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# A POSSIBLE ROMAN TIDE MILL

BY

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## **A POSSIBLE ROMAN TIDE-MILL**

By

Robert Spain

### **ABSTRACT**

*During the years from 1988 to 1992 a massive building development within London gave archaeologists the opportunity to explore the lower valley of the River Fleet. They found two hitherto unknown islands on the east side of the Fleet estuary that during the early Roman period were developed and used for industrial purposes. The archaeologists have proposed that a tide-mill existed on the northern island. No tide-mills have ever been found in the Roman world dated before 600 A.D.*

*An examination of the archaeological archives has facilitated a detailed analysis of the Roman structures and artificial channels and concludes that a possible tide-mill operated on the north island. A theoretical tidal profile has been generated that has been used to determine realistic diurnal and lunar mill power-generation cycles. This has provided enlightenment on the impact of tidal regression in the second century A.D. supporting the theory of abandonment of tidal power in the Fleet estuary. On the east bank of the estuary a major Roman landscape feature, the purpose of which was not determined, has been re-examined and identified as an aqueduct, probably built to provide water-power for grain milling close to Londinium. Its interaction with the tide-mill has been explored.*

## 1. Introduction.

During the last few decades our knowledge of Roman water-mills has increased at such a rate that historians of technology had performed repeatedly to revise their understanding of the part played by water-power in Roman industry. In the ever-growing archaeological and interpreted documentary corpus of Roman water-mills no example of tidal power had come to light until, that is, 1998, when a fleeting reference appeared<sup>1</sup> as follows.

During excavations undertaken between 1988 and 1992, along the east side of the lower valley of the River Fleet in London, two small eyots<sup>2</sup> were discovered that had existed in the Roman period. A brief note of this work recorded that the upstream island '*was used for the processing of imported wheat and the remains of a substantial tide-mill were found here during the excavation*'. It was also reported that both islands were abandoned by sometime towards the end of the second century A.D., which coincided with a tidal regression in the lower Thames. The archives of this very large series of excavations, known as the Fleet Valley Report<sup>3</sup>, have not yet been published but are now available for public research<sup>4</sup>. See Figure 1. The writer examined this evidence<sup>5</sup> during August and October 2002 with the objective of determining whether or not a Roman tide-mill existed here, and if considered worthwhile, to publish the findings. This paper is a report of that work.

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<sup>1</sup> Archaeology in the City of London 1907-1991. The Archaeological Gazetteer Series vol.1 (MoL 1998), p.283/4. The writer is grateful to Jenny Hall, Curator of the Roman Museum of London for bringing this reference to his attention.

<sup>2</sup> Eyot, a variation of *ait*, a small island especially in a river. This term prevails throughout the archaeological reports and is henceforth used in this study.

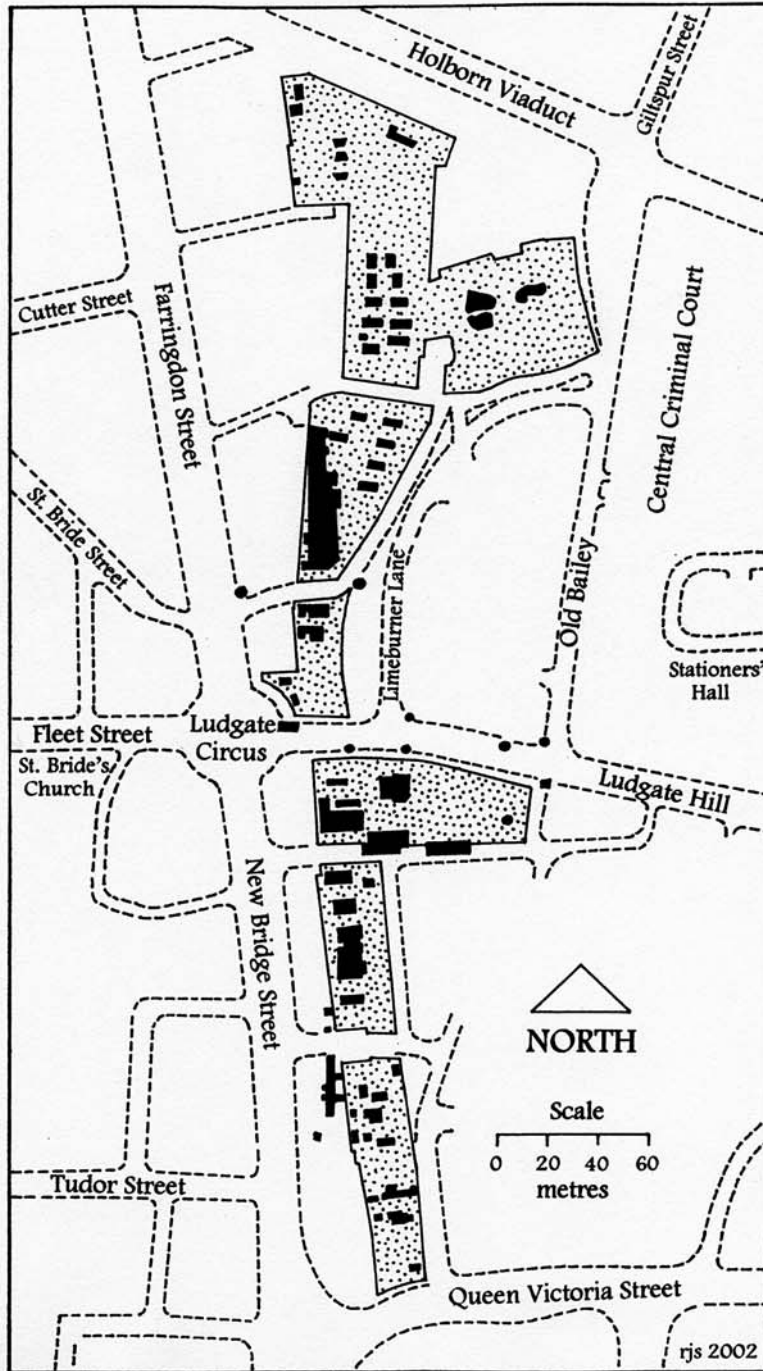
<sup>3</sup> Carried out by the then Department of Urban Archaeology (DUA) between 1988 and 1992 as part of the Ludgate Development Scheme of Rosehaugh Stanhope Developments PLC (RSD). The approximate area covered by the excavation was 50,000m<sup>2</sup> involving more than 100 separate areas of excavation.

<sup>4</sup> Held by the London Archaeological Archive and Research Centre (LAARC) that opened in February 2002. The Fleet Valley archives are ref. VAL 88 volumes 1-54. The work is summarised in vol. 54, Final Interim Report edited by Bill McCann, May 1993.

<sup>5</sup> The writer is most grateful to Cath Maloney, Archives Record Officer, for her support, patience and expertise whilst searching and interpreting this exceptionally large archive.

FIGURE 1

Ludgate Development Scheme 1988-92  
Showing areas of excavation (black) and watching brief (shaded)



In this study of ancient water-power the writer has been influenced by our knowledge of contemporaneous Roman water-mills, whilst being very conscious that our view of the ancient world is always liable to distortion because of the bias and prejudice deriving from modern experience. Unfortunately this approach is singularly disadvantaged by the obvious fact that we have neither Roman parallels, nor other examples of tide-mills on the Atlantic coast providing us with archaeological data from which might be obtained an insight of their design and operation. In this situation, where any knowledge of tide-mills that might be brought to bear is going to be essentially from modern evidence and oral traditions, the writer considers that great caution must be used in assessing this evidence.

## **2. The archaeological evidence.**

### **[a] General.**

Figure 2 shows the areas of excavation superimposed upon the Roman Fleet estuary. In the early Roman period with which we are concerned, two eyots existed in the upper tidal basin of the Fleet, with the channel banks and margins, and no doubt both eyots, colonised by vegetation<sup>6</sup>. Both eyots were within the tidal-reach that extended north to just beyond the location of the modern Holborn viaduct. The western edge of the northern eyot was not observed in the excavation and its position has been influenced by nineteenth century contour surveys and borehole data<sup>7</sup>. The southern tip of the south eyot was found but the western edge, which has been estimated, has a similar status to that of the northern eyot. The highest level recorded on the northern eyot was +2.8 m OD<sup>8</sup> and +2.34 m OD on the southern eyot. Structures, features and finds dated to the early Roman period 43-200 AD were found on both eyots.

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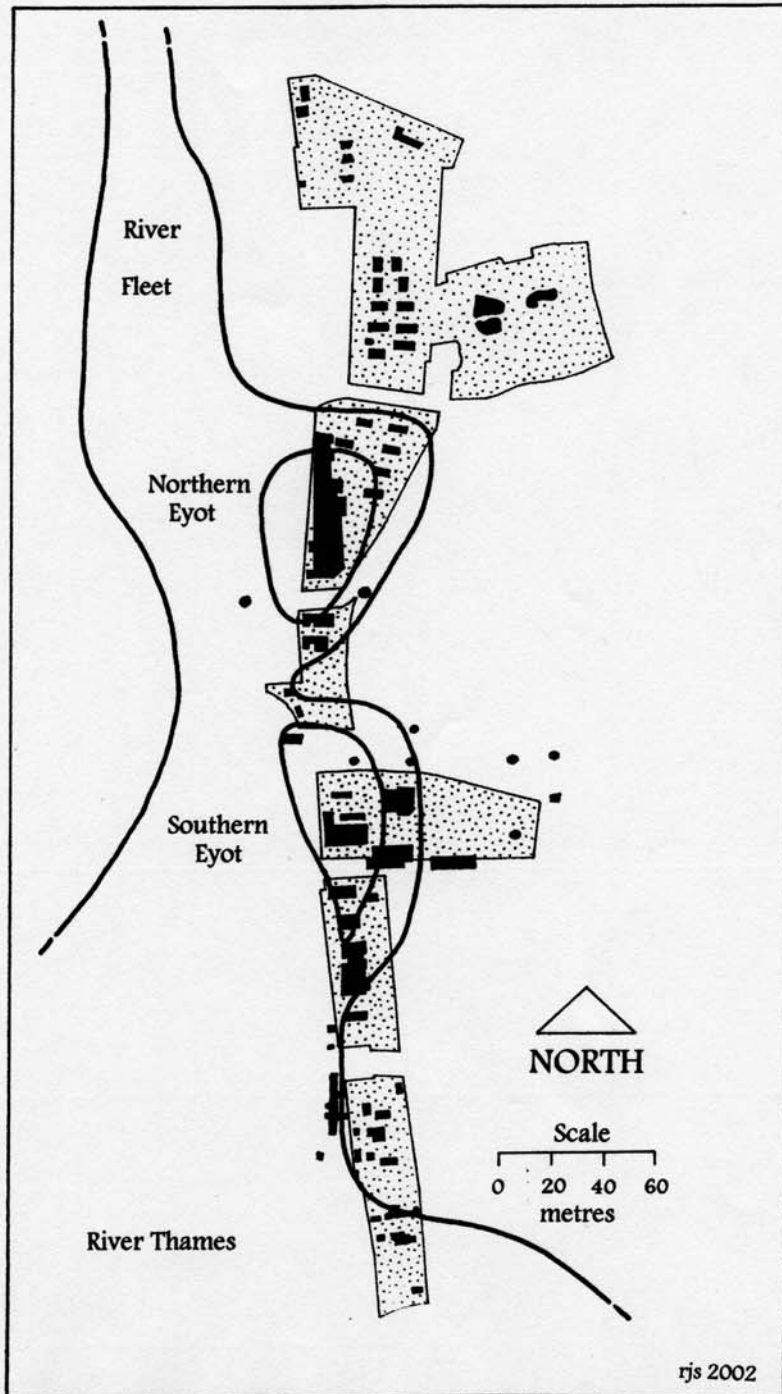
<sup>6</sup> A comprehensive introduction to the historical geography and evolution of the lower Fleet valley is given in VAL 88, vol. 54.

<sup>7</sup> VAL 88, vol. 54, 20.

<sup>8</sup> Ordnance Datum, mean sea level as defined for Ordnance Survey.

FIGURE 2

The Fleet Estuary - Early Roman Period  
Showing areas of excavation (black) and watching brief (shaded)



[b] The southern eyot.

At the north end a large piece of masonry consisting of a course of Roman tiles supporting roughly hewn ragstone blocks has been interpreted as a probable abutment of a bridge over the Fleet<sup>9</sup>. Its longitudinal alignment agrees with the projected Roman road coming from Ludgate (see Figure 3.) that has been suggested as dating from mid-first century AD<sup>10</sup>. The road may indicate the presence of an earlier bridge. Evidence was also found of a revetted quay extending from the east bank to enclose a small dock on the northern side of the bridge. One massive oak pile in the revetment gave a dendrochronological date of 158-195 AD, but the silting associated with the revetment contained a large assemblage of Trajanic pottery (100-120 AD) suggesting the pile may have been introduced later.

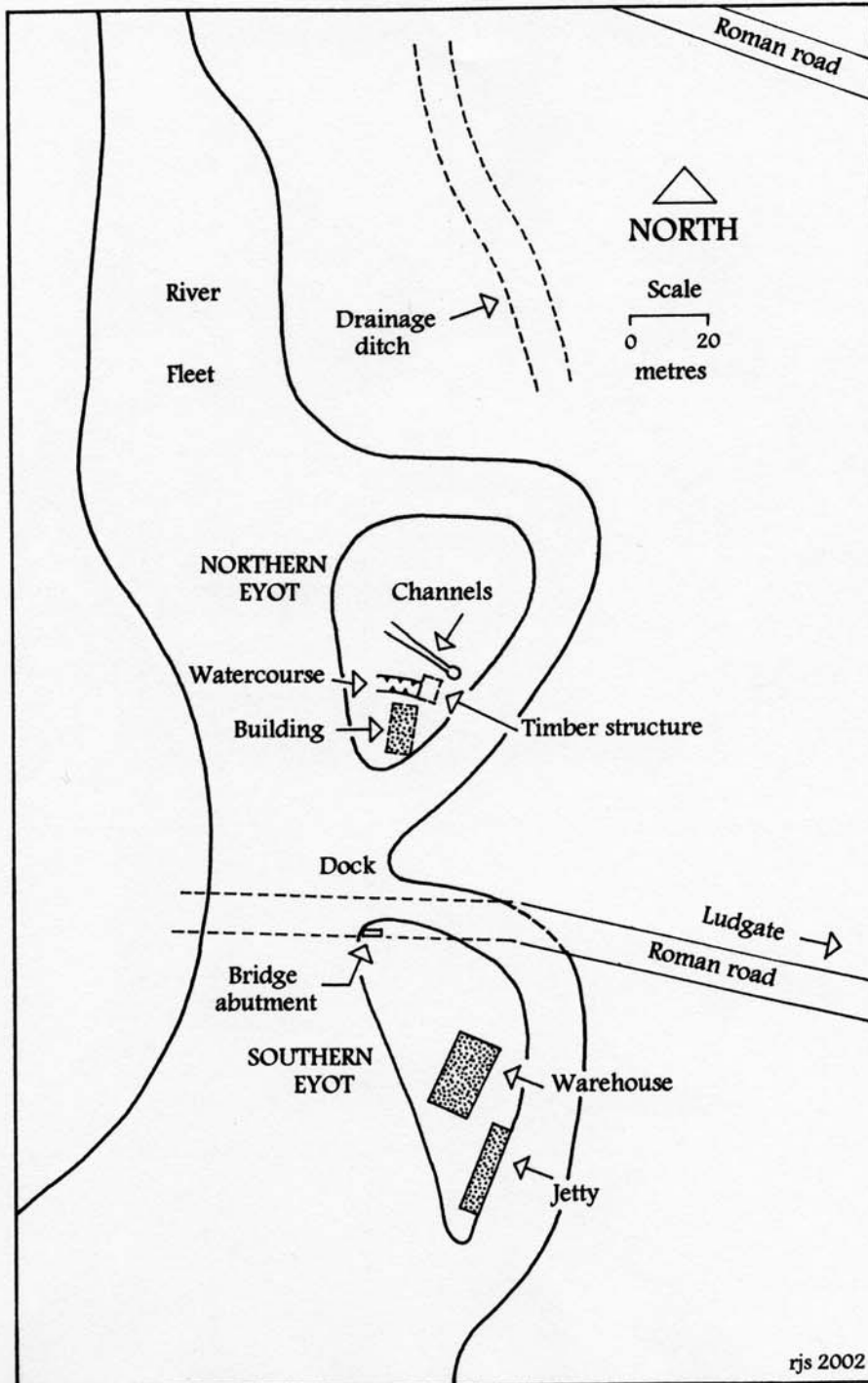
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<sup>9</sup> VAL 88, vol 48, Phasing and Synthesis, Zones C and D, 9, 10; an area of 1.5 m x 3.8 m but extending outside the excavations limits.

<sup>10</sup> Morris 1982, 100.

FIGURE 3

Principle features from excavations - Early Roman Period





Excavations on this eyot revealed on its southern tip a structure that has been interpreted as a jetty constructed with a timber base-plate that would have supported inserted uprights and a superstructure. Beneath the jetty deposits of brushwood and large quantities of spelt<sup>11</sup> wheat and chaff were found. These were thought to have been carried down on the current from the northern eyot although some threshing activity may have taken place on this eyot. The archaeologists have concluded that this area was used as an access point for shallow barges because of the high amount of lost coins and discarded goods in the area suggesting dealing between the boats and the jetty<sup>12</sup>.

The design of this jetty feature is puzzling<sup>13</sup>. A section revealed that it was approximately 2.60 m wide and parallel with the channel separating the eyot from the mainland. Only evidence of its foundations remained that on its west side comprised a 200 mm wide base-plate beam set above very irregular, mostly triangular-sectioned, piles. Two upright posts, one dislocated, were recorded as having been mortised into the base-plate some 3 m apart. Parallel to the base-plate, 2.60 m away to the east on the edge of the natural channel was a line of very irregular spaced timber posts. The ground between the two parallel features sloped down by 440 mm towards the east and was covered with alluvial deposits. These features, with their irregularity and crudeness of design, have been identified as a jetty, in spite of its insubstantial foundation for its width. A suggestion has been made that this feature may have been a watercourse, possibly a mill-race. Although its section, at 2.60 m wide with vertical timber framed sides and alluvial deposits might suggest a water channel, its position and axis next to the natural channel separating the eyot from the mainland, is illogical and impracticable. There was no evidence of any horizontal planking or wattle lining, although this could conceivably have decayed and been swept away. However, most telling was the height of the base-plate, which lay at +1.04 m OD<sup>14</sup>; that places the entire structure well above the mean tide level of +0.5 m OD that has been determined later in this study (see section 4(b) below). Such a level certainly rules out any possibility of it being a mill-race and having regard to its position on the landscape makes it most unlikely that it was intended as a water channel. Towards the northern end of the eyot a chalk and mortar floor surfaces have been interpreted as part of a warehouse. It was concluded by the archaeologists that the main activity on the southern eyot was wharfage, which ceased at the end of the second century AD.

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<sup>11</sup> Spelt, *Triticum spelta*, a primitive variety of common wheat, still grown during the early nineteenth century in certain parts of Europe, notably in the south of Germany and Switzerland.

<sup>12</sup> VAL 88, vol. 47, Phasing and Synthesis, Zones B and C, 11.

<sup>13</sup> The writer is grateful to Ryszard Bartkowiak for drawing his attention to this feature.

<sup>14</sup> VAL 88, vol. 47, Phases and Synthesis, Zones B and C, 10.

[c] The northern eyot.

The earliest activity on this eyot has been dated to circa 60–100 AD and has been interpreted as drainage and revetment work<sup>15</sup> intended to make the area usable. At about 100 AD a large and deep watercourse was cut through the eyot on an east-west axis. At least 12 m of the channel was found and it is believed that it connected to the estuary in the west and to the channel in the east. It was at least 2 m deep but was not bottomed. Shortly after this a large timber structure was constructed that has been dated by dendrochronology to circa 116 AD. The timber structure comprised massive vertical earth-fast posts aligned on rectilinear axes. No evidence of horizontal beams, braces or walls was found that might have suggested the superstructure arrangement. The structure straddled the artificial channel with its timber posts set deep into the sides and base of the channel<sup>16</sup>. North of this structure a series of smaller linear artificial channels were found, thought to be for drainage, that had been re-cut into the natural and occupation deposits. The direction of flow within these parallel channels was from east to west and they appear to have been connected to a large oval sump at their east end. Further to the south, between the larger artificial channel and the southern tip of the eyot, evidence was found that a large building had existed. The finds from the northern eyot included several wooden objects<sup>17</sup> and fragments of leather shoes preserved in the backfill of the artificial channel. There were also fragments of glass containers and iron objects of personal use. Two fragments of quern<sup>18</sup> were found, one in Roman context<sup>19</sup> with an original diameter of circa 0.40 m.

The large artificial channel was later backfilled and its makeup and occupation layers on its edges contained large quantities of charred spelt wheat and chaff which has been interpreted as representing the advanced stages of grain processing, particularly threshing, required before milling can take place. Unfortunately no other features or finds have been recorded coming from outside the excavation areas within the larger development zones that were subject to a watching brief<sup>20</sup>.

Dating evidence shows that the activity on the northern eyot was intensive around the end of the first and the early part of the second century AD. It is considered that activity ceased at the end of the second century AD because only a very small proportion of the pottery from the eyot dates from after that

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<sup>15</sup> This structural work that has not been shown on the plan is considered to be unrelated to the later possible water-mill.

<sup>16</sup> Vol. 49, Zone F, Phase E4, Industrial Activity, 18.

<sup>17</sup> The finds included part of a writing tablet and a carpenter's peg but no wooden or metal artefacts of industrial or mechanical significance.

<sup>18</sup> A hand-mill for grinding corn, usually consisting of two circular stones, the upper of which is rotated above the stationary lower one.

<sup>19</sup> [13165] <5592> E/04, 029.

<sup>20</sup> Fig. 1, the shaded areas.

period. The archaeologists have concluded that a tidal-powered corn-milling complex existed on the northern eyot, where they postulate that a threshing floor, drying area and warehouse probably existed, close to a tide-mill and a sluice-gate. These activities they saw as integral with the sea-borne grain deliveries and storage on the southern eyot. The smaller linear channels north of the structure are thought to have been an overflow related to the mill-pond and to have acted as drainage to prevent general flooding.

[d] The mainland 'drainage ditch'.

To the north of the site, on the mainland, an artificial channel was found running north to south, 9.5 m wide and 3 m deep<sup>21</sup>. Its profile was terraced and it followed the contours of the hill that lies to the east. It was considered to be a major feature whose construction must have involved much labour. The dating evidence for this ditch is not very accurate, and suggests that it was cut in the first or second centuries AD and may have finally silted up, or deliberately back-filled in the early third century AD.

### **3. Interpretation of the northern eyot structure and watercourse.**

[a] The timber structure – a sluice?

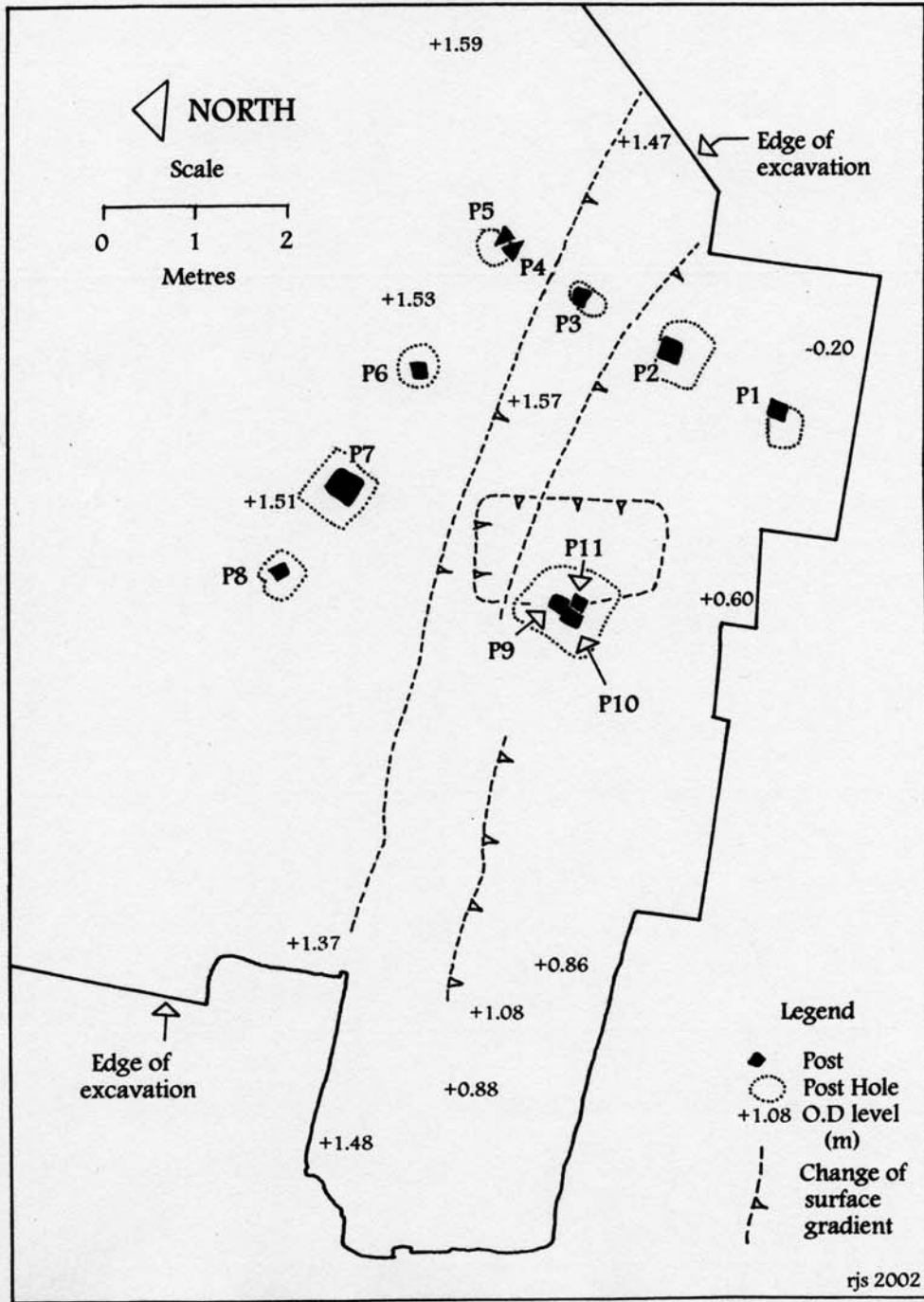
It has been suggested that the timber structure, (posts P1-P11 in Fig 4.) represents the remains of a sluice. See Appendix A for detailed information concerning the posts. When we examine the position of these posts in relation to the 'mill-race' channel it can be seen that it spans the channel cut, with post P1 set into its base, and P2 and P9-11, set into its steep northern flank. Posts P1-P5 clearly lie on a major axis as do P4-P8. In the analysis of stratigraphic sequence all of these have been identified as one structure, but because P1 and P9-11 are on the edge of the excavation, it has been suggested that the structure may have extended beyond the area of excavation, towards the south-west and the south-east. Excavation to the north makes it fairly certain that the north limit of the construction was on the line of P4-8. Under the base of P7 was a horizontal plate, broken in antiquity probably by the weight of the post, 0.55 m x 0.40 m x 30 mm thick.

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<sup>21</sup> VAL 88, vol 54, Final Interim Report, 25; However, Vol. 8, Zone C Summary, gives dimensions of 'about 6.50m wide and at least 2.50m deep'. The drawings appear to support the larger dimensions.

FIGURE 4

The Northern Eyot - The Timber Structure



The major axes of these posts are clear, being a WNW/ESE direction. This is confirmed by the minor axes of the majority of the posts, including the sub-group P9-11<sup>22</sup>, with the exception of P8<sup>23</sup> and P6. It should be noted however that the post hole for P8 agrees with the major axes. Posts P4 and P5 are two triangular section stakes that were placed together to form a rectangular outline having the same minor axes as the other posts. The major axes of this structure, which does not align with the feature at the south end of the eyot, suggests a separate structure *relating* to the channel, which was almost certainly open to the river on the eastern side of the eyot<sup>24</sup>. In the analysis by the archaeologists, the conclusion is drawn that this structure, built out over the artificial channel, was probably a sluice<sup>25</sup>. Let us consider this in more detail.

A sluice comprises two substantial vertical earth-fast parallel posts, braced across at the top, that act as guides for a vertical sliding gate. The moving gate itself would be made from solid planks, framed or cross-braced for strength, and either constrained by vertical mortises cut within the face of the side frames or held between parallel posts. There is no obvious evidence of this structural arrangement on the posts within the channel (P1, P2, sub-group P9-11).

However, a vertical north-south section taken through post P2 shows that this artificial channel was at least –0.2 m OD deep at the edge of the excavation, and its northern flank was still sloping appreciably at that point. In other words the structure that we are examining lies to the north of the centre of the channel, so that if a sluice-gate was positioned here we would expect to find it in the centre of the channel, perhaps in the region of P1 or SW of the cluster P9-11. One wonders if the cluster P9-11 could have been the side frame of a sluice gate. The position and arrangement of these posts suggests that they might have been a frame on the north side of a sluice, but there should be an appreciable parallel gap between P10 and P11 to act as a vertical groove for the gate, but this is apparently absent in the recorded data and plan.

We should also realise that if a sluice-gate were positioned in this channel, it would form part of a linear structure crossing the channel. Each side of the central gate would have needed an earthen, or far more likely, a wooden dam to hold the water back. No trace of either vertical or horizontal planks have been found embedded in the channel bank nor have any posts been recorded that exhibited evidence of such arrangements. But look to posts P7 and sub-group P9-11. The huge scantling of P7 that was supported underneath by a base-plate and the collective strength of P9-11, are outstanding in the whole structure. Their

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<sup>22</sup> One of these was replaced at some time in its life; vol. 49, Zone E, Phasing and Synthesis, 19.

<sup>23</sup> The plan does not agree with the schedule providing context description that defines two posts (13363 and 13108) in the position of P8. Moreover there is an error in the dimensions of one of them (13108). It seems likely having regard to the detail of the schedule, that two posts existed in this position, but in absence of any drawings showing them, we can only note that the foundations at this point were stronger than illustrated.

<sup>24</sup> Vol. 49, Zone E, Phasing and Synthesis, 18.

<sup>25</sup> *Ibid.*, 19, 20.

WNW axis, is normal to the axis of the channel, and their size positively suggests a line of structural strength. Might this be the residual evidence of a bulkhead on the upstream face of the structure? But this supposition is incapable of proof and it is considered imprudent to advance this any further.

Although there is no clear confident evidence of a sluice or related dam in this structure, we cannot reject the idea mainly because of the limits of excavation in relation to the scale of the channel. We need to remember that absence of evidence is not evidence of absence, and that in this estuarine situation, it is likely that natural decay and floods have removed everything except the ends of deep and substantial earth-fast posts.

What we can be far more certain of is that the entire structure was not *solely* a sluice. The sizes of the posts, some of which are massive and clearly intended to support substantial weight (or side-thrust) have been installed into<sup>26</sup> and across the artificial channel. What could the structure be, that projects into or passes over an artificial channel, that was created at about the same time, and cut right across the eyot adjacent to tidal waters? Currently, there appear to be only two possible suggestions, either a jetty or a watermill.

The archaeologists consider that this major timber structure does not apparently represent a conventional building<sup>27</sup>, but they do not give a reasoned basis for this conclusion except that the posts '*do not make an obvious pattern from which a building outline might be inferred*' (!). The idea of a jetty has been examined but rejected, on the basis that it makes no sense at all to erect a jetty within this artificial channel, which was cut through natural deposits<sup>28</sup>. Additionally it was thought that the series of gullies and channels near the centre of the eyot would make access to a jetty difficult from the landward side. Furthermore, the remains of the structure found at the south end of the northern eyot, adjacent to the river bank, is a superior position for a jetty. Remember as well, that a jetty had been identified on the south eyot, which seems to be the prime position in this complex for unloading river traffic.

At this juncture, we should remind ourselves that the occupation of this eyot required a bridge from the mainland. The archaeologists have not identified any remains of one, or suggested the possible site for it, but the writer favours a location for a road bridge nearer the south end of the eyot, mainly because no evidence of road surfaces or supporting structures were found north of the artificial channel. A bridge in the south also places the occupied zone nearer the Roman road coming out of the city down Ludgate Hill towards the eyots. The absence of evidence to the north of this structure also rules out it forming part of a road carried over the artificial channel and continued northwards. The idea of a bridge can be rejected solely on the basis that the artificial channel was built at

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<sup>26</sup> Posts P2 and P9-11 have been identified as having been driven into the channel walls and bed.

<sup>27</sup> Vol. 49, Zone E, Phasing and Synthesis, 18, 19.

<sup>28</sup> *Ibid.*, 19.

about the same time; the simultaneous building of a bridge and a watercourse beneath appears nonsensical.

If we conclude that this structure was not related to transportation, either road haulage or wharfage, then we must surely arrive at the conclusion that this building related *directly* to the artificial channel. We must now examine the idea that a water-mill operated in this area.

A water-mill requires a headrace<sup>29</sup> that is constrained and channelled into the wheel or alternatively, a continuously flowing body of water into which the wheel can be immersed. In a river mill the water entering the wheel does not necessarily need to be channelled any distance upstream providing there is ample flow close to the mill. If the flow is sluggish or its direction or volume adversely affected by the bank or bed of the river immediately upstream of the wheel, then revetment work will be needed to narrow or concentrate the channel and improve the flow into the wheel.

If the mill is sited in the lower reaches of a river where deposition and alluvial deposits have occurred, the building work to obtain a secure foundation and a clear revetted channel upstream of the wheel, could be considerable. In an estuarine situation – probably the worst for deposition and insecure ground – the problems and scale of work are much greater. Where the landscape lends itself to an alternative arrangement to harness water-power, considerable advantage is to be gained by cutting through the ground from the water source to the mill. This allows the most suitable watercourse section and gradient to be created and readily facilitates revetments of the races, both head and tail as required. Digging out new ground is much easier than excavating underwater or between tides, or erecting and working within a caisson. The water supply to most Roman water-mills was taken to and from the mill by a man-made watercourse<sup>30</sup>.

Where the wheel was an overshot or served by an accelerated headrace, there was no alternative but to take the water to the wheel in a designed mill-race. With undershot wheels of relatively low velocity (and low head), which is the arrangement that we are concerned with, the advantages of cutting a headrace are equally valid. This is the reasoning and logic behind the watercourse cut through the Northern eyot.

#### [b] A tide-mill?

One of the reasons why corn-milling operations have been suggested for the northern eyot was that large quantities of charred spelt wheat, chaff, and possibly barley, were found in the artificial channel and adjacent excavation

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<sup>29</sup> A channel carrying water to the water-wheel. Syn. Flume, Lade, Leat and Mill flume.

<sup>30</sup> Spain 1984 (a), 1984 (b). Other examples existed at Saint-Pierre/Les Laurons (Les Arcs) and at Les Mesclans (La Crau), both in the Department of Var, France; Saepinum, Italy; Dasing, Bavaria; Hagendorn and En Chaplix, Switzerland.

areas<sup>31</sup>. The parching implied by the charring is interpreted as the final stages of grain processing, used to make the inner glumes brittle and therefore easily separable from the grain by milling<sup>32</sup>. Finds of burnt and parched cereals on Roman sites suggests that grain drying was common practice and probably integrated with bulk milling using animate or water-power<sup>33</sup>. It seems very likely, as suggested by the archaeologists that these operations were carried out in the building(s) on the eyot. The large fragment of a quern-stone was also found on the northern eyot, original diameter circa 0.4 m, which supports the suggestion of milling. The quern itself would not have been the primary method for grain reduction, but several Roman water-mills have yielded querns alongside millstones<sup>34</sup>, which suggests that they were used for ancillary functions<sup>35</sup>.

If a water-mill existed on, or adjacent to the northern eyot, it was clearly positioned in either a natural or artificial channel, which was estuarine – subject to the tides. To be effective, the undershot water-wheel of a tide-mill needed to be (a) at a level so that it could use the stored water whilst the ebb-tide continued to drop away from the underside of the wheel, and (b) in a position so that its headrace and tailrace<sup>36</sup> allowed unimpeded flow downstream from the millpond to the lower estuary. In a tide-mill, all of the pond water above the level of the bottom of the wheel can, in theory, be usefully used for powering the wheel, which in this estuary situation, is a combination of tidal water and flow from the Fleet river. Only by building a mill-dam could a head of water be created to ensure that flow would occur through the head-race to the mill.

If we are considering a tide-mill either within the north eyot or on its banks the mill-dam cannot be downstream of, and unattached from the eyot, (see Figure 5, position A), which would put the mill upstream of the dam in an unworkable position. The question has been asked if the mill-dam could have been integrated with the river bridge that crossed the northern end of the southern eyot. The major problem with this suggestion is that the water from the mill can only be taken downstream using the channel to the east of the southern eyot, if the dam was extended between the two eyots. This impractical arrangement, which would involve a doubling of the length of the dam, meant that boats using the southern jetty and the dock, had to work against the flow coming from the

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<sup>31</sup> Vol. 49, Zone E, Phase E4, Industrial Activity, Abstract, 19.

<sup>32</sup> Parching is essential for stabilising large batches of grain following a wet harvest or shorter drying season and was also a means of killing pests such as weevil. Drier grain, although slightly harder, is easier to mill and feed into the stones. The parching of wheat using drying kilns, was a common feature in later centuries, particularly in northern and western British Isles.

<sup>33</sup> Milne 1995, 46, 64.

<sup>34</sup> For example Haltwhistle Burn Head, Ickham and the Athenian Agora.

<sup>35</sup> Most likely for testing grain to establish its condition in readiness for milling. Querns might also deal with small volumes of different grains, pulses or other seeds from customers. They might also have provided further refinement of a product or a quality control datum for the main milling work.

<sup>36</sup> The water-course flowing away from the water-wheel.



mill. The suggestion of integrating the dam with the river bridge is therefore rejected.

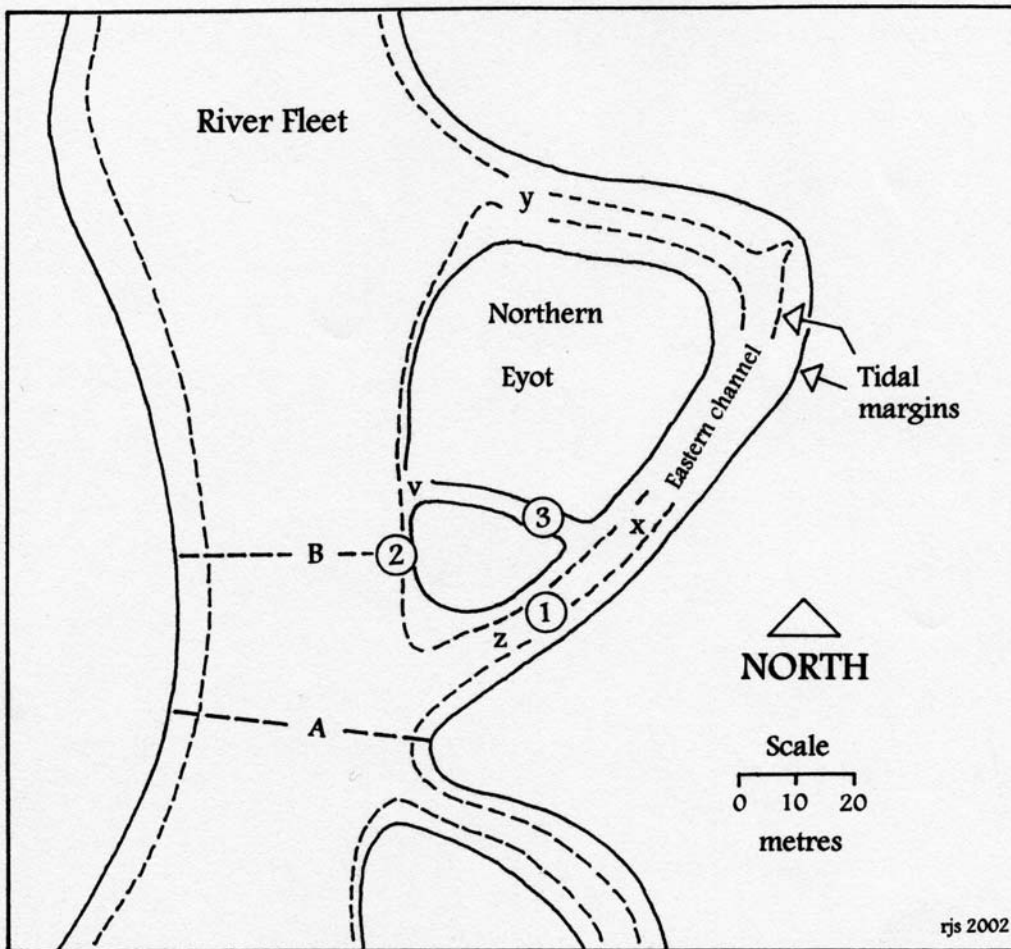
It is concluded that the main dam has to be in position B to be effective. Moreover, it has to be supplemented by another dam in the channel to the east of the eyot. If the artificial channel was a mill-race, that is either a headrace (taking water to the wheel) or a tailrace (taking water from the wheel), the supplementary dam had to be positioned somewhere between  $y$  and upstream of  $x$ , where the mill-race entered the eastern channel. We have one small clue that the supplementary dam may have been positioned at  $x$  rather than  $y$ . The linear artificial channels and sump north of the timber structure (see Figure 3) might just be an attempt to move water away that had over-spilled the eastern bank of the eyot. One can imagine that in times of spate, the Fleet might have overcome its banks in this area, and the channels were cut to remove the threat that this may have posed to the buildings nearby. But the most obvious advantage in having the dam at  $x$  is that it places it close to the occupied southern area of the eyot.

We can conclude from the levels found that the artificial channel carried water from west to east. Not enough of the channel was found to confirm this but we can confidently suggest that the water would flow away from the millpond, so that as the mill continued to work, it would deplete the storage. The alternative direction of flow is unworkable.

Having outlined the primary physical features we can now postulate the options for positioning the tide-mill, which must be somewhere on, or very close to, the triangular axis of  $v$ ,  $x$  and  $z$ . There appear to be three basic positions, indexed 1, 2 and 3 on Fig. 5.

FIGURE 5

Optional positions  
Mill-dams and water-mills



[c] Position One - The Eastern channel.

Let us first consider the natural watercourse between x and z. The siting of a water-wheel in the natural East channel would have involved substantial structural works. First the wheel needed to be positioned over the channel; that would have required driving large posts into its bed to support the horizontal beams carrying the wheel-shaft bearings. The wheel could either be in

mid-stream or be close to the bank of the eyot where the bed of the channel would need to be deepened and revetted to produce an emplacement for the wheel. No matter where the wheel was positioned in the channel, that was some 12.5 m wide, the water would need to be constrained and directed to the face of the wheel by a timber dam with a sluice-gate immediately upstream of the wheel, otherwise the flow from the pond would be lost in the channel and be ineffective on the wheel.

If a water-wheel was in this stretch of water, the advantage that the artificial channel gave is to be questioned. Theory suggests that there was no need to create such a large artificial channel while the water-wheel could receive water through the natural channel between *y* and *x*. However, accepting that the bed of the River Fleet had a gradient from *y* to *v*, one might argue the channel at *y* would cease to flow when the level of the water held by the mill-dam reached the level of the bed at *y*. The artificial channel therefore had the advantage theoretically of removing more water than the natural channel at *y*, however in reality this may have been largely negated by a practical necessity concerning the management of the water.

With a tide-mill the water-wheel can only work when the ebb-tide is close to or falls below the bottom of the wheel. It follows therefore that the bottom of the wheel had to be some distance *above* low tide to create an effective work period. This requirement would tend to place the bottom of the wheel above the bed of the channel at *v*, thereby reducing and even negating the advantage that the artificial channel had over the natural channel at *y* to drain the millpond<sup>37</sup>. Furthermore, the archaeologists have determined that the eastern channel still carried water at low tide, as indicated by the tidal margins on their plans (see Figure 5). But our conclusion must be that with the water-wheel in position One, we are unable to explain the function of the artificial channel, having regard to the natural eastern channel that existed between *y* and *x*.

#### [d] Position Two – The main estuary.

Obviously the water-wheel emplacement could be integrated with the main mill-dam running between the west bank of the eyot to the west bank of the Fleet. The best position for this would be at the east end, where the mill-house could be built on the bank of the eyot in position Two. The scale and design of the structural works in this position are virtually identical to those for position One, except that they would still need a supplementary dam between *y* and *x* to complete the millpond.

With the wheel in this position the artificial channel serves no purpose to the mill, because a bypass or overflow, where water in excess of the mill's requirements could circumvent the wheel, could easily be provided on the dam. Our

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<sup>37</sup> A more detailed theoretical analysis concerning wheel height in relation to tide-profiles is given below in section 4.

experience of water-milling during the last few centuries shows that the most practical arrangement for allowing excess water to bypass the wheel was to create an overflow or flood-sill within the mill-dam close to the mill. This would allow water above a predetermined level to flow to the tail-race, in this case downstream, to the estuary. Such an arrangement was very necessary, to ensure that in times of storm and spate the waters would not cause damage to the wheel or mill. Experience would dictate how long the flood-sill needed to be, but with this length of mill-dam across the estuary, about 40m, there was ample space to allow a considerable volume of water to overflow downstream. And so once again the existence of the artificial channel renders position Two for the mill untenable.

[e] Position Three – Within the northern eyot.

We must now consider a water-mill positioned within the artificial channel. Naturally our thoughts will be influenced by the structure found adjacent to the channel, which we have concluded was not a jetty or related to transportation, but was built in association with the artificial channel. We need to be slightly cautious because the channel was thought to have been cut in c.100 AD and the dendrochronological date for the structure is c.116 AD. It would be easy to suggest that perhaps the structure underwent change and alteration – indeed we know that there was one post inserted subsequently – but unless further evidence is brought to bear on this point we can only note that both dates are approximate.

It is interesting to note that evidence was found that one of the posts in group P9-11 was replaced at some time, which shows that both the structure and the channel was in use for some while.

First it might be helpful to look at the evidence we have of the artificial channel. We are told that during the excavation the channel was not '*bottomed out*' but that it was at least 2 m deep<sup>38</sup>, and the '*levels in the mill-race*' are given as 1.48 m to -0.38 m OD<sup>39</sup>. Furthermore we do not know its full width, but if we assume that the limit of excavation, close to post P1, revealed a minimum half width of approximately 2.3 m, and that the channel section was roughly symmetrical, then the total width may have been in the order of 4.6 m perhaps 5.0 m.

The cross-section of this water-course is, at first glance, unusual for a mill-race. Its v-shape and its great size make it quite different to other examples of Roman mill-races cut through ground, which in the Roman north-west provinces are often revetted and timber-lined on the bed in the vicinity of the water-wheel<sup>40</sup>. No

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<sup>38</sup> Vol. 54, 4 Period 1, Early Roman AD 43-200, 26.

<sup>39</sup> Ditto, p.34. The plans and sections showing levels do not appear to support the stated lower level figure, but something less measuring -0.2 m OD.

<sup>40</sup> Examples include Haltwhistle Burn Head, Northumberland (See Spain 1984a, 105-107.); Ickham, Kent two separate sites (See Spain 1984(b); also forthcoming publication of the Ickham

evidence of revetment was found here, although we need to be cautious because of the erosion that may have occurred. Additionally our initial thoughts should be tempered by the fact that we have no comparative examples of Roman tide-mills and we need to bear in mind that the tidal range would have necessarily influenced its depth.

Although mindful that the section of the channel may have been influenced by deposition and erosion, the slope of its sides are steeper towards the east<sup>41</sup>, which suggests that if a waterwheel worked in this area, it lay to the east of the structure, beyond the edge of the excavated area. As we have determined, the water-wheel would require a sluice-gate immediately upstream for regulation and control, and having regard to the nearness of the East channel, it was most likely integrated with the structure found.

We need to take a view on the volume of water flowing in the River Fleet because this could influence our thoughts on the day to day water management and mill operation, the interpretation of tide profiles and the possibility of more than one water-wheel co-existing.

There is one inescapable and obvious fact that has great influence on several aspects of this study. This is that the flow issuing from the River Fleet during the Roman period was greatly in excess of the power needs of one water-mill. The position in its valley which we are examining, is downstream of all its tributaries, thus we are receiving its full flow level with the northern eyot. Let us see if we can put this assertion into some kind of perspective. Firstly, let us attempt to picture what the scale of the Fleet was in early Roman times at the tidal head. Understandably all of the information concerning the size of the Fleet comes from more recent sources. Stow<sup>42</sup> writing in 1598 describes five bridges over the lower part of the Fleet but we have to turn to later, mostly nineteenth century sources to gain a clearer picture of its size. A 1676 map of the City, which appears to depict the Fleet very accurately, shows it to be canalised below Holborn Bridge (Viaduct) and between 35-40ft. (12.2 m) wide<sup>43</sup>. The words New Canal are applied to the stretch between the Holborn Bridge and the Thames. In 1825 the Fleet was reported to be 13 ft. (4 m) wide in flood<sup>44</sup> where the eastern source of the Fleet crosses the Highgate Road, which is perhaps 15% of its distance towards the Thames. A little further down the valley, where the two main sources united close by Kentish Town road, perhaps 40% of its journey

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archives by Canterbury Archaeological Trust under the auspices of English Heritage); Dasing, in Bavaria, (See Czysz, 1994); Chaplix, near Avanches, Switzerland (See Castella, 1994); Oderzo, Italy (pers. comm. from Roberto Trovò. See Trovò. 1996); and Hagendorn, Switzerland (See Gähwiler and Speck 1991).

<sup>41</sup> Vol. 49, Abstract, Phase E4, Zone E, 20.

<sup>42</sup> Stow 1598.

<sup>43</sup> Ogilby and Morgan 1676.

<sup>44</sup> According to a report of a Committee of Magistrates on the Public Bridges of Middlesex. Barton 1962, 27.

towards the Thames, it formed a stream reported as 65 ft. (19.8 m) wide at flood in 1826<sup>45</sup>. Downstream of here four other tributaries entered the Fleet. Two early Victorian illustrations suggest that the river at Battle Bridge was at least 6 m wide and downstream at the Fleet Bridge a similar width<sup>46</sup>. What its bed section was we can only guess, but it may have had a minimum area at the tidal head of, let us say, between 5 and 8 m<sup>2</sup>. But this is an indefinite view of the river less than two centuries ago. We can have more confidence surely, in one aspect of its scale in early Roman times; it would have been larger.

The area of the mill-pond upstream of the suggested dams *B* and *y* is substantial. The pond area at high tide measures 11,500 m<sup>2</sup>, that is a large area for a water-wheel of the period, but by comparison is smaller than those found in modern tide-mills. Nonetheless, we can be confident that this volume of water was ample for the power needs of a single pair of Roman millstones, requiring say 2 HP, which was much less than modern wheels that would have powered a minimum of two, possibly three millstones, that would need, with a margin for ancillary machinery, a nominal 5 HP per set of stones.

A typical pair of Roman disc millstones needed approximately 1.0 to 2.0 HP for operation<sup>47</sup> that is to be compared with 4.0 HP for a typical pair of nineteenth century four foot diameter millstones grinding wheat<sup>48</sup>. But using theoretical power figures is somewhat misleading because our concern is with rate of water flow, which can vary considerably with the type of water-wheel. Our undershot water-wheel would be classified as a low-head application, where the head of water is a maximum at the commencement of work, reducing to a minimum as the tide-pond emptied. Essentially it utilises a large flow-rate at a low velocity, which is similar to several other Roman water-mills that have been found<sup>49</sup> and is distinctly different from low flow-rate high-velocity Roman water-wheels where the power is generated mainly by an accelerated headrace<sup>50</sup>. Let us, to avoid entering into burdensome theoretical detail, take a very simplified view of the amount of water necessary to apply to an undershot wheel. Assume that our wheel is 1.0 m wide and the depth of water that is required was, say, 0.5 m. If, for the moment, we avoid the subject of velocity and think solely in terms of the section of the body of water, or more aptly, the headrace, then our wheel would

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<sup>45</sup> Barton 1962, 27. An anchor was reputedly found in the river bed near here suggesting that it was navigable to small boats three miles from the Thames.

<sup>46</sup> Barton 1962, 96-7, 78. Battle Bridge c. 1840 and Fleet Bridge 1839, illustrations from the Crosby Collection, Guildhall Library.

<sup>47</sup> Spain 1992. Hydro-mechanical analysis of the Haltwhistle Burn Head mill suggested 1.25 HP; Athenian Agora, millstones as found, less than 1.0 Hp; Venafro, 2.0 HP; Barbegal a maximum of 2.4 HP.

<sup>48</sup> Box 1882, 63. A common 4ft. (1.2m) diameter millstone grinding four bushels of corn per hour making 125rpm requires about four horsepower. Spain 1972. Oral tradition and operational experience at Wickhambreux Mill, Kent, shows that 5 H.P. was needed, including power for ancillary machinery.

<sup>49</sup> Such as Ickham, Kent, and the mills of the Aqua Traiana on the Janiculum Hill, Rome.

<sup>50</sup> For example Venafro, Haltwhistle Burn Head, Losnich, Athenian Agora, etc.

need a section of 0.5 m<sup>2</sup>. Let us double this to allow for water that might bypass the wheel in the emplacement and perhaps over-application by the miller controlling the sluice-gate, and we arrive at 1.0 m<sup>2</sup> of channel section<sup>51</sup>. Whilst we do not know the channel section of the Fleet at the tide-head, the writer is of the opinion that it could have easily powered several water-wheels in *parallel*. We should accept that the builders might well have built a second watermill served by the same large mill-race to drive another pair of millstones<sup>52</sup>.

Let us now return to the mill on the northern eyot. How does this information concerning river flow rate in relation to water-wheel demand affect our analysis? First, it suggests that the artificial channel, the 'mill-race', could deliver water greatly in excess of the needs of a single water-wheel. Why such a large channel? Clearly it could have served more than one wheel. Our second development is that when the pond was full and the sluice-gates allowing the tide in were closed, from that moment, the flow from the Fleet would be adding to the mill-pond. This would allow the miller to continue to store more water if needed, up to a flood-sill level on one or both mill-dams. This would take the surface of the mill-pond to any level that the miller chose beyond the influence of the tide, but not of course to a height that would adversely affect the milling operations. One further alternative arrangement needs to be examined, could the water-mill work without the use of dams? Might the builders have attempted to use the River flow only? The answer is an emphatic no. The river flow would follow the natural channels especially the main one. There would be no reason for it to flow through the artificial mill-race especially if the mill-wheel and the posts presented an obstruction to flow.

One other basic question comes to mind. With the river Fleet feeding the mill-pond with ample water for one or more water-wheels, we must ask the question was the tide needed to fill the pond? Again, the answer is no, in theory. The mill-dam could have been set at a height above the general high tide level with the sluice-gates closed, thus keeping out the tide and keeping in the Fleet. But when the tide was in flood the volume of water entering the estuary was surely substantial and likely to have exceeded the flow rate coming downstream from the Fleet. The creation of the artificial channel and the structure has the same validity for the Fleet as for the tide, with the exception of one important fact. The bed of the mill-race that was not '*bottomed out*' was at least -0.2 m and possibly as much as -0.38 m below OD<sup>53</sup>. This level equates to mean low-tide, which indicates a strong argument for the channel to have been tidal. Why otherwise dig it so deep? Why not avoid the difficulties of excavating a tidal

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<sup>51</sup> At a head of 0.5m and a velocity of 1.5m/s this volume of water has a potential of 9.9 H.P. If we assume an efficiency of 22% for a simple design of undershot wheel, this would provide over 2.0 H.P which is ample for the grinding, gearing and bearing friction of a Roman mill.

<sup>52</sup> No Roman water-mill has been found where a wheel powered more than one pair of millstones. A greater production was always facilitated by building another wheel driving a separate pair of stones.

<sup>53</sup> See above; plans and sections suggest -0.2 m. OD whilst the text states -0.38 m. OD.

channel and build the water-wheels at a higher level? The answer seems unavoidable; they chose to use the tide for power, not the river. Perhaps they saw the rise and fall of the tide in conjunction with the great volume of water entering the estuary as the most obvious potential power-source, and the flow of the Fleet, being less obvious was thought to be secondary and less significant. But we shall return to this discussion later following further analysis.

[f] Thoughts on the water-wheel design.

With so many variables and imponderables, it is questionable whether we should attempt to describe possible arrangements for the wheel and sluice. However we might formulate some ideas on the design of the water-wheel.

The wheel of a Roman tide-mill would have had radial floats<sup>54</sup> and was probably not shrouded<sup>55</sup>. Planks would have lined the bed of the wheel-pit and the first few metres of the tail-race, for without such protection the water would have quickly scoured the bed of the mill-race, thus allowing the water to pass under the wheel without having a positive effect on the floats. The same principle of constraint applies to the sides of the wheel-pit where we can imagine that the builders realised the obvious advantage of close-boarding the walls so that the wheel was a reasonable fit in the emplacement.

On the question of sole-boards<sup>56</sup> we need to be cautious. In many ways a tide-wheel is similar to a basic river wheel, where the body of the water has considerable volume but low velocity, and the floats of the wheel can operate quite deep, indeed, wholly immersed in the water. When there is plenty of water – and this assertion will be made for this site below – and the wheel operates within an emplacement, the advantage gained by having sole boards is minimal. The danger with sole boards is that they might constrain water surging into the wheel above the floor and cause an upward thrust, which could unseat the journals in the bearings. Light upward thrusts could easily be checked by top covers or straps above the journals which would probably be present anyway, but the forces that might occur with freak waves or flash floods could have catastrophic results. We may conclude that sole boards were unlikely to have been present in the wheel.

Our discussions on the day to day water management that come later in this study shows that the water-wheel would spend some hours each tide cycle deeply immersed in water, which also would probably mean that the pit-gear, mounted on the shaft, was partly submerged.

Roman water-wheels varied greatly in diameter from as small as 2 m to more than 4 m in size. The drainage wheels employed in their mines are testimony to

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<sup>54</sup> Floats, the projecting wooden or metal paddles or blades on water-wheels. If shrouded with sole-boards they are called buckets.

<sup>55</sup> The shroud is a vertical rim or flange enclosing the buckets or paddles of a water-wheel.

<sup>56</sup> Sole – the bottom boards or plates forming the bottom of the buckets of a water-wheel.



their ability to make fairly complex, accurate and graceful designs<sup>57</sup>, but an undershot tide-wheel would need to have inherent strength to withstand tidal surges and spate. The miller would quickly learn that an essential feature was a device to stop floating debris, branches etc, from being carried into the wheel and smashing the paddles. In modern mills this would take the form of a 'trash grille', usually vertical bars or staves immediately upstream of the sluice-gate. Sometimes a floating boom can help.

If we assume that tide-mills were essentially a feature of the Atlantic coast, Roman tide-mills may well have been rare and so we ought to acknowledge that they may have had limited experience of what diameter to make their wheel in relation to tidal range. The specimen that we are contemplating may have occurred early in their experience, and may therefore have been a size poorly suited to the site; it is doubtful that we shall ever know. The lesson here is that our thoughts should not be dominated by our expectations, the reality could have been quite different.

Whilst there are many variables and alternative arrangements to deal with, the most likely design was a radial-armed single bay wheel carrying fairly deep radial floats supported by segmented rims. Concerning the diameter of the wheel, the larger the better up to a limit. The greater the radius that the paddles are set, the greater the torque generated on the wheel-shaft. A larger diameter also means that more of the wheel is out of the water, where some advantage exists with the shaft and bearings being kept above water for most of the time. Of course when the wheel was working water would be splashing everywhere so that for much of the time the shaft and the wheel would be saturated. A 3 m diameter wheel would seem to be a reasonable suggestion but it is speculative.

On a point of operational detail we might briefly debate whether or not the miller 'locked' his wheel in some way to prevent it from revolving when mill-work stopped. An incoming tide could cause the wheel to move backwards and rotate the millstones the wrong way, which would not cause harm whilst grain remained between the faces. The answer to this might be to raise the top stone but then he would lose the 'load' off the wheel helping to prevent rotation. He might have disengaged the gears<sup>58</sup> so that the vertical spindle and millstones become inoperable, leaving the water-wheel to swing free with the currents. But occasionally he would have needed to be able to hold fast the wheel for maintenance purposes when the wheel itself, the pit gear and bearings needed attention or to remove debris that had become entangled in the arms and the paddles. On balance the writer favours the wheel being held firm by some simple device when the mill was not working.

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<sup>57</sup> Such as Rio Tinto, Tarsis, Logrno (Spain); Leon, Tharsis (Huelva); San Domingos, Minos dos Mouros (Portugal); Rudo, Verespatak (Transylvania).

<sup>58</sup> The modern methods include slipping one or more cogs out of position, sliding the driven smaller gear up the vertical spindle and out of mesh, or, pivoting the vertical spindle out of its footstep bearing.

#### 4. Roman tide profiles, analysis and regression.

##### [a] Generating a theoretical Fleet estuary tide profile.

To have a better understanding of the workings of a tide-mill we need to generate a tide profile as realistic to the time as possible and then interpret how different levels of water-wheel affect the diurnal operation of the mill. When the range<sup>59</sup> is shown for a full tidal cycle with the level of the water-wheel on a common height scale, the periods for pond filling, waiting and working of the mill become easier to ascertain. This will then help us to determine the effect of tidal regression from the middle of the first century A.D. But before we obtain an appropriate tide profile we need first to be aware of the natural forces that influence tides.

The height of tides varies according to the positions of the Moon and Sun relative to the earth. *Spring* tides occur when the Earth, Moon and Sun are all in the same line, and they are either in conjunction or opposition. The gravitational forces acting upon the Earth cause the lunar and solar tides to coincide; that results in a large tidal range i.e, very high and low level tides that occur approximately twice a month during the time of the full moon and new moon. When the Sun and Moon are at right angles to each other relative to the earth the solar and lunar tides are out of phase and the tidal range is smaller. These tides are known as *neap* tides<sup>60</sup> and occur in the first and third quarters of the moon's phase's midway between the *spring* tides. This continuous interaction of the solar and lunar tides creates approximately each month two occasions when the tidal range is at a maximum (*spring*s) and two when it is a minimum (*neap*s). Figure 6 shows a typical tide profile for the River Thames illustrating this cycle<sup>61</sup>.

Two other tidal phenomena occur which we need to be aware of. The semi-diurnal spring tides reach their highest levels around the *equinoxes*<sup>62</sup> and their lowest levels at the *solstices*<sup>63</sup>. Approximately every eighteen months when the spring tides coincide with perigee, the closest approach of the Moon, extremely high levels of tide can occur called *perigean* spring tides.

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<sup>59</sup> Throughout this paper the term range is used for difference between levels of successive high and low tides. Some historians have adopted the term amplitude in lieu of range for the total displacement of the tide, which is misleading and in strict nautical and mathematical terminology incorrect. See *Admiralty Manual of Navigation* vol. 1, (1970), 371, 'amplitude.. is equal to half the range'.

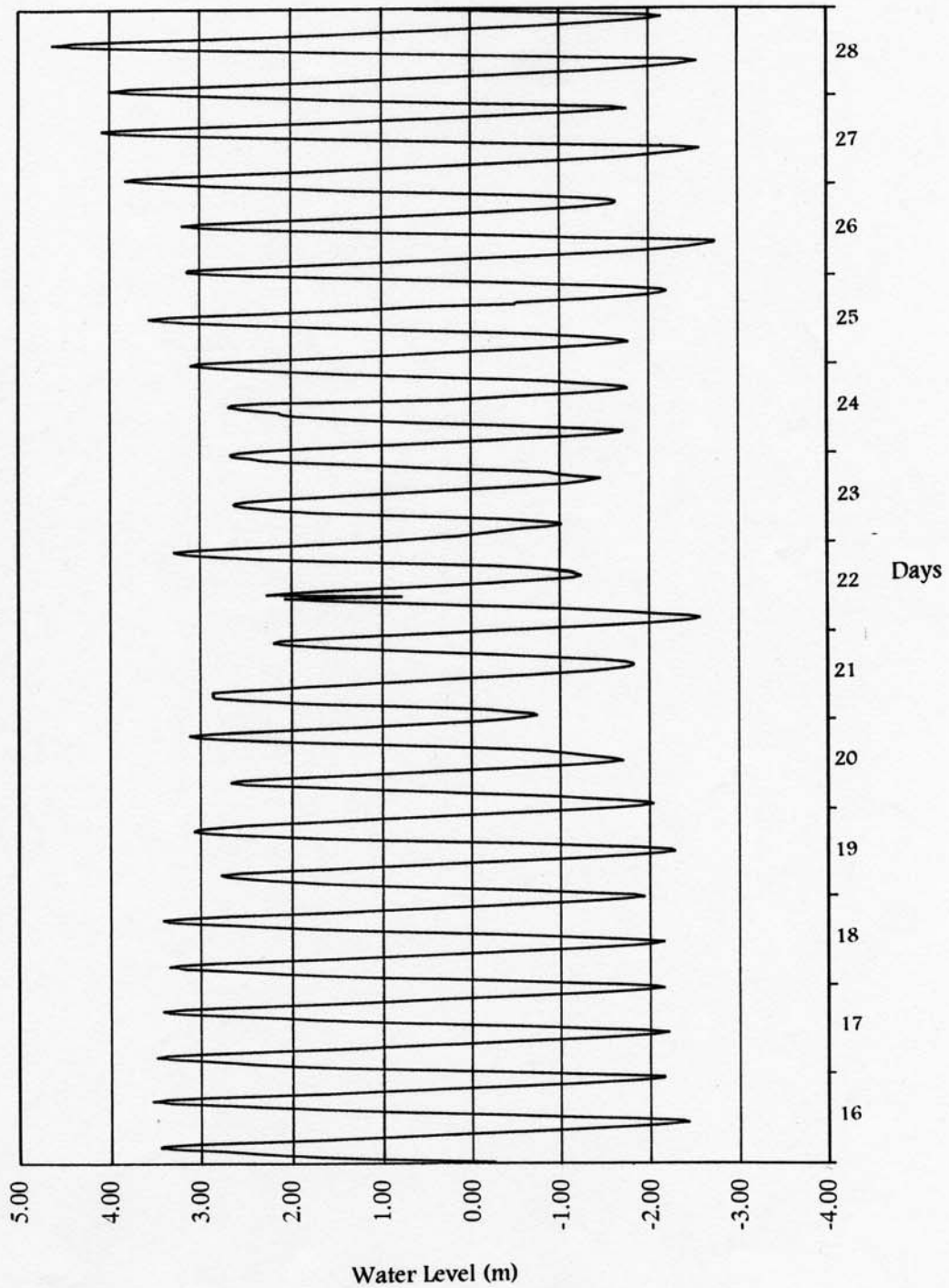
<sup>60</sup> Spring and neap tides are often referred to as 'long' and 'short' tides by inshore fishermen.

<sup>61</sup> The writer is grateful to Mr. Martin Earlam of Thames Barrier for providing and advising on the interpretation of the tide profiles for Tower Pier.

<sup>62</sup> When the Sun crosses the equator and the length of day is equal throughout the world.

<sup>63</sup> When the Sun is furthest from the equator at noon, marked by the longest and shortest day.

**FIGURE 6**  
**Typical tide profile of the River Thames**  
Taken at Tower Pier 16-28 February 2002



Essentially a tide profile is sinusoidal where the movement of the water is not affected by geographic or meteorological influences<sup>64</sup>. However in an estuary the profile is affected by two influences. First, the speed of tidal propagation into an estuary depends upon water depth. Hence the high water wave crest will travel faster than the low water wave trough. Secondly, the ebb current will last longer than the flood, because the freshwater flow of the river results in a net seaward discharge of water. The combination of these influences produces an asymmetric tide profile, which is steeper on the flood tide than the ebb tide.

Another influence on the profile within coastal areas is shallow water, which makes the prediction of tides more complex than for simple oceanic tides<sup>65</sup>. Essentially shallow water causes an amplification of tidal range, which can also be affected by secondary bifurcations of the inlet<sup>66</sup>. During the period which we are concerned with the mouth of the river Fleet was wide and marshy on the west bank<sup>67</sup> with the channel margins colonised by vegetation. The south bank of the Thames in this region during the first century AD was as much as 700 m south of the modern Southwark waterfront with braided channels intersecting islands and mud flats<sup>68</sup>. Shallow water can affect the times but the influence on height, or rather the range, is invariably small<sup>69</sup>. However its effect on the tide profile is unfortunately unclear. It is possible to construct a tide profile by generating an estuary model but this requires a series of river-bed cross-sections, which for the Fleet are unknown to us. Figure 7 shows the tide profile for London Bridge<sup>70</sup>, close to Tower Pier, which is close to the River Fleet<sup>71</sup>. Separate profiles are given for the mean values of neap and spring tides. Note the asymmetry of the profiles. It is proposed that these profiles be used as a basis for our analysis of the River Fleet in Roman times.

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<sup>64</sup> Air pressure, wind strength and direction can have great effect on the tide range but for the purposes of this analysis these variables can be put aside.

<sup>65</sup> *Admiralty Manual of Navigation*, vol.1, rev. 1964, 370.

<sup>66</sup> Hoare and Haggett 1978.

<sup>67</sup> For more detail concerning preliminary sedimentological assessment of the deposits in the estuary including both eyots, see vol. 54, 21 for Fleet Valley, City of London Field Report and Sedimentological Assessments.

<sup>68</sup> Milne 1985, 81.

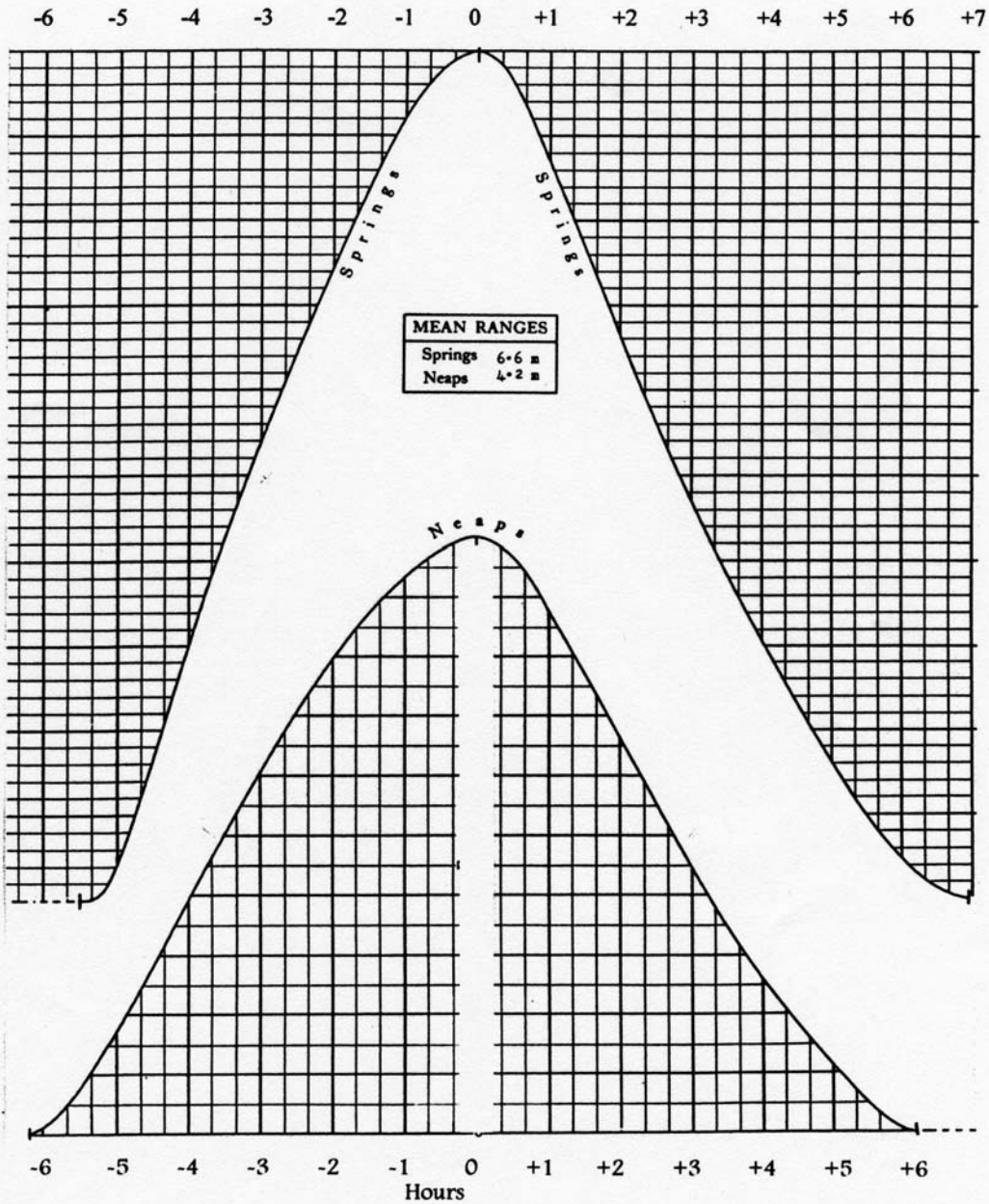
<sup>69</sup> *Admiralty Tide Tables*, Part III, 2<sup>nd</sup> edit. 1941, 11.

<sup>70</sup> The tidal curves are derived from hydrographic publications produced by the Hydrographer of the Navy.

<sup>71</sup> Approximately 1.08 miles downstream of the Fleet's mouth.

FIGURE 7

Tide profiles – London Bridge  
Mean spring and neap curves



There have been changes to the Thames during the last two millennia, in addition to the disappearance of the shallows in the Southwark area. A degree of confidence may be gained by the fact that downstream of the River Fleet the Thames has undergone comparatively little change in its shape or course. Upstream however, the two major man-made influences on behaviour, aside from natural changes, are the drainage works of Bazalgette and the reclamation of the embankment. The Bazalgette works essentially re-routed surface drainage and sewerage from the old rivers and sewers of London to outfalls well downstream, whilst the embankment works, being upstream of the Fleet estuary, may have had limited effect on the London Bridge tide profile. What difference these relatively recent developments would have made on the tide profile at London Bridge, remains to be determined. Hopefully, the asymmetry of the profile, which is essentially caused by the depth of the river bed and the interaction of the River Thames and the tides, would be similar to that which existed in the estuarine lower reaches of the River Fleet. The writer is aware of the weaknesses and uncertainty of this assumption, but considers that this analysis, which has raised our awareness to the complex subject of estuarine tidal behaviour, hopefully has identified the limitations in attempting to establish Roman tide profiles in the Fleet estuary, and has provided us with a satisfactory tool to complete our analysis.

#### [b] Roman tide levels.

Over the last thirty years our knowledge of the behaviour of the sea and land levels during the Roman period has been much advanced. A great many multi-disciplinary studies have been published concerning this complex subject of changes in sea level (eustatic change) and land subsidence and uplift (tectonic or isostatic change). For the south-east of England studies of the Roman sea and land levels appear to be concentrated on the River Thames<sup>72</sup> and its estuary<sup>73</sup>, the Essex coast<sup>74</sup> and the Romney Marsh<sup>75</sup>. It is now the accepted view based on both archaeological and palaeoecological data that the River Thames in London was tidal and that the range for the mid-first century AD has been proposed as circa +1.5 m OD (MHWS) to -0.5 m OD (MLWS)<sup>76</sup>. The range at the end of the first century AD has been assumed to be similar at 2.0 m. The London Bridge tide profile that we have adopted (See Figure 7) relates to a mean tidal range of 6.6 m *springs* and 4.2 m *neaps*, which we need to transpose to the tidal range that existed in the first and second centuries AD in the Fleet estuary.

Fig. 8 shows these profiles that have been converted to a tidal range of 2.0 m (*springs*) and 1.27 m (*neaps*), which corresponds to the relative range relationship at London Bridge. The horizontal scale shows 12 hrs. 25 mins. for a

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<sup>72</sup> Milne 1985.

<sup>73</sup> Devoy 1979.

<sup>74</sup> Wilkinson and Murphy 1986. Greensmith and Tucker 1973.

<sup>75</sup> Brigham, 1990, 146. Cunliffe 1980.

<sup>76</sup> Milne 1985, graph 50.

full tide cycle<sup>77</sup>. Fig. 8 also shows a vertical OD scale on which the tidal profiles have been positioned to agree with the mean high water (*springs*) postulated to have existed in c.100 AD that is when the watercourse was cut across the north eyot<sup>78</sup>.

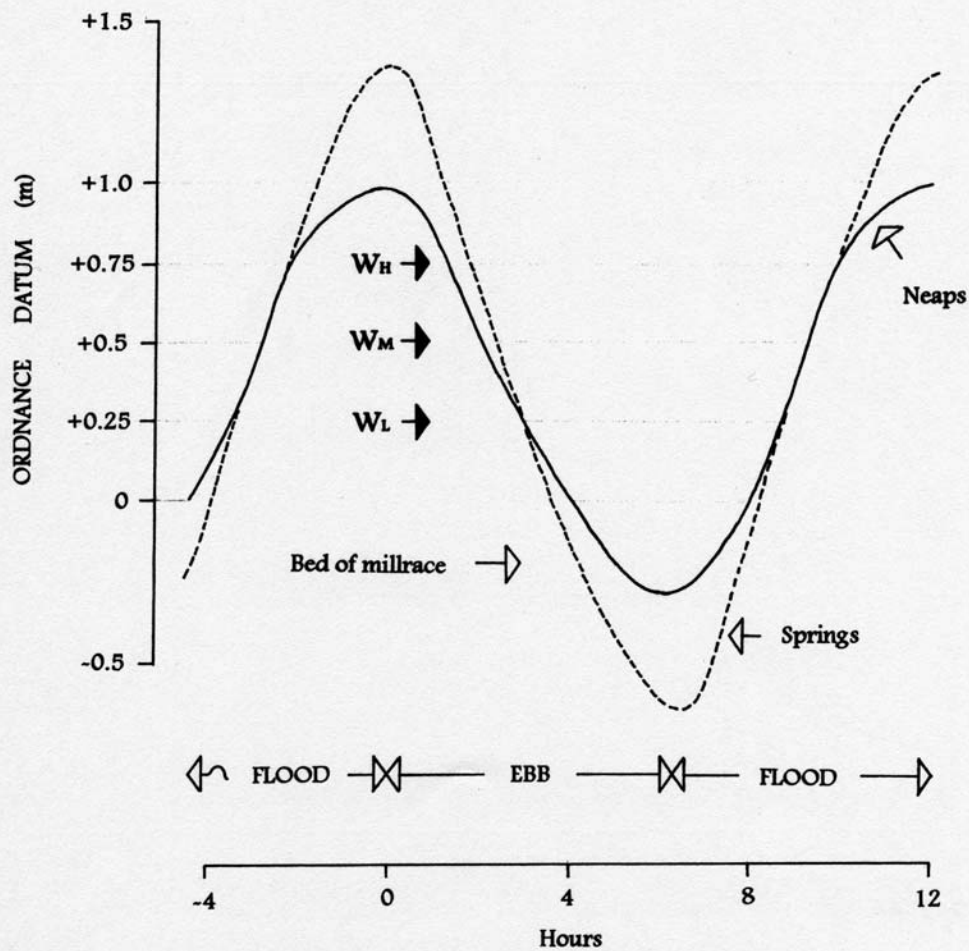
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<sup>77</sup> Twice per *lunar day* which is 24 hrs. 50 mins.

<sup>78</sup> Interpolated from graphs of river levels of the Thames based on archaeological evidence. See Brigham 1990. Watson, Brigham and Dyson 2001.

FIGURE 8

Theoretical spring and neap tide curves  
River Fleet estuary c. 100 A.D.



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The ground levels on the various plans and section of the mill-race indicate that the level of its northern bank was a maximum of +1.62 m. OD close to the structure and +1.5 m OD at its western end. Note that the mortar/chalk surfaces



of the warehouse(?) on the southern eyot had a fairly even level of +1.9 m OD<sup>79</sup>. Milne has provided clear evidence for the level for the Roman river Thames on the north bank in the late first century, where two features suggested a high tide level of +1.6 m. OD, one apparently to curb flooding up to that level. There is also first century AD evidence that the height of the lowest operative road surfaces were +1.5 m. OD, suggesting that the river level was not expected to exceed this level<sup>80</sup>. More recent studies indicate that embankments and revetments on the south bank of the Thames support this proposed mean high tide level.

In examining water levels our concern is with the highest astronomical tide (HAT), the maximum height to which the sea level will rise at any specific place. In theory the greatest possible tide raising force is with the Earth at perihelion, the Moon in perigee (closest to the Earth), the Sun and Moon in conjunction and both at zero inclination. This situation is very rare and is due 6580 in AD. With a reasonable range of human experience, extremes such as the *perigean* springs are the memorable tides.

Studies have shown that the HAT peaks and minor peaks occur with such regularity<sup>81</sup> that it can be assumed that coastal inhabitants' experience of any four years' tide would teach them the level<sup>82</sup>. If we can assume that this tidal phenomenon has remained unchanged then the builders of our tide-mill hopefully would have established building levels, which would have endured without regular flood damage. But it would be imprudent to accept this simplistic theory and ignore our maritime experience. A combination of low pressure and wind can produce unpredictable high water levels especially in the Thames estuary, as modern man can testify.

#### [c] Analysis – water management and operational cycles.

To examine day-to-day water management let us follow one tidal cycle, starting at high tide. First, it must be made clear that the mill-dam across the estuary of the river (position B on Fig. 5) would require sluice-gates to admit the tide to the mill-pond which would be separate from, and additional to, the sluice-gate that controlled the water being applied to the wheel. To avoid confusion the sluice-gates for admitting the tide will henceforth be referred to as the *tide-gates* for brevity.

To hold back the water an additional dam would have been needed to prevent the water from passing around the northern eyot and it is suggested that this may have been in position x. See Fig. 5. The dam in this position need not have had gates for level control because the favoured position for these would be in the

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<sup>79</sup> VAL 88, vol. 48, 7.

<sup>80</sup> Milne 1985, 81.

<sup>81</sup> Amin 1979.

<sup>82</sup> Waddelove and Waddelove 1990, 254.

main estuary dam adjacent to the bank of the eyot for easy access and rapid attention by the miller.

When the flood-tide had reached its utmost height it may have coincided with slack water (zero current) on the seaward side of the dam<sup>83</sup>. At about this time the miller would close the tide-gates and his waterwheel would be stationary. The miller then had to wait theoretically before commencing work for the ebb-tide to recede below his wheel to avoid working in standing water<sup>84</sup> when it would move slower and be less efficient. This might not apply to a river-mill if the wheel normally operated immersed in water but for all other types, served by stream or mill-pond, the disadvantage would hold true. However with a tide-mill, where a much greater volume of water is applied to the wheel, the retardation caused by tail-water is less critical and can be tolerated to a degree. Thus it is suggested that the miller may have started his wheel and commenced grinding before the ebb-tide dropped below his wheel.

Unfortunately the operational experience of tide-mills has virtually disappeared from our shores, in spite of there having been approximately 170 sites on the shores of England and Wales at one time<sup>85</sup>. However, there is one tide-mill in England still occasionally working which sheds some light on this question<sup>86</sup>. The mill is Eling Mill, on the River Bartley Water that runs into Southampton Water. The tide profile for the mill is unusual, having two high waters in each twelve and a half hours tide cycle, an unusual phenomenon within Southampton Water caused by the Isle of Wight. This double tide affects the tide profile, which is far from sinusoidal and appears to give an extended period of working for the wheel. In each tide-cycle the waterwheel can run for seven hours but for part of this time the wheel is immersed and moves too slowly for effective grain milling, leaving five hours for quality work<sup>87</sup>. For approximately an hour prior to the ebb-tide dropping below the bottom of the wheel, the head of water is such that it can be used to turn the wheel even though perhaps half the wheel is under water. A similar situation occurs with the flood tide. As it rises above the bottom of the wheel it creates more drag on the wheel until effective grinding ceases approximately one hour later. When the Eling wheel moves slower, the product from the stones becomes finer. In modern times this would be less acceptable, causing the fractions of refinement to change, but in the Roman period the meal

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<sup>83</sup> Further down the estuary, the maximum speed of the flood-tide probably coincided with high water, and continued to flow for a while. At the ebb-tide, the same phenomena would occur, a characteristic of estuaries well known to River Pilots.

<sup>84</sup> Usually called backwater or tail-water; water in the tail-race that does not readily flow away from the wheel and therefore impedes its movement. In the oral traditions associated with water-mills, it was a well-known fact that if a wheel stood in tail-water it was a sign of a poorly maintained tail-race, which was to be avoided.

<sup>85</sup> Minchinton 1977, 339-53. In 1938 it was reported that ten tide-mills in England and Wales were still being worked by the tide. Wailes, 1938. 1.

<sup>86</sup> There are at least two other tide-mills that are occasionally worked, Woodbridge Mill on the River Deben, Suffolk and Carew Mill, on the Carew River, Wales.

<sup>87</sup> Blackwell-Eaton 1999, 21.

issuing from disc millstones was much coarser<sup>88</sup> and the tolerance of quality was probably much wider than modern man's. Let us therefore assume that the miller used the wheel before the tide dropped below it.

What little we know of other English tide-mills does shed some light upon working periods. At Birdham Mill, Sussex, the working period was five and a half hours; at Wootton Bridge Mill, Hampshire, powered by tide and stream it was four hours each normal tide, and at Strood Mill, Kent, a spring tide would provide six hours work, but no work was possible with a neap tide or if the wind held up the water<sup>89</sup>. One other tide-mill at Ile de Bréhat, northern Brittany, has been estimated as providing 2-3 hours of work each tide, which is a dubious figure for an average tidal range of 5.51 m, unless the undershot wheel was set inexplicably low<sup>90</sup>. But we should realise that these operating periods would be different at each site, determined by the tidal range and the size and position of the wheel. Working practices, products and standards might also influence the operational periods.

From the moment the miller set the wheel in motion the hydraulic head across the wheel (the difference between the water levels say  $H = H_{head} - H_{tail}$ ) reduced until the paddles were above water. From that moment the head on the tail-race side  $H_{tail}$  is effectively the underside of the floats<sup>91</sup>. Meanwhile, the wheel is taking water from the millpond. If the wheel's flow rate, together with any leakage through the dams, exceeded the flow entering the pond from the River Fleet, its level would drop. In this circumstance the head of water  $H$  would reduce and the miller might open the sluice to apply more water in an attempt to maintain power. On the other hand, if there was ample water and the wheel provided enough power for the millstones, he need not have been so sensitive to the changing head of the millpond.

The mill could continue to work through the ebb-tide and the turn of the tide until the rising flood tide reached the paddles and slowed the wheel. The point at which the miller stopped the wheel and ceased grinding is debatable, determined largely by the differential heads of water each side of the dam, the diameter and position of the wheel and probably the quality of meal issuing from the stones.

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<sup>88</sup> Spain, 1992. The thesis included a laboratory test using Roman style disc lava millstones to determine the coefficient of rotary friction. Analysis of the meal samples showed that lava stones have a natural limit on the fineness of the product and that the ancient product was much coarser than the modern one. A comparison of the production/power ratio of these experiments with various 19<sup>th</sup> and 20<sup>th</sup> century authorities appears to confirm the relative coarseness of the product. See also Jasny 1944, 135-170. We should note that the relationship between power and coarseness of product is disproportionate, so that for an increase in coarseness the power required is proportionally much less.

<sup>89</sup> Wailes 1938, 12, 15 and 11.

<sup>90</sup> The spring tides reach 11-12 m. With such a great head of water the differential across the wheel would surely have provided satisfactory power and speed for milling work. See Royle 1982, 241-4.

<sup>91</sup> Below this level there is no water being applied to the floats and therefore no generation of torque or power.

With the tide-gates closed and the wheel still working, the effective head of water on the wheel – the difference in water levels – would steadily reduce.

The miller could open the tide-gates anytime after he stopped the wheel, assuming that the rising tide was above the sill of the gates. But in practice he probably waited until the waters each side of the dam were equal, otherwise he would seem to lose storage and the surging waterfall might threaten the stability of the dam. Alternatively, if the miller allowed the water to rise on the downstream side above the mill-pond level, it would put the mill-dam under backpressure, assuming it to be a post and plank structure. But it is unlikely that a difference in height of say even 1 m would have caused any problems having regard to the scantlings they used in riverside revetment work. This semi-diurnal work cycle would be complete when high tide was reached and the tide-gates closed.

From the moment the gates were lowered and closed the mill-pond would receive the flow from the Fleet, its surface would rise, increasing the volume of impounded water and thus the storage that could serve the water-mill. We do not know what flow rate the Fleet may have provided in those times, nor how it may have compared in volume with the tidal water held by the dam, but we can be certain that from the moment the gates were closed, the surface would rise above the high tide level that prevailed that day, assuming that any leakage through the dams was negligible. The mill-dam would have needed to be quite substantial with large vertical posts driven fairly deep through the alluvial deposits into the bed of the Fleet to gain stability. We can be confident that such civil works would not have been beyond Roman capabilities but they would nonetheless be significant. Following the building of a mill-dam the mill-pond would continue to be saline and tidal but its existence would interrupt the natural tidal flow and ebb through the estuary, causing lower velocities and inducing siltation and deposition, which would be particularly noticeable on the upstream face of the mill-dam.

The sill height of the tide-gates was probably at a level that would allow most of the millpond to be drained to facilitate work being done on revetments, the dam itself and the water-wheel. Quite likely, bearing in mind the length of the mill-dam, there were two or more frames or bays having tide-gates, which might also have had different sill heights.

The top of the dam, that was undoubtedly above normal high-tide, would have had a section of its length at a lower level to form a spill-way<sup>92</sup> that automatically allowed water above that level to overflow and escape downstream. This arrangement is most likely to have existed for two reasons. First our experience of modern water-mills tells us that mill-ponds or headraces always had to have the facility of limiting the head of water - a safety feature most necessary in times of spate and flood and secondly, the mill operators could not have allowed the water to rise too high for fear of flooding the northern eyot and affecting the

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<sup>92</sup> Sometimes known as a flood-sill, overspill or tumbling bay.

structure there including the mill. The levels found in the excavations suggest that the impounded water could not have been much above +1.5 m OD, suggesting that the flood-sill had to be near that level. When high tide was reached and the gates closed, the miller then had to wait for the tide to recede, a delay that would have been some 2.4 hours according to our time graph. See Fig. 8.

The operators would quickly learn at what level to set their overflow sills to ensure that they had sufficient water to last for the work period. After the maximum flood tide passed each successive flood tide would tend to be slightly lower following the endless neap and spring tide cycles. During those days when the tidal range was less, i.e, a lower profile, the working period would lengthen and the idle period would be correspondingly less. Both the head and volume of water provided by the tide in the millpond would decrease until the nadir of the spring tide cycle was reached. During these periods of lower flood tides the miller would rely more on the River Fleet to top up the millpond.

From our earlier analysis we have determined that the wheel could be used for milling before the ebb-tide dropped below the bottom paddles, and continue in use after the flood-tide reached the bottom of the wheel. This has been concluded from our very limited experience of tide-mill operation combined with our rather more confident view concerning the acceptance and use of relatively coarse meal in the second century AD. These operational allowances are not easily translated to a waterwheel working in different depths of tide. This is essentially a question of hydraulics and could be presented in simplified terms. The question is, in what depth of backwater would a water-wheel continue to rotate at a reasonable speed, assuming that the head on the mill-pond is constant – remember the Fleet provides more than enough water for a single water-wheel – and the water below the wheel is steadily rising? It is suggested, to avoid an imponderable situation, we assume that the critical point is when the tide reaches a level one quarter of the vertical distance between the surface of the mill-pond and the bottom of the wheel, measured above the bottom of the wheel. Even above this level the wheel would probably still turn, but we have to select a point at which theoretically the millstones produces a product unacceptable to the Romano-British populace.

Table A shows the theoretical operational cycles that result with having the underside of the water-wheel set at different heights above OD. Additionally, figures are provided that include operating the wheel in backwater.

**Table A**                      **Operational cycles**

<i>Level of bottom of wheel</i>  <i>(m. OD)</i>	<i>Mill work (hours)</i>		<i>Idle period (hours)</i>	
	<i>Springs</i>	<i>Neaps</i>	<i>Springs</i>	<i>Neaps</i>
+0.75 m <b>W<sub>H</sub></b>	8.3 [9.1]	8.9 [9.4]	4.1 [3.3]	3.5 [3.0]
+0.50 m <b>W<sub>M</sub></b>	7.2 [8.2]	7.5 [8.0]	5.2 [4.2]	4.9 [4.4]
+0.25 m <b>W<sub>L</sub></b>	5.9 [7.2]	5.9 [7.0]	6.5 [5.2]	6.5 [5.4]

[ ] Denotes time periods that include for running the wheel in backwater.

The level of the water-wheel is unlikely to have been at +0.75 m OD, position **W<sub>H</sub>** on Figure 8, because the head of water was less than 0.25 m during neap tides. Level +0.50 m OD, position **W<sub>M</sub>**, would allow theoretically an average working period across all tides of 8.1 hours. In this position the head of water is improved, varying from 0.85 m maximum to 0.50 m minimum. Lowering the wheel further to position +0.25 m OD, position **W<sub>L</sub>**, reduces the average working period to 7.1 hours across the tides but greatly increases the head from between 0.73 m to 1.10 m. This position also enjoys the maximum storage of water in the mill-pond. Below this level, as the wheel position is lowered, the working period rapidly reduces, particularly at neap tides, and so it is considered unlikely that the bottom of the wheel was below +0.25 m OD.

From this analysis, the favoured position that brings a balance between working periods, head of water and storage is  $W_L$ . At this position the axis of the shaft and bearings of a 2.5 m diameter water-wheel would be 150 mm above the spring tides. A slightly larger wheel would keep the shaft and bearings above virtually all water levels although the pit-gear would probably run partly immersed<sup>93</sup>.

Once the mill and dam were built, they would quickly have learnt the contribution that the river made to the mill-pond, and the disadvantages that they may have unwittingly incurred by setting the wheel at a height that did not enjoy the full benefit of all tides would have been quickly realised.

[d] Tidal regression.

Most important to this study is that archaeology of the Roman water-front in London has identified a tidal regression or progressive fall in the river level of 1.5 m between circa 50 and 300 AD.<sup>94</sup> The net result of that tidal regression was that by the third century the high tide in the Thames barely exceeded the first century low watermark. This meant that unless the Thames waterfront was regularly extended, cargo boats would have found it increasingly difficult to unload without lighters or extended piers. An identical situation would have occurred in the Fleet estuary.

Fig. 9 illustrates the tidal regression on a time scale from 60 – 200 AD. Also shown are some critical dates and the waterwheel level  $W_L$ . The regression graph shows that by c.130. AD. the level of the MHWN tides had reduced to 0.2 m above level  $W_L$ . The miller could probably still obtain sufficient power from this tidal head, but this gradual regression of the tides would have become very noticeable, certainly by mid-second century.

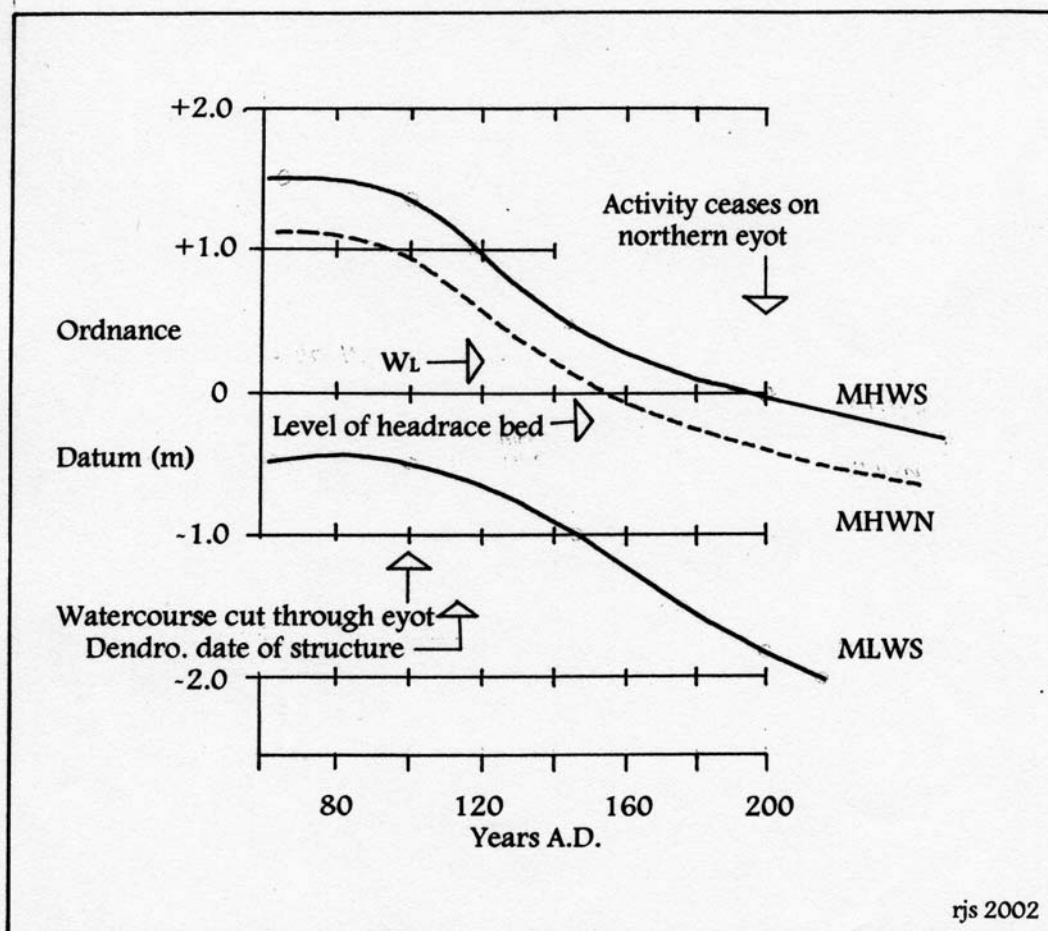
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<sup>93</sup> It would be possible to generate theoretically the size of the pit-gear assuming the diameter of the water-wheel, driving a six-stave Zugmantel-type lantern gear to produce a runner millstone speed of between 90-120 rpm. But this is considered too speculative.

<sup>94</sup> Watson, Brigham and Dyson 2001, 33.

FIGURE 9

Graph of river levels in the City of London  
showing tidal regression during the Early Roman period  
[Source of graph – Watson, Brigham and Dyson (2001)]



As tidal regression continued the miller would come to increasingly rely on the Fleet for make-up especially when the neap tides no longer reached his wheel. When this situation was developing the miller had three possible solutions to arrest or slow down the inevitable reduction in mill working time. These are;

- [i] He could attempt to increase the diameter of his water-wheel. He might do this by extending the arms and floats or he might install a larger new wheel.
- [ii] He could lower the existing wheel to 'chase' the dropping tide levels, which would involve lowering the wheel-shaft and bearings. The position of the gear engagement would also change and the most likely way to address this would be to lower the footstep bearing and lengthen the vertical shaft.
- [iii] He could build a new water-mill to suit the changing tide levels and range.



Our modern experience of wooden water-wheels would suggest that the wooden wheel might well have needed major repair work after a few decades of life, which could have provided the right opportunity for the miller to adopt one of the above options.

If the wheel remained at the same level, the miller's use of tidal water for powering his wheel diminished and by mid-second-century, was probably abandoned because the MHWN no longer reached the wheel and only the higher spring tides provided a head of water. But remember, that if the flow from the Fleet was as substantial as we believe it may have been, the miller could easily, without effort, use the river for most of his supply. Whenever he stopped using the tides and his tide-gates, his wheel was probably still rendered inoperable some of the time by the backwater from the high tides. Ironically, if the Fleet provided a reasonable head of water, there was probably an advantage to be gained by *raising the wheel*, a reversal of his previous situation!

This observation brings us to an interesting phenomenon. As the tidal regression continued, the *level* of the tide profiles dropped relative to the water-wheel. In terms of operation and hours of millwork, this had the same affect as raising the level of the wheel higher up the tide profiles. See Figure 8. In other words, the hours of possible millwork would *increase*, because the duration of the hours that the wheel was adversely affected by standing in 'backwater' was *reducing* over time. If he kept the wheel at the same level the interruption that the tide caused on the miller's working day and night, would have become spasmodic by c.150 AD and would have virtually disappeared by 160 AD.

The generation of tide profiles might be taken as an example of being too easily tempted into time-consuming byways. But the writer has hopefully shown that we needed to raise our understanding of tidal behaviour, not only to explore the different physical arrangements that may have existed for harnessing the tides, but also to help us interpret the impact of tidal regression on the estuary as a whole.

## **5. The aqueduct**

[a] Interpretation.

Our attention should now turn to the 'ditch' feature, which ran for at least 90 m along the east bank of the estuary, was about 9.5 m wide and 3 m deep with a stepped profile, following the contour of the slope.

This man-made cut has been recognised by the archaeologists as a major feature that involved much labour, but no satisfactory or convincing purpose for its creation has been given. One idea put forward was that it might have been a drain, but it has not been possible to identify what activity it related to on the hillside above. Horticulture has been considered but is very unlikely. As a drain it

was extremely large and for the reason that it is inconceivable that such a volume of water could originate above this level, the drain suggestion is rejected. Another, equally unconvincing explanation offered was that it was a quarry<sup>95</sup> but no explanation of this suggestion is given.

Another perhaps inevitable suggestion is that it related to the military activities in the area, and could be the remnants of an early military camp or fort. The dating evidence, which is unfortunately vague, suggests that it was cut in the first or second centuries AD. and finally silted up, or deliberately backfilled in the early third century AD. It could therefore be consistent with a military use following the construction of the Cripplegate fort in circa 110 AD. But why would the army dig such a ditch in this position? For defence? Unlikely by itself and incongruous with the much larger natural barrier offered by the River Fleet in the valley below. When a wall was built around the City in c.200 AD it lay some 100 m to the east on higher ground. The two features are neither parallel nor close to each other, and are therefore probably unrelated.

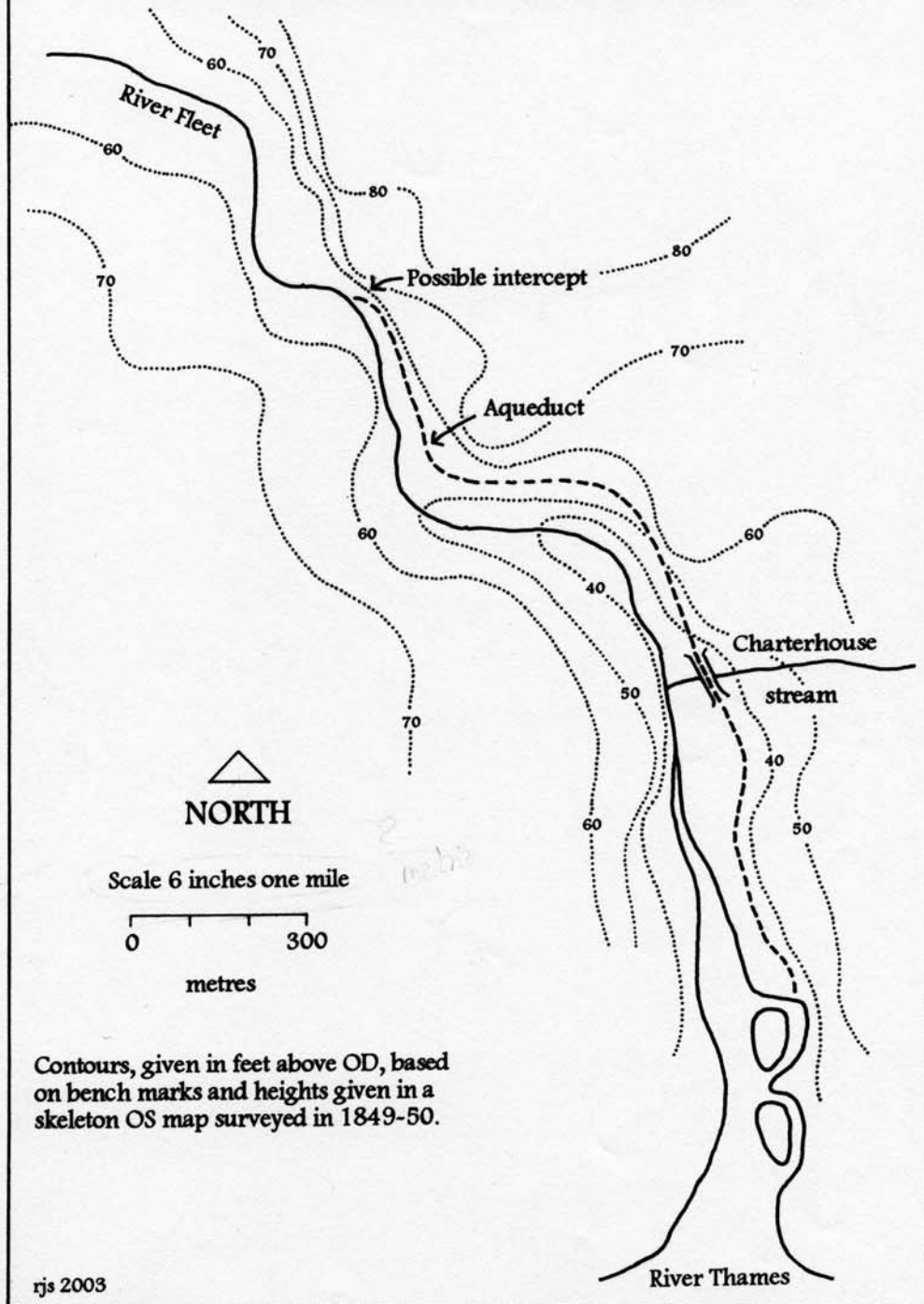
A fourth suggestion is that it was associated with some industrial process which harnessed the run-off water from the hill, but this idea, although not dismissed, was not developed. If a sufficient natural flow existed on the hill-side it would surely have created its own channel, and the natural landscape would have evolved to bear witness to this, as other tributaries have done further up the valley on both flanks. Anyway, the section of the channel is surely much greater than any flow that may have resulted from natural run-off.

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<sup>95</sup> Vol. 8, Zone C summary, 8.

FIGURE 10

Physical landscape and suggested route of aqueduct.



Fortunately for this analysis, two small excavations fortuitously placed some 80 m apart provided us with the levels of this artificial channel. The northern level was +4.44 m OD, and the southern +3.84 m OD showing that it had a gradient of 0.6 m/80 m. = 0.0075 (1 in 133) towards the south. The plan of the feature shows that its southern end was aligned with the natural channel on the east side of the Northern eyot. The archaeologists report that this feature consisted of nine fills all representing *'wet use and slow silting of the features'*<sup>96</sup>. The writer proposes that this channel was dug as a millrace to facilitate an increase in milling activity in the region of the northern eyot.

This substantial channel was clearly made for carrying water from higher up the Fleet valley down to the junction with the Eastern channel and the only source which could provide this volume of water was the river Fleet itself. The lowest tributary that existed on the east side of the Fleet came from a source near the Charterhouse<sup>97</sup>, but was not of sufficient volume to feed the aqueduct. We may postulate that the aqueduct was carried over this tributary, having been brought down the east flank of the valley from a point of origin where its gradient intercepted the Fleet. See Figure 10.

There are two, almost insurmountable difficulties, that present themselves when we attempt to determine the probable route of the Roman aqueduct. One is the problem in seeking the shape or contours of the lower Fleet valley 2000 years ago, and the second, the position and gradient of the old river itself. Both of these are inter-related and essential components of a changing river regime through time. The writer has purposely limited the research on this subject and accepted reluctantly a solution based primarily upon relatively modern geographic surveys. Our limited archaeological knowledge of the Fleet valley sheds very little on the Roman Fleet and valley although a search using bore-hole data might help<sup>98</sup>. One of the earliest surveys providing ground heights in the form of bench marks and spot heights at sufficient scale and density to allow the contours of the valley to be generated is the skeleton OS map of 1849/50<sup>99</sup>. This has been used as the basis for Fig. 10. The shape of the valley that this provides has to be considered as a very approximate guide to the Roman landscape; the palimpsest of human occupation had surely generated higher ground levels and it is noteworthy that the Charterhouse stream (or rivulet?) cannot be detected in the early Victorian survey<sup>100</sup>.

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<sup>96</sup> VAL 88, vol. 8, Zone C, Summary, 8.

<sup>97</sup> Barton date? 20. In 1197 AD described as 'super rivulum de Fackeswell'. Stow speaks of 'Fagges well, near unto Smithfield by Charterhouse, now lately dammed up'. The bed of a stream was discovered in 1924 and what was believed to be the well itself at no. 81 Cowcross Street.

<sup>98</sup> A cursory view suggests that bore-hole data could well provide some information on Roman horizons in the valley, but a thorough examination would be costly and time consuming. See British Geological Survey, Geoscience Data Index, web address, < [www.bgs.ac.uk/geoindex](http://www.bgs.ac.uk/geoindex) >

<sup>99</sup> London Metropolitan Archives SC/OS/LN/11.

<sup>100</sup> It is interesting that a digital elevation contour map of the lower Fleet valley, which has been derived from deposit survival forms, also fails to show any distinct valley for the Charterhouse stream. The writer is indebted to David Jamieson of MOLAS for providing this information.

A survey of the Fleet undertaken in 1817 for the Commissioners of the Sewers<sup>101</sup> shows the gradient of the river approximately every 200 m, north from the City boundary at Holbourn Viaduct to its source. Transposing this gradient onto a graph, together with the position of the aqueduct bed (the northernmost section found) and a theoretical aqueduct gradient of say 1 in 200, would hopefully give us a clue as to where it may have intercepted the river – but it cannot be determined with any confidence. Common sense immediately warns us that the 1817 longitudinal bed profile could be a different shape according to the regime of erosion and deposition that has occurred in 1700 years. Moreover, the effect of human occupation on the landscape, especially in the lower valley, is difficult to measure. Wherever the intercept existed, it is almost certainly different from the 1817 river-bed level; for it to coincide with the node of erosion/deposition would be pure coincidence.

However, the interesting feature of the 1817 profile is that there was a distinct change of slope approximately 1170m north of the City boundary. Upstream of this point, the slope is one quarter of the gradient below the point, although higher nearer the source, the gradient once again becomes steeper probably generated by erosive forces. The position of this dramatic change of slope appears to coincide with the boundary of the clay (northwards) and the river terrace deposits (southwards). Where the river cuts through this geological boundary, a natural shoulder is produced as it erodes more quickly the softer deposits to the south of the clay beds. It is at this point, or a short distance downstream, that the writer suggests the intercept may have existed. As the surveyors of the aqueduct moved up the valley determining the course and gradient to maintain the flow and delivery head for the water-mills, they needed to bridge the Charterhouse stream. In the early Victorian survey its natural valley cannot be defined with confidence, so we are unable to suggest whether or not the surveyor may have deflected the aqueduct to follow the contours of the spur valley to the east. Figure 10 shows the alternative arrangement of the aqueduct bridging the stream nearer the Fleet, that would have shortened its length but involved building a brick or stone channel above ground - a *substructio*<sup>102</sup>. Further up the valley the surveyors would have met the increased natural gradient of the Fleet approaching the boundary of the clay and river terrace deposits, and whatever head they needed they would have quickly acquired in a short distance. With the intercept in this area, the total length of the aqueduct was approximately 1750 m.

The gradient of the aqueduct, as shown by the two excavations 80 m apart, is steep, suggesting that in this area, approaching its confluence with the Fleet, its velocity was purposely increased to create an accelerated headrace to drive

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<sup>101</sup> John Ogle, 1817, *Plans and Sections of the Main Line of the River Fleet Sewer*, London Metropolitan Archives, HFCS/P20.

<sup>102</sup> If the 'Charterhouse' valley was wider and deeper it would have been economical to support the channel on arches.

water-wheels. No profile of the aqueduct section has apparently been produced<sup>103</sup> but its overall dimensions and the observation that it was stepped, suggests a minimum section of 15 m<sup>2</sup> and a maximum of 25 m<sup>2</sup>.

It is proposed that the aqueduct served water-mills at its southern end near the east channel of the Northern eyot. Its considerable size, especially width, suggests that two water-mills could easily be accommodated side by side in parallel. However we should be cautious in suggesting this arrangement. Each water-wheel would have required a sluice-gate immediately upstream for control purposes, which would have been integrated with the foundation and frames on the water-side of the mill. This would mean that when the sluice-gate was closed, it effectively reduced the aqueduct section and created an obstruction to flow. If the sluice-gate and frame were, say, a minimum of 1.25 m wide, the restriction that this would cause on the mill-race, which was, say no more than 9 m wide, or perhaps less, between revetted banks, is considerable. Its effect on velocity was not important for it is almost certain that the bank opposite the wheel would have been revetted to prevent scouring as was probably the bed of the channel. But with the sluice-gate closed the effect on flow would have been very noticeable. They might have deflected the stream to reduce the baffle effect of surfaces normal to the direction of flow, or perhaps cutwaters, if the millstream bifurcated. But whatever the arrangement, laminar flow would have been much reduced and turbulence and eddies would have dominated at this point. The increased resistance and obstruction to flow would tend to cause a rise in the surface of the water immediately upstream and adjacent to the mill so that in times of spate, this section of the aqueduct would be the most critical in terms of flooding and safety. The presence of two water-wheels in parallel, creating such obstructions opposite each other is therefore considered most unlikely, and the favoured arrangement is of water-mills in series.

An alternative and sensible arrangement would be for the aqueduct to bifurcate and create one channel as the headrace for the mills and the other to act as a common bypass, but the evidence from the excavations indicated that this did not exist near the eyot. Of course this bifurcation could have occurred upstream, and one is tempted to suggest the feature 'the boundary ditch' might relate to this, but the evidence is inconclusive. Another favourite position for a group of water-mills would be where the aqueduct meets the Roman road coming from Newgate to the east, where transportation of the finished products to the City might be slightly easier, but the delivery of river-borne grain, was more extended.

Although the writer favours more than one water-mill on the east bank of the aqueduct, how many is open to debate. The scale of the aqueduct and its position would have provided a most practical facility for military or urban industry. The Walbrook, which we know to have been the site of water-mills from the millstones found there, was the obvious and prime site for water-power, being

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<sup>103</sup> Unfortunately a section of this feature could not be located in the Archives. It was thought that it may not have yet been catalogued.

literally in the centre of the city. However as the population of Londinium expanded other natural sites for water-power would have been quickly exploited. The next attractive site of equal or probably greater power potential was the Fleet just outside the Roman walls on the west flank of the city. The excavations on the North and South eyots have now confirmed that this estuary became an ancillary port to the City, with jetties, warehouses and water and land transport infrastructure. A natural development of these valuable facilities would be for grain mills to be established close to the port. In seeking suitable power sources, the advantage of water-power over animate sources would have been well-known to the Romans, and its potential in this port, very obvious.

[b] Interaction with the tide-mill.

We should note that the excavation identified activity on the northern eyot as commencing after 60 AD and became fairly intensive towards the end of the first century AD and early part of the second century AD. One of the first actions was to improve the drainage and a large timber-lined drain was found that has been dated to circa 70 AD. Consolidation of the drained marshy area, including revetment work, occurred in circa 100 AD. This work coincided with similar reclamation of marshy and marginal land during the first century AD in the lower Walbrook valley. All of this evidence of activity shows that there was a determined and sustained commitment to improve and bring into use the northern eyot from an early date.

Unfortunately the dating evidence for the aqueduct is very indistinct, being cut in the first or second century AD and abandoned during the third century AD. It would be imprudent to use this dating evidence for chronological analysis to contemplate which was built first, the aqueduct or the tide-mill, but let us see whether or not we can learn anything concerning their physical or operational interaction with each other.

With the aqueduct in use we can be reasonably certain that a considerable portion of the Fleet's water would be continually flowing into the eastern channel. If the ancillary dam were at *y* (see Figure 5) this flow would have an obvious effect on the eyot mill in *position 3*, which is that it would cause greater reliance on the tides for power. If the ancillary dam were at *x* the aqueduct flow would feed the millpond via the northern channel and thereby provide useful water to the eyot mill. One other obvious advantage in having the dam at *x* was that its sluice-gate and overflow sill would be nearby for observation, adjustment and maintenance. A disadvantage with this arrangement would have been the turbulence and scouring at the junction of the aqueduct and the eastern channel which may have affected the banks of the Northern Eyot; might the drainage channels and sump (see Section 2 (c) above) relate to this?

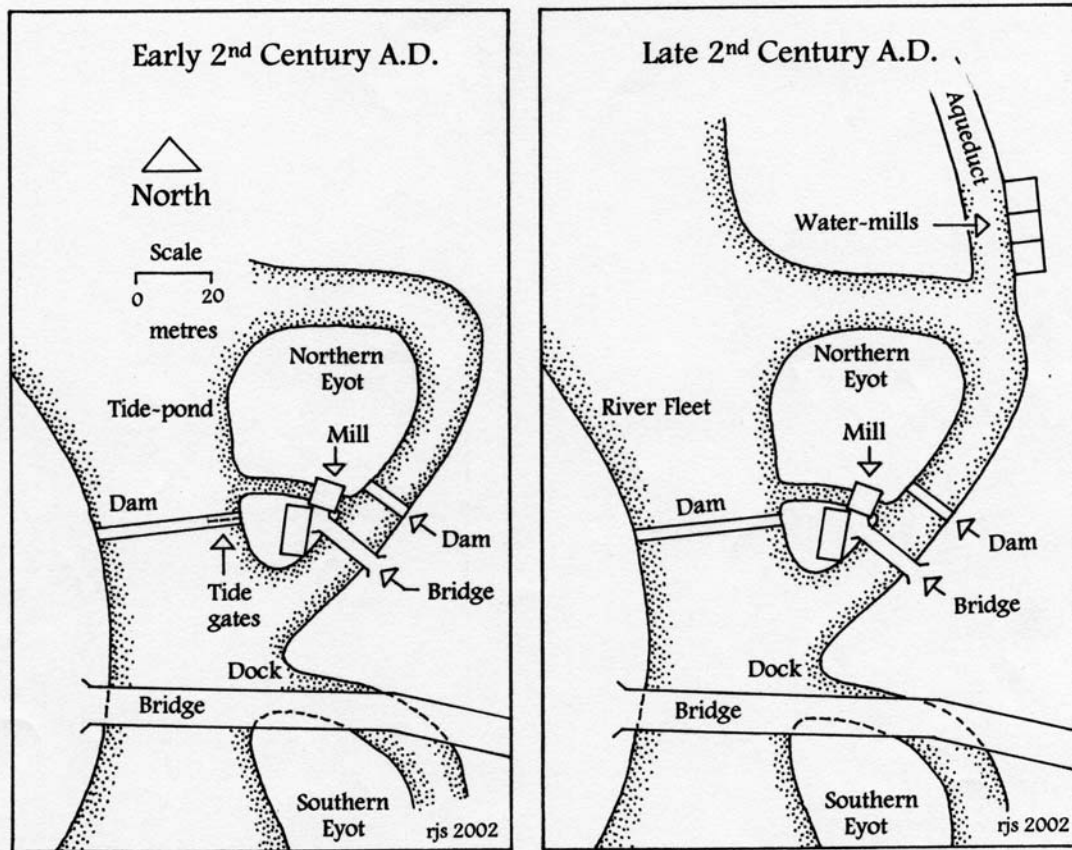
Although our favoured position for the ancillary dam is at *x*, where operational advantages existed, nonetheless, the dam may have been built first at *y*. If the

aqueduct was built after the dam at y, then this may have caused it to be rebuilt at x.

Clearly at some time whilst the Romans were developing this estuary as a port, they saw the need to harness water-power. We can presume that they wished to site the mill close to the City where the delivery of river-borne grain and the growing demands of the military and civilian population came close together. In this landscape they had two choices for siting the mill. They *either* dug a millrace from upstream to bring the water to a new built mill as the Romans had done at other sites, *or*, they cut a new channel through the Northern eyot and impounded the tidal estuary with dams. Both of these options avoided the difficulties of trying to create an enduring headrace and tailrace on the banks of the river or its creeks, where a considerable amount of piling and revetment work in sedimentary and unstable margins would have been risky and problematic. Faced with these two major options, the tidal power solution placed the mill closer to the grain deliveries than the longer headrace fed by the Fleet. We might also conclude, that the manpower and resources for building 50 m of dams and a headrace of 30 m, was much less than building a large aqueduct 1750 m long. Fig. 11 shows the conjectured water-power arrangements for the second century AD.



FIGURE 11



The building of the aqueduct and related mills gave an immediate substantial increase in milling throughputs with the 24 hour potential operation unaffected by the tides. With water-power limited within the city to the Walbrook stream, the Fleet water-mills on the aqueduct would have provided a considerable increase in water-powered corn-milling for Londinium. The corollary of this conclusion is that the advantages of building the eyot mill after the aqueduct were very marginal, indeed, it is unlikely to have occurred having regard to the cyclical tidal power source and the structural works including the mill-dams combined with the buildings on what was a marshy and less stable area.

Does the creation and operation of an aqueduct in any way indicate the presence of tidal power? No. As has been suggested its building may have been prompted in part by a realisation of the potential power of the river because of the experience of operating the tide-mill, but this could have occurred in absence

of a tide-mill. Suggesting that the aqueduct was built because a water-mill was already established in the estuary is equally invalid.

## 6. Historical and cultural context.

Having analysed the evidence in its site context we need finally to widen our vision and briefly consider its technological context and historical significance.

It is an accepted view that the Romans contribution to technology was largely in the field of practical application<sup>104</sup>. One of the best illustrations of this, certainly most relevant to this study, is their demonstrable exploitation and application of water-power. Although the above analysis has been supported by numerous references of Roman water-mills a brief overview would not be inappropriate. We have a steadily increasing corpus of Roman water-mills from archaeological sites in many Roman provinces providing evidence that their diffusion around the Mediterranean and into Northern Europe had probably occurred by the first century AD. Their incidence throughout the Empire in rural, urban and military landscapes confirms that water-power was widely used for corn-milling. Recently, the remains of a water-powered saw-mill for stone was identified at Jerash, Jordan<sup>105</sup>, and we also have tantalising evidence of a hammer-mill from the Romano-British site at Ickham, Kent<sup>106</sup>. Water-power was also used in linear motion machines as shown by circumstantial evidence for ore-crushing at Dolaucothi, Wales, and in the Iberian peninsula. Pliny also mentions the use of water-power for hulling and pounding of grain that he states was used *in the greater part of Italy*<sup>107</sup>. But their innovative flexibility is far more evident in the way that they adapted and harnessed rivers and streams to create different hydraulic arrangements. First on the question of scale, the Romans have given us clear evidence of water-wheels operating in series<sup>108</sup>, both undershot and overshot. We also have good examples of accelerated headraces where comparatively small water flows were brought to a fruitful potential power for milling. But perhaps most relevant to this study was that they were capable of harnessing power from rivers and streams where the flow rate was relatively large but the velocity slow. Some of these might be called river-mills, where the undershot wheel was immersed in the millstream – where the volume of water entering the wheel was such that there was no need to accelerate it by grading the bed or aligning the walls of the headrace as it approached the wheel. It was these slower moving wheels that would have required higher mechanical ratios in their gearing to achieve satisfactory millstone speeds. It is this type of machine, with a slow water-wheel and high gear ratios, that comes closest to the hydro-mechanical requirements of a tidal-mill. Thus we may conclude, the engineering experience and innovative capabilities demonstrated by these numerous

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<sup>104</sup> Landels 2000, 186.

<sup>105</sup> Seigne 2002.

<sup>106</sup> Spain 1984, 121.

<sup>107</sup> Wilson 2002, 16.

<sup>108</sup> For example, Ickham, Kent; Aqua Traiana on the Janiculum Hill, Rome; Barbegal, France.

advanced applications of hydro-mechanical technology, suggests that the Romans would have had no difficulty in recognising and harnessing the potential power within a tidal estuary.

We should view the Roman use of water-power as an innovative technology that is reflected in the designs and arrangements to suit different landscape applications. This adaptive approach in terms of scale and practical ingenuity in the use of water-power, is impressive, and can be found in other areas of Roman hydraulic technology during this period. By the first century AD pumping technology was being used in mining, harbour construction, shipping, bath installations etc., to great effect<sup>109</sup>. Recognising that the Roman army was a reservoir of advanced technology, military organisation and colonial administration would have ensured the diffusion of hydraulic technology including water-power throughout north-western Europe under Roman control.

The tidal range of the Mediterranean is small, at a maximum of 0.8 m at Gibraltar and as little as 0.2 m along the French coast. There are modern examples of tide-mills that can work with relatively small ranges<sup>110</sup> and areas of the English coast that have an average neap tidal range of 2 m or less, where tide-mills have existed<sup>111</sup>. We should remember that modern man has brought his experience and ingenuity to harness such small tidal ranges and not lose sight of the fact that it makes power generation precarious and sensitive to the vicissitudes of nature. Although we know that their use of water-power developed at least as early as the third century BC, it seems improbable that tidal-power was discovered and developed prior to the expansion of the empire to the Atlantic coast. The opportunity to exploit tidal-power may have been realised when the newly founded Carthaginian empire in the Iberian peninsula fell to Rome after the Second Punic War (218-201 BC) or later, Gaul. Their conquest of Gaul in 58 – 50 BC would have brought substantial lengths of the Atlantic coast within their control and with it, we may presume, a fraternization with the maritime tribes having a far better working knowledge and understanding of tides. We might take the carefully planned and executed invasion of Britain in the summer of 43 AD, with its intense naval activity and transportation of troops and supplies as an indication of confidence and some mastery of the sea and its changing faces. But what are we to make of Caesar's comments, of the storm and exceptionally high tide at full moon that caused disaster on the fourth day after landing in 55 BC, that it was a phenomenon unknown to the Romans?

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<sup>109</sup> Oleson 1984, 386-408. The development and application of mechanical water-lifting devices is particularly noteworthy in the force pump, water-screw, compartmented wheel and the bucket chain.

<sup>110</sup> Rupelmonde Tide Mill, on the Scheldt, Belgium with a tidal range as low as 0.9 m; Mystic River Tide Mills, near Arlington, Massachusetts with a tidal range of 0.6 to 0.9 m. See *Proceedings of an International Conference on Tide Mills*, held on 11 September 1999, organised by The International Molinological Society.

<sup>111</sup> *Dunwich*, Norfolk; *West Medina* and *Yarmouth*, Isle of Wight; *Lymington*, Southampton, *Fawley* and *Beaulieu*, Hampshire.

Concerning the Roman Atlantic coast, there is an impressive early tide-mill at Le Yaudet near Ploulec'h, Brittany, adjacent to a major Roman site<sup>112</sup>. The remains of a massive dam some 5 m thick, made of large dressed stone blocks stretching across a natural river-fed bay, having three identifiable sluice positions cut through and where a millstone has been found close by, is clearly evidence of a tide-mill. Unfortunately, there no evidence has yet been found indicating the date of the structure.

None of the principal Greek or Roman writers of the ancient world mention tide-mills, although several clearly had knowledge of water-mills<sup>113</sup>. However, it has been claimed that attempts were made in classical times to harness the tidal currents of the Euripus channel separating Boeotia and Euboea, and in the Evrepos Strait in Cephalonia<sup>114</sup>, but the writer has been unable to date, to identify the classical source for this assertion. Such mills that are driven by tidal currents are not true tide-mills in the modern meaning of the term, where the power is derived from the hydraulic head created by the rise and fall of tides. These water-mills may have been floating mills, which we know to have been used to great effect when Rome was besieged by the Goths in 537 AD. Alternatively, they may have had wheels in a fixed position, which could effectively engage, like river mills, larges masses of flowing water with negligible changes in water level.

We know the Romans had a good understanding of tides from the writings of Strabo<sup>115</sup> (64 BC to 21 AD) and Pliny the Elder (23 to 79 AD). Their accounts reveal knowledge of diurnal and monthly tides, and the equinoctial/solstitial inequality that causes the springs to reach their highest levels around the equinoxes twice each year. Their intellectual enquiries may have revealed to them that every four and a half years the spring tides coincide with perigee, the closest approach of the moon to the earth, when *perigean* tides occur. But whether or not this knowledge of tides provided them with an alternative source of water-power is the question that this study is facing.

Currently, the earliest tide-mills that we are aware of in Europe are Irish, dating from the seventh and eighth centuries AD. On Mahee Island, Strangford Lough, Co. Down, three horizontal-wheeled tide-mills have been identified, serving the nearby Nendrum monastery<sup>116</sup>. The oldest mill, that has been dated by dendrochronology to 619-621 AD, was served by a mill-dam approximately 8 m wide, enclosing an area of c 6500 m<sup>2</sup> of water. The mill-dam was built on two parallel trenches, the landward one lined with clay and filled with stones, the

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<sup>112</sup> The writer is most grateful to Prof. Barry Cunliffe for bringing this site to his attention.

<sup>113</sup> Including Antipater of Thessalonica, Ausonius, Diocletian, Eurchromeios, Hesychius and Vitruvius. See Olsen 1984 for a summary and interpretation of these texts. Pliny the Elder and Strabo have rather more dubious references to water-power.

<sup>114</sup> Charlier 1978, A1-2.

<sup>115</sup> Strabo, *Geography*, (17 vols.) trans. H.L.Jones, see Book 3, Ch. 5, Loeb, 1917-1933. See Cartwright 1999.

<sup>116</sup> McErlean and Crothers 2001, 16-19. See also *Archaeology Ireland*, vol. 15, no.2, issue no. 56, Summer 2001.

seaward trench lined with holly branches filled with humic material and capped with a sloping revetment of wattle work. The intervening core had vertical oak beams at 3 m spaces joined by horizontal planking and filled with silt, clay and soil. Further strength was provided by two wattle fences buried in the core, and the whole dam was covered by clay and topped by stones. In the late seventh or early eighth century this mill was abandoned and replaced by a new mill and pond enclosing a rectangular area higher up the foreshore. This new mill-dam was constructed differently, involving an inner core of red marine clay sealed with blue estuarine clay and revetted with stones. A great amount of moss was used for sealing between the stones and within the internal layers. Parts of a wooden flume, a wheel hub and fragments of millstones were found. Towards the end of the eighth century, a third mill, largely constructed of stone, was built on the site of the second mill, using the same millpond. This has been dated by dendrochronological to 787 AD. Numerous artefacts were found including a pair of millstones, wooden wheel paddles and a massive wedge-shaped flume carved from two 4.7 m long blocks of sandstone. The flume delivered water to the wheel at a level of  $-0.12$  m OD, and the tail-race is recorded as  $-0.68$  m OD<sup>117</sup>. The present day tide ranges in Strangford Lough are 1.9 m (mean neap) to 3.1 m (mean spring). What they may have been in the seventh century is unknown to the writer.

In 1979 the remains of two water-mills were discovered on Little Island, Cork harbour, Co. Cork, which have been dated by dendrochronological to c. 630 A.D.<sup>118</sup>. One of the mills was a vertical-wheeled mill, the other a double horizontal-wheeled mill<sup>119</sup>. The mills were apparently built on riverine mud and the site was covered by up to 1.5 m of estuarine deposits. Although the mill site is approximately 250 m from the present shoreline, these deposits have been interpreted as possibly indicating that the tidal waters of nearby Lough Mahon was used to power the wheels<sup>120</sup>.

Within England and Wales the earliest record of a tide-mill is considered to be the mill mentioned in the Domesday Survey at Dover, Kent<sup>121</sup>. The chronology of

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<sup>117</sup> The publication gives the MHWS as +1.90 m OD and the MHWN as +1.40 m OD. These figures are at variance with the tidal information published by the Hydrographer of the Navy that gives Strangford Lough tides as MHWS 3.5, MHWN 3.0, MLWN 1.1, and MLWS 0.4 OD.

<sup>118</sup> Rynne 1992, 22-4.

<sup>119</sup> It is interesting to note that some 'modern' tide-mills in France, Spain and America had horizontal wheels.

<sup>120</sup> This article does not include site plans, sections, critical levels or details of finds. Post-excavation reports are being sought to confirm these claims.

<sup>121</sup> This mill, that was recorded as being built at the entrance to the harbour and was damaging nearly all the shipping because it greatly disturbed the sea, '*In introitu portus de Douere est unum molendinum quod omnes pene naves confringit per magnam turbationem maris*', has invited the suggestion of a tide-mill from many historians. But the physical arrangement is perplexing. This unusual mill is worthy of more research and until this is undertaken, the writer considers it imprudent to assume that this was a tide-mill.

tide-mills shows by the twelfth century AD. eleven existed and thereafter a growing number are recorded<sup>122</sup>.

The advantage that water-power milling has over human or animal power sources is considerable. Experiments have shown that the output from Roman lava disc millstones equates to over 50kg/hp. hr.<sup>123</sup>. It has been calculated that the Haltwhistle Mill could have provided daily enough meal for 460 people in addition to offals for animal feed<sup>124</sup>. For other water-mills, such as the Athenian Agora and Barbegal<sup>125</sup> where more power was generated and absorbed by the stones, the population served would have been twice as many for each pair of stones. This use of water-power in their corn-milling industry is evident throughout the Empire especially Gaul and Italy, where examples of large-scale water-powered factories have been found<sup>126</sup>.

Within Britain the archaeology of Roman milling shows us that the incidence of Pompeian-type millstones compared with disc type is very small. Although they had a theoretical advantage over disc millstones in terms of output when moving at the same speed<sup>127</sup>, the higher speed of water-powered disc millstones gave them an advantage in output of approximately six times that of a Pompeian mill of the same diameter. In London the remains of very few Pompeian mills, mostly fragments have been found, and only two or three elsewhere in Britain<sup>128</sup>. This is undoubtedly due to the combination of the native stones being unsuitable for this large monolithic type of stone and the high cost of transporting such lava stones from abroad. Putting aside querns, the number of Roman disc millstones is comparatively large, probably numbering a few hundred. Whilst there may be

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<sup>122</sup> Minchinton 1977, 343.

<sup>123</sup> Although if a very much coarser product was accepted then the production could have been increased by up to 75% using the same power. See Spain 1992, the Westree Millstone Rig, 75-119.

<sup>124</sup> Spain 1992, 156. Allowing that the mill produces 57.6 kg/hr of meal; 90% for human consumption; 8hr day, 7 days per week; 900 grams/day per person. The proportion for human consumption is very speculative. See Jasny 1944.

<sup>125</sup> The output of c25 kg/hour for each pair of Barbegal millstones derived from Sellin's figures and quoted by Hodge is much too low. Hodge 1990, 60. Sellin 1983.

<sup>126</sup> The ruins close by *la Grand Barbegal* near Arles; the *Janiculum* complex in Rome; and the *Ephesos* complex in Asia Minor.

<sup>127</sup> Assuming that power is proportional to throughput, which is reasonable within fairly wide pressure limits, the theoretical power of a Pompeian mill suggests an output 3.5 times that of a disc millstone of the same diameter and speed. But the greater speeds of water-powered stones using gears gave them an obvious advantage. See Spain 1992, 259-261.

<sup>128</sup> The *catillus* of a Pompeian-style mill, found in Princes Street, London, and dated late first century AD, is on display at the Museum of London. It is intriguing that this mill, which was not water-powered, was found next to the Walbrook stream. See *Antiq. Jnl.* IX, 1929, 219ff. Also Merrifield, 1965, 240-1. Other examples have been recorded as being found in London in the nineteenth century but are now lost. A *catillus* fragment, probably Roman, was found at Corfe Mullen, Dorset, and a complete mill, post-Roman(?), was found at Hamworthy, Dorset. A fragment has also been found at Canterbury.

some doubt as to what proportion of these were water-powered<sup>129</sup>, there is now a growing body of evidence suggesting that the Romans readily exploited water-power for corn milling.

The growing number of water-mill sites being found throughout the Empire combined with sites where millstones were found close to water-courses, shows us that water-mills were widespread in towns, rural settings and in military zones. The evidence in Britannia is encouraging. At least three auxiliary forts on the Hadrian frontier had water-mills nearby<sup>130</sup> and the juxtaposition of forts and suitable rivers or streams at many other sites suggests that the military use of water-power for corn-milling may have been a common practice<sup>131</sup>. It is reasonable to propose therefore that the military activity associated with the establishment and building of Cripplegate fort in c.120 A.D, might be related to the building of the aqueduct and its conjectured water-mills.

The River Walbrook, which flows from north to south between the hills of Ludgate and Cornhill through the centre of Londinium, was an obvious source of water-power for the Romans. See Fig. 12. Several Roman disc millstones have been found in the valley providing a strong indication that water-mills operated here<sup>132</sup>. Various archaeological works, that have shown that the stream was used for trade and industry, have identified several rivulets entering both banks of the Walbrook within the Roman city. In the late first century A.D the central stream in its middle course below the Temple of Mithras, was found to be c4.0 m wide<sup>133</sup>, but narrower in the upper reaches and revetted with timber<sup>134</sup>. During the first century AD the lower 200 m formed a tidal estuary that was lined with quays and was probably navigable to the point where it was crossed by a road bridge. Later the Walbrook's confluence with the Thames was radically altered, to create two separate revetted channels entering the Thames. This has been interpreted as probably indicating the existence of one or more watermills operating in this area<sup>135</sup>.

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<sup>129</sup> For example animate-powered disc millstones have been found at *Kenchester* in Hertfordshire, *Orton Hall Farm* at Peterborough and at *Silchester*.

<sup>130</sup> At Willowford, Birdoswald Fort [*Camboglanna*]; Haltwhistle Burn, Greatchesters Fort [*Aesica*]; and North Tyne, Chesters Fort [*Cilurnum*].

<sup>131</sup> Spain 1993, 'Military water-mills', 145-150. Examples are the forts of Carvoran, Vindolanda, Housesteads, High Rochester, Risingham, Newstead and Netherby.

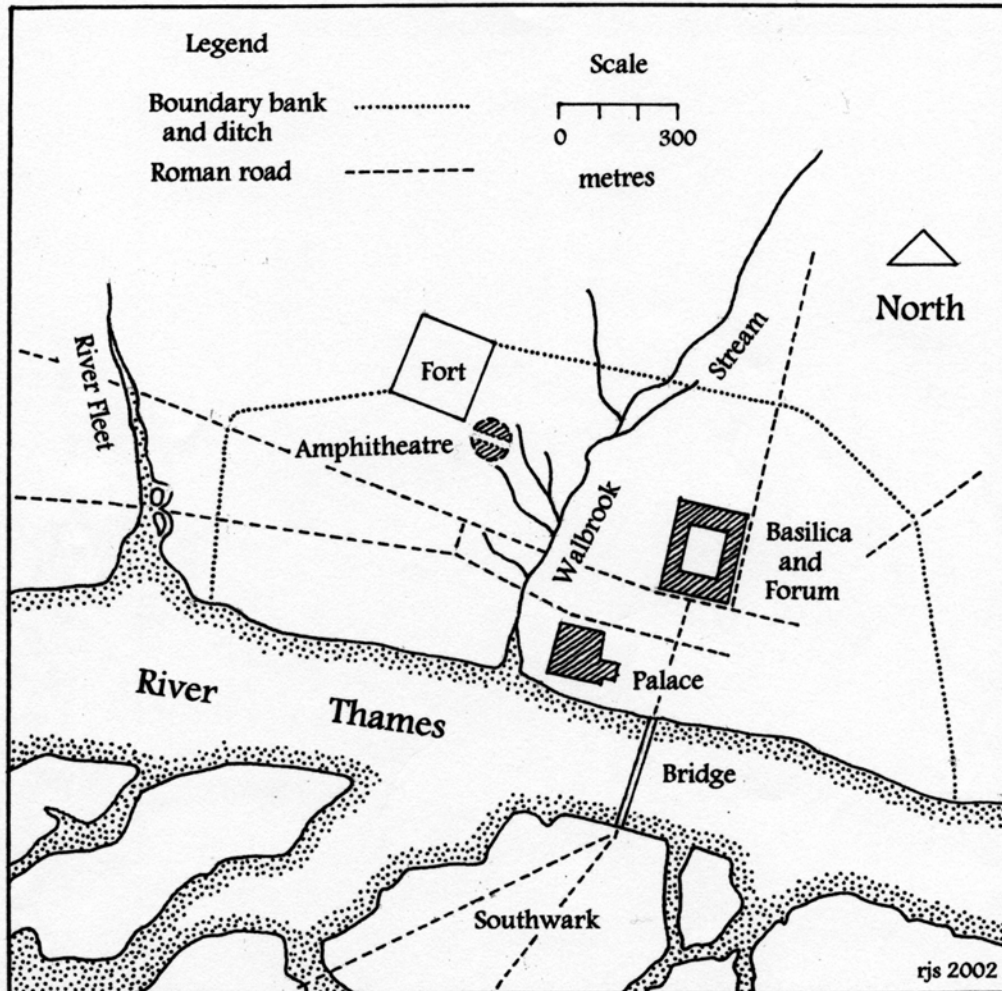
<sup>132</sup> Milne 1995, 46, 64; Merrifield 1965, 282, 240-1. Some of these millstones are on display at the Museum of London. They are very good examples of dressed grinding faces.

<sup>133</sup> Wilmot 1991, 12, see also 20, Fig.7.

<sup>134</sup> Shepherd 1998, 216-7.

<sup>135</sup> Milne 1995, 64.

FIGURE 12  
Londinium mid 2<sup>ND</sup> Century AD



It has been suggested that Sextus Julius Frontinus, who was Governor of Britain AD 74-78, may have started the canalisation and drainage of the upper Walbrook<sup>136</sup>. He clearly had experience of water supplies and probably water-power coming from his military commands. The development of the Walbrook valley appears to have coincided with that of the Fleet estuary, beginning with an identical programme of reclamation and drainage. In the upper valley, within the City, several of the streams, including the main one, were canalised, many being revetted with timber. Ground profiles were raised with massive dumping of clay and gravel. When water-power was exploited is unclear, but some of the

<sup>136</sup> LAMAS 1995, 46, 40.



canalised streams were probably used for mill-races as suggested by Marsden<sup>137</sup>, such as the one on the Bucklersbury House site, which he noted as being reduced in width from 4.0 m to 2.4 m. The levels of the middle and upper sections of the stream bed confirm gradients<sup>138</sup> showing that the water would have flowed fairly fast, providing accelerated headraces for the water-mills that apparently existed here. Another Roman drainage channel entering the north bank of the Thames approximately 300 m west of the Fleet estuary, has been identified<sup>139</sup>, but is considered too small for powering a waterwheel.

Numerous archaeological sites and observations of the Walbrook and its tributaries have shown that during the late second century A.D. the area suffered from inadequate drainage with increasing wet ground conditions affecting foundations and building methods<sup>140</sup>. Many of the water courses showed evidence of silting up and subsequent re-cutting and rebuilding of banks. Any water-mills that existed on these streams would have needed both their head and tail-races to be kept clear of deposits to maintain both flow and velocity. If a miller was unable to manage these hydrological and topographical changes or if they were beyond his control, (eg, due to changes in ownership boundaries or diversion of water supplies) he would have needed to re-position or re-site his water-wheel to continue operations. These changes in the landscape may have contributed to the general decline in activity that the archaeologists have concluded occurred in the valley in the second half of the second century AD. But we should note that a general decline in activity has been postulated for London and elsewhere during this period<sup>141</sup>. These increasingly adverse physical conditions would have stimulated the exploration of water-power sites outside the Walbrook valley. In this process the River Fleet would have surely attracted attention.

The evidence indicates that wheat was entering the port and probably being unloaded from shallow barges. No doubt other goods were passing through but our focus is understandably on grain and its conversion to meal using water-power. The occurrence of charred spelt wheat and chaff on the northern eyot shows us that grain was being prepared for milling close by. The delivery of grain may have been seasonal at harvest times or alternatively shipped from granaries elsewhere in batches as demand dictated. Once landed, double handling of the grain prior to milling was unavoidable, because the storage in the mill was limited, probably to small bins and the hopper above the stones. Regardless of the pattern of grain deliveries during the year, the mills would be at work more or less continuously, meeting the local demands, both civilian and military. It was an advantage to have the water-mills close to the customers, the bakeries [*pistrina*],

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<sup>137</sup> P.M..Marsden 1980, 72.

<sup>138</sup> Wilmott 1991, 15, Fig. 3 showing spot heights. See also Maloney 1990, 15-25.

<sup>139</sup> Wilmott 1982, Fig 1.

<sup>140</sup> Maloney 1990, 120-22.

<sup>141</sup> Merryfield 1983, 140-8.

for wheat meal has a limited life<sup>142</sup> and, when wheat is ground, there is a 60% increase in volume, adding to the transportation problems.

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The powers of erosion and transportation provided by rivers are manifest in the ever-changing interface of land and water. It is ironic that the natural force that water-mills harness for man, is the instrument of their preservation or destruction. Water-mills, probably more than any other building on the early landscape, suffer most from the forces of nature. Even bridges, although subject to the same forces, have the singular advantage of their position usually being known to the archaeologist, Ancient roads do not move, rivers do. What other type of abandoned building within a valley could be obliterated by the downstream migration of incipient meanders or other manifestations of river flow and regime? Our areas of excavation occur in the lower reaches of the Fleet where essentially deposition rather than erosion would occur. Nonetheless, we may well have lost much evidence from the timber structures in the early and late Roman horizons.

Turning to the archives, on which so much has depended, are there any weaknesses that may have coloured or influenced this analysis? Searches within the archives reveal that several areas identified as excavations were in fact not dug, but fortunately they were relatively small areas. There also appears to be a dearth of evidence, especially observational, coming from the areas where a watching brief existed. Having regard to the vast areas opened, their contribution to the archives appears to have been insignificant and disappointing. But to be fair to the archaeologists, the conditions under which they laboured are unknown to us. We do not know what obstacles they may have encountered concerning access or the phasing of the work in the four years of the development. This study is dominated by the analysis of potential water-power, tidal and river, and its influence in the estuarine landscape of the lower Fleet valley. The physical limits of the excavations coupled with the limited nature of the evidence found, has resulted in a great burgeoning of speculations. There has also been a progressive interpretation of the evidence that has meant that reappraisals have to be made as each new interpretation changes our perspective on the last. The hypothesis presented in this study is founded largely on circumstantial evidence, strengthened by our inability to sustain an alternative and secure interpretation of the northern eyot's major man-made features and the mainland 'ditch' feature. The paucity and incomplete nature of the archaeological evidence in the vicinity of the proposed tide-mill has prevented us from reaching the threshold of certainty, and we must reluctantly accept that this hypothesis, whilst plausible, is unproven. This debate must rest pending further evidence.

*The hypothesis - that fairly soon after both eyots were improved and developed for grain importation and processing the industry took advantage of local water-power for milling. Early in this development they impounded the estuary waters*

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<sup>142</sup> Six weeks, by which time oxidation of the germ oil causes rancidity that is intolerable to the human palate.

*and harnessed the tides, and shortly afterwards, substantially increased the scale of the industry by diverting the Fleet higher up the valley with a substantial aqueduct to power water-mills built nearby. Tidal regression caused an abandonment of tidal-power in the mid-second century AD and then progressed to ultimately bring about a demise of the port at the end of the second or early third century AD.*

Dr. Robert Spain, Boxley, England, 2002.

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7.

### Appendix A

#### Northern Eyot – Details of the posts in the timber structure.

Post One Vertical stake, very decayed, 0.98m x 0.15m x 0.13m, originally a quartered boxed, tool marks: apart from tapered part seems unworked. Timber within cut.

Post Two Vertical square post, top eroded, otherwise fairly well preserved, 2.61m x 0.19m x 0.21m. Conversion box heart, axeface on tip, blade edge finely striated, face undulating, probably axe hewn. Driven post.

Post Three Vertical square stake, upper part decayed, lower well preserved, 1.68m x 0.20m x 0.16m, whole timber is shaped by axe and adze and squared. Timber post at bottom of cut.

Post Four Vertical triangular stake, sap and heartwood, in fair condition, 0.53m x 0.15m x 0.90m, radially cleft, axe blade marked and thin axe marks (irregularity of blade). Timber at bottom of cut.

Post Five Vertical post, heartwood curved on one side, a triangle cut square half way down; fairly well preserved, 0.83m x 0.20m x 0.13m; pointed end, axe marks and striations visible on 3 sides of the square point; this timber had large cracks filled with clay and natural erosion at top. Timber next to Post Four within posthole.

Post Six Vertical square box stake in good condition, boxed heart conversion, recorded in section and plan. Driven stake?

Post Seven Vertical square stake, decayed and truncated when excavated, 0.40m x 0.30m x 0.30m, apart from sawn bottom and squared sides no tool marks. At base of cut.

Horizontal base-plate under Post Seven, broken in antiquity (probably by weight of timber on top of it), approx. 0.55m x 0.40m x 30mm thick; possibly radially split, edges very decayed; no other than the obvious planning/adzing marks to achieve shape. Lies at foot of cut.

Post Eight Large vertical subtriangular timber stake, decayed at top, 0.57m x 1.40m x 1.10m [sic], partially cleft and hewn, axe? Facets on tip only. Post within cut.

Post Nine Vertical post in very good condition, 2.62m x 0.18m x 0.18m, box squared worked to a neat point at bottom. Upright within cut.

Post Ten Vertical squared and evenly quartered post in very good condition, 2.67m x 0.17m x 0.12m, worked to a very sharp point at bottom. Upright within cut.

Post Eleven Vertical squared post in very good condition, 2.37m x 0.15m x 0.14m, worked to a point at bottom. Upright within cut.

Post Twelve Vertical post in very good condition, 2.62m x 0.18m x 0.18m, box squared worked to a neat point at bottom. Upright within cut.

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