Wells and Bucket-Chains: Unforeseen Elements of Water Supply in Early Roman London

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FOREWORD By Ivor Noël Hume

It is humbling but at the same time gratifying to be asked to contribute in some minuscule way to this splendid, indeed Holmesian, analysis of clues to Londinium’s water supply. The gratitude stems from the pleasure of knowing that my work done so long ago still has value, but the humbling comes from the reminder that it was so inadequately completed. The 1956 salvage work that Blair describes took place in the Dark Ages of urban archaeology when the recovery of eye-catching artefacts was still the yardstick for successful salvage.

At the Guildhall Museum, which was responsible for archaeological efforts within the City limits, I was its lone field archaeologist supplied with neither transportation nor transit, indeed, with no tools beyond a trowel, tape measure, ranging pole, and camera. With more time and a team of hard-hatted helpers so much more could have been learned about the Cheapside building that turned out to be a second-century bath-house. Nevertheless, and in spite of the primitive conservation procedures performed in a Guildhall attic, two enigmatic wooden boxes from the bath-house well have survived sufficiently intact to make their contribution to the present study. Now, half a century later, they are an enigma no more — and a reminder to modern archaeologists that if you don’t know what it is, don’t throw it away. It may have been part of something interesting.

INTRODUCTION

‘It is a wretched business to be digging a well just as thirst is mastering you’
Plautus, Mostellaria 11.1.32

Since the earliest times, having an adequate and sustainable water supply has been pivotal in establishing any settlement — but the means by which this resource is exploited and ultimately managed and maintained are critical for life itself. In the past it has often been surmised that the Romans would have built an extra-mural aqueduct linked to a piped system to bring fresh water into Londinium, just as over a thousand years later the great medieval conduits brought water to selected parts of the City.¹ There is, however, little archaeological

¹ Rowsome 2000, 61–2; Barber and Thomas 2002, 32, fig. 37.
evidence to support this theory, with the exception of a few short runs of wood and ceramic water pipes, and it is generally accepted that such an elaborate system of water distribution was never built.\footnote{Wacher 1974, 100; Wilmott 1991, 52–4; Merrifield 1965, 146; Morris 1982, 223.}

It would appear that first-century \textit{Londinium} might have had one distinct advantage over many Roman cities across the Empire: the freely available water that could be tapped from rivers or springs which flowed through the city. The water from these natural sources on the surface was supplemented by hundreds of small private wells which tapped into the shallow aquifer, which percolated through the natural sand and gravel above the impermeable London Clay.\footnote{Wilmott 1982 and 1984.} The waterlogged remains of these small wells have been found on many sites throughout the city, and their relatively small size indicates that each would have served only a few households. The construction of these wells is standardised, with most having a simple box frame composed of oak boards, jointed together at the corners. Given the small width of the typical well shaft, it is clear that the only effective method of drawing water from them would be by the simple means of a bucket on a rope.

During archaeological excavations in 2001 at 30 Gresham Street (Site 1; MoL site code...
something extraordinary occurred which has made us completely reassess the subject of water supply in Roman London (FIGS 1–2). Four massive, first- and second-century, plank-lined wells (Wells 1–4) were discovered — all of which were far larger than any that had previously been found, with the notable exception of the Cheapside baths well (see below). The careful excavation of these waterlogged structures took several weeks, allowing ample time for the excavators to ponder as to how the water would have been efficiently drawn from the wells (FIG. 3). Conveniently, the answer lay preserved in the anaerobic waterlogged silts that had accumulated at the bases of the three deepest structures, where the remains of two different types of mechanical water-lifting machines or bucket-chains were found.

The field records, finds, and other details pertaining to the excavations at both sites will be archived by the Museum of London under the relevant site codes following the completion of analysis and publication work for 30 Gresham Street (Blair and Watson in prep.) and 12 Arthur Street (Swift in prep.). The archive may be consulted by prior arrangement at the Museum’s London Archaeological Archive and Research Centre (LAARC) at Mortimer Wheeler House, 46 Eagle Wharf Road, London N1 7ED.
FIG. 3. Archaeological excavation of Well 1 at 30 Gresham Street.
Prior to the 2001 excavations, no evidence had been found to suggest that bucket-chains played an important and perhaps pivotal role in supplying fresh water in Londinium during the first and second centuries A.D. It is extraordinary that the remains of four bucket-chain systems had been found by the end of the year. The findings included two distinct types of device, hereafter referred to as Type A and Type B. These discoveries led to the retrospective identification of a fragmentary Type A device which had been found 50 years earlier by the Guildhall Museum’s archaeologist Ivor Noël Hume in a similarly massive well (Well 5) on the site of the Cheapside Roman baths (Site 3; GM37), immediately to the south of Site 1 (FIGS 4–5).

The geology in the area of the Gresham Street and Cheapside baths sites (Sites 1 and 3) consists of London Clay overlain by a Pleistocene terrace gravel known as the Taplow Gravel, which acts as an aquifer for ground-water. The surface of the gravel is partly overlain by brickearth in this area of the city. Although located on relatively high ground, it is clear that the site of the wells had been chosen specifically because of the unusually high water-table and depth of ground-water in the area.

Information on the local geology and hydrology was provided by a series of boreholes sunk across Site 1 in advance of the archaeological excavation. The boreholes showed that the surface of London Clay is roughly constant at 6m OD (Ordnance Datum), but rose consistently along the eastern side of the site to over 6.50m OD. The gravel has a local high point at 10.50m OD in the locality of the wells, falling away to the north, east, and south. The existing level of ground-water was found to fall towards the north, from 10.00m OD at the well location to below 8.75m OD under Gresham Street, a gradient of 1:120. The depth of ground-water above the London Clay at the well locations was found to be c. 3.5 to 4.0m. The modern water level was consistent with the preservation level of the Roman timbers in the well structures.

The Gresham Street and Cheapside baths sites are located in the same insulae on the east side of the western hill of the Roman city — immediately to the south of the amphitheatre and south-east of the second-century fort at Cripplegate (FIGS 2 and 4). This area, developed in the last quarter of the first century as part of the Flavian expansion of the Roman city northward from the main east–west axial road across the settlement, has seen a large number of archaeological excavations in the past 25 years.

The Arthur Street site (Site 2), situated to the west of the Roman bridgehead in the area behind the waterfront quays and warehouses, lay at a much lower elevation than the sites north of Cheapside, but it too had an abundant and plentiful supply of water that could be tapped below the surface. This took the form of water from the natural spring-line that flowed through the exposed face of the lower terrace gravels at the junction with the London Clay along the north bank of the Thames. It is notable that with the exception of the Cheapside baths, the other Roman bath-houses at Huggin Hill and Billingsgate, and the recently discovered extra-mural bath-house at Shadwell, were sited on the edge of the river terrace and utilised the spring-line to supply their water-tanks and other needs.

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5 Type A water-box: a narrow, hollowed-out rectangular oak box with a concealed water-chamber covered by a nailed lid — the water entering and leaving the box via a narrow slot or ‘port’ in its side and having a single stage water transfer. The boxes were joined together by pairs of straight iron links.

Type B box-bucket: a jointed rectangular oak box completely open at the top and having a two-stage water transfer. The buckets were held between pairs of articulated iron straps and cranked links in a continuous chain.

6 Guildhall Museum site records are referred by their site number (GM-) and Excavation Register (ER) number and are also now archived at the LAARC.

7 Pell Frischmann Consulting Engineers report on the Ground Investigation at 30 Gresham Street, London EC2, unpublished report in the GHT00 site archive at LAARC.

8 Interim engineering report on the Roman well mechanisms discovered at 30 Gresham Street, Tony Taylor and Robert Spain 2002, unpublished report in the GHT00 site archive.

FIG. 4. Plan of Site 1 and immediate environs, showing Wells 1–3 and the Cheapside baths and Well 5.
This paper summarises relevant aspects of the first- and second-century sequences on the three well sites and then goes on to describe the individual well structures and their associated bucket-chains in detail. Subsequent sections describe the 2002 reconstruction of a full-size working replica of the second-century water-lifting machine from Site 1, explore the significance of the bucket-chains to the supply of Londinium’s water, and discuss evidence for the use of bucket-chains elsewhere in the Roman world.

THE STUDY SITES: WELL STRUCTURES AND BUCKET-CHAINS

30 GRESHAM STREET (SITE 1)

The archaeological excavation at 30 Gresham Street took place in advance of a redevelopment which entailed the demolition of ten adjoining buildings and the loss of a road within the footprint of the site. The last of the buildings to be demolished was the State Bank of India, the

10 The excavation was a joint venture between MoLAS and AOC Archaeology during 2000–2001 (Blair and Watson 2004).
location of one of the first controlled excavations in the City of London just 25 years earlier.\footnote{The excavation at Milk Street (MLK76) was undertaken by the Museum of London’s Department of Urban Archaeology (DUA) in 1976–77, see Perring et al. 1991, 44.} The site has had a long history of archaeological intervention, with the earliest works being carried out by Gerald Dunning over 70 years ago in 1930.\footnote{Shepherd 1987, 13.}

The pre-Roman ground surface at the 30 Gresham Street site consisted of a truncated brickearth subsoil at c. 11.24–10.80m OD (which overlay brickearth and terrace gravels at c. 10.36–10.22m OD). The original land surface was relatively flat but included significant undulations which may have impeded surface drainage. The local topography shows a slight slope from the north-west towards the south and south-east. It appears that a combination of a high natural water table, impeded subsurface drainage, and relatively level ground surface is key to understanding the subsequent development of the site. Early Roman external dumping raised the ground level to create building plots and features connected with water collection and extraction.

The largest extant early Roman feature at 30 Gresham Street was a 20m by 10m, east–west-aligned cut located on the eastern side of the site. The feature appears to have quickly become a pond of standing water, perhaps due to the high water table (FIG. 4). The feature probably began as a quarry for brickearth and gravel extraction, but its large size and regular basal profile suggest that it was also intended as a water reservoir, and it lay only 20m north-east of the contemporary Well 1. Sediments within the feature included the life-sized left hand and forearm of a gilded, cast bronze statue <740>, presumably part of a civic or public statue which was hacked apart and unceremoniously dumped to place it beyond easy recovery.\footnote{It has been suggested that the arm may originally have been part of a statue of the disgraced emperor Nero (A.D. 54–68), which had been torn down and broken up following his fall from grace; <740> is the MoL accession number for the item.}

By c. A.D. 70–75 the character of the area was changing, and a series of gravel roads (Roads 1–4) were laid out across the site, defining parts of four separate insulae (FIG. 4). The roads were associated with the reconstruction of Londinium after the Boudican revolt, with the area of settlement expanding to include the site and the area further north. The pond area was not systematically in-filled until the early second century and appears to have constrained the position of the central road (Road 4), which lay immediately to the south. Whilst the north side of Road 4 was flanked by a series of boundary and drainage ditches, there were no corresponding roadside drains along its south side in the area adjacent to the wells (see below).

There was little evidence of early Roman settlement at the site apart from three late first-century masonry buildings discovered along the Milk Street frontage to the west. The buildings were rectangular in plan and were probably houses with stone foundations and timber-framed superstructures (FIG. 4). Their internal walls were founded on wooden sill-beams and constructed of mud-brick or wattle-and-daub. One of the buildings contained at least nine rooms, many with opus signinum floors. One room possessed a large second-century mosaic, which had been removed in antiquity apart from fragments of its plain border.\footnote{Perring et al. 1991, 44–8.} The building fronted onto the west side of Road 2, alongside another building with substantial masonry foundations. These buildings may represent two adjoining shop units with living-quarters above.

It became clear at an early stage of the excavation that the nature of the development within the insulae to the east of Road 2 was quite different from that recorded to the west. Large areas to the east were not built on during the early Roman period, but were used to dump soil and rubbish to create a raised ground surface for building.\footnote{The vast bulk of the Roman finds, including 38 per cent of the pottery, was derived from these dumps, much of which is of Flavian date c. A.D. 70–100.} Although a number of fragmentary clay-
and-timber buildings were found, their insubstantial nature and low density contrasts with the situation to the west of the road. The discovery of three massive wells east of the road, and the proximity of the Cheapside baths in the southern part of the same insula, suggests a specialised land use associated with the extraction, distribution, and use of water. This may have involved the establishment of a zone dedicated to civic water supply.

The well structures and bucket-chains

The discovery of two early Roman plank-lined wells (Wells 1 and 2) and a similar but much shallower well (Well 3) within a 12m radius was unforeseen. Due to the depth of twentieth-century basements in the area, the wells’ contemporary ground surface did not survive. Consequently there was no evidence of the original buildings or ‘well-houses’ that must have covered the wells and housed the water-lifting machinery. The size and depth of the wells, and the immense pressure exerted on the outside of the structures by the surrounding waterlogged sand and gravel during their recent excavation, obliged the archaeological team to brace the linings internally with a close-boarded shoring-frame during excavation to prevent collapse. This shoring masked much of the original lining and only keyhole recording of the lower lining of the structures was possible.

Western well (Well 1)

The existence of the earlier ‘western’ well (Well 1) was not immediately apparent, as the top of the structure had been partly dismantled in antiquity. Only the massive combined construction/robbing cut of the well (measuring c. 6.50m by 7.50m) filled with dark grey silt was visible on the surface, giving the feature a pond-like appearance. The well lining measured 2.60m square in plan, and at least 4.50m in depth, with its base recorded at c. 6.25m OD; all the timber used in its construction was oak as is typical of Roman London. The lining was constructed of tiers of close-fitting planks which were set behind four corner posts and four centrally-placed intermediate posts (FIG. 6). The posts came from relatively small diameter, fairly straight oaks, c. 0.30–0.35m diameter at chest height and less than 50 years old. Seven tiers of the lining survived, with the individual sawn planks varying in width between 0.40m and 0.45m by 50mm thick. There was a suggestion that some of the planks had been rebated, but it is now thought that this feature was caused by the weight of the upper well frame bearing on and compressing the soft, decayed sapwood at the edges of the planks. Several pieces of one of the lining planks from the east wall of the well screen, at a level between c. 8.76m and 8.40m OD, were found with curved scratches on its internal face. It has been suggested that these marks could be catenaries, possibly caused by projecting linkage pins on the box-chain, although it is equally possible that these marks are from the return stroke of a saw.

In the lower half of the well the central posts retaining the lining were secured by three sets of oak cross-braces, and it is likely that there would have been similar braces in the upper levels of the well which have not survived (FIG. 7). In contrast to the posts, the braces were radially cleft from large, slow-grown, straight-grained oaks at least 0.7m in diameter and c. 200 years old. Only the lower cross-braces were articulated — with crude halvings cut where they crossed

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17 The trees were probably derived from managed woodland and were felled young at the size required to make individual beams.
18 This form of oak was probably derived from natural woodland/wildwood where large logs were split up into handy sections after felling.
each other secured by one iron nail. In contrast, the four cross-bracing timbers above them were simply crossed one over another at irregular intervals. The ends of the beams had short tenons which were housed in crude axe- and chisel-cut mortices in the posts. The insubstantial nature and roughness of these joints strongly suggest that many of the cross-braces were added late in the construction process and would have been hammered into place.

Dendrochronological dating of these timbers showed that the well had been constructed around A.D. 63. This construction date indicates that the well was built in the years following the Boudican revolt of A.D. 60, and that it was most likely part of a well-planned enterprise, carried out during the rebuilding of the infrastructure of the Roman city. Significantly, the Regis House quay close to the Roman bridgehead also dates to A.D. 63 and is thought to have been built by the army. Evidence from several sites indicates that the renewal of infrastructure such

19 The samples were analysed by Dr Anne Crone of AOC Archaeology Group.
20 Brigham and Watson in prep.
as roads and water supply preceded the general re-establishment of roadside properties and new building.\textsuperscript{21}

Building a structure of the size and depth of Well 1 in unstable, saturated ground required ingenuity on the part of the Roman engineers and well-builders. It is likely that the well lining was built as a simple, partly free-standing tower with earth-fast posts set within a comparatively shallow construction pit. The heavy planking was then added and nailed to the outside of the posts a few courses at a time and as the structure was carefully undermined it would have settled gradually under its own weight into the well shaft.\textsuperscript{22} The lining with its interior cross-bracing would also have acted as a caisson or shield for those digging the lower part of the well shaft in the unstable saturated ground. This simple but practical method avoided the need for elaborate jointing and prefabrication, and it was not strictly speaking a timber frame, as was the case with Wells 3 and 4.

Set into a cut into the London Clay at the base of the well, beneath the lower cross-frame, was a superbly-preserved, softwood, halved barrel bound with hardwood hoops (FIGS 6 and 8). The barrel was made from alpine softwood, probably silver fir, with the binding hoops possibly made of hazel.\textsuperscript{23} Roman barrel hoops are rarely well-preserved, especially their bindings, but in this

\begin{footnotes}
\item[21] Hill and Rowsome in prep.
\item[22] It is calculated that the total weight of the well structure would have been 3.58 tons. Taylor and Spain, op. cit. (note 8).
\item[23] The barrel consisted of 20 staves, 5 head pieces, and 11 hoops.
\end{footnotes}
case the ends of the D-shaped sections of whole deciduous stem hoops were bound with a fibre, possibly flax. The internal surfaces of the barrel appear to have been coated with pine resin to seal the timber and fill any tiny gaps between the staves. Analysis has shown that the use of pine resin as a caulking agent on buckets and barrels appears to have been standard practice in the Roman period. When the barrel was lifted it was found that there were several scribed marks and one lettered stamp on the staves and several cursive script letters on the outside of the head piece (FIG. 9).

The function of the barrel is somewhat enigmatic, although it was originally thought that it might have acted as a silt-trap at the bottom of the well. Given its position and relative inaccessibility beneath the lower cross-brace this now seems unlikely, and an alternative and more plausible explanation is that the barrel was the base of a small pilot well sunk to test the aquifer or a drainage-sump to assist in de-watering the well shaft during its construction.

**The Type A bucket-chain**

The most significant finds from the well were recovered from its lower levels, including many from the barrel at its base, which contained a number of parts of a Type A bucket-chain. These included parts of twelve rectangular water-boxes, a number of associated iron rods or connecting-

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pins, and a small wooden roller. The roller <3733> had clear wear on the end spindles, showing that they had turned inside a hole, and also a narrow worn zone around the middle of the roller. Unlike the longer roller from Well 5 at the Cheapside baths, which is interpreted as being a rung or cross-bar from a lantern drum that carried the bucket-chain (see below), the wear patterns do not appear to be consistent with this function and its use as a roller for a simple rope hoist seems more likely (FIG. 10).

FIG. 9. Stamped and scribed inscriptions on header piece of barrel (Scale 1:8).

FIG. 10. Oak roller <3733> found in barrel at base of Well 1 (Scale 1:4).
The water-boxes had been carefully made from hollowed-out blocks of oak, with each of the containers originally covered by a board lid, which was nailed over the water chamber (FIG. 11). The boxes appear to have been made from 1/16th split sections of very large, straight-grained logs. The lid-boards were also radially cleft, mainly from slow-grown trees, but at less than 10mm thick it is likely that they were 1/64th or 1/128th section clefts similar to fence pales and were probably achieved using a froe-and-brake system rather than wedges alone.25 With such fine boards, finely-tapered, flat-headed iron nails were used, driven into pre-bored 3mm holes.

At each end of the boxes were two parallel slots, which originally housed a pair of pivoting iron links held in place by an iron rod or pin; these joined the buckets together in a continuous loop or chain. Several

25 Goodburn in Hill and Rowsome in prep.
of the connecting-pins were found in the barrel at the base of the well but none of the linkage (<3699>, <3701>, <3702>, <3704>) (FIG. 12). All of the pins were broken close to the ends, but their original form was that of a flat-headed rod similar to a nail, which was clenched over at the opposite end to secure it in place. Some of the water-boxes had a circular, washer-like depression around the holes for the connecting-pins, which it is assumed was the result of wear caused by the clenched end of the pin rotating whilst the bucket-chain was in motion. Surviving on the surfaces of some of the boxes were traces of pine resin, which had been applied as a sealant to make the joints watertight.

The only complete water-box to be found had been thrown into the bottom of the robber cut behind the south side of the well lining, and though slightly distorted by compression, its individual faces could be measured directly to get close to the original dimensions (FIG. 13a). This process was aided by the very distinctive engineering feature of the preserved, accurately-scribed lines laid out with a rule and probably a metal square on the base and sides of the box (FIG. 13b). The lines clearly marked both the position of the water chamber and more importantly...
the slots for the paired links of iron used to form the chain. Another interesting feature of this water-box was that it had chamfered edges beneath the linkage slots, presumably to maximise the clearance between the individual boxes when they flexed and were drawn closer together as they rotated around the drive-wheel. Interestingly, none of the other Type A water-boxes that have been found has this feature, so one assumes that it was not essential to the smooth operation of the bucket-chain and was therefore not replicated.

Each of the boxes could hold about 1.75

FIG. 13a. Complete Type A water-box <2168> found in the robber cut behind the south side of the well lining.
FIG. 13b. Drawing of Type A water-box <2168> showing marking-out lines (Scale 1:8).
litres of water, which entered and exited the water chamber via a small rectangular port cut into the upper side of each of the boxes. Importantly, amongst the water-boxes was one having the port on the opposite face to all of the other boxes, including those from the Cheapside baths and Arthur Street (see below). This port arrangement would have created a discharge in the opposite direction to the other boxes, which raises a number of possibilities:

(a) the different boxes operating on the same chain, discharging into two parallel troughs or lauders, one each side of the chain;
(b) two separate chains operating on a common drive-shaft discharging into either separate troughs or a common trough between the two chains;
(c) two separate chains, each mounted on its own shaft, probably discharging into a common trough;
(d) two different chain discharge arrangements that did not co-exist.

Option (a) is considered unlikely because the duplication of the discharge is impractical and brings no advantage to a single supply-trough that could serve more than one controlled outlet. Option (b) brings the obvious advantage of potentially doubling the output but it would require twice the power for the operation. Such a machine could still be man-powered, operating either by a tread-wheel or a capstan via gears. Option (c) is essentially two similar or identical machines co-existing. The face area of the well (2.60m by 2.60m) is probably of sufficient size to allow two machines to work side-by-side with their shafts parallel, but if they were driven by tread-wheels, the wheels would have to be lapped in plan view. Duplication of the machines could provide the operational advantages of different flow rates and the maintenance advantage of a stand-by to effect repairs without interrupting the service. Option (d), two different machines but not co-existing, whilst possible, seems unlikely in view of the short operating life of the well, which is thought to have been approximately ten years.\(^{27}\)

**Disuse, robbing and abandonment**

Despite the undoubtedly large investment in time, energy, and materials in building the well and its bucket-chain, something clearly went wrong and in less than ten years the well had been abandoned and partly dismantled. The lower fills of the well relating to its disuse and silting date to A.D. 70–85, but a closer date of A.D. 69–71 was obtained from dendrochronological dating of several lengths of roughly-trimmed cleft oak which had been thrown into the well.\(^{26}\) These timbers are likely to have been high quality firewood and, allowing for perhaps a little drying of the material, would suggest that the well was out of use by the winter of A.D. 70 or a little later. The dating of a number of the upper disuse fills in the well suggests that the structure was gradually backfilled in the period between A.D. 70 and 100.

It would be inconceivable that the well was abandoned without very good cause and it is likely therefore that there must have been an irreparable and catastrophic failure of part of the well structure. The most likely area to fail would not be at the top, where new bracing could easily be added, but at the base where the greatest forces occur and which is the most difficult area in which to effect repair. There was evidence that the lower lining of the well had twisted and in doing so had significantly displaced the bases of the internal posts by \(c. 200–400\) mm. It is tempting to suggest that the relatively lightweight well frame started to fail because of the surrounding ground pressure and the weight of the heavy drive-system and its supporting frame bearing directly onto it. It is clear that at least some of the upper lining of the well had been robbed as is evidenced by the internal posts which projected above the surviving lining planks.

\(^{26}\) Probably cleft irregular ‘top wood’ from a large oak.

\(^{27}\) Spain and Taylor in prep.
Eastern well (Well 2)

The second deep well on the Gresham Street site (Well 2) was part of an improved and larger structure, dated to the early second century A.D. Dendrochronological dating of one of the posts showed that the well had been constructed c. A.D. 108–109, precluding its having been a direct replacement for the earlier well (Well 1).\(^{28}\) The well was also made entirely of oak, and was

\(^{28}\) The post had surviving bark edge and was one of the intermediate posts retaining the north side of the well.
seen in plan to be 3.60m square, and 5.00m in depth, with its base recorded at c. 5.15m OD. The lining was composed of tiers of close-fitting sawn planks set behind four corner posts and eight centrally-placed intermediate posts (FIG. 14). The planking was halved at the corners and large iron nails driven into the plank end-grain, and the east–west planking was fastened directly to the reverse of the corner posts. The intermediate posts were originally braced by at least three sets of cross-braces, which were found collapsed over one another in the lower levels of the well, with only the lowest frame likely to have remained in situ (FIG. 15). Some of the cross-braces were crudely halved over each other and secured with one iron nail at the junction; these effectively sub-divided the well into nine square compartments.

The order of construction seems to have been essentially the same as that used in the adjoining first-century well described above, although the precise method of the jointing of the cross-braces to the posts is uncertain. In some cases crude mortices were present in the upper sections of the posts but no corresponding mortices were present in the opposing posts. This suggests that one end of the cross-braces would have been lapped around the posts rather than tenoned in, a procedure that would have allowed easier fitting during assembly.

29 The nails had c. 20mm square heads, c. 6mm by 10mm shanks and were over 120mm long.
30 It is calculated that the total weight of the well structure was 5.23 tons.
WELLS AND BUCKET-CHAINS: ELEMENTS OF WATER SUPPLY IN EARLY ROMAN LONDON

The Type B bucket-chain

Found in the bottom of the well beneath the lowest cross-brace were several large semi-articulated parts of a contrasting Type B bucket-chain (FIG. 16). The mechanism was made of wrought iron, forming a heavy double chain supporting open-topped, oak-board box-buckets held between flat links alternating between pairs of cranked iron links (FIG. 17). In this mechanism the iron links bore the entire weight of the bucket-chain, in contrast to the Type A device where the tension and load were transferred directly through the body of the oak water-boxes.

The Roman architect Vitruvius, writing in the first century B.C., describes a similar double iron chain (duplex ferrea catena) in De Architectura 10.4:

But if a supply is required at a still greater height, a double iron chain is made to revolve on the axle of the same wheel and let down to the lower level, with bronze buckets suspended to the chain, each holding a congius (3.3 litres). Thus the turning of the wheel makes the chain revolve round the axle, and carries the buckets to the top. These are carried over the axle; they are made to turn over and pour into the conduit the water they have raised.31

All the water containers had been heavily burnt, and much of the ironwork distorted by heat, indicating that the upper sections of the bucket-chain and the overlying well-house had been destroyed by fire.32 Laboratory analysis of the metalwork has shown that the iron had a quenched

31 Vitruvius (Loeb, p. 303).
32 The date of the fire that destroyed the well-house and the water-lifting machinery cannot be precisely established, but it may well have been the Hadrianic Fire of c. A.D. 120–130.
FIG. 17 (left). Articulated section of Type B wrought-iron bucket-chain from the early second-century Well 2.

FIG. 18 (right). The reconstructed box-buckets of the second-century Type B bucket-chain from 30 Gresham Street.
structure, that is it had been heated up until it was red-hot and then plunged into water. Given that the bucket-chain was intended to be under tension, it is thought that quenching, which would have hardened the metal but at the same time made it more brittle, was unlikely to have been part of the original manufacturing process. It is assumed, therefore, that the quenching was unintentional and that it had taken place when the bucket-chain collapsed into the well water during the fire that destroyed the structure. Because all the recovered elements appear to be heat-damaged, and large sections of the bucket-chain were clearly missing, it is evident that the undamaged (below water) section of the bucket-chain had been salvaged after the fire. The salvaging of the undamaged section of the bucket-chain from the lower level of the well clearly illustrates the value and importance of the device to the Romans, who would presumably have repaired it and reused it elsewhere.

Although the box-buckets were badly damaged, enough fragments survived to reconstruct how they were made and how they articulated with the iron bucket-chain (FIG. 18). The straight links of the chain were nailed onto, and in isolated cases had been recessed into, the outer sides of the boxes and were joined at each end to the intermediate cranked links by a large pin (FIG. 19), held in place by a split-ring (FIG. 20). The base of the box was recessed beneath the water chamber to allow the lower pin to pass through the walls of the box. This system of duplicated linked elements meant that the bucket-chain could possibly be shortened or lengthened dependent on the relative cyclical or seasonal water level in the well. The boxes were open at the top unlike the side-discharge system used in the much smaller Type A water-boxes from the adjoining well, and

those found on Sites 2 and 3. The boxes had a forward discharge, with the cranked links located in the open mouth of the containers (Fig. 21). In order to stop the cranked links from moving inwards, two guide-pins or nails had been driven through the recessed base to restrict any lateral movement across the end of the boxes. It is interesting that only one box-bucket was found to have holes for retaining-pins at the opposite, open, mouth end, indicating that the cranked links only required anchoring at one end of each box.

The box-buckets were a similar length to the Type A water-boxes but were much wider at c. 250mm wide by 170mm deep and 25–28mm thick, and were made up of five jointed boards held together with finely-tapered, wrought-iron nails. At the lower end of the box, the inside faces of the boards were grooved for a 15mm-thick base-board. All the original boards were of radially-cleft oak, with the exception of one piece of pale softwood, probably part of a silver-fir barrel-stave, that had been reworked to make a base-board. The proportions of the boards suggest that they were \( \frac{1}{32} \)nd split sections and tool-marks showed that they had then been trimmed with axes. The final truing was done with small planes used diagonally across the grain (traces of the use of serrated plane-irons were found on some fragments). The thinner base-boards were quite possibly planed fence pales and would have been \( \frac{1}{64} \)th or even \( \frac{1}{128} \)th split sections made in an identical fashion to the board lids of the Type A water-boxes described above. Again, imported pine resin was used to seal the boxes, presumably applied hot.

It is calculated that in order to lift water from the lower levels of the well it would have required a chain of at least thirty box-buckets. This is based on discharging at a height over 7m above the well water surface backed up by the calculated structural strength of the chain. Assuming the well surface to vary between 1 and 3m below ground level, this would lead to an assumed discharge height of 4m above ground. Each of the containers held approximately 6 litres of water when full, or three times the amount of one of the water-boxes from the smaller Type A bucket-chains described above. It has been calculated that it would be capable of raising more than 72,000 litres (16,000 gallons) of water over a ten-hour operating day depending on
the power available from humans or animals. To put this output figure into perspective, this volume of water would be capable of providing a subsistence level of drinking water to around 8,000 people, or approximately one third of the estimated population of Roman London in the second century A.D. Water may also have been supplied to trades and industries or used to flush out drainage systems.

Found in association with the bucket-chain elements were two contrasting iron fittings of uncertain function but which are likely to have been part of the superstructure which had been destroyed by fire. Both were clearly made to be attached to substantial wooden elements which had not survived. One was a circular iron collar with an upturned flange at one end that was pierced by six punched and countersunk nail-holes — with one of the 70mm long nails still *in situ* (<2189>) (FIG. 22). It is possible that this iron fitting was a bearing or sleeve for a vertical or horizontal shaft which may have rotated inside it, although no obvious signs of wear were apparent on its internal surfaces. It is perhaps more likely to have held a vertical than a horizontal shaft where the weight would be transferred through the nails attaching the collar, creating a potential weak spot.

The other fitting was an unusual, roughly T-shaped iron plate with a tapering surface and down-turned flanges to the terminals at its wider end (<2190>). The main body of the fitting incorporated a 30mm centrally-located circular hole with the lower end of the fitting flared with rounded terminals. Seven iron nails originally attached the plate to the missing timber elements, one of which had broken but was still located in its nail-hole (FIG. 23). The unusual shape of the fitting suggests that it had been made to fit over, and possibly around, more than one timber; the function of the circular hole and what it would have held is uncertain, although its size suggests that it would have been a metal rod. A complete copper-alloy cauldron with an iron handle (<1366>) (FIG. 24) was also found at the base of the well.

**Disuse, robbing and abandonment**

Following the fire that destroyed the well-house, the well was abandoned and its shaft gradually filled during the mid- to late second century. The

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34 Taylor and Spain, op. cit. (note 8); Spain and Taylor in prep.
35 Rowsome 2000, 33.
FIG. 24. Copper-alloy cauldron found in the bottom of Well 2.
bulk of the finds were derived from domestic refuse, including pottery, dated A.D. 50–200, and large quantities of ceramic building material. The building material from the lower fills included a number of complete box-flue tiles and tegula roofing-tiles, three of which had procuratorial tile-stamps in the top surface reading PPBRILON (die 2A). One unexpected feature of the box-flue tiles is that certain tiles have relief-patterned keying on one side and scored keying on the opposite face. The presence of scoring and relief-patterned keying has been noted on box-flue tiles from Huggin Hill baths, but otherwise seems to have been a rare occurrence.

Although it is conceivable that the stamped tiles could have come from the roof of the well-house building, the presence of the box-flue tiles in the assemblage suggests that all of the tile could have come from the demolition or alteration of a nearby public bath-house or official building — with the neighbouring Cheapside baths being the most likely candidate. However, it is odd that complete, reusable, tiles should be discarded in this way. This possible link between material discarded in Well 2 and the baths complex to the south would suggest that there was a direct association and that water lifted from the well was being used to supplement the supply to the bath-house.

**Central well (Well 3)**

The third of the massive timber-lined wells to be found at 30 Gresham Street (Well 3) was located immediately to the south-west of Well 2 and measured c. 2.60m by 2.80m with a truncated depth of 1.80m (FIGS 25–26). It was a radically different structure to those described above, as it had  

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36 Stamped tiles of this type were intended to be used in public buildings in the city and are thought to derive from the procuratorial tileworks situated in the Brockley Hill area (Betts 1995).

37 Ian Betts, MoLAS, pers. comm.
been built as a prefabricated timber frame including sill-beams jointed at the corners with cross-halvings in typical Roman style. Some of the scribing marks for the joint-cutting survived. In one case the joint was cut a little over-size and tightened with a wedge; no pegs were used in any joints as is typical of Roman structural woodwork. The structure had clearly been assembled in a rather wet construction-pit rather than lowered down by undermining as was the case with the much deeper Wells 1 and 2. The backfill included cleft oak off-cuts, fence pale fragments, and a very rare moulded timber that had been used as packing behind the plank lining of the well. The last was an ogee-profile bracket, similar to those framing Georgian classical-style doorways and supporting projecting pediment roofs.

The sill-beams had typical square Roman mortices for stub-tenoned posts (which were removed in antiquity) around which the sheathing planking was then nailed acting as a lining and also bracing. The end of one east–west cross-brace was found in situ where it had originally been lapped round the lower section of the central post on the east side of the structure. This beam is likely to have been part of a cruciform cross-bracing frame extending between the intermediate posts. The sill-beams were a little weathered with some redundant cuts and at least one ‘extra’ mortice, which seems to indicate they may have been second-hand timber. Despite this, fairly straight axe marks up to 140mm wide were found on them. The beams were hewn from whole logs and varied a little in dimensions, the largest being c. 200mm by 120mm.

The much shallower depth of this structure, when compared with the adjoining wells, could indicate that it was built as a temporary well. The construction date of A.D. 104 is derived from a fresh, radially-cleft off-cut of oak with bark edge that had been used as packing in the construction trench behind the lining. The similar early second-century date of this structure and the adjoining Well 2 could suggest that they were associated and were part of a larger, unified system of water extraction. It is equally conceivable that the well was a short-lived temporary
structure constructed to help de-water the area and facilitate the construction of the adjoining deeper well. Later features suggest that this well had gone out use by c. A.D. 120–130.

12 ARTHUR STREET (SITE 2)

Archaeological work at 12 Arthur Street (formerly Minster House) took place during 2001/02, with two phases of excavation following on from an archaeological evaluation. It was known from previous rescue work at Miles Lane to the east, and Suffolk House to the west, that at least one Roman waterfront would bisect the site. 38

The first phase of work consisted of the hand excavation of the pile-caps for the larger diameter piles. Trenches c. 2.5m by c. 2.5m in plan were opened up across the site with the intention of excavating all archaeological deposits down to sterile natural deposits. Whilst this was not fully possible in the south of the site where over 6.5m of waterlogged stratigraphy existed, the trenches to the north of this were excavated to depth. This gives a good idea of the steep profile of the north bank of the Thames, and some indication of the character of the prehistoric foreshore. It was during this phase of work that the north-western corner of a massive timber-lined Roman well (Well 4) was first encountered, with a number of water-boxes from a Type A bucket-chain found in its basal fill (FIGS 27–28).

Before the second phase of work began an archaeological watching-brief was conducted on various ground-works in advance of piling. It was at this point that the south-eastern corner of what was clearly part of the same well was exposed. Given the now recognised rarity and significance of the find, which came only a few months after the discovery of the wells and bucket-chains at 30 Gresham Street, it was decided that rather than excavate the well any further, the structure would be recorded and then preserved \textit{in situ}, and that the proposed pile would be moved to avoid damage to the structure.

The second phase of work entailed the excavation of archaeological deposits to varying depths according to proposed formation levels dictated by the foundation design. During these works the north-eastern corner of the well was exposed, effectively linking the two previously recorded parts. Set within the corner angle of the well frame was a much smaller secondary box-lined well (see below) that had been constructed after the larger well had fallen out of use and been at least partly infilled (FIG. 33). The south-western corner of the well was never exposed as it was not affected by the proposed building works.

A large proportion of the southern half and some of the north-eastern part of the well should survive \textit{in situ} beneath the new building at 12 Arthur Street. Additional parts of the water-lifting device may be preserved within it and may lead to further research when the site is next redeveloped.

\textbf{FIG. 28.} Axonometric reconstruction of Well 4.
The environs of the Arthur Street well

The Arthur Street well was situated in a gravel yard to the rear of a large first-century masonry building. Elements of substantial flint-and-chalk foundations as well as parts of the brick-and-tile superstructure of the building were excavated. These indicated that the building was at least 12m wide east–west by 20m long north–south. A large destruction horizon overlay the building remains, and it seems from the finds that it was destroyed by fire no later than A.D. 120. The character of the remains and the waterfront location near a palatial complex may indicate a building of significant status.40

The gravel yard occupied a space between the back of the building and the first terrace-retaining wall to the north. A felling date of after A.D. 54 was obtained from dendrochronological samples taken from the timber piles on which the wall was founded. On the terrace above, 27 timber piles of an apsidal building or room, that was at least 4.70m wide east–west, were recorded. Dendrochronological samples suggest a construction date of between A.D. 51 and 87. Unfortunately, none of the superstructure of the building survived, but its form and proximity to the well suggests that it was part of a bath-house or temple.

Well 4

The well structure

The shape of the well is unusual, for whereas the other massive wells built to accommodate bucket-chains at Gresham Street (Site 1) and the Cheapside baths (Site 3) are roughly square in plan, the Arthur Street well was rectangular and measured approximately 5.80m east–west by 2.50m north–south, and reached a (truncated) depth of c. 2.20m with its base at 1.15m OD (FIG. 28). The well is conjectured to have originally been constructed from a level of c. 4.50–5.00m OD which would have given it an overall depth of 3.35–3.80m.

Although the well was never fully exposed (see above), enough of the structure was seen to reconstruct its original form and how it was assembled. The lower frame was composed of four base-plates which overlapped one another at the corners — with the front edge of the base-plate anchored by small vertical stakes driven into the underlying sediment to hold the assembly in place during construction. Set into the base-plates were upright corner posts and a series of regularly-spaced intermediate posts (four along the sides and one at each end). The corner posts were jointed to the base-plates via tenons located within square mortices, whilst the intermediate posts were located via bare-faced tenons set into rectangular mortices. A thin batten made from a trimmed branch was found nailed onto the bottom end of one of the posts, overlapping the front of the base-plate and reaching the base of the well. The function of this flimsy element is unclear but it is likely to have been added to help guide the posts onto the base-plate during assembly.

The posts retained large, sawn planks which were set on edge to form the sides of the well — with the ends of the planks housed in vertical rebates cut into the corner posts. The bottom planks were further retained by battens nailed to the horizontal base-plates, presumably in an attempt to counter lateral thrust from the surrounding waterlogged sand and gravel bearing on the reverse of the lining.

In order to brace the structure internally, squared timber beams were set horizontally across the short axis of the well between the intermediate posts to act as cross-braces. These had bare-faced tenons that were set into long mortices on the opposing intermediate posts along the sides of the

39 Completion of the forthcoming analysis of finds from this layer will hopefully shed some light on the building’s possible form and function (Swift 2003).
40 Marsden 1983, 89–100.
structure. It was clear from the curved bases of these wide mortice joints that the cross-braces were hammered into place during the construction of the well. Although there may have been more than one layer of cross-braces, as was the case with Wells 1 and 2 on the Gresham Street site (see Site 1 above), this may not have been necessary given the shallower depth of the Arthur Street well.

The well was built by first excavating the cut in its entirety and then constructing the timber frame within it. There was evidence that on the south side steps were cut into the natural gravel. Here, once the timber frame was complete, the space between the construction cut and the frame itself was filled with light-yellow clay, presumably to act as a watertight sealant behind the framework. This was only recorded in section during the watching-brief phase and was also noted along the south-eastern side of the lining. The other sides of the well were not sealed in this way, where the gap between the construction cut and the frame was much less; and along the west side the timber was flush up against the gravel. In these areas, the construction backfill consisted of silty-pebbly sand that contained numerous fragments of timber, presumably working waste from the on-site fabrication of the timber frame.

It is worth noting that during the archaeological excavation water was literally pouring in through the gravel from the north side of the well — ground water flowing down the hill through the terrace gravels towards the Thames. One cannot help concluding from this that the absence of clay on the northern and western sides, as opposed to the use of clay on the southern and south-eastern sides, was deliberate and had the sole purpose of maximising the amount of water coming into the well, trapping it within the timber framework and increasing the water-holding capacity of the well. No evidence was found of the upper superstructure of the bucket-chain, or any building that contained the well.

Dendrochronological samples were taken from the timber frame of the well.\textsuperscript{41} There was little or no sapwood in the samples taken, and an estimated felling date of A.D. 61–97 was calculated. Ceramic building materials from the construction backfill of the well have been dated to between A.D. 60 and 160.

\textit{The bucket-chain}

In the lower fills of the north-western corner of the well, the only part to be fully excavated, were found three complete, well-preserved Type A rectangular, oak water-boxes and five less-complete examples of very similar dimensions to those found on Sites 1 and 3, but slightly heavier and more crudely made than the examples found on Site 1.\textsuperscript{42} Uniquely, one of the boxes <79> still retained its original linkage, an important detail missing from all of the examples previously found (\textit{FIG. 29}). The short, 170mm-long, pairs of wrought-iron links, which connected the boxes together, were held in place by and pivoted on a round, clenched iron nail which contrasts markedly with the purpose-made rods or connecting-pins used in the Type A bucket-chain from Site 1.

The geometry of the boxes and links is such that when an identical box is joined to the links and then displaced as though passing around a wheel, the adjacent corners come surprisingly close together. Analysis shows that a drive-wheel with not less than eight faces or registers would be required to provide effective engagement of the boxes and avoid interference with the iron links. The favoured arrangement is for the boxes to be supported by fairly large-diameter wooden rungs positioned between their ends. The rungs would be held between two parallel wooden discs, creating a lantern drum, mounted on the drive-shaft. Several of the boxes found

\textsuperscript{41} The samples were analysed by Ian Tyers of the University of Sheffield (ARCUS).
\textsuperscript{42} The water-boxes were made of the same raw materials and processed and worked in the same way as those from Sites 1 and 3.
FIG. 29a. Complete Type A water-box with linkage from Well 4; the narrow entry port can be seen in the upper-right-hand side of the box.

FIG. 29b. Drawing of complete water-box with linkage (Scale 1:8).
had wear on the corners of their bases (parallel to the wheel-shaft axis) which supports the notion of them being carried by registers between the boxes.

Although it is likely that the pairs of links would have connected directly to the water-box in front, it is conceivable that each box was separated by two pairs of straight links. Such a configuration would have increased the space between the containers and provided a mobile pivot point where the links joined one another, effectively creating a cranked link. Given the difficulties inherent in removing the clenched iron nail that fastened the linkage on the water-box as found, such a configuration would have some advantages in that it would have been easier to lengthen or shorten the chain if required.

Interestingly, the other complete water-boxes were noticeably smaller than the box described above and the linkage slots were much closer together (FIGS 30–32). These small but important differences in design clearly indicate that more than one bucket-chain had been used in the well, as it would have been impossible for water-boxes of different dimensions and linkage configurations to work as part of a single bucket-chain. Considering the unusual, rectangular
plan of the well, it is conceivable that the structure was specifically designed to accommodate two bucket-chains working simultaneously, possibly turning around a common axle.

**Disuse and abandonment**

Dating of the disuse of the well is problematic due to the partial excavation of the feature. A small quantity of Central Gaulish samian (A.D. 120–250) was found within the basal fill, of which less than 10 per cent was excavated. There was also some ceramic building material dated to A.D. 50–80 within this fill. The upper fills of the well, which only have an indirect stratigraphic relationship to the basal fill, contained Roman ceramic building material in fabrics dated to A.D. 50–80 and in some cases as later than A.D. 60, and some Highgate Wood ware ‘C’ sherds (A.D. 70–160) and Moselkeramik sherds (A.D. 200–275), although the latter material is probably intrusive. It seems likely therefore that the well had fallen out of use sometime between A.D. 120 and 160.
The secondary box-lined well

At some point following the abandonment of Well 4 and the systematic dismantling of its bucket-chain and well-house, a small, neatly-constructed, box-lined well was inserted into the north-east corner of the structure (FIG. 33). Five samples were taken of the lining for dendrochronological
dating, but none was dateable. Dating of the well from the recovered finds is also problematic as only a small part of the top of the well was excavated with the remainder preserved in situ below formation level. However, within the upper construction backfill seven sherds were recovered. These included a sherd from a Moselkeramik beaker, dating c. A.D. 200–275; this may be intrusive, but the presence of a Nene Valley beaker dated A.D. 150–400 and a Central Gaulish 7DR45 dated c. A.D. 150–250 suggests a late second-century construction date. A small amount of pottery retrieved from the upper disuse fill of the well is dated to between A.D. 150 and 250.

THE CHEAPSIDE BATHS (SITE 3)

The Cheapside baths at Site 3 was discovered on the Sun Life Assurance site immediately to the

FIG. 34. The Cheapside baths site in 1955.
That any meaningful record of the site’s archaeology was salvaged by Ivor Noël Hume almost single-handedly is nothing short of miraculous given that the archaeological levels were removed by drag-line excavator and unceremoniously dumped into the back of trucks (FIG. 34). It was during these works at the north-east corner of the bath-house complex that a massive two-tiered, plank-lined well (Well 5), interpreted as being the principal water source for the baths, was found. In similar fashion to the first-century well on Site 1 (Well 1), the more accessible upper section of the well lining had been dismantled in antiquity and the lower structure lay beneath a massive pond-like robbing cut filled with black silt — with the likely construction level of the well estimated to be at c. 11.0m OD.

The lining of the well measured 2.50m by 3.30m at its upper level, but narrowed to 2.40m square in its lower ‘stepped’ section; combined, the lining survived to a depth of 2m, with the base of the well estimated to have been at c. 7.25m OD. The most likely reason for the stepped profile to the lining is that it would have made the excavation of the well shaft simpler, as the upper section could be shored to stop the sides from collapse prior to work commencing on the offset lower section. The well was built of oak planks that were retained by a series of internal and external posts with horizontal diagonal cross-beams bracing the corners of the upper section of the structure (FIG. 35). The well was cut into the natural brickearth and gravels but did not

FIG. 35. Axonometric reconstruction of Well 5 from the Cheapside baths site.

Noël Hume 1956.
penetrate to the level of the London Clay and was recorded as having clay packed around the outside of the lining to help make the structure watertight, as was the case with the Arthur Street well.

The original site records show that it was not possible to excavate the whole of the well as the bulk of the fills were hauled out by the grab, although it was possible to recover a small number of objects from the bottom of the feature. Importantly, these included a ‘curious box-shaped wooden object whose purpose can only be conjectured’ and ‘a round-sectioned length of oak with two projecting lugs, one at either end. It is possible that this object had formed part of a winch’ (FIGS 36–37). Other finds from the basal fill included two jugs of late first- to early second-century date, with the well abandoned and backfilled no later than the mid-second century.

When a fuller report of the Cheapside baths was published in 1976, these curious wooden objects remained unidentified, and indeed it was remarked that: ‘No indications were found to suggest how the water was transferred from the tank to the baths, though amongst the finds was

![FIG. 36. Type A water-box <ER 356 B> found in 1955 in Well 5 at the Cheapside baths (Scale 1:8).](image-url)

![FIG. 37. Oak roller <ER 356 B> found in 1955 in Well 5 at the Cheapside baths (Scale 1:4).](image-url)

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44 The GM 37 excavation register indicates that the well structure was numbered [ER 356 A] with the finds from its lower fills, including the water-box and roller, assigned [ER 356 B].
what might have been the roller of a winch, and two complex box-like wooden constructions of uncertain use. An illustration of the more complete wooden box shows it to be identical to the Type A water-boxes from Sites 1 and 2 (Wells 1 and 4) and its retrospective identification in 2001 brought to an end a mystery that had lasted for 50 years (FIG. 36).

The wooden roller is an equally significant find from the well. Although the object is now worn and slightly shrunken, it shows clear signs of shaping and wear on two faces of the middle section set at about 90 degrees to each other (FIG. 37). On these flattened areas there is a zone of wear around 180–220mm wide. An explanation for this wear is that the object was a cross-bar from a lantern drum which carried the c. 180+mm-wide bucket-chain (as proposed for the Arthur Street well described above). The discovery of a cylindrical slatted drum of this general type in a massive rock-cut Roman well at Barzan in France which also had a bucket-chain operating in it is perhaps supporting evidence (see below).

Power calculations for the Cheapside baths’ well show that the bucket-chain could have been comfortably powered by a tread-wheel with one man climbing the wheel-face rather than walking nearer the top (FIGS 5 and 38). A tread-wheel diameter between 2.2m and 3.0m is thought to have been sufficient to provide the torque, with the man seeking the operating position on the wheel rim to balance comfort, duration, and the optimum operational speed to allow the boxes to empty efficiently.

Two other features recorded on the site by Noël Hume are potentially very significant and could indicate that there were other large unidentified wells capable of housing bucket-chains in the area to the north and west of the Cheapside baths. The first of these features was a large, timber-lined structure (ER 330) which was partly revealed by the mechanical excavator in the north-west corner of the site and was full of water. The edges of the structure were maintained by the use of heavy vertical posts which held the boards in place. Fragments of three coarseware jars recovered from the feature suggest a first-century date. It is likely that this substantial, plank-lined feature represents the remains of another large well, although it is interesting that the structure lies on the opposite side of Road 2 from the Cheapside baths and the other massive wells.

The other significant feature was the upper section of a large, partially-defined cut, measuring 22ft (6.70m) from rim to rim, filled with black soil turning to mud near the water level (ER 311); this was recorded in the section of a piling trench along the northern frontage of the site. Although this feature was interpreted as a ditch or pond, its size and profile is very similar to the pond-like robbing cuts that overlay the remains of Wells 1 and 5, raising the possibility that it too may have masked a robbed well. The dating of this feature is uncertain, although the uppermost level of the fill overlay the east side of a substantial Roman masonry wall foundation forming the south-eastern corner of a building.

Given the number of wells within the Cheapside baths insulae, it would be inconceivable that there would not have been a replacement for the short-lived Well 1 in the last quarter of the first century prior to Well 2 being constructed in the early second century; these ‘missing’ wells may have been located close to the baths. Although the archaeological record of the Cheapside baths is far from complete, it is interesting that there was no evidence to suggest that the baths had been destroyed in the Hadrianic fire of A.D. 120–130, which could suggest that the bath-house complex was sufficiently removed from surrounding buildings to have survived intact.

45 Marsden 1976, 40, fig. 26.
46 Coadic and Bouet 2005, 38.
47 The boards are recorded in the GM 37 site notebook as measuring 1'x 9"x 1".
48 The dating evidence for both the construction and the abandonment of the Cheapside bath-house is very limited. It appears that the baths were probably constructed during the late first century, and went of use during the later second or third century (Marsden 1976, 34–8).
Soon after the completion of the excavations on Site 1, the Museum of London decided to build a full-scale replica of the unique Type B water-lifting machine that had existed in the early second-century A.D. well. The Museum wanted the replica to be a public demonstration of

49 Blair and Hall 2003; Blair and Swift 2003, 6; Blair et al. 2005.
Roman technology and to allow visitors, including families and children, to power the machine. The process of the reconstruction was filmed for a Time Team Special ‘Hadrian’s Well’ which was aired in April 2003, and was a follow up to the 2002 Time Team Special ‘Londinium: Edge of Empire’ which followed the year-long excavation on Gresham Street and focused on the discovery and excavation of the massive wells and their bucket-chains.

When the theoretical reconstruction began, the first and most important problem to solve was how the water was transferred from the ascending wooden buckets to the trough taking the water away from the machine. No remains were found of the machinery that carried and drove the bucket-chain above the well.

In the Type A bucket-chains, which were made up of hollow boxes carved out of solid oak blocks covered with a lid, the water was admitted and discharged via a port in the side of the box (FIG. 29). Technical analysis has shown that these hollow boxes, joined together with straight iron links, were probably carried and driven by an octagonal, faceted wheel. Clearly these could discharge sideways straight into the take-away trough; they were very similar in function to the compartmented rims of Roman drainage wheels.50

With the Type B bucket-chain, the first method of water transfer that the engineers discounted was for the water to be emptied forward from the buckets and collected by a trough immediately in front of the wheel carrying the chain. Simple experimentation proved that this was unworkable. An alternative arrangement, whereby the boxes emptied over the descending chain passing through a collection tray, was inefficient due to the large water-loss involved. An alternative method, considered but also rejected, was that the bucket-chain could be carried by an ‘open cage’ wheel, where the chain is supported by cantilevered arms and the water is collected in a trough in the ‘hollow’ side of the wheel. Although this design was used in recent centuries and can still be found in parts of North Africa and the Middle East, for example, it was considered to be most unlikely to have existed at this site because of the great weight of the bucket-chain and the water raised.

The engineers realised that the bucket-chain required a two-stage transfer, whereby the water is first discharged from the bucket into a compartment and second discharged from the compartment through a port into the take-away trough positioned alongside the wheel.

Using mechanical and hydraulic theory, a number of options were developed for the size of the driving wheel and the way in which the water could be transferred. Theoretically, as the wheel was made larger, the transfer period become larger, enabling the delivery rate of the machine to be increased. However, more power was required and the increased internal stresses required a stronger mechanism. The engineers determined that the Type A water-boxes in the earlier first-century well probably delivered approximately 0.75 litres per second. Furthermore, two different designs of boxes were found which suggested the probable existence of two bucket-chains operating simultaneously. Noting that the later well, which was built 30 years after the adjoining well was abandoned, had more than twice the water capacity and bucket capacity per unit length of chain, the engineers considered it prudent to adopt a provisional target of 2 litres per second for the replica machine. There also remains the unresolved question as to what output of water the well structure could sustain over a long period. Provisional calculations suggested that the adopted provisional target output was realistic.

Although the Type A bucket-chain was very probably carried and driven by a faceted wheel, the engineers believe that the open buckets of the Type B bucket-chain were not engaging with a faceted wheel. In the absence of a faceted wheel, it is believed that a positive drive could have been obtained by using ‘registers’ that would have engaged with the underside of the cranked links (FIG. 21). This aspect of the design was much debated, because the angle of the cranked chain links showed no evidence of wear underneath. This meant that the ‘registers’ that engaged

50 Stein 2004 and ongoing research by Robert Spain.
them and drove the wheel around could not have been made of iron, and it was decided that these would have to be made of hardwood and with a sacrificial bearing surface.

At the commencement of the project alternative methods of powering the machine were considered and sketch drawings were produced of possible arrangements. The first option was a tread-wheel mounted on the wheel-shaft that would allow one or more men walking on the rim to power the machine. The second option was for the machine to be driven by a capstan using animal or human power driving through two gears. In the final design a capstan-and-gear drive was adopted because the alternative use of animal power could not be discounted and it provided a demonstration of the early use of gearing.

A considerable amount of theoretical design work was devoted to exploring the design of the two-stage transfer; this work mainly concentrated on the number of registers, that is the diameter of the wheel engaging the bucket-chain. Designs varied considerably, ranging from a 5-register wheel, the smallest possible arrangement, to a much larger 12-register wheel. It was essential that the two-stage water transfer work efficiently, and this required development work on the collection compartment, and the transfer port design. The engineers realised that the programme of replication would need to include experimentation with a prototype wheel, which would help to decide the final design. The engineering design aimed to determine a workable machine arrangement demonstrating the principle utilising a prototype wheel at the lower end of the range. However, as the reconstruction was also intended for public demonstration a tread-wheel drive was not preferred on Health and Safety grounds.

With preliminary designs of the machine and support frames finalised and a specification and drawings produced, tenders were invited. A contractor was appointed and the works commenced in August 2002. Initially a 7-register wheel was built and the design of the water compartments and transfer ports were developed at the builder’s site. Numerous trials helped to determine the most efficient shape and speed for the two-stage transfer and this led to the adoption of an 8-register wheel that gave a more efficient transfer and easier construction.

Very little is known about the design of gearing that the Romans used in their water-mills and other machines. The experiments showed that the two gears needed to be 1 to 1 and therefore approximately the same diameter. One of the gears was provided with one cog more than the other gear to ensure an extended cyclical wear pattern of cog engagement. The 55mm diameter of the cogs was determined by the torque to be transferred, and their shape and pitch was developed from full-scale prototypes that ensured a smooth engagement and disengagement. With a gear diameter close to 1m and 1:1 ratio it was considered inappropriate to have a lantern gear and a contrate (teeth perpendicular to gear face) gear form was chosen with a simple design of cog, circular in section, driven tight into the body onto a shoulder, with the ends split and wedged (FIG. 39).

The machine was framed and supported to provide a delivery head approximately 3m above ground, although, as has been previously noted, the original machine would have delivered water at a higher level. This reduced level worked well with the overhead horizontal shaft and gearing. In the replica machine the water level is 1m below platform level, but in the original well it is believed that the water level varied, and in dry periods could have been up to 3m or more below ground level. More power would therefore have been required than is needed to drive the replica machine.

Preliminary tests have shown that an output of 2 litres per second (l/s) can be achieved at a capstan speed of 2.72 revolutions per minute (RPM). At higher speeds the water-loss due to splashing and less efficient transfer increased disproportionately and at 6 RPM it is estimated the net output is 3.7 litres per second. Torque measurements showed that at the lower speed of 2.72

51 Spain and Taylor 2002.
RPM the power necessary to maintain constant speed was approximately 0.16 horse power rising to 0.35 HP at 6 RPM. Assuming that the original machine had a lift twice that of the replica, these power requirements would double. Using a figure of 0.1 HP per man, this indicates that several men would have been used to work the original machine. However, it is just as likely that it was powered by two animals, probably donkeys or mules with a walking circle somewhat larger than used in the replica.

Working the machine shows that there is an optimum speed of operation: too fast and the trough fails to collect all of the water in the transfer compartment, while if the operators walk too slowly, the transfer potential is under-used. In the replica machine the water is purposely diverted from the collection trough and recycled down into the well within a transparent conduit so that operators can see the products of their labour (FIG. 40). In the original machine the water would possibly have been distributed to other parts of Londinium using wooden or stone troughs or conduits, or even lead pipes, at levels that maintained a head of delivery (see below).

THE EVOLUTION OF THE LONDINIUM BUCKET-CHAINS AND WELLS

We have already recognised the substantial differences between the early second-century Type

52 Spain and Taylor 2003.
open-box buckets of Well 2 and the Type A water-boxes with side ports from the other three wells. The volume of the water-boxes in relation to their port size suggests a relatively low chain velocity, unlike the open buckets with the potential of much quicker emptying and thereby higher chain velocities. The bucket type of container held approximately three times as much as the box type, which meant that the bucket-chain had twice the capacity of the box type per metre length of chain. Moreover, the east well (Well 2) had exactly double the capacity of the nearby west well (Well 1), and its screen area (submerged wall area which is a major influence on inflow rate) was 46 per cent more. To achieve a greater output from the later machine, the designers increased all of the major determinants affecting throughput of the machine. Screen area, bucket volume, chain velocity, and power input were all increased. The comparison between the box- and the bucket-chain machines provides a dramatic illustration of change in both the technology and its scale.

If an increase in volume had been provided by a larger side-port box, its dimensions and weight would have been greatly increased, raising the question of its strength and durability. The design of the boxes, having thin lids and bases much thicker than the walls, shows that the base acted as a wood link in tension between the connecting link-pins. It also explains why the link-pins were not on the axis of the boxes, but noticeably closer to the base of the box, nearer to the wheel-shaft. The weakness in this design is where the link-pins pass through the box ends, where mortices exist for the iron connecting-rods.

This line of exploration of making the boxes larger becomes increasingly problematic, such as to suggest that the builders may have approached or exceeded the limits of strength and

FIG 40. The finished full-size reconstruction of the second-century water-lifting machine being demonstrated outside the Museum of London in 2003.
durability of this wood-link design. If this was the case, their solution was surely initially to install duplicate machines within larger wells. The evidence that we have identified above of variations in alternative machine design, involving box lengths and port orientation, suggests that more than one machine operated simultaneously in some of these larger wells.

We can estimate that the box-chain machines had an output of approximately 0.25–0.4l/s. The output of the bucket-chain machine was considerably higher as its design suggests, and the full-scale reconstructed machine showed that a minimum delivery of 2.0l/s could be comfortably achieved and greater outputs at higher speeds with more power applied. This evolution in water-lifting technology, moving from tread-wheel-powered box-chains with side-ports to bucket-chains using capstan and gears, appears to have occurred in Londinium in the early second century A.D. But we should admit that our evidence is very limited and that it is quite likely that earlier, less efficient, but simpler-to-construct machines probably co-existed with the larger-scale improved machines utilising the best in metal-working techniques. In due course these chain water-lifting machines were superseded by wood-block force-pumps; the latter evolved from the earlier bronze force-pumps, and appeared in the Western provinces after the first century A.D.

CONCLUSIONS

Although the subject of water supply, distribution, and drainage is critical to our understanding of how Roman London evolved, it remains a relatively under-researched area that requires a comprehensive review. The topic was most recently summarised in 2003, but there is a wealth of material in the archaeological archive which could greatly expand this study. The unforeseen discovery of the wells and their bucket-chains in 2001 opened up an unexplored avenue of research and has forced archaeologists and historians to reassess the means by which water was collected and distributed within the Roman city in the first and second centuries A.D.

The absence of any clear archaeological evidence for an extra-mural aqueduct bringing water into Londinium has long suggested that the water requirements for the city were met by local sources such as wells and spring-lines. Nevertheless, prior to the 2001 discovery of the Gresham Street and Arthur Street wells and their elaborate water-lifting machines we had an incomplete and simplistic view of the elements that made up the water supply within the city — namely that water could be tapped from streams or springs, drawn from small wells, and one assumes, to a lesser extent, rain-water could be collected in tanks or butts from run-off from roofs.

There is no doubt that the hydrology of the city would have been carefully studied and mapped out at an early period, probably by the simple expedient of monitoring the excavation of the earliest wells. By comparing findings from a number of well headings, it would have been possible to determine the relative level of the water table in different parts of the city, and consequently highlight sites where it was advantageous to dig wells. It is evident that the area of 30 Gresham Street and the Cheapside baths had been chosen as especially suited for well-digging by virtue of its ample subterranean water reserves. The succession of massive wells and their associated water-lifting machines clearly demonstrates that there was a continuing tradition for large-scale water extraction on these sites.

It is clear that bucket-chains operating in necessarily massive wells were capable of lifting huge amounts of water, as has been demonstrated with the Type B device from Well 2 on 30 Gresham Street, and as such these devices clearly represent a key element in supplying water in the Roman city during the first and second centuries A.D. Although three of the four wells

53 Williams 2003.
54 Rowsome 1999.
that contained bucket-chains at 30 Gresham Street and 12 Arthur Street were discovered within a few months of one another in 2001, it is significant that the other similarly-sized well at the Cheapside baths site had been found 50 years ago, and that no comparable structures have been found in over a century despite intensive redevelopment and archaeological excavation across the city. This would suggest that only a small number of these massive well structures were ever built, and that these are likely to have been located in key areas of the Roman city.

The relatively high elevation at 30 Gresham Street and Cheapside would have meant that a simple gravity-fed system of gently sloping, elevated channels would have been capable of carrying water over reasonably large distances if required. By contrast, the lower elevation at 12 Arthur Street suggests that the water lifted from Well 4 would have been used locally to supply buildings and perhaps even to provision ships leaving the port. Another potentially large water-user is the possible bath-house or public building located on the adjoining terrace immediately to the north (see above).

A significant feature of the bucket-chains is that their drive-systems, whether powered by a tread-wheel or a capstan using overhead gearing, were designed to lift water to a height several metres above the ground. It would be inconceivable that this ‘head’ of water was not utilised by the bucket-chain discharging directly into high-level, elevated wooden or stone-lined channels, so that it could be distributed to surrounding areas of the city — much in the way that the water tanks in the Cheapside baths are thought to have been supplied (see Figs 5 and 38). This opens up the possibility that the wells and bucket-chains formed the start of an intra-mural water distribution system capable of feeding distribution tanks, or castella, at strategic points around the city.

Although it is clear that bucket-chains were in use in Londinium from an early date, as evidenced from Well 1 which was constructed in A.D. 63, it is likely that their importance increased by the late first century. By this date the Walbrook stream, perhaps the largest source of fresh water in the city, had been polluted by industrial activity along its banks and by surface run-off. There is no archaeological evidence of massive wells or bucket-chains later than the mid-second century, suggesting that they too were replaced by another means of supply. The later Roman period may have placed a greater reliance on smaller, box-lined wells which appear to have become more numerous and commonplace throughout the city and could have served the smaller population of the third and fourth centuries.\footnote{A large number of these wells appear to be of second- to third-century date, but much could be learnt about their collective significance by undertaking a study of the location and dating of these structures.}

Whilst it is conceivable that wood-block force-pumps may have been the natural successor to bucket-chains as a means of lifting large amounts of water from wells in the second century, no evidence has ever been found of these devices in London, and indeed only two examples have been found in Roman Britain.\footnote{Both were found in wells in southern England: at Silchester in 1895 and Tarrant Hinton in Dorset in 1983.} The absence of even small parts of these pumps or evidence of their housings is somewhat surprising given the ideal anaerobic conditions that exist for the preservation of wood and organic materials in the waterlogged lower levels of wells, and it is possible that they may not have played a significant role in Londinium’s water supply.\footnote{Stein 2004, 223–4.}

Bucket-chains or pot-garlands evolved in the Classical world as a means of lifting water from wells where the depth of the water source precluded the use of larger water-wheels, or norias, which collected water in compartments around their rims as the wheel was turned through the water. Although norias were capable of raising large volumes of water, their enormous size meant that an equally large pit had to be built to house the wheel and this would only be a viable option when the source of the water lay close to the surface. Although bucket-chains were used
as a means of lifting water from wells or cisterns throughout the Roman world, there is a notable
dearth of the remains of these devices found on archaeological sites.\textsuperscript{58}

Prior to the discovery of the bucket-chains at 30 Gresham Street and 12 Arthur Street, the only
place to have yielded evidence of a bucket-chain was the Cosa Spring House, 100km north-west
of Rome.\textsuperscript{59} The various phases of the Spring House, which was originally built early in the first
century B.C. and existed for c. 250 years, all incorporated bucket-chain systems to lift water from
a ground-level spring to a cistern located at a high level.

The remains recovered include one complete but crushed pine box-bucket and fragments of six
other buckets, all of which had been damaged in a fire that had destroyed the last bucket-chain
to have lifted water in the Spring House (\textit{FIG. 41}).\textsuperscript{60} From the evidence found the archaeologists
determined that spring water was lifted up to 13m by a chain of c. 24 wooden buckets suspended
on a pair of ropes carried by a vertical bucket-chain wheel. This wheel, which probably had

\textsuperscript{58} Blair \textit{et al.} 2005.
\textsuperscript{59} Olesen 1987; McCann 2002.
\textsuperscript{60} McCann 2002, 42.
7 or 8 registers, may have used troughs on the perimeter to funnel or re-direct the water to a collecting trough beside the wheel, in other words a two-stage transfer similar to the Type B bucket-chain from Site 1 (see above). This machine was driven from a capstan via two gears and an elevated horizontal shaft.\textsuperscript{61}

The water lifted by this bucket-chain was channelled from the collecting tank via an aqueduct leading across the lagoon to the harbour area. This device was destroyed at the end of the first century B.C. Sometime during the second half of the first century A.D. the structure was altered so that a new bucket-chain could elevate water high enough to flow west along a newly-constructed aqueduct into a cistern. This system, which probably supplied water to a nearby villa, fell out of use before the end of the second century A.D.\textsuperscript{62}

Coincidentally, at the same time that the bucket-chains were being excavated in London, an excavation by Bordeaux University in a 16m-deep rock-cut well in the Roman thermal baths at Barzan (Charente Maritime, France) had recovered the well-preserved waterlogged remains of parts of the drive system and possible gearing of a bucket-chain, although no parts of the actual suspended bucket-chain were found. It is clear, however, that, like the Cosa device, the bucket-chain would have been linked together with rope with no iron linkage being used.\textsuperscript{63}

The well-preserved woodwork is unparalleled at either Cosa or London and significantly included a slatted cog wheel or lantern drum, which was originally mounted horizontally on a square drive-shaft with rounded axle ends. The lantern drum was a compact structure with an internal width of only c. 0.57m, around which the bucket-chain would have been drawn whilst engaging with or gaining traction with the open radial slats. Although the bath-house complex at Barzan was built at the start of the second century A.D., dendrochronological dating of the lantern drum (A.D. 149–166) indicates that the bucket-chain is likely to be associated with a later phase of rebuilding in the bath-house.

It was surmised that the absence of surviving wood or perhaps even leather buckets from the bucket-chain in the ideal waterlogged conditions at the bottom of the well suggests that the water containers were made of metal and were possibly similar to the ‘bronze buckets’ described by Vitruvius (see above).\textsuperscript{64} Such a system seems to be overly elaborate and would have been expensive to make and potentially more difficult to work. It seems likely therefore that the water containers would have been made of wood and of similar ‘open-topped’ form to the wooden box-buckets of the Cosa and London bucket-chains which were also in operation during the second century A.D.

It is likely that at the end of the functioning life of the well the entire bucket-chain would have been dismantled so that it could be reused elsewhere, and consequently the absence of these portable elements is perhaps understandable. The only reason that any evidence survived of the box-buckets in London and the Cosa Spring House is that both bucket-chains had been badly damaged in fires that destroyed the well-house buildings. It was only the damaged elements that had not been salvaged and were discarded.

Viewed collectively, one of the most interesting aspects of the bucket-chains and their drive systems that have been found to date in England, France, and Italy is their diversity; it is clear that we are looking at contrasting water-lifting machines which would have required completely different bucket-chains and drive configurations for them to have worked.\textsuperscript{65} The remains of the two distinct forms of bucket-chains from London are unique in Roman Britain, but also represent the largest and best-preserved group of these devices yet to have been found from

\textsuperscript{61} Oleson 1987, 121.
\textsuperscript{62} Oleson 1987, 121.
\textsuperscript{63} Coadic and Bouet 2005, 41–2.
\textsuperscript{64} Coadic and Bouet 2005, 43.
\textsuperscript{65} Blair et al. 2005, 110; Oleson 1984.
the Roman Empire as a whole. The analysis of these bucket-chains has opened a window on the earliest evidence for mechanical engineering in Britain and has shown Roman mechanical engineering as a distinctive and highly-specialised branch of woodworking, with its own set of tools and techniques intimately combining oak and iron.

The engineering woodwork stands out as quite distinct from the civil engineering ‘carpentry’ used in constructing the massive well structures (Wells 1 and 2), the timber framing of Wells 3 and 4, and the cooperage work exemplified in the half barrel used in the western well (Well 1). The use of oak timber converted by radial splitting, followed by trimming with axes, and finishing with planes to precise sizes and trueness, shows the quite deliberate selection of the most stable, readily available material for the water-boxes and box-buckets of the bucket-chains.

These examples of some of the best technology that the Romans possessed would probably not have survived in many comparable-sized wells in the hotter and drier regions of the Empire. The wet conditions that were prevalent in Londinium provided the perfect anaerobic, waterlogged environment to preserve the wells and parts of their bucket-chains intact. Without these conditions, we could only guess at the technological brilliance that the Romans showed in solving the problem of how to lift large volumes of water from deep wells at the edges of their world.

APPENDIX. SUPPLEMENTARY TECHNICAL INFORMATION

The well structures

<table>
<thead>
<tr>
<th>Site</th>
<th>Dimensions of well</th>
<th>Depth</th>
<th>Bucket-chain</th>
<th>Date of structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 (Well 1)</td>
<td>2.60m x 2.60m</td>
<td>4.50m</td>
<td>Type A</td>
<td>c. A.D. 63</td>
</tr>
<tr>
<td>Site 1 (Well 2)</td>
<td>3.60m x 3.60m</td>
<td>5.00m</td>
<td>Type B</td>
<td>c. A.D. 108</td>
</tr>
<tr>
<td>Site 1 (Well 3)</td>
<td>2.60m x 2.80m</td>
<td>1.80m (truncated)</td>
<td>(none found)</td>
<td>c. A.D. 104?</td>
</tr>
<tr>
<td>Site 2 (Well 4)</td>
<td>5.85m x 2.50m</td>
<td>2.00m (truncated)</td>
<td>Type A</td>
<td>late 1st century</td>
</tr>
<tr>
<td>Site 3 (Well 5)</td>
<td>stepped profile :</td>
<td>2.00m (truncated)</td>
<td>Type A</td>
<td>c. A.D. 61–97</td>
</tr>
<tr>
<td></td>
<td>top 2.80m x 3.70m</td>
<td></td>
<td></td>
<td>early 2nd century?</td>
</tr>
<tr>
<td></td>
<td>base 2.80m x 2.80m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dimensions of Type A bucket-chain elements

<table>
<thead>
<tr>
<th>Site</th>
<th>Bucket-chain</th>
<th>Water boxes</th>
<th>Straight connecting-links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 (Well 1)</td>
<td>Type A</td>
<td>c. 390mm x 152mm x 105mm-125mm</td>
<td>(not found)</td>
</tr>
<tr>
<td>Site 2 (Well 4)</td>
<td>Type A</td>
<td>c. 385mm x 180mm x 102mm-110mm</td>
<td>c. 170mm x 20mm x 10mm</td>
</tr>
<tr>
<td>Site 2 (Well 4)</td>
<td>Type A</td>
<td>c. 355mm x 145mm x 100mm</td>
<td>(not found)</td>
</tr>
<tr>
<td>Site 3 (Well 5)</td>
<td>Type A</td>
<td>c. 390mm x 170mm x 105mm-120mm</td>
<td>(not found)</td>
</tr>
</tbody>
</table>
WELLS AND BUCKET-CHAINS: ELEMENTS OF WATER SUPPLY IN EARLY ROMAN LONDON

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The author (I.B.) would like to acknowledge the contributions of the following people who have been closely involved in the project from the outset and whose work has been integrated within this article: Dan Swift senior archaeologist on the Arthur Street site, Robert Spain and Tony Taylor for detailing the engineering aspects of the bucket-chains and the reconstruction project, Damian Goodburn for his summary on the ancient woodwork, and finally Ivor Noël Hume who kindly wrote the foreword to this article and whose pioneering work as an archaeologist for the Guildhall Museum in the post-War years formed the foundation for modern archaeological excavation in the City of London.

The drawings are by Sophie Lamb and Faith Vardy of the MoLAS drawing office, with the reconstruction figures (FIGS 5, 21 and 38) the work of Robert Spain. The photographs are by Maggie Cox and Andy Chopping of MoLAS with the exception of (FIG. 41) which was kindly provided by J.P. Oleson.

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Dimensions of Type B bucket-chain elements

<table>
<thead>
<tr>
<th>Site</th>
<th>Bucket-chain</th>
<th>Box-buckets</th>
<th>Straight links on box sides</th>
<th>Cranked connecting-links</th>
<th>Linkage pins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 (Well 2)</td>
<td>Type B</td>
<td>c. 400mm x 170mm x 170mm (reconstructed)</td>
<td>c. 315mm x 30mm x 5mm-9mm</td>
<td>c. 275mm x 23mm-28mm x 13mm-16mm</td>
<td>c. 265mm x 23-24mm</td>
</tr>
</tbody>
</table>
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