coming up with a version close to the “crow flies” map. However, this type of map does not account for terrain, which makes the map guilty of oversimplifying.
5. Conclusions

So how can a spatial process help us understand the breadth of materials that went into the construction of monumental architecture in Rome, such as the Baths of Caracalla? First, a spatial process helps us visualize the holistic system of transportation, physical terrain, stone quarries, and the Bath site itself. Once you have a broad picture of all the variables involved in the transportation of materials mapped out, it becomes much easier to visualize and understand the difficulties that went into transporting bulk building materials. At the start of this project, there were various resources and databases that I tried to piece together to get a sense of the system of transportation for materials in the Roman Empire. The map I have created acts as a heuristic tool in the sense that it is an aggregation of historical data by other scholars that not only creates a broad picture but offers a different product in the outcome – a customized model designed to show the difficulty of transportation for one material type (and possibly the heaviest and most expensive to transport). It would be interesting in the future to test this map against other monumental building projects throughout the Roman Empire, and to analyze how those projects would have manipulated or made use of the transportation system I have created.

After the creation of the map, I was brought back to one of my original questions that I had initially proposed at the start of my project. That question is, why did ancient builders go to these great lengths to procure and import marble that was often available domestically, such as white marble? Some reasons that have been offered by previous scholarship focus on the political statement that polychrome marbles from different regions broadcast to the public the breadth and authority of the Roman Empire. Emperors imported marbles from areas that they and previous rulers had conquered in an effort to
show Roman imperial dominance and the control of a vast amount of resources. A sophisticated way to demonstrate and exert this power was by incorporating imported material into the monumental architecture of imperial building projects in Rome that the majority of the Roman public would have access to. DeLaine in particular agrees with this notion of signaling imperial dominance to the public through architecture during the Severan period (for the purpose of the Baths of Caracalla). The expanse of the empire alone can be shown just by importing marble from these locations. Displaying them in a public monumental structure such as the Baths of Caracalla would have indeed been an impressive site to witness.

The nature of this project was not aimed at disputing past research or theories, but rather to delve into the complexities of this subject and to ask new questions using digital applications. I was not challenging DeLaine’s thesis through the creation of a marble transportation map; rather I was curious as to see how it held up to a geospatial analysis. The result is convincing; as seen with the spatial analysis maps of the direct routes from the marble quarries to the Baths of Caracalla. The following is an example of a least-cost path from a marble quarry at the site of Penteli in Greece to the Baths of Caracalla in Rome (fig. 28). The LCP creates a path (in red) from the quarry to the nearest major road, and from the road to the closest port. The path then travels along the coastline until it reaches the isthmus between mainland Greece and the Peloponnese. This was an interesting discovery to observe in that the LCP determined it was cheaper to reach the isthmus by sea route, then unload the marble and move it across the land by oxcart (using the major roads), and then reloading the marble onto ships at the port and continuing to the Baths of Caracalla. This example demonstrates how my initial interpretation of how
the sea routes and roads would be used to transport marble were changed through the least cost path analysis.

Figure 28. Example of Least Cost Path.

For the purposes of future research and the continuation of similar digital humanities projects, I am opting to share my cost map and make it publicly available to anyone who has an interest in adding their own features or would like to explore different analyses using my data. A large part of the data used in my project was open sourced and readily available, which allowed for this project to be seen to fruition. I would like to offer the same opportunity to others who are interested in using my research, data, and maps in the future for their own research.

133 The link provided is the Story Map I created using ESRI’S Story Map Builder: http://arcg.is/0bbLKS
Bibliography

GENERAL HISTORY OF ROMAN BATHS AND BATHS OF CARACALLA


**ANCIENT SOURCES**


Hieronymus (Jerome). *Ab Abraham.* 2231.


**MATERIAL SOURCES, PRODUCTION, AND TRANSPORTATION ROUTES**


DEcoration


DIGITAL COMPONENT


ARCGIS PRO MAP LAYERS


