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The origin of watermilling and functions of watermills in medieval Europe

Abstract. This article presents the findings of comparative molinological studies examining the origin of watermilling in medieval Europe and the functional diversity of watermills.

Keywords: history of technology, medieval watermills, molinology, watermilling.

Introduction

Archaeological research has a significant impact on the field of molinology. Nevertheless, the number of meta-analyses incorporating the results of archaeological excavations of medieval watermills from different European regions is still very limited (e.g., Galusová 2015; Rünger 2019). So far, there has been a notable absence of comprehensive studies that would integrate a large number of available research results and compare them in many aspects.

The lack of that type of studies prompted the author to devise a dissertation based on an extensive, original dataset of archaeological excavations spanning fifteen European countries. The primary aim was to evaluate the role of archaeology in medieval molinology, specifically, to determine which research questions archaeological data can resolve and identifying inherent methodological limitations. As a result of this scientific purpose, the author created the comparative studies based on a catalogue containing 200 watermill sites (both confirmed and alleged) that have been found during archaeological excavation, supported by the selected written, iconographic, and ethnological sources. This article presents two key topics: the origin of watermilling in medieval Europe and the functional diversity of watermills, which was originally part of that dissertation[1]. It focuses on the

[1] This article is a revised version and translation of three chapters from the author's doctoral dissertation titled, *Młynarstwo wodne w średniowiecznej Europie w świetle badań archeologicznych* (*Water milling in medieval Europe in archaeological research*), defended at the Jagiellonian University in Kraków in October 2024.

contribution of archaeological research to the understanding of the genesis and diffusion of milling technology across European countries as well as its impact on various manufacturing processes that occurred between 500 and 1600 AD.

The ancient roots of the watermilling

Before outlining the diffusion of watermill technology across medieval Europe, the ancient origin of watermills needs to be briefly discussed. The earliest evidence confirming the existence of a water wheel is considered to be the mentions contained in two treatises *Pneumatica* and *Parasceuastica* by Philo of Byzantium who lived between 280 and 220 BC and was the first to describe a water wheel (e.g., Lucas 2011, pp. 29, 52; Dyduch *et al.* 2017, p. 29; Ney 2018, p. 13). A slightly later example illustrating the technology of the scoop wheel[2] is a wall painting from the Ptolemaic period in Egypt (Alexandria). A fresco dated to the 2nd century BC depicts a scoop wheel of the so-called Persian wheel (Sakiya) powered by two oxen (Oleson 2000, p. 234).

If Philo of Byzantium is indeed to be considered the inventor of the waterwheel, his design appears to have been rapidly adapted for milling applications. The earliest known use of a watermill with horizontal wheels is attributed to the inhabitants of the Greek city of Byzantium as early as in the 3rd century BC. It is postulated that the first use of a vertical wheel may have occurred in Alexandria around 240 BC (Deckers *et al.* 2002, p. 11) or 260–200 BC (Ney 2018, p. 13).

Archaeological researchers have identified over 50 archaeological sites where the remains of ancient watermills have been discovered. Ancient mills have been excavated in France, Germany, England, Algeria, Greece, Italy, Israel, and Turkey, among other places (Lucas 2011, p. 18; Rünger 2019, p. 116). A prominent example of a monumental mill complex is the Barbegal mill in France, where sixteen overshot waterwheels were installed on a hillside for grain processing. It is estimated to have been built in the early 2nd century AD (Lucas 2011, pp. 18, 32; Ney 2018, p. 14). Owing to the cascading arrangement of the watermills along the slope, all the wheels could operate simultaneously, powered by water supplied by two aqueducts. A structure operating on a similar principle was built in Rome on the Janiculum Hill in the 4th century AD (Chastagnol 1981, p. 408; Bell 1994, p. 73–89).

Beyond the archaeological research, watermills have been described by many ancient writers, such as Strabo, Vitruvius, Antipater of Thessalonica, Pliny (Chastagnol 1981, pp. 407–408; Wikander 2000a, p. 375; 2000b, p. 402; Lucas 2011, p. 32;

[2] A scoop wheel is a device similar to a water wheel in terms of technology. However, its purpose is completely different. A water wheel uses the energy of flowing water to power the mill apparatus, whereas a scoop wheel is a type of pump used for transporting water upwards.

Ney 2018, pp. 13–14) or even in Chinese written sources dating back to the 1st century BC (Lucas 2011, pp. 54, 60).

Apart from information in written sources and archaeological research to date, a small number of iconographic representations of ancient watermills are also known. A slightly better-known mosaic from the Great Palace in Constantinople depicts at least one watermill (Fig. 1)[3]. It dates to the 5th/6th century AD (Tsivikis 2020, pp. 45–47). A much earlier depiction is the relief found on the sarcophagus of Marcus Aurelius Ammianos discovered in Hierapolis (Fig. 2). This artifact is dated to the second half of the 3rd century AD. The preserved depiction shows two water saws cutting stone blocks. It includes a vertical water wheel, a mill channel, a horizontal axis, gears, a crank, a lantern pinion, a shaft and two saws (Grewe *et al.* 2007, p. 140). This is most likely the oldest known depiction of a water saw.

Two important scientific questions linked to the ancient origin of the watermill pertain to the significance of ancient mills in relation to medieval mills and the continuity between late antique and early medieval mills (more about that in the next chapter). In relation to the first question, Adam R. Lucas (2005) points out



Fig. 1. Mosaic from the Great Palace in Constantinople depicting a watermill (after Tsivikis 2020, p. 47)

[3] Nikos Tsivikis mentions two depictions of mills in the mosaics of this palace. However, in his paper he presents only one of them (Tsivikis 2020, p. 47).

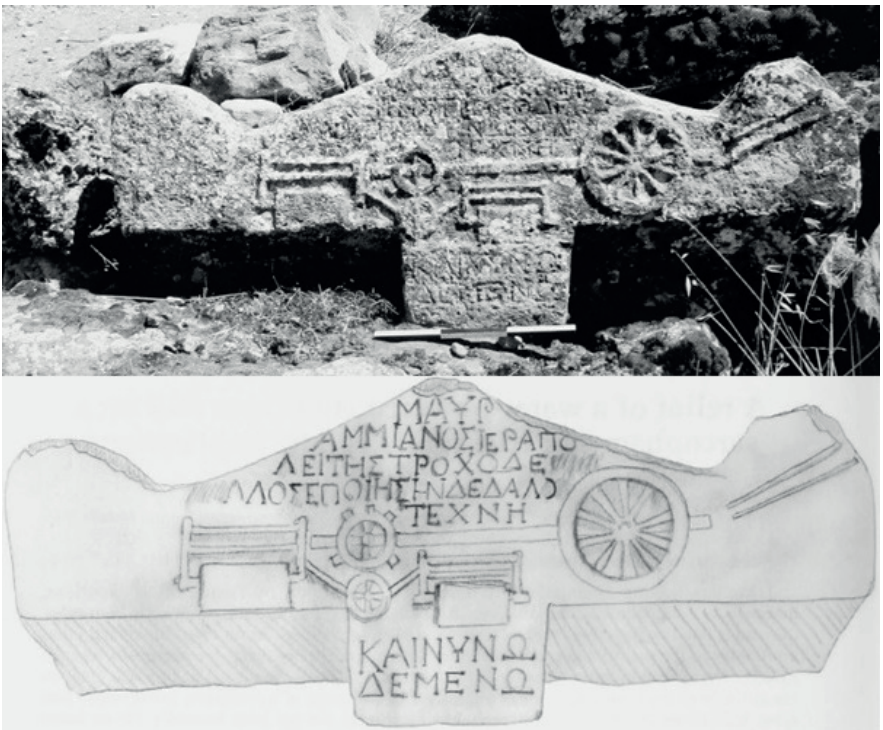


Fig. 2. Depiction (up) and drawing (down) of a relief from the sarcophagus of Marcus Aurelius Ammianos found in Hierapolis presenting a water saw (after Grewe *et al*. 2007, p. 140, Fig. 2)

in the context of industrial mills that there are two groups of researchers with opposing views on the importance of watermills in antiquity. Representatives of the former, such as Lewis Mumford, Robert Forbres, and Lynne White Jr., postulated that watermills, although existed in antiquity, were of marginal importance. They believed that the true flourishing of watermilling occurred in the Middle Ages, partly due to the innovations introduced at that time. Researchers representing the other group, such as Örian Wikander, Kenneth White, Kevin Greene, and Adam Lucas, believe that the innovativeness of medieval people is overestimated, and that during antiquity, watermills with various functions had already been widely used (Lucas 2011, pp. 42–50).

Resolving this dilemma requires distinguishing between the knowledge of a technology and its widespread application. The aforementioned relief from Hierapolis, monumental mills, and preserved written sources indicate a relatively advanced knowledge among ancient societies regarding the construction and use of watermills, including non-grain mills. The limited though growing number of identified ancient watermill sites most likely reflects the current state of research

rather than the actual prevalence of milling technology in antiquity. Nevertheless, it has to be highlighted that the Middle Ages saw the development of water-powered workshops unknown in antiquity, such as paper mills and minting mills.

The spread of watermills and the level of knowledge of this technology in various regions are two separate issues. The current state of research does not allow for a reliable assessment of the prevalence of grain and non-grain watermills in specific regions of the ancient world. Analyzing the distribution of excavated archaeological sites and examples of mills documented in written sources, we can conclude that this technology was known in the western part of the Roman Empire, Greece, Asia Minor, and Israel. The different state of research in countries with post-Roman origins should be taken into account. It is clearly visible that watermill technology was known in the ancient Roman Empire[4] and China (Lucas 2011, pp. 54–60), but its widespread use is difficult to determine.

In this context, the Middle Ages appear as an era in which watermills spread throughout Europe. It seems reasonable to argue that the Middle Ages saw the flourishing of milling technology, which was already known and used in ancient times.

The beginnings of medieval milling in various parts of Europe

The spread of watermills across Europe is a key issue in understanding the history of medieval milling. Archaeological research helps determine the earliest mill locations in a given region, as exemplified by research conducted in Scandinavia and Ireland. In these regions, the earliest medieval mills are identified exclusively through archaeological excavation, as contemporary written records are non-existent. It is important to remember that for most areas of Europe, archaeological research complements historical sources containing information about the first watermills in a given country.

We can identify two lines of development of watermills: stationary mills and boat mills. This paper focuses on the former. Figure 3 presents the oldest known medieval watermills in each modern European country[5]. This map based on the information gathered by Terry S. Reynolds (1983, pp. 49–50) updated with the most recent findings by the author (Fig. 3). The exact year of the oldest medieval watermill in a particular country has been placed in the brackets. For areas that the author was unable to obtain the updated data for, the information provided by

[4] Used in at least part of its territory.

[5] Or general dating if it has not been possible to determine the oldest known mill in a given country.



Fig. 3. Map showing the dating of the first medieval watermills in various European countries, updating the data collected by T.S. Reynolds (1983, pp. 49–50). The data presented by Reynolds is marked in blue, while updates introduced by the author of this study are marked in red. Map created by author and D. Urbański is based on the map from Wikipedia Commons: https://commons.wikimedia.org/wiki/File:Europe_blank_laea_location_map.svg under the Creative Commons Attribution-Share Alike 3.0 Unported license

T.S. Reynolds has been retained[6]. The analysis of this dataset allowed the author to identify five zones of watermill spread in Europe.

Zone One comprises the successor states of the Western Roman Empire. In the areas of the present-day France, Germany, Switzerland, Great Britain, and Italy, milling technology has been known since antiquity (Wikander 2000a, pp. 373–378; Rünger 2019, p.122). It is difficult to definitively determine whether the fall of the Roman Empire caused the decline of watermilling. Watermills dating back to the 6th century are known from France, Germany, Switzerland and Italy (Reynolds 1983, pp. 49–51). Therefore, any potential decline or hiatus in mill usage was most

[6] Marked in blue.

likely temporary. According to Torsten Rünger, we can speak of uninterrupted use of watermills from ancient times to the early Middle Ages in the Rhine and Moselle basins and parts of modern France. Torsten Rünger claims that this territory was coextensive with the core regions of the Frankish Empire (Rünger 2019, p. 122).

Zone Two consists of areas that in antiquity were located on the outskirts of the Roman Empire, where mill technology may have been known in ancient times, but the earliest mentions of medieval mills appear between the 7th and 10th centuries. These include countries such as Austria, Belgium, the Netherlands, Spain, and possibly Portugal (Reynolds 1983, pp. 49–51). This hiatus may be due to the insufficient state of research in these areas and the lack of written sources mentioning mills. However, it is also possible that the technology fell into disuse and was subsequently reintroduced.

Zone Three includes areas of Scandinavia where the oldest known watermills date back to the 8th century[7]. Their appearance may be related to the expansion of the Frankish Empire, which bordered present-day Denmark from 797 onward (Parker 2021, p. 59). The Vikings may also have encountered watermill technology during their raids on the British Isles, where watermills were already known. It is worth noting that there are no written sources from Scandinavia from this period that would mention the oldest watermills. For this reason, some publications, especially older literature, claim that watermills in Scandinavia appear in the 10th or 12th century (Reynolds 1983, pp. 49–50). However, over the last two decades, archaeological research findings have shifted this dating to the 8th century. Scandinavia is an example of a region where archaeological data effectively offsets the lack of early written sources regarding medieval watermills.

Zone Four includes territories that were not under the direct rule of the Roman Empire, and watermills appear there starting from the 12th century. The current research offers no definitive explanation for the delayed adoption of watermill technology in this region. In this context, it is worth mentioning the history of Prague mills said to be operating on the Vltava River as early as 993. However, this technology failed to establish itself in Prague and therefore was not implemented in other areas. If the account of the Prague mills is accepted as authentic, it could be assumed that this technology spread to Central and Eastern Europe as early as the end of the 10th century. It should be noted however, that the preserved foundation document of the Benedictine Abbey in Břevnov, which mentions mills on the Vltava River, is considered a 13th-century forgery (Maříková 2005, p. 107). For this reason, the credibility of the mention of these mills may be questionable. Even if we assume that the author of the forged document relied on the original record and

[7] The dendrochronological date for the Kragevig (Skorly) site, indicating the year 675, albeit not certain (Fischer 2004, p. 83; Brink 2011, p. 25).

made no changes when copying it, the existence of 10th-century watermills would be unique in the Czech lands. Watermills did not appear in these lands until the 12th century. According to the preserved written sources, the first mention of the existing mills in the territory of today's Czech Republic appears in the context of the years 1125–1140[8]. It appears in a donation deed from the Prague canon Zbyhněv concerning a mill in Slatívnice[9] (Maříková 2005, p. 107). In the area of the present-day Poland, the first watermills begin to appear around the mid-12th century, not earlier than 1138[10] (Buczek 1969, pp. 26–27).

Zone Five consists of areas that, after the collapse of the Roman Empire, fell under the influence of the Eastern Roman Empire. Earlier scholarship posited that the first medieval watermills appeared in the Byzantine territories in the 9th century (tentatively in Greece) and in the 11th century in the Balkans (Reynolds 1983, pp. 49–51). The results of more recent research indicate the continuity of mills in the territory of the present-day Greece from ancient times to the end of the Middle Ages. New data on this issue have been provided by archaeological and historical studies of watermills from the early Byzantine period in Athens, Eleusis, Messenia, Thebes, and the Athos Peninsula (Germanidou 2014, pp. 188–198). The structures of three mills discovered in Athens date back to the 5th–6th centuries (Germanidou 2014, pp. 188–190). The mill discovered in Messenia, according to its researchers, operated between 578 and 886–912 (Germanidou 2014, pp. 192–193). The Theban mill is dated back to the 9th century and the first mention of a mill on the Athos Peninsula appears in 897 (Germanidou 2014, pp. 195–197). There is no precise dating of the mill discovered during archaeological excavations in Eleusis (Germanidou 2014, pp. 191–192). At least five mills are known from the middle and late Byzantine period, which have been archaeologically examined. They were discovered in Apokoronas, Gorge/Faraggi Mylon (Canavas 2019, p. 49), Polichni (Germanidou 2016, p. 167; Siaxampani-Stephanou 2019, p. 2), Volvi (Siaxampani-Stephanou 2019, pp. 4–5) and Zaharomylos (Michailidou 2019, pp. 52–53). Written sources concerning the Athos Peninsula provide data on the existence of watermills in this area, both in the 4th and 9th–11th centuries. This may indicate a long tradition of watermill operation since late antiquity, which could have been related to the development of the monastic movement (Germanidou 2014, pp. 197–199). As Sophia Germanidou notes, knowledge about early medieval mills from the Byzantine Empire is very limited due to the small number of publications and archaeological studies of early watermills (Germanidou 2014, p. 198). This is particularly evident

[8] There are older documents permitting the construction of a watermill, but the first such permission granted directly for Czech territories dates back to 1169 (Maříková 2005, pp. 105–107).

[9] Today, it is the Únětický stream.

[10] Although there is a view in the earlier scholarship suggesting that mills appeared in Poland at the turn of the 12th century, the attempt at interpellating the appearance of mills in Poland before 1138 was criticized as unjustified in terms of historical sources (Buczek 1969, pp. 18–27).

in the other Balkan countries. The author of this article obtained very little data on the beginnings of medieval milling in those territories. Therefore, this area requires further study.

Another aspect of the spread of watermills is how milling technology was transferred between regions of Europe. There are several social groups that may have been the *spiritus movens* behind this process.

Foremost among these were monarchs and dukes who financed the development of milling technology in the territories they controlled (Lucas 2014, pp. 58–65). Their significant financial resources necessary for founding mills, riparian rights (water regalia), and the desire to technologically modernize the areas under their rule support the thesis about the significant impact of secular rulers in the foundation of the first mills. The implementation of mill regalia (parts of the riparian rights) and the milling obligation indicate that the development of watermills, which legally underpinned the feudal seigniorial system and allowed for the collection of new rent from tenants, brought profits to the rulers (Ney 2018, pp. 19–21). It is worth mentioning again the alleged 10th-century Prague mills, whose foundation may have stemmed from a desire to test whether the new technology would benefit the Czech ruler. It can be assumed that the benefits obtained were smaller than expected, which resulted in the rejection of milling technology in the Czech lands in the 10th century. Although the approval of the landowner was necessary for the introduction of technology in his lands, it appears that the feudal lords were not directly responsible for the construction of subsequent mills.

Courtiers, knights, and nobility constituted another, rather heterogeneous group that had a significant influence on the development of milling technology in the Middle Ages (Lucas 2014, pp. 58–65). Much like dukes, they profited from the introduction of compulsory milling and rent from leased mills. It is worth noting that in addition to the extra profit from rent, they had to invest in mill construction and adjudicate disputes related to the negative impact of mill operation on farmland near the rivers where the mills operated (Ney 2018, pp. 16–17). Extant written sources contain numerous references to mill grants, construction permits, and records of conflicts between millers and peasants. An extensive network of watermills may also have hindered inland navigation (Schich 1995, pp. 10–11, 13–15). However, considering the history of milling, the benefits that the introduction of watermilling brought to the nobility must have outweighed the long-term problems it caused. At each stage of medieval milling's development, the nobility seems to have played a significant role in the establishment of new mills and the spread of milling technology to new territories.

The clergy and monks in particular constitute the third group contributing to the development of milling. In many regions of Europe, there was a widespread belief in a strong connection between the development of the monastic network and the transfer of milling technology to new areas. The carriers of this technology and

the driving force behind its development were the monks who, upon establishing a new monastery, also built a mill within it. This technology was then implemented in areas outside the monastery. Monastic communities possessed the knowledge, capabilities and opportunity to drive the construction and management of mills. This view is particularly prevalent in older historiography (Ney 2018, pp. 5, 18–19). However, it has to be noticed that the last decade has brought numerous publications that point to the overestimation of the importance of monasteries in the development of milling technology. The paradigm of the significant role of monasteries in this process is being challenged, for example in Scandinavia and Great Britain (Ney 2018, pp. 18–19).

In Scandinavia, archaeological findings and the earliest written sources seem to precede the emergence of the first monastic orders in Scandinavian lands. Kristoffer Brink (2011), among others, discusses this issue.

Regarding the German territories, this dispute was taken up by, among others, Andreas Ney (2018). He points out that watermills had been operating in the German Empire before the monks were brought there. The previously existing mills were leased to the monasteries or they were given the right to collect rent from selected mills (Ney 2018, pp. 5, 16–19, 41–42). Torsten Rünger (2019, p. 119) also expressed doubts in this regard.

When it comes to the British Isles, the key source for learning about the history of watermills is Domesday Book. This book was created after the conquest of the British Isles by William the Conqueror and is a kind of property inventory of the conquered lands. This source indicates the existence of 6,082 watermills operating in 1066 (Langdon 1991, p. 424; Lucas 2014, p. 68; Rünger 2019, p. 123), which shows that watermilling was deeply rooted in these lands. As A. Lucas (2014, pp. 87–268) postulates in his analysis of medieval England, the influence of religious orders in the 12th and 13th centuries on the development of milling was not homogeneous. Based on the preserved written sources, he indicates that the Augustinians were the leaders in establishing new mills in the territories under their control. Other orders (the Benedictines, the Cistercians, the Premonstratensians) and bishops covered by his analysis show much less interest in building new mills in favour of deriving profits from the existing ones. According to A. Lucas, they preferred collecting rent and compel their tenants to grind grain at these mills rather than exercised direct control over the mill (Lucas 2014, pp. 87–268). We can observe a similar diversity in this respect in the territories of the State of the Teutonic Order (Grochowski 2023, pp. 77–79). The horizon of the early medieval Irish tide mills is also closely linked to monastic foundations. The example of the tide mill in Nendrum, whose construction dates back to 619 (Brady 2006, p. 48; Lucas 2011, p. 89; Miller 2014; Rynne 2023, p. 46), may constitute evidence of the implementation of innovative technologies in the early medieval Irish monasteries (Lucas 2011, p. 92). It seems equally likely that this technology was brought to Ireland or that it was implemented

independently, by adapting the watermilling technology known to the monks to the local conditions. The first hypothesis is supported by the discovery of the remains of the oldest known tide mill in St. Pol-de- Léon in French Brittany dated to 585/588 (Bernard *et al*. 2021, pp. 59–60; Rynne 2023, pp. 46, 49). The second is supported by the significant number of early medieval tide mills found on the island of Ireland and the hydrological conditions that may have inspired Irish monks to create the new technology (Lucas 2011, p. 92; Rynne 2023, p. 46).

In Central and Eastern Europe, the establishment of the first monasteries predates the appearance of watermills. While this chronology suggests that the clergy could have played a role in introducing this innovation, only a few mills from the 12th century are known from the written sources. Therefore, it remains difficult to clearly assess the actual degree to which the clergy was involved in the development of milling technology. Based on the preserved written records of medieval monastic mills, it is reasonable to claim that the monasteries that emerged in these lands, even if playing no significant role in the transmission of milling technology, certainly implemented and benefited from it, particularly in the late Middle Ages. A noteworthy example is the Teutonic Order, which operated a network of watermills throughout its territory between the 13th and the 15th centuries (Kubicki 2012). However, it should be remembered that in the context of creating opportunities for milling technology development, the Teutonic Order was closer to the category of landed rulers than other orders operating in these regions. The published research on milling in the lands ruled by military orders significantly broadens the perspective on this topic (Kubicki 2012). Aside from monasteries, bishops also contributed to the development of milling technology in Central and Eastern Europe. The preserved *Liber fundationis episcopatus Vratislaviensis* written in the early 14th century demonstrates the extent to which milling technology was widespread within the ecclesiastical jurisdiction of the bishops of Wrocław (*Liber fundationis* 1889). This book consists of five registers covering the territories of the Duchy of Nysa and four archdeaconries: Wrocław, Opole, Legnica, and Głogów. The work entails two annexes (*Anhang I* and *Anhang II*). It lists towns and villages subject to the Wrocław episcopacy, containing information on the buildings located in each town and the tithes that each town was required to pay to the bishops. This source contains one hundred and twenty-eight mentions of mills[11]. Eighty-five of these are found in the section devoted to the Duchy of Nysa, twenty-eight in the register of the Archdeaconry of Wrocław, three in the Archdeaconry of Opole, three in the Archdeaconry of Legnica, two in the Archdeaconry of Głogów, and seven in the annexes I. In total, this source contains information about one hundred and forty-three existing mills. The designation "miller" appears twice. Mentions of mills can

[11] Taking into consideration the chronology of the appearance of windmills in Poland, these are probably watermills, although the term "water" in relation to the mill does not appear in the source itself.

be divided into several categories. The first concerns the existence of a watermill or watermills in a given locality and the number of wheels the mentioned mills had. Examples include the following fragments from the register of the Duchy of Nysa: *Woytitz habet LII) mansos parvos*, *ecclesia habet I)*, *scultetus habet VII)*, *molendinum cum II) rotis*, *inventory XLII)*[12] or *Belitz habet L parvos mansos, ecclesia I), scultetus habet X, thabernam, molendinum cum duabus rotis*[13]. The second type of entries is information on financial liabilities related to the mills' operations, e.g., *Et eciam in eadem villa est molendinum, quod solvit ad septimanam I) mensuram*[14], *Item in Cornica et Cirintha decime valent V marcas, quas dominus archidiaconus accipit pro molendino suo in Vyasd*[15] or *Item sunt duo molendina | ante civitate Glogovie et quodlibet molendinum debit XX scotos annuatim*[16]. Although the *Liber fundationis episcopatus Vratislaviensis* does not directly indicate the level of involvement of the bishops of Wrocław in the dissemination of milling technology, it provides evidence of the development of a network of watermills in the areas under their jurisdiction and offers limited insights into their operation[17].

In the Byzantine Empire, the extent of monastic involvement in the development of milling technology is particularly well documented on the Athos Peninsula. Based on the preserved accounts from the 9th to 11th centuries, S. Germanidou argues that the monastic movement in this area initiated the construction of new mills and contributed to the development of milling technology. These activities were believed to be related to the mass production of goods by monasteries in the region (Germanidou 2014, pp. 197–198). Late antique written sources indicate the existence of watermills on the Athos Peninsula as early as in the 4th century. According to some researchers, this may suggest the implementation of milling technology in the first centres of monastic life established in this region (Germanidou 2014, p. 199).

Similarly, the burgher class supported the construction of new mills in cities. Historical records show examples of urban mills built at the behest of the city

[12] "The village of Wójcice has 52 small farms/buildings [of which] the church has 1, the village head has 7, a watermill with two wheels and 42 buildings remain" (translated by the author).

[13] "The village of Bielice has 50 small buildings [of which] the church has 1, the village head has 10, an inn and a watermill with two wheels" (translated by the author).

[14] "Also, in the same village, there is a watermill that pays one measure a week" (translated by the author).

[15] "Similarly, in Kornice and Czerwieńcice, the tithe due is 5 marks, which the archdeacon receives for his watermill in Ujazd" (translated by the author).

[16] "There are also two watermills outside of the city of Głogów and each/any watermill owes 20 scots (?) per year" (translated by the author).

[17] There are other, analogous documents from the period covered by the study an analysis of which could help us better understand this issue. However, the purpose of the above fragment is to illustrate the possibilities of using historical documents in molinological research, rather than to provide a complete analysis of all the surviving source texts. The considerable number of such records precludes such a review within the scope of this paper.

council. Mills built at the initiative of the burgher appear in the High and Late Middle Ages (Kubicki 2012, pp. 268–270; Ney 2018, pp. 44–45). However, one should bear in mind that not every mill located in a city was built at the behest of the city council. Investments such as the alleged 10th-century Prague mills or the Great Mill built in Gdańsk in 1349 were initiated by the rulers, not the burgher class (Trzoska 1973, p. 48; Kochanowski 1998, pp. 90–92).

Another aspect of the burgher involvement in the mill construction process is the activity of millwrights. They were specialized craftsmen involved in the building of new mills. Afterwards, they could assume the role of a miller, but the millwright and the miller were, at least in some regions of Europe, different professions.

Village administrators or village heads (Latin: *sculteti*) played an important role in the process of establishing new mills and thus indirectly in their expansion into new areas. As tenants of new villages, they could receive a grant or privilege to establish a mill. This privilege facilitated the selection of a suitable location for the mill relative to other buildings, ensure grain milling for residents and provide an additional source of income for the village head. According to Rafał Kubicki, the mill was most often a separate administrative unit, part of the village head's personal estate, although there are also cases where it was located within the village borders (Kubicki 2012, pp. 59, 97). Written sources from the Middle Ages indicate that they had to pay fees to the feudal landlords for the mills they owned: *Et scultetus solvit I marcam de molendino suo*[18]. Regardless of the legal conditions, granting mill privileges to village heads contributed to the development of the mill network, especially during the period of intensive colonization. Although granting a privilege to build a mill did not necessarily guarantee its construction (Kubicki 2012, p. 93). The existence of the "suit of mill" (soke rights) made investing in a mill in a newly established village seemingly profitable, especially in the long term. The likelihood of inheriting a mill by the village head's successors (Kubicki 2012, p. 87) increased the profitability of such investments. This situation meant that with the colonization of new areas, not only did the number of operating mills increase, but their importance as the primary method of grain grinding also grew.

The last medieval society group associated with milling operations were the peasants. They appear to have had the least influence on the spread of milling technology to other areas, but they did have a significant impact on the maintenance and proper operation of the mill. Peasants could be employed in mills, become millers themselves, or even obtain hereditary rights to operate them (in the Late Middle Ages).

[18] "And the village head pays a mark from his mill". An excerpt from the *Liber fundationis episcopatus Vratislaviensis* translated by the author.

Functions of watermills

Watermill technology was used in the processing of many materials in the Middle Ages. The fundamental functional classification divides mill into agricultural (grain-processing) and industrial categories[19]. The former refers to grain processing, the latter to all other mill functions (e.g., Lucas 2005; 2011; Reynolds 2006, p. 250). This division has two fundamental weaknesses. Firstly, it seems reasonable to include all mills whose end product is food, not just those processing grain, in the agricultural category. Consequently, sugar mills or olive mills should be included in this category. Secondly, the term "industrial" is inaccurate, as it evokes associations with the Industrial Revolution, rather than the processing workshops of antiquity or the Middle Ages.

In the Polish language, most industrial mills developed distinct nomenclatures unrelated to the root word for "mill" (e.g., *folusz*, *kuźnica*, *hamernia*, *papiernia*). The opposite trend is visible, for instance, in English and Portuguese, where most names of industrial mills contain a stem directly referring to the mill structure. The functional diversity of watermills is evident in the study dataset (Fig. 4). This chapter characterizes several functions of watermills, based on the collected research sample and ethnographic and historical data. Nevertheless, this is not a comprehensive description of all the functions of watermills known in the Middle Ages.

Grain and malt mills

The most common function of a watermill was grain processing. This category encompassed the production of all types of flour. In the grain milling process, water power was transferred via a horizontal shaft, cogwheel (or face gear), lantern pinion, and spindle to the millstone's rynd, an elongated metal or stone element seated at the top of the vertical spindle. The rynd (rind) was placed in a similarly shaped groove in the upper millstone, called the runner. This runner stone was positioned above the bedstone (nether millstone). The grain to be ground was placed between two stones, using for example a sleeve. The runner stone, driven by the water force transmitted through the mill mechanism, rotated, and the grain between it and the bedstone was ground by friction. The distance between the runner stone and the bedstone could be adjusted. Depending on this distance, different grades of flour were obtained. The greater the distance between the stones, the coarser the resulting flour. After the process was completed, the flour was separated from the unground grains using several sieves (screens) of varying mesh thickness. The milling process could be repeated several times to obtain a looser flour, considered

[19] In Anglo-Saxon literature, this branch of processing is named "industrial milling".

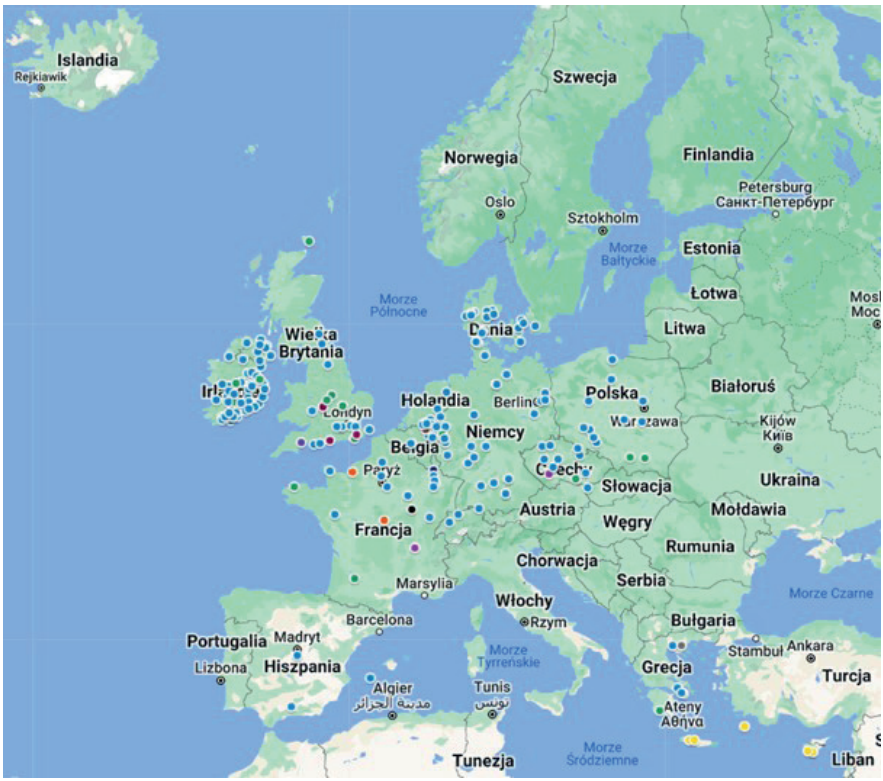


Fig. 4. Map presents the location of medieval watermills archaeologically researched in Europe divided by function: sugar mills (yellow), bark mills (light green), bark or paper mills (red), forges (burgundy), linen mills (grey), olive mills (dark grey), ore mills (purple), textile and grain mills (navy blue), grain mills (green), grain or forges (light purple), grain and oil mills (brown), iron ore mills (black), unspecified mills (blue) Map prepared by the author based on Google Maps

of higher quality (Baranowski 1977, pp. 39–40). Malt, necessary for beer production, was ground in a similar manner.

In the collected research database, twenty mills served as grain mills[20], although two of them, according to the researchers, may have also served a different function[21]. However, it is quite likely that a significant number of unspecified mills

[20] These are the watermills: Mstěnice, Czech Republic; Audun-le-Tiche, France; Barbaste, France; Saint-Pol-de- Léon, France; Athens, Greece; Mesini, Greece; Bergeijk, the Netherlands; Ballyine, Ireland; Kilbegly, Ireland; Raystown, Ireland; Grevenbroich (Elfgen), Germany; Kraków, Poland; Tarnów, Poland; Abbotsbury, UK; Batsford, UK; Castle Donington, UK; Exeter, UK; Orkney Islands, UK; Raunds I and II, UK; Tamworth, UK.

[21] The mill in Audun-le-Tiche could also have served as a cloth fulling mill, while Bergeijk could been an oil mill.

served the same function, even if not explicitly stated by the authors of these studies. This assumption also appears in the articles of some historians, when there is no information about the type of substance processed in the mill (Grochowski 2023, p. 167). This function of the mill may be indicated by a millstone with an oval hole[22] and grooves or by a combination of two types of millstones. The grooves of the millstone were worn away during the grinding process, and therefore capturing them in the archaeological material on the millstone may be difficult. However, it should be remembered that millstones were also used for grinding metal ores[23]. The presence of a millstone in the archaeological record cannot therefore be definitive proof that the discovered mill served as a grain or malt mill. Additional research like petrographic analysis or X-ray fluorescence are necessary to determine the material ground on the millstone. Considering ethnographic analogies, a bolter (flour dresser) could also be a good indicator of this function of the watermill. Nevertheless, no trace of this element was preserved in the studied dataset. Watermills have been grinding grain into flour since ancient times (Wikander 2000a).

Sugar mills

The process of refining sugar from sugarcane in the Middle Ages is known primarily from Al-Nuwari's account of the operation of an Egyptian sugar mill and from a preserved engraving from the work of Jan van der Straet (Fig. 5). In the 17th century, there is evidence of the use of a vertical beam press in Spain (Galloway 1977, p. 185). In the 18th century, information on the sugar refining process is known from travellers' accounts and a detailed description of the sugar refining process was created by French encyclopaedists. According to these sources, sugar production began with the harvesting of the sugarcane, two to three months after flowering. The cane was then cut into pieces several centimetres long. The next step was crushing and squashing the cane, which could be performed in a variety of ways. One of these was the use of a watermill, which powered a cane-grinding mechanism (Galloway 1977, pp. 184–185; Michailidou 2019, p. 51). There are at least two methods of grinding sugarcane. The first involved using two millstones, analogous to a grain mill. The second involved using a stone wheel placed vertically in a recess into which the cut cane was placed. A horizontal shaft passing through the wheel set the wheel in motion, which initiated the cane crushing process. The first method allowed the implementation of a watermill. The second method was made possible by using the human or animal power. The ground sugarcane was then fed to a beam or screw press, where the final juice extraction took place. The beam press consisted of a tree trunk or beam and a stone surface. The screw press,

[22] The millstone may also contain a space for installing a rynd.

[23] More information can be found below.



Fig. 5. Illustration from *Nova Reperta* by Jan "Stradanus" van der Straet (1523–1605), published around 1570. The illustration comes from the Antwerp edition of Philippus Gallaeus from around 1600. It depicts labourers at work in a sugar refinery in Sicily (after Galloway 1977, p. 184)

on the other hand, consisted of wooden boards stacked one on top of the other, with reeds placed between them and secured with a screw (Galloway 1977, pp. 184–185). Some researchers overlook the necessity of using a press in this process, probably assuming that the crushing/grinding process was sufficient for extraction (Michailidou 2019, p. 51). The product of the extraction was a dark, sweet-tasting liquid. The next step was boiling the extracted juice in copper cauldrons, adding lye or limewater. The purpose of this step was to purify the solution. The boiling process was repeated several times, changing cauldrons, resulting in a sugar syrup. The cooled product was placed in special conical clay vessels with a hole in the bottom, resembling a funnel. The conical vessels called "formes" with closed holes were then placed on a slender clay vessel, which served as a container for the molasses. The stopper prevented the substance from leaking out before the sugar had solidified. After 24 hours, the stopper was opened, allowing the molasses to slowly flow into the slender container below. The sugar, however, remained in crystallized form within the funnel. This stage lasted about a week. Following this, the refinement process was initiated by transferring the conical vessel to a ceramic

collection jar. The outer, thin layer of sugar was removed and a layer of wet, white clay was applied over the remaining crystallized sugar. The water in the clay dissolved the dark substances contained in the sugar, which flowed down the conical vessel. After nine to twelve days, the clay was removed and new clay was applied. This stage was repeated several times until the sugar in the conical vessel turned white. This process could take over a month. The final step was drying the white sugar, after which the final product was obtained (Michailidou 2019, p. 51). The white clay refining step was not essential to the process and was likely not used in all refineries[24]. Molasses, a byproduct of the process, could be re-boiled to obtain more sugar. Sugar was sold in various forms, such as powder, cubes, or larger lumps, and in various scents, such as rosewater or violets (Galloway 1977, p. 188).

A significant step in the development of the sugar refining process was the development of so-called three-cylinder mills (Fig. 6). These consisted of three vertically arranged cylinders or presses, between which sugarcane stalks were placed without prior crushing. The cane was then ground by rotating two adjacent cylinders. This design shortened the first stage of the refining process. According

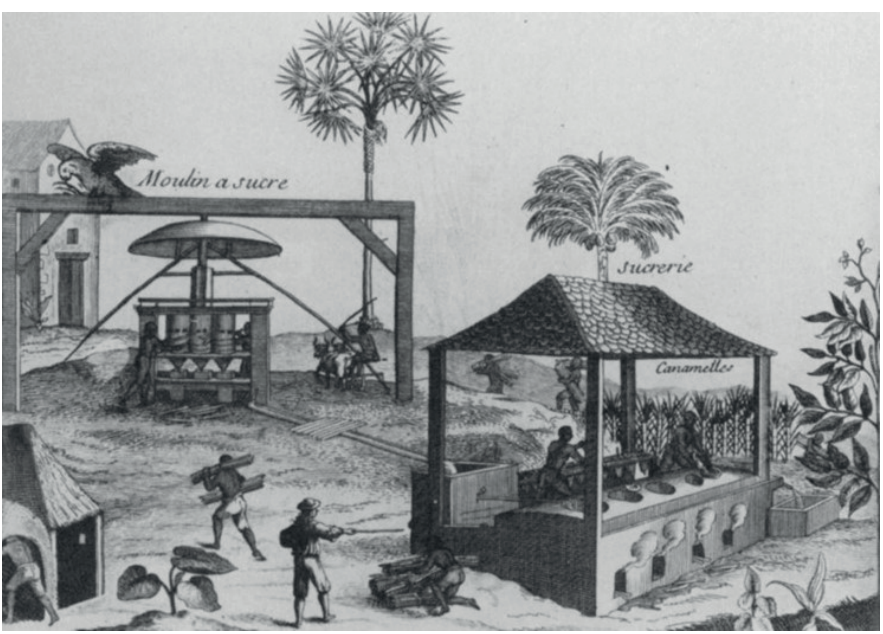


Fig. 6. Depiction from Pierre Pomet's *Histoire générale des drogues*, 1694 edition, Paris, p. 94 (after Galloway 1977, p. 184)

[24] It is postulated that refinement using white clay was used, among others, in a refinery in Morocco (Galloway 1977, p. 188).

to John H. Galloway, this mill could exist in all its variants, including a watermill. The literature on the subject offers two hypotheses regarding the time and place of the three-cylinder mill's invention. According to the first, it was built in 1449 in Sicily. Other researchers believe it was built between 1608 and 1612 in Peru, from where the technology spread to Brazil. Regardless of the adopted point of view concerning its origins, it is assumed that the three-cylinder mill was created with the sugar industry in mind, finding wide application in the New World (Galloway 1977, p. 186).

The analysed dataset includes six archaeologically excavated sugar mills. Three were discovered in Cyprus[25], which was a centre of sugar refining and export in the Middle Ages (Galloway 1977, p. 177). The remaining three were discovered on mainland Greece[26]. Numerous remains of ceramic vessels found during the excavations in Cyprus and other sites have led some researchers to postulate the local production of these vessels, especially of the conical pots known as "formes", used in the refining process (Michailidou 2019, pp. 51, 54).

The first medieval sugar mill appears in written sources in 1176 (Lucas 2011, p. 216), although it is postulated that sugar refining in Europe began around 700 (Galloway 1977, p. 177).

Oil mills

The process of olive oil production and extraction is a branch of processing with ancient origins. Henryk Olszański presents the oil production process in four stages: crushing the oilseeds, kneading the dough/raw material, also known as matting, browning the dough/raw material, and pressing the oil (Olszański 1989, p. 85). The purpose of the first stage was to separate the fats from other substances present in the plant. Therefore, the seeds were separated from their outer covering and granulated. Next, they were rubbed and crushed. This last step could be mechanized thanks to the use of watermills. Extant medieval written sources contain information about oil mills that used stone stamps or wooden the trip hammers, powered by a watermill, to crush the grains located in trough. These stamp mill could be used in two variants: horizontal and vertical[27]. The key element of the horizontal stamp watermill was the use of a horizontal wooden camshaft with wooden cam/wiper attached to

[25] These are the mills in Episkopi-Serayia, Kolossi, Kouklia-Stavros (Herscher 1995, p. 292; 1998, p. 351).

[26] These are the mills in Apokoronas, the alleged Gorge mill (Faraggi Mylon) and Zaharomylos (Canavas 2019, p. 49; Michailidou 2019, p. 53).

[27] These names derive from the arrangement of the troughs. It should be noted that the stamps (or hammers) used to compress the seeds within the troughs operated in opposing planes. In troughs positioned horizontally, the stamps were raised and lowered in a vertical movement. In vertical troughs, the movement of the stamps occurred in a plane close to horizontal.

it. The rotating wheel caused the horizontal wooden camshaft to rotate and the wooden cam/wiper raised the stamps/hammers by touching the tappet attached to them. When the stamps/hammers reached their maximum height, the cam/wiper released tappets and the stamps/hammers, which crushed the grain in the trough. The process repeated during the next rotation. In vertical stamp mills, the stamps/hammers were placed in a frame that held them in a fixed, slightly diagonal position relative to the ground plane. The tappets on the stamps/hammers were struck by the cams/wipers on the horizontal wooden camshaft of the waterwheel. As a result of this interaction, the hammers were pulled diagonally upward. At the point of maximum separation (maximum height), tappet on the hammers lost contact with the wooden camshaft's cams/wipers, causing the hammers to return to their original position, striking the grain placed in the vertical/cylindrical trough. In this variant, the tappets on the hammers could be located at the top of the hammers' heads, which was typical of treadmills or at the bottom of them. The second scenario was typical for the watermills, which could be related to the relatively low position of the waterwheel wooden shaft (Olszański 1989, pp. 91–92).

The collected research dataset does not include any archaeologically examined watermill operating as an oil mill. The characteristic elements of oil mill are the trough and the stamps/hammers. However, it should be noted that they were also used in mills with other functions (discussed later in this chapter). Hence, identifying this mill function requires correlation of archaeological data with information contained in other sources or an attempt to detect microremains of fats/plant residues in mill apparatus. Whatsoever, the author has not encountered any studies identifying this type of plant remains in the context of oil mill research.

The author has been unable to identify the the earliest instance of a medieval oil mill driven by a waterwheel. Oil mills have been operating in Poland since at least the 14th century, as evidenced by a record from 1367 concerning an oil mill operating in Gdańsk (Olszański 1989, p. 16).

Olive mills

Olive oil literature mentions the implementation of watermills in olive oil production in the Middle Ages (Lucas 2011, p. 216; Siaxampani-Stephanou 2019, pp. 4–5). The olive oil production process, known since antiquity, consisted of three stages: crushing the olives, pressing them and separating the olive oil from the water. The first stage began with washing the harvested olives. Then, the olives were crushed using for example a vertical wheel with a horizontal wooden shaft running through its centre. The wheel was placed on a concave stone platform, onto which the olives were thrown. The force of human or animal muscles on the shaft, moved the vertical wheel, which crushed the olives. In the second stage of production, the resulting mass was packed into linen bags, which were then placed under a manual press.

After the initial pressing, the bags were doused with hot water. The liquid that leaked out under pressure was then poured into a separate container. The third step involved separating the oil from the water. The oil could be scooped out using ladles, poured through a hole in the top of the container or poured through a hole at the base of the container[28]. The resulting oil was left to settle until the impurities settled to the bottom of the container. After this time, the oil was ready for use (Niaounakis 2011, pp. 412–413).

Based on historical records, the authors of the Volvi mill research suggest that it may have been used in the olive oil extraction process (Siaxampani-Stephanou 2019, pp. 4–5). This is the only mill of this type in the collected database. Nevertheless, the author of this article has not been able to determine at what specific stage of the medieval olive oil extraction process watermills were used. Illustration from the 16th-century work *Nova Reperta* (Fig. 7) that depicts the work inside the olive refinery, can suggest that a watermill (not visible in the illustration) was not



Fig. 7. Illustration from *Nova Reperta* by Jan "Stradanus" van der Straet (1523–1605), published under the title, *New Discoveries; the Sciences, Inventions, and Discoveries of the Middle Ages and the Renaissance as Represented in 24 Engravings Issued in the Early 1580s by Stradanus*, 1953 edition (English). It depicts the interior of an olive oil refinery with a visible hand press and a treadmill powering a vertical wheel that crushed olives (after Van der Straet 1953, n.p.; Niaounakis 2011, p. 413)

[28] In ancient times, the water obtained in this process was called *Amurca* and after boiling it could be used as a skin paste or for medical purposes (Niaounakis 2011, p. 422).

necessary in this process. In the case of 20th-century mills from the Mediterranean, water power was used to move two vertically arranged massive stone wheels called "Volia", rotating in a metal bowl. Olives were thrown into the bowl and the moving wheels, driven by the watermill, crushed the olives into a uniform mass[29]. The forerunner of this mechanism was the vertical wheel driven by a treadmill, described above. However, based on such a chronologically distant analogy, it is impossible to determine whether watermills found similar use in the Middle Ages.

Adam Lucas suggests that the first known mention of a medieval olive oil press using a watermill has been dated back to the end of the 13th century (Lucas 2011, p. 216).

Fulling mills

Watermills were also used in the process of manufacturing wool into cloth. Their function was to drive wooden hammers or stamps that kneaded the wool. This improved the fulling process, also known as cloth fulling (Baranowski 1977, p. 49; Grochowski 2023, p. 176). Adam Lucas draws attention to two basic types of water fulling mills: trip hammers (also known as falling stocks) and walk-stocks (also called driving stocks or hanging stocks). He also mentions a third type in the form of a vertical stamps, which was distinguished by Rouillard. According to A. Lucas, there is no evidence for the use of the third type of mechanism in medieval fulling mills (Lucas 2016, p. 592).

In the first type, the wool was dipped into a trough filled with water. The mill wheel powered a wooden camshaft, which held rectangular wooden cam/wiper. On the top of trip hammers the wooden tappets have been located. The rotating shaft caused its cams/wipers to strike the tappets of the hammers, lifting them. Once they reached their maximum height, the hammers fell, crushing the wool (Fig. 8).

The second variant of the fulling mill mechanism has been presented in the 17th century work *Theatrum Machinarum Novum* by Georg Andreas Böckler. The operation of the water wheel and shaft was similar to the first type. Wooden cams/wipers on the shaft pulled back the elongated hammer handles which, when they reached their maximum distance, "slid out" from the cams/wipers on the shaft, striking the wool. In this case, the hammers moved in an arc and the wool was stored in a wooden box open on the side of the striking hammers (*Theatrum Machinarum* 1661). The use of a water wheel in wool processing significantly improved the process. The fulling mill could operate around the clock, kneading the wool using the force of the flowing water.

[29] https://www.miaelia.com/traditional-olive-oil-making-in-lesvos/ (access date: 19.03.2024).

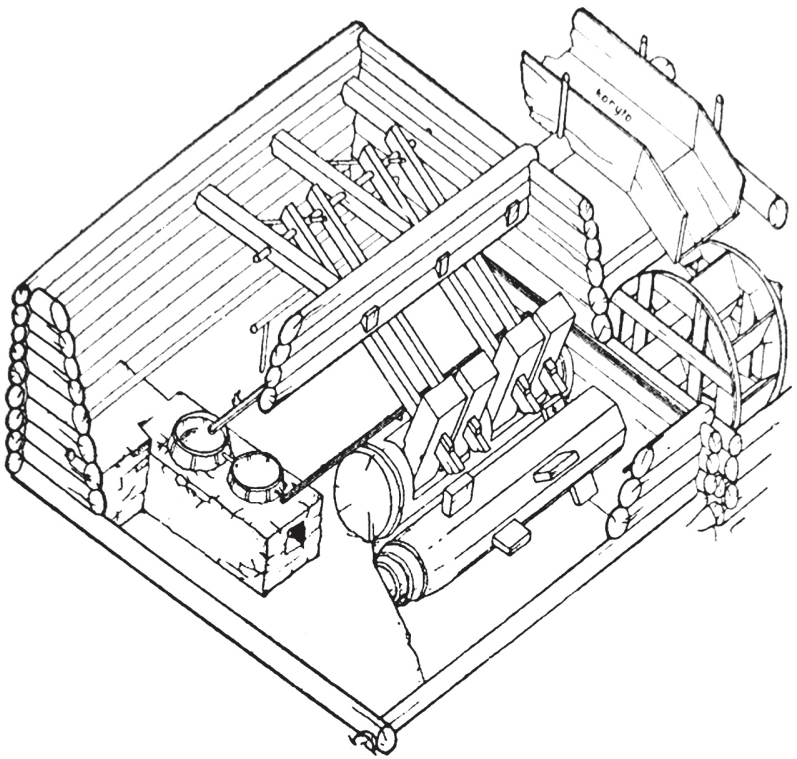


Fig. 8. Scheme illustrating the operation of a fulling mill (after Długokęcki *et al.* 2004, p. 65)

The collected dataset includes one[30] archaeologically examined watermill, which has been interpreted as a fulling mill. Unfortunately, no remnants of the fulling mill apparatus, such as a wooden camshaft or hammers were found. However, it appears that the shaft with cams/wipers and the wooden trip hammers are elements that allow us to determine whether the discovered mill could have served as a fulling mill.

The first recorded medieval fulling mill dates back to 1080 in France (Lucas 2011, p. 218) or 10/11th century Islamic Spain and North Africa (Lucas 2016, p. 583). Nevertheless, the fulling mills were operating also in ancient times (Lohrmann 1989, pp. 367–368; Lucas 2005, pp. 1–9; 2016 p. 583).

Research conducted by John Langdon, Richard Holt and Adam Lucas provides evidence of a process of converting grain mills to fulling mills, which was recorded in 14th and 15th century sources in England. According to the researchers, the

[30] At the site of Audun-le-Tiche, France, although the researchers suggest that it could also have been a grain mill.

conversion process was relatively simple due to the similarities in some of the mechanical components of both type of mills. It is possible that instances of watermills changing their functions also occurred in other regions of medieval Europe (Lucas 2016, pp. 591–592).

Hemp mills

Hemp mills used hammers to crush dried flax or hemp stalks. The resulting fibers were used to make ropes or twines. A similar milling mechanism to that used in fulling mills was used in hemp mills (Lucas 2011, p. 241).

The analysed database does not contain any mills identified as hemp mills. Characteristic features of the hemp mill include a shaft with wooden cam/wiper, as well as stamps and trough. The similarity of this design to those used in stamp mills with other functions presented in this chapter indicates that the presence of these elements is insufficient to determine the function of the mills discovered during excavations. Difficulties with the proper identification of hemp mills also occur in written sources, as noted in the literature (Lucas 2011, pp. 241–242).

The first undisputed hemp watermill was recorded in 1209 in the Aisne region of France (Lucas 2011, p. 218).

Paper mills

The mill mechanism was used in the production of handmade paper from linen or more precisely, from linen rags. The papermaking process was a form of "recycling" of worn garments which, after processing, became handmade paper. It began with the gathering of white linen rags intended to be transformed into paper. These materials were then placed in wooden tubs or a trough filled with boiling water. Similar to fulling mills, the watermill powered wooden trip hammers that beat the linen soaked in hot water. The purpose of this stage was to crush the linen into a thick slurry consisting of individual linen fibres floating in the water. Then, using a fine-mesh sieve, the linen slurry was extracted and placed under a press. The compressed linen sheet was left to dry, during which it had to release all its absorbed water. After drying, which took several hours, the sheet of paper was ready for use.

The collected database includes one mill[31] that may have served this function[32]. Unfortunately, no typical paper mill elements were found during the research. Wooden hammers or a wooden shaft with a cam/wiper, similar to those found in

[31] At the Pennedepie site, Calvados (Benoit 2013).

[32] However, this is not the only possibility. Paul Benoit suggests that it could have also been a bark mill (Benoit 2013).

the fulling mill, may provide evidence that the mill may have served as a paper mill. The discovery of the remains of a wooden press could also be considered circumstantial evidence regarding the mill's function.

The use of a watermill in papermaking first appears in medieval Spain in 1238 (Le Goff 2022, p. 270) or 1276 (Lucas 2011, p. 216). The widespread use of mills for papermaking purposes should be associated with the end of the Middle Ages.

Bark mills

Watermills were also used in the tanning process. They were employed for grinding previously dried tree bark into a powder containing tannins (Baranowski 1977, p. 50; Grochowski 2023, p. 175). This powder was used in the process of tanning hides. A water wheel, via a transmission shaft, powered trip hammers with blades[33] located at the ends of the hammers' heads. These blades chopped larger pieces of bark into smaller fragments. The next stages of the process involved sifting the bark and soaking the resulting powder in water to produce the desired product, called tanning liquor. The extracted tannin gave the leather elasticity and caused the proteins to coagulate (Długokęcki *et al.* 2004, pp. 68–69). Birch, oak, spruce or willow bark was used in this process (Baranowski 1977, p. 50).

Similarly to fulling mills, the water-powered bark mill significantly improved the process of tanning hides and skins. It is characteristic feature is the use of trip hammers with blades. The database includes one or two[34] mills classified as bark mills.

The oldest documented bark mill comes from France, from 1138 (Lucas 2011, pp. 216, 249).

Sawmills and water saws

Sawmills and various types of saws were other mechanisms where watermill technology has been applied. The use of water power in the process of cutting materials such as stone or wood involved setting the saw in motion via gears and shafts connected to a water wheel. The saw could cut both horizontally and vertically, relative to the surface. In the latter case, the vertical saw or saws were part of a sash saw[35]. It was necessary to move the material being cut, usually a wooden block or bale, from which the lumber was formed. A dedicated carriage was used for

[33] These hammers were called tannery hammers.

[34] This applies to the remains of mills in Antselse (De Kort *et al.* 2010, p. 10) and Pennedepie (Calvados). The Pennedepie (Calvados) mill may also have been a paper mill (Benoit 2013).

[35] A sash saw is a device used to cut stone blocks into slabs or logs into lumber. A sash saw is also called a frame saw, gate saw or gang saw (if there are more than one saw).

this purpose and to ensure a constant speed under varying loads, an additional element was introduced in the form of a flywheel. In addition to elements known from grain mills, such as the cogwheel/face gear, lantern pinion or horizontal shaft, sawmills also used crankshaft to drive the frame saw. Diagrams of the operation of a vertical water saw and the transmission elements of a water sawmill could be presented in Stanisław Solski's work, *Architekt Polski To Iest Navka Vlzenia Wszelkich Ciezarow, Vżywania potrzebnych Machin, ziemnych y wodnych, Stawiania ozdobnych Kościołow* published in 1690 (Baranowski 1977, pp. 50–52, 66)[36].

The analysed dataset includes one mill[37] that may have served as a sawmill, but this is only one of the hypotheses put forward. The key evidence identifying mills that functioned as sawmills is the saw blade itself. Elements of the frame of a sash saw, in which the blade was installed, may also provide a clue.

Mills with this function have been known since antiquity (Lohrmann 1989, pp. 367–368; Lucas 2005, pp. 1–9), although they were likely not as common as grain mills. One of the earliest known examples is a depiction of a mill from Hierapolis, dating to the 3rd century. It is a bas-relief depiction found on the sarcophagus of Marcus Aurelius Ammianos (Grewe *et al.* 2007). Physical remains of ancient mills with this function are also known from the archaeological record.

The first medieval sawmill with a water saw appears in historical sources around 1300 in France (Lucas 2011, pp. 216, 218).

Pipe boring mill/water augers

The mill mechanism was used to drive mechanical augers, which were used to drill into wood. These augers were used to produce wooden pipes from tree trunks. Depictions of this type of mechanism are visible, for example, in an engraving from 1420 (Vienna), as well as in early modern sources, such as the work of Salomon de Caus dated 1624 (Niemiec 2024, p. 214).

Not a single water auger has been recorded in the analysed archaeological materials.

[36] In his work, Bohdan Baranowski states that the presented diagrams are found on pages 216 and 211 of Stanisław Solski's work (Baranowski 1977, p. 139). The author of this work has obtained three digital versions of this old print, made available by the Jagiellonian Library and the Lower Silesian Digital Library. In each case, the old print ended on page 200. The existence of the cited engravings on the available pages of the old print has not been confirmed. Therefore, this citation should be treated with considerable scholarly caution.

[37] This concerns an alleged sawmill, which could have been powered by water, discovered during research at site no. 16 in Mniszek (Opracowanie 2008, p. 51).

Forges/hammer mills, grinderies, bellows

The watermill was widely used in the production of metal objects. Water-powered forges, also known as hammer mills, utilized a waterwheel to operate. This mechanism could be used to drive metal hammers striking an anvil, bellows fanning the forge's embers (Fig. 9) or rotating grindstones (brus) on which tools or weapons could be sharpened (Lucas 2011, pp. 214–226). In the modern period, grindstones powered by a water wheel were also used to sharpen firearm flints.

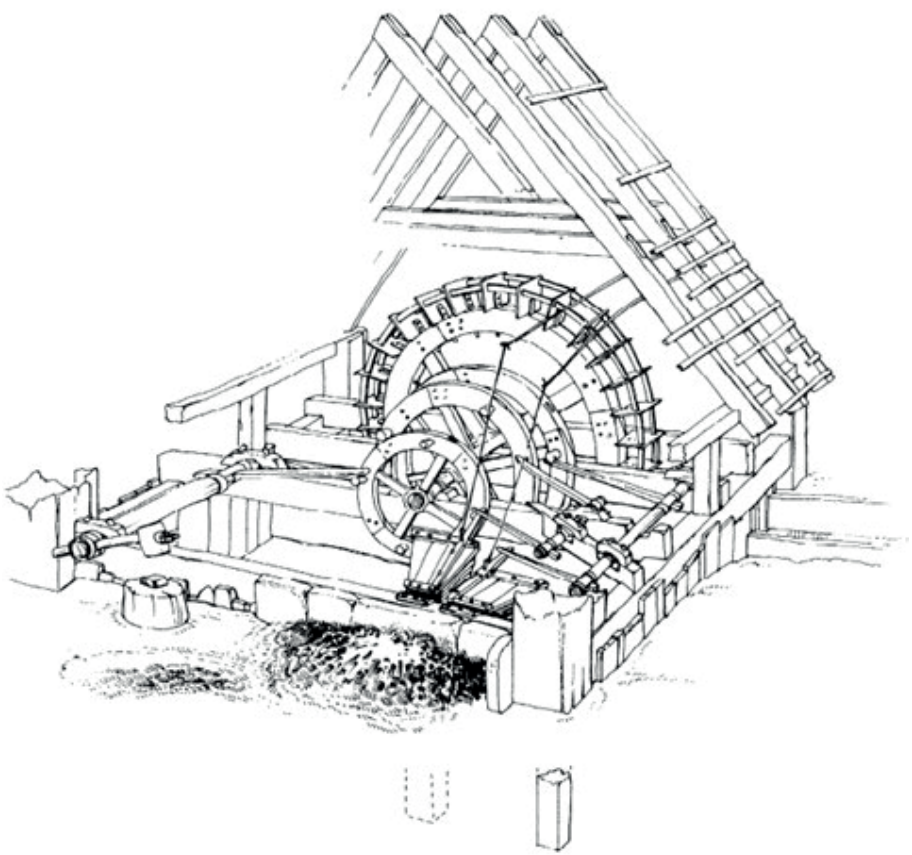


Fig. 9. Bordesley Abbey, Redditch, Worcestershire, England, United Kingdom. Reconstruction of the Bordesley Abbey forge mill mechanism during the third period of occupation. The illustration shows the forge and bellows powered by a watermill (after Astill 1993, p. 270)

In the study database, five mills with this function were identified[38]. Forges are the most representative of this function, while bellows are the least. Evidence confirming the forging function of the mill appears to be the discovery of metal hammers. In the case of a grinding mill, it is necessary to find a grindstone with a hole in it, through which a shaft connecting the stone to the water wheel could be inserted. Interpretations of millstones found during archaeological excavations suggest that they may have been reused as grindstones. It is difficult to definitively determine whether such a millstone was connected to a water wheel or served as a free-standing grinding stone (brus) powered by human power. Water-powered bellows are by far the most difficult to identify in the archaeological material. Finding the remains of a bellows along with wooden elements and/or a waterwheel could prove this function of the mill. Bordesley Abbey site was most likely the site where such a discovery was made (Astill 1993, p. 216). Reconstruction of this site suggests that both bellows and water-powered trip hammers operated within a single forge. It should be emphasized that not all molinologists accept the existence of water-powered bellows in the Middle Ages (Reynolds 2006, p. 250).

The first medieval forges date back to around 1200 come from England and France. In 1203, the first medieval grinding mill appeared in France. The first bellows most likely powered by water appeared in 1269 in present-day Slovakia and in 1283 in France (Lucas 2011, pp. 216, 218)[39].

Ore mills

Another function of the watermill was the grinding of metal ore. The so-called ore mills could grind iron, copper or gold ore using millstones.

The sample includes three mills identified as ore mills[40], although according to the researchers, the Fontenay mill (Côte-d'Or) was likely a forge. It appears that identifying ore mills requires petrographic examination of the millstone grooves or microscopic analysis of the residues trapped within them, for example, using X-ray fluorescence spectroscopy (XRF).

The first medieval ore mill known from the written sources appears in 1317 in the present-day Germany (Lucas 2005, p. 18).

[38] This includes mills in Cork, Ireland; Beaulieu (Astill), UK; Bordesley Abbey, UK; Exeter, UK; and Goudhurst, UK.

[39] Adam Lucas also provides information that the first water-powered bellows known from medieval written sources is mentioned in 1214 (Lucas 2011, p. 216); however, the author of this paper was not able find the reason behind this discrepancy.

[40] At the sites of Písek, Czech Republic; Fontenay (Côte-d'Or), France; Pampailly (Rhone), France.

Gunpowder mills

In addition to crushing ore, mills were also used in the production of black powder. Powered by a waterwheel, the mill featured a variable number of stamps. Saltpetre, sulphur, and charcoal were placed in the trough and crushed using stamps raised by cams/wipers attached to a horizontal shaft connected to the waterwheel. The mechanism was quite similar to that used in fulling mills (Fig. 10). The substance obtained was mixed with water. The resulting slurry was subjected to a graining process and then the grains were sifted through a sieve. The final product of this process was black powder (Długokęcki *et al.* 2004, pp. 72–73).

The analysed database does not contain mills with this function. The characteristic features of a gunpowder mill include stamps, troughs and a horizontal shaft with wooden cams/wipers. However, the similarity of these elements to those used in fulling mills means they cannot be considered conclusive evidence of a gunpowder mill. Identifying this function requires determining the context of the find, comparing it with the data from other sources or conducting microscopic analyses to identify micro-residues of gunpowder components and determine their chemical composition.

The author of this paper has not found any information about the first gunpowder mill. A water-powered gunpowder mill is known from the present-day Poland, providing gunpowder for the royal arsenal in Malbork. The written sources indicate that it existed as early as 1540 (Długokęcki *et al.* 2004, p. 72).

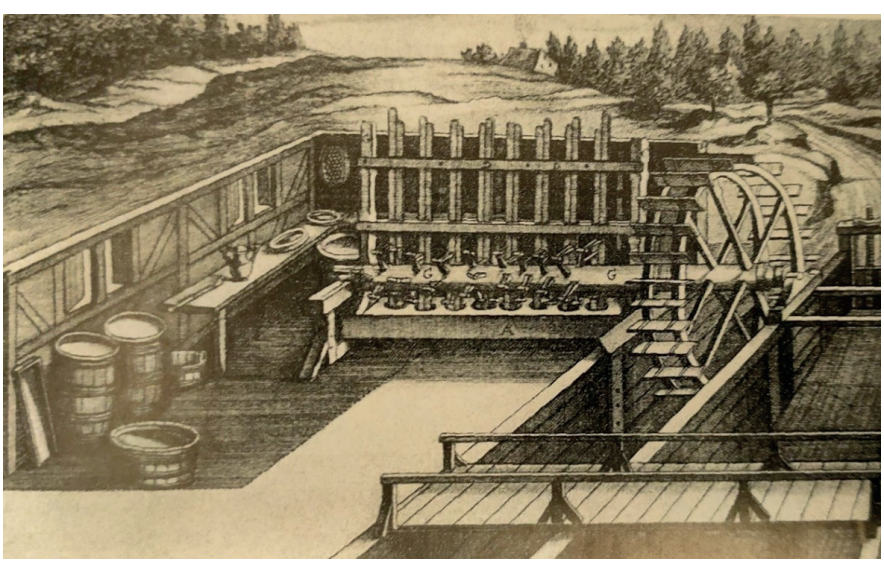


Fig. 10. Illustration of a gunpowder watermill dating back to the 17th century (after Długokęcki *et al.* 2004, p. 73)

Coin mills/mint mills

Mills could also be used to mint coins in the mints. They were a type of hydraulic press in which wheels drove metal rollers. These rollers could flatten pieces of metal blanks and strike images on bronze, silver or gold coins (Długokęcki *et al.* 2004, pp. 69–72; Scotter 2021, p. 46).

No mill of this type was recorded in the analysed dataset. The mill's function can be identified by the presence of a shaft equipped with a minting die, which was used to strike the design onto a metal blank.

The technology of minting mills appears around 1550. One early example known from the written sources is the mill in Segovia, Spain, which operated between 1586 and 1869 (Scotter 2021, p. 46).

Summary and conclusions

In summary, watermills were invented in the 3rd century BC. Both horizontal and vertical wheels were in use in antiquity, as evidenced by the preserved written and iconographic sources, as well as archaeological research. For almost the entire 20th century, the prevailing paradigm assumed the marginal importance of watermills, especially industrial ones. However, archaeological and iconographic research has since overturned this view. Contemporary sources indicate that this technology was known in many regions of the Roman Empire. In addition to the most common grain mills, mills serving other functions also appeared in antiquity, such as fulling mills, water saws, and sawmills (Lohrmann 1989, pp. 367–368; Lucas 2005, pp. 1–9). The decline the ancient world is associated with a crisis that affected many fields, including watermilling. While this technology undoubtedly did not escape the disruptions associated with the crises of the 5th century and the fall of the Western Roman Empire, the knowledge of this technology did not disappear. The decline in milling affected post-Roman territories to varying degrees.

Based on the analysis of the emergence of the first medieval mills in specific areas, five zones of watermill development in Europe can be distinguished. It appears that in some post-Roman areas, watermilling continued from antiquity. In most of medieval Europe, there was a hiatus in the use of watermills or the emergence of milling technology in areas where it was previously unknown. The earliest medieval watermills in Scandinavia are known primarily from archaeological evidence. This example illustrates that in areas with few preserved written sources, archaeological research is the only source of information about the origins of watermilling. In other regions, archaeology provides an important complement to the evidence contained in written sources. Another important question is which social groups were involved in the spread of watermilling in Europe. A wide range

of medieval social groups contributed to the development of milling technology. In the Early Middle Ages, rulers and nobles played a dominant role in introducing and developing the technology in territories under their authority. Monasteries also played a significant role, although the extent of their dominance in this regard is widely contested in contemporary literature. Further regional research is needed to determine whether the foundation of new monasteries was connected with the construction of new mills. The clergy, like the nobility, were also interested in the development of milling technology and the profits it generated. In the High and Late Middle Ages, burghers and peasants also gained the opportunity to derive profits from milling through the establishment of urban mills or the rights to hereditary mill tenancy, which wealthy peasants could obtain.

In this context, it must be emphasized that watermills likely fulfilled a variety of functions, streamlining work in many different manufacturing processes. Archaeological, ethnographic and historical research provides extensive information on the functions of watermills. Archaeological studies allow us to determine the type of product processed in the mill and to identify and subsequently reconstruct the operation of the mechanisms used during the milling process. Furthermore, owing to extensive archaeological excavations, it is possible to correlate the function of a mill with the types of buildings located within mill complexes. This allows us to determine, for example, what other buildings or facilities were part of a refinery or whether a sawmill also operated alongside a grain mill. It seems crucial to determine which elements discovered during fieldwork can be used for identifying a given mill's function. The relatively small number of mills whose functions have been determined compared to the entire research dataset demonstrates that such identification is difficult. This also highlights a significant problem with researchers not making any assumptions or hypotheses about the function of a newly discovered mill. The lack of information about the mills' functions in the published materials may indicate that the authors of the respective studies were unable to determine their functions based on the excavated remains, or that the mills simply served as grain mills[41]. Unfortunately, for most of the analysed sites, no information on this subject is available, which further complicates the interpretation of the published research findings.

Despite these challenges, this study has enabled the construction of a model for the diffusion of watermilling technology across medieval Europe in the context of its ancient origins and has presented various watermill functions together with indicators that could help identify them during archaeological excavations. This not only facilitates tracking the development of watermilling technology in medieval Europe, but also demonstrates the versatility of this technology, which was applied in many different branches of medieval manufacturing.

[41] This may reflect the language in which the article describing the research results was written. In at least several languages, including Polish, the word "mill" is clearly associated with grain processing.

Table 1. List of excavated watermilling sites by country. These two hundred sites became research dataset/database for presented comparative research

No.	Country	Location
1	Austria	Rabensburg
2	Belgium	Braine-le-Château
3	Belgium	Oeter
4	Cyprus	Episkopi-Serayia
5	Cyprus	Kolossi
6	Cyprus	Kouklia-Stavros
7	Czechia	Jahodov
8	Czechia	Krasova
9	Czechia	Libkovice
10	Czechia	Mstenice
11	Czechia	Písek
12	Czechia	Spáleném
13	Czechia	Touchořiny
14	Czechia	Tyrov/Karlova Ves
15	Czechia	Ustupenice
16	Czechia	Velké Poříčí
17	Denmark	Æbelholt
18	Denmark	Borup Riis
19	Denmark	Galten
20	Denmark	Gjern Bro
21	Denmark	Gl. Lejre
22	Denmark	Hadsten
23	Denmark	Hessel
24	Denmark	Kolding
25	Denmark	Kragevig (Skorly)
26	Denmark	Kærbygård Mølle
27	Denmark	Lille Drenderup (Ødis)
28	Denmark	Ljørring
29	Denmark	Løgumgårde
30	Denmark	Nymølle (Mølleåen)
31	Denmark	Øm
32	Denmark	Omgård
33	Denmark	Ringkøbing
34	Denmark	Sandbækken
35	Denmark	Tovstrup
36	Denmark	Vejerslev
37	Denmark	Voer
38	France	Audun-le-Tiche
39	France	Barbaste
40	France	Belle-Eglise
41	France	Bourges
42	France	Bréviandes
43	France	Colomby (Manche)
44	France	Dieulouard
45	France	Fontenay (Côte-d'Or)
46	France	Grand Moulin du Cornillot/Mill of Brie-Comte-Robert
47	France	Hatrize
48	France	Marillais
49	France	Pampailly (Rhone)
50	France	Pennedepie (Calvados)
51	France	Prény
52	France	Saint-Pol-de-Léon
53	France	Saleux
54	France	Thervay
55	France	Toul
56	Germany	Ahrensfelde
57	Germany	Bardowick
58	Germany	Bergheim-Kenten
59	Germany	Bergheim-Paffendorf
60	Germany	Chorin
61	Germany	Dasing I
62	Germany	Dasing II
63	Germany	Duisburg Limbeck-Platz
64	Germany	Erftstadt-Niederberg
65	Germany	Esslingen
66	Germany	Fulda
67	Germany	Gadebusch
68	Germany	Gielsdorf
69	Germany	Gimbsheim
70	Germany	Grevenbroich (Elfgen)
71	Germany	Großhöbing I
72	Germany	Großhöbing II
73	Germany	Hedeby (Haithabu)

Table 1. continued

No.	Country	Location
74	Germany	Ilmenau Bardowick
75	Germany	Jüterbog
76	Germany	Konstanz-Stadelhofen
77	Germany	Lage-Müssen
78	Germany	Lahnau-Dorlar
79	Germany	Lauchheim
80	Germany	Rennigishausen
81	Germany	Rotbachtal
82	Germany	Saxler
83	Great Britain	Abbotsbury
84	Great Britain	Ballinderry
85	Great Britain	Barking Abbey
86	Great Britain	Barrowburn
87	Great Britain	Batsford
88	Great Britain	Beaulieu
89	Great Britain	Bordesley Abbey
90	Great Britain	Castle Donington
91	Great Britain	Corbridge
92	Great Britain	Deer Park Farm,
93	Great Britain	Drumard
94	Great Britain	Ebbsfleet
95	Great Britain	Exeter
96	Great Britain	Fountains
97	Great Britain	Goudhurst
98	Great Britain	Greenwich Wharf, Londyn
99	Great Britain	Killylane
100	Great Britain	Maghnavery
101	Great Britain	Moycraig
102	Great Britain	Nendrum
103	Great Britain	Northfleet
104	Great Britain	Old Windsor I
105	Great Britain	Old Windsor II
106	Great Britain	Orkady
107	Great Britain	Rasharkin
108	Great Britain	Raunds I
109	Great Britain	Raunds II
110	Great Britain	Rossorry
111	Great Britain	St. Giles/Reading
112	Great Britain	Tamworth
113	Great Britain	Wellington
114	Great Britain	Worgret
115	Greece	Apokoronas
116	Greece	Ateny
117	Greece	Eleusis
118	Greece	Gorge (Faraggi Mylon)
119	Greece	Mesini
120	Greece	Polichni
121	Greece	Teby
122	Greece	Volvi
123	Greece	Zaharomylos
124	Ireland	Ardcloyne
125	Ireland	Ardnagross
126	Ireland	Athassel
127	Ireland	Ballydowan West
128	Ireland	Ballygeardra
129	Ireland	Ballygormill South
130	Ireland	Ballyine
131	Ireland	Ballykilleen
132	Ireland	Ballymascanlan
133	Ireland	Ballynoe
134	Ireland	Ballyrafton
135	Ireland	Ballyroe
136	Ireland	Barryscourt
137	Ireland	Boherduff
138	Ireland	Brabstown
139	Ireland	Bridgetown
140	Ireland	Carrickmines Great
141	Ireland	Chapelizod
142	Ireland	Cloghbally Upper
143	Ireland	Clonlea
144	Ireland	Clonlonan
145	Ireland	Cloongowna
146	Ireland	Cloontycarthy
147	Ireland	Coolboy

Table 1. continued

No.	Country	Location
148	Ireland	Corcannon
149	Ireland	Cork
150	Ireland	Crushyriree
151	Ireland	Dublin, Patrick Street
152	Ireland	Farranmareen
153	Ireland	Feall A'Mhuilinn, Inishmurray
154	Ireland	Johnstown
155	Ireland	Keelaraheen
156	Ireland	Kilbegly
157	Ireland	Killoteran
158	Ireland	Kilphillibeen
159	Ireland	Knocknacarragh Cross
160	Ireland	Knocknagranshy
161	Ireland	Little Island I
162	Ireland	Little Island II
163	Ireland	Lowesgreen
164	Ireland	Mashanaglass
165	Ireland	Morett
166	Ireland	Mourneabbey
167	Ireland	Mullantine
168	Ireland	Newcastle Upper
169	Ireland	Newtown
170	Ireland	Raystown
171	Ireland	Scattery Island
172	Netherlands	Antselse
173	Netherlands	Bergeijk
174	Netherlands	Bronneger
175	Netherlands	Epse
176	Netherlands	Escharen
177	Netherlands	Gemert
178	Netherlands	Lomm
179	Netherlands	Moergestel
180	Netherlands	Sint-Oedenrode
181	Netherlands	Sweikhuizen
182	Netherlands	Ulft
183	Poland	Gdańsk
184	Poland	Kantorowice/Ptakowice
185	Poland	Kraków
186	Poland	Łódź
187	Poland	Mniszek, stanowisko nr 16
188	Poland	Moczydlnica Klasztorna
189	Poland	Nasielsk
190	Poland	Oława-Baumgarten
191	Poland	Otalążka
192	Poland	Raduszyn
193	Poland	Tarnów
194	Poland	Trzebnica
195	Spain	Es Molinot (Ibiza/Baleary)
196	Spain	Ratonera
197	Spain	Yeles
198	Sweden	Kv. Färgaren, Lund
199	Switzerland	Reigoldswil-Kilchli
200	Switzerland	Thielle

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