ROMAN WATER-POWER

A New Look at Old Problems

by

Robert James Spain, C.Eng., M.I.Mech.E.

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Imperial College of Science and Technology
London SW7

BIBL
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ABSTRACT

This thesis explores a fresh approach to the subject of Roman watermills by re-examination of the archaeological evidence using hydromechanical theory to provide retrospective analysis of the more complete specimens of Roman watermills. Different types of waterwheel are examined facilitating a better understanding of their behaviour and performance. From this work comes the concept of a developmental sequence relating to acceleration of the headrace in conjunction with smaller faster wheels. An evolutionary model is proposed which embraces both vertical and horizontal waterwheels.

Part of the thesis describes the making and operation of a millstone rig, an experimental approach considered necessary to determine a coefficient for grinding friction used in the mechanical analysis. This work has prompted a discussion of the advantages and problems of replication and modelling.

The intensity of the Romano-British archaeological evidence is the basis for a fresh view of the typology and settlement patterns of military watermills.

The author has supported this examination of Roman watermills by visiting and surveying the Athenian Agora, Baths of Caracalla and Barbegal sites. This has facilitated a better understanding of their building, layouts and operation, which in the case of Barbegal has been made the subject of a special study within the thesis.

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Chapter One

INTRODUCTION

It may seem strange and puzzling to admit that one of the objectives of this study, a resolution of the origins of water-power, is beyond reach and impossible to give definition to. The nature and incidence of the evidence cannot provide, currently or in the foreseeable future, either a comprehensive or a confident view of evolution or origins. Water-power is an area of ancient history whose study progresses more by speculation and hypothesis than substantiality and confidence. How can it be otherwise when we have hydro-mechanical knowledge of no more than ten Roman watermills in the whole of the Empire, a small fraction of what surely existed? To pretend that such a pitifully small and rudimentary corpus will provide historians with anything more than a high level of ignorance, or more than a flash of enlightenment, is foolish. But this is not to say that we cannot advance, as the following chapters will attempt to show. Adopting different strategies of approach, may not allow us to reach as far as we would wish, but they may well offer us some views of our objectives.

There are many areas of history, especially ancient and medieval, where advancement relies upon archaeological discovery and interpretation, where the formative years of speculation and synthesis depend so often on fragmentary and disparate evidence. In this respect the study of water-power is little different from other emerging histories. How then might we proceed?

The evolution of any artefact can only be approached from two directions, either in chronological order looking forward or, moving backwards in hindsight springing from a knowledge of subsequent developments. In the ancient history of technology, earlier periods are unable to provide much more than archaeological evidence, so that our knowledge is heavily dependent on earth-born advances. Moreover, the earlier the period, the more scant the evidence, so that moving back in time to take a view becomes increasingly difficult. It follows that the most promising way to shed light on the evolution of water-

power is to gain a knowledge of subsequent developments and take a retrospective view towards an earlier period. This has been the approach used in this thesis when considering evolution.

For some thirty years the author directed his interests in the history of water-power to the county of Kent, undertaking intensive studies of how, where and when it was applied to rural industries during the last few centuries. Initially entire river systems were studied by using all known archival and archaeological sources, site surveys of extant buildings and machinery, and oral traditions of owners and operators. Later much wider areas were embraced because of the obvious need to record the disappearing site evidence and the memory of man. Interspersed in this work was the occasional private commission where the author acted as a consultant providing advice on hyrdrological studies, water-power generation for electrical supplies, the feasibility of recommissioning abandoned watermills and overseeing the work of local industrial archaeology groups refurbishing old watermills.
All of this work provided a rich experience and understanding of water-power generation, its technology and application.

As the years passed, the author found that he was inexorably drawn to earlier periods of history, a journey that so many students make, attracted probably by a thirst for knowledge, and perhaps the opportunity to experience the pleasure of discovery and contributing to history. First the medieval period with its tantalising glimpse of water-power afforded by the domesday survey, with its thousands of mills but archaeologically sterile - dark ages indeed. And so the author came to the Roman period.

There is a view amongst historians that the Romans knew of the watermill, but that it was not widely used for a variety of reasons, part of the orthodox view of technological stagnation for the Roman period. Recently this view has been challenged as increasing archaeological evidence has suggested that water-mills were more used and widespread than was hitherto imagined.

Parts of this thesis, where it proposes a greater incidence of military water-mills and later, with the hypothesis that technological evolution had occurred, contributes to a re-appraisal of this conventional view.

In the 1970's, two developments occurred which provided major contributions to the existing corpus of evidence and had considerable influence on the author's interest and direction in the study of ancient water-power. First, the long overdue publication of the Haltwhistle Roman watermill appeared. With the help of Grace Simpson, the author was able to obtain, prior to publication, information from original archaeological field notes and photographs to undertake a full hydro-mechanical analysis of the Haltwhistle mill. This was the first, and perhaps the most illuminating, analysis of an ancient watermill undertaken by the author.
Following on this work came the discovery of the unique Ickham watermills, near Canterbury, where the author found himself in the enviable position of having exclusivity of interpretation of the evidence of the older mill, and holding the initiative on publication.

Both works showed that retrospective analysis was a potent and fruitful tool for the study of ancient water-power. With the completion of the Haltwhistle and Ickham studies came the author's realisation that it was possible to transpose his modern experience and knowledge to the Roman period, and learn more about the performance and behaviour of a machine which archaeology, by itself, could not provide.
Here then was a way forward, a new approach for the historian of technology to examine the limited evidence which was but slowly appearing. Inspired by these developments, the author sought academic support and direction to bring his energies and vision to fruition.

Chapter three discusses the theory of hydro-mechanical analysis of watermills, identifying the different types of analyses and giving examples of the different equation sequences as illustrated by their application to the more complete Roman watermill sites.

During the development of the hydro-mechanical analysis on the Haltwhistle evidence, the author realised that the resulting balance of power, expressed in terms of speed and gear ratios, was greatly affected by the coefficient of grinding for the millstones. In these early analyses the author was obliged to use a coefficient of grinding which he determined by using fragments of lava stones in non-rotary tests. He therefore intended that part of his studies should be devoted to an experiment using full-scale Roman-style lava millstones to establish a more reliable coefficient of grinding. Thus the Westree millstone rig was conceived, named after the annexe of the College where the work of construction and operation was done. The design, construction and operation of the millstone rig, and the results of the grinding tests, are given in chapter four.

The making of the millstone rig naturally raised questions concerning the validity, advantages and problems, of using replication and modelling. These are discussed at length in chapter two together with the concepts and principles of static and dynamic analyses.

For some time prior to embarking on this study, the author, realising the difficulties which archaeologists have in recognising watermill remains, especially the fragmented and depleted sites so typical of the Romano-British landscape, undertook searches amongst the major archaeological publications for further evidence of unknown watermill sites. The discovery of several possible sites and involvement with active sites and their interpretation, led to recognition of the need for criteria of assessment, and the determinants of probability as expressed by the component evidence. The Britannia evidence is an ideal test-bed for such a study, because the sustained intensity of archaeological work offers a very wide range of material reflecting all the variations of provenancing, dating and the fragmented evidence of buildings, watercourses, millstones and quernstones.
This work provides a useful introduction to chapter five which is devoted to the watermills of Britannia.

Hadrian's Wall has provided us with more evidence of water-power than any other Roman frontier, including the Domitianic and Antonine *limes* of South West Germany where sustained archaeological attention has apparently failed to produce any evidence of Roman water-power. The author has examined the Britannia evidence, first by exploring its relationship with the landscape and human settlement patterns. This is developed and brought into focus in the military context, with the theory of watermills being annexed to frontier forts.

In direct contrast, the Continental evidence, with its better preserved, disparate and outstanding specimens, has been approached in a quite different manner.
As part of the thesis preparation the author visited the three major watermill sites of the Agora, Baths of Caracalla and Barbegal, to survey, observe and obtain a better understanding and appreciation of their construction, environs and their builders problems and achievements.

At the Baths of Caracalla the author undertook a detailed site survey of the wheel and gearing emplacements and waterways to facilitate a hydro-mechanical analysis. This work also supported an examination of the development and phasing of the watermills in the underground chamber.

During 1988, the author visited Barbegal and undertook a detailed survey of all the remaining accessible water-wheel and gear-pit chambers, together with waterways, which provided the basis for a hydro-mechanical analysis. Additional site observations, supplemented by Benoit's site drawings has facilitated a discussion of the sites development, building design and sequence including the aqueducts. The origins of Barbegal, who built it and for what purpose, provided the objectives of a stimulating debate which attempts to bring fresh light on these long-standing problems, but we cannot avoid the impossibility of providing definitive answers to many of the questions. Barbegal, as the largest known water-power milling establishment of

the ancient world, remains a delightful enigma, worthy of far more attention than can be given within this thesis. The author has devoted chapter six to Barbegal.

It was decided that the Continental sites of Agora, Baths of Caracalla, Lösnich and Venafro could be the subject of a single chapter within this work. Hydro-mechanical analysis has identified the advantages of accelerating the headrace, a feature which is common to all the major Continental sites. This provided a satisfactory basis of approach for their discussion which is contained in chapter seven.

This thesis can be seen as comprising several different views of the wide-ranging subject of ancient water-power. Some of these views are determined by the evidence and are an examination of exemplars or a wider body of evidence having common features or geographic origins. Other views relate to the methodology of analysing and treatment of the evidence. These different images are brought into focus when the subject of evolution is discussed in chapter eight.
A development sequence for the waterwheel is proposed as evolution which related to maintaining or increasing a level of power generation, sufficient for milling according to the prevailing tradition, by increasing prime mover speed, improving the waterwheel design and reducing the size and mass of the mechanical components of generation and transmission. In other words an engine which was sequentially developed, through vertical and horizontal forms, to become faster and smaller.

Chapter Two

DYNAMIC ANALYSIS AND REPLICATION

The historian of technology is fortunate in being able to use methods of analysis of which his fellow historians do not have the advantage. Both replication and theoretical analysis provide information which cannot be found by alternative methods of enquiry. The study of watermills lends itself very well to this analysis technique and it is the object of this chapter to identify the advantages and problems of such methods. The exploration of theoretical analysis and modelling of artefacts is considered to be a valid part of this study and by way of an introduction to the subject, diverse examples are provided as illustrations.

A. Static and Functional Analyses of Artefacts.

When an artefact of any kind, technological or not, which has been abandoned by man, is to be examined and studied with a view to determining its original design characteristics, function and performance, the analysis might be described as either static or functional.
The description of an artefact can be given in terms of colour, shape and form, materials, state of decay and so on, and expressed in dimensions and other quantitative factors including the usual physical terms such as density, hardness, weight, and texture. This description, or specification, is of an artefact in an inoperative state. This is static analysis.
Natural decay in one form or another affects all bodies and matter and occurs with the passage of time. Artefacts additionally suffer from human influence which combines with natural decay to cause changes of state to occur. For those in which motion is a feature of their function, wear accelerates their change of state. This metamorphosis begins the moment an artefact is created and continues until its destruction occurs. Thus a static analysis is valid only for the moment the description was made; before or after that moment the artefact was different.[1]

A static analysis provides no information, beyond mere speculation, as to how an artefact functioned, or what was the mode of action by which it fulfilled its purpose, or how it performed in terms of utility and efficiency.

The knowledge which can be gained by the functional analysis of an artefact, additional to that provided by static analysis, may not always be evident. For instance, an earthenware vase, which might at first be considered as lifeless and unchanging, can be examined by its performance, together with the physical and aesthetic functions which occur during its life. The following questions could form the basis of a functional analysis.

First we might consider aesthetic and other functions of the vase when it is at rest: for example, is it pleasing in colour and shape, nice to handle, porous and needing frequent replenishment? Does it blend with its surroundings, have the capacity for different arrangements throughout the seasons? What effect does its shape have on flower arrangement? Does it leak?

Secondly there are enquiries related to the movement of the vase such as: is it too heavy, is it prone to chipping and scratching, is it easy to hold when filling and moving, can it be easily cleaned inside, is the base scratchy or smooth, can it be topped up easily when full of flowers, does it pour without spillage, does its porosity provide humidification? These are all potentially valid questions related to moving functions.

Finally we should ask how it decays through time and question its durability. Does it lose colour or become stained? Is the incised or impressed maker's mark on the base wearing away? How does it look and function after 50 or 150 years of use and neglect?

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1. It follows that when analysing an artefact that has been abandoned by man, the student of history must limit his examination to its working state and performance during use; he must ignore all changes that occurred afterwards. The artefact may have had other functions subsequent to the one with which the historian is concerned, for example, a millstone at the end of its working life discarded and used as a reciprocating quern and finally degraded by whetstone work.

Functional analysis may be divided into two distinct parts, each a mode of treatment. The first mode is theoretical or dynamic analysis, which involves the application of mathematics or theoretical mechanics to investigate function and evaluate performance. In this analysis the artefact itself or a replica does not feature. The second treatment is analysis of function by practice, where the artefact, or a replica, is subjected to its mode of working.

Thus, we may summarise that there are three orders in the analysis of artefacts. See Table One.

Table One. ANALYSIS OF ARTEFACTS

Analytical Order	Type of Analysis		State of Artefact
First	Static		Non-operational
Second	Functional	Dynamic	Functioning in theory
Third		Practice	Actual function of artefact or replica

The concept of dynamic analysis can be approached by examining the types of motion associated with artefacts and the interaction they have with their environment when functioning. The analysis can be facilitated by asking three basic questions. Does it have moving parts? Does the whole artefact move? Does the artefact have a primary function in association with liquids, gasses, solids or other artefacts?

Nearly all artefacts which either have moving parts or move themselves provide opportunities for analysis related to motion. Another large group of quite different artefacts are those associated with water. Here the laws of fluids and hydro-dynamics offer opportunities for theoretical analysis.

In ancient history, static analysis is the language of the archaeologist. With few exceptions all of his finds are defined in a quiescent or non-operational state. When he derives functions from such evidence he rarely has recourse to functional analysis. For the historian of ancient technology, the archaeologist's work is the source material, the foundation stone, good, bad or indifferent in quality, on which he depends and builds. Unfortunately many earlier archaeologists' reports tended to be intuitive and speculative with conclusions sometimes influenced by emotion and volition. Too often the archaeologist failed to recognise the technological content of the artefacts, making casual observations and giving poor definitions in ignorance of the technologist's requirements.

For the historian of more recent technology this dependence on another discipline for excavation and interpretational skills rarely occurs. The last few centuries of technology are so well endowed with extant artefacts, recorded sources, written and printed, that excavation work is rare. And it is true that within the modern and early modern periods the industrial archaeologist has become more proficient, perforce, in acquiring those skills and techniques hitherto monopolised by the traditional archaeologist.[2] Nonetheless, virtually all of the field evidence for ancient technology has come from the professional archaeologists[3] working on sites associated with the classical cultures of the Mediterranean.

Of course the skills necessary to win artefacts from the earth are different from those needed to analyse and interpret them. One could argue that excavation work is the archaeologist's province and interpretation the historian's. This distinction might work if the excavation records were perfect and gave all that the historian, in particular the technologist, needed, but in reality this is never so.

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2. This trend has been accelerated by the emergence, growth and continued success of specialist groups at national, county and local levels, devoted to various aspects of industrial archaeology.

3. The exception appears to be England, where a surprising amount of high-standard amateur archaeological activity continues to occur.

An archaeologist would not necessarily know if he had discovered something unique or of technological importance; and if he had, would he record a mechanism or a machine in the same way that a technologist would? Even if an excavation report met all current needs, what of future technologists?

There is a need for the various disciplines involved to be aware of each other's needs and problems and to recognise their respective responsibilities.[4] Örjan Wikander suggests that the communication between classical archaeologists and historians of technology should be improved,[5] though recognition of this problem is one thing, while how to overcome it is quite another. Maurice Daumas appears to see the problem in a slightly different light when he says, '..In order to overcome its own deficiencies and to relieve itself of too-heavy pressure from neighbouring disciplines, the history of technology must further elaborate the methods of investigation and analysis enabling it to pursue its objectives effectively'.[6] But his recommendation is clearly supportive of developing and using new methods of analysis, including those involving performance and dynamic methods.

B. Why Functional Analysis?

A static analysis may fail to convey certain information, not so much by what is missing, but because we have not developed information latent within the subject. One form this can take is when we do not have a full understanding of the artefact; we might know its purpose but not how it was used, for example a Roman gaming board or die. Or

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4. R.J.Spain, 'Romano-British Watermills', Arch.Cant., Vol.100, 1984, pp.101-128. See page 102.

5. Ö.J.Wikander, 'Archaeological Evidence for Early Water-mills, an Interim Report', History of Technology, Vol.10, 1985, pp.151-179.

6. Maurice Daumas, 'The History of Technology : its Aims, its Limits, its Methods', History of Technology, Vol.5, 1976, pp.85-112, translated by A.Rupert Hall.

the reverse might hold true, we may know how it was used but not its purpose. The querns found in Roman watermills would fit this category.[7] On the other hand an abandoned artefact can be a complete enigma. For example the Romano-British barrel-shaped stone with equi-spaced mortises around its girth found at Chesters Bridge, Hadrian's Wall,[8] which has been described as a waterwheel hub (a silly suggestion), counterweight (why such a complicated design for such a simple function) and a rammer/mortar for a number of men (more plausible but not entirely convincing). Some functional tests with a replica would help to shed some light on its purpose, if only to rule out some of the suggestions. However, some artefacts may be so enigmatic as to be beyond analysis, where we do not know what tests to devise. Finally there are artefacts which are completely misunderstood, later revealed as something quite different. In the history of the seventeenth and eighteenth centuries it is not difficult to find examples of archaeological artefacts whose purpose was misunderstood, but in modern times examples are much harder to come by.

Sometimes the viewer is unable to comprehend the function, to imagine movement and effect, to relate scale and space to reality. Complex artefacts, especially mechanisms, door locks for example, and machines such as some forms of heat engines, fall into this category where the function of the elements are not self-evident and perplex the observer. In other artefacts, such as a bridge or a medieval cathedral an observer might use them hundreds or thousands of times over the years, but could never comprehend their obscure and complex mode of behaviour. However we need to differentiate between two forms

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7. The sites at the Athenian Agora, and Haltwhistle Burn Head.

8. J.Liversidge, Britain in the Roman Empire, 1968, p.184; S.Holmes, PSAN, Series 2, Vol.ii, p.178; PSAN, Series 3, Vol.ii, p.283; Bruce and Richmond, p.79; I.A.Richmond, Roman Britain, 1955, p.171. A similar stone found at Lincoln in 1950 beneath the east side of the High Bridge was also thought to have been a waterwheel hub, which it was not.

of complexity, appearance and action. An artefact can appear complex but function simply, while another can appear simple but function in a complex manner. Two examples are offered as illustrations.

The first illustrates how the senses can be confused by a mass of elements and yet the function is very simple. The water-powered trip-hammers and shears in the workshop at Sticklepath, near Okehampton, Devon, present to the observer a mass of structural and mechanical elements, a concentration of mechanisms and contrivances to cut and hammer iron. See Plate 1.

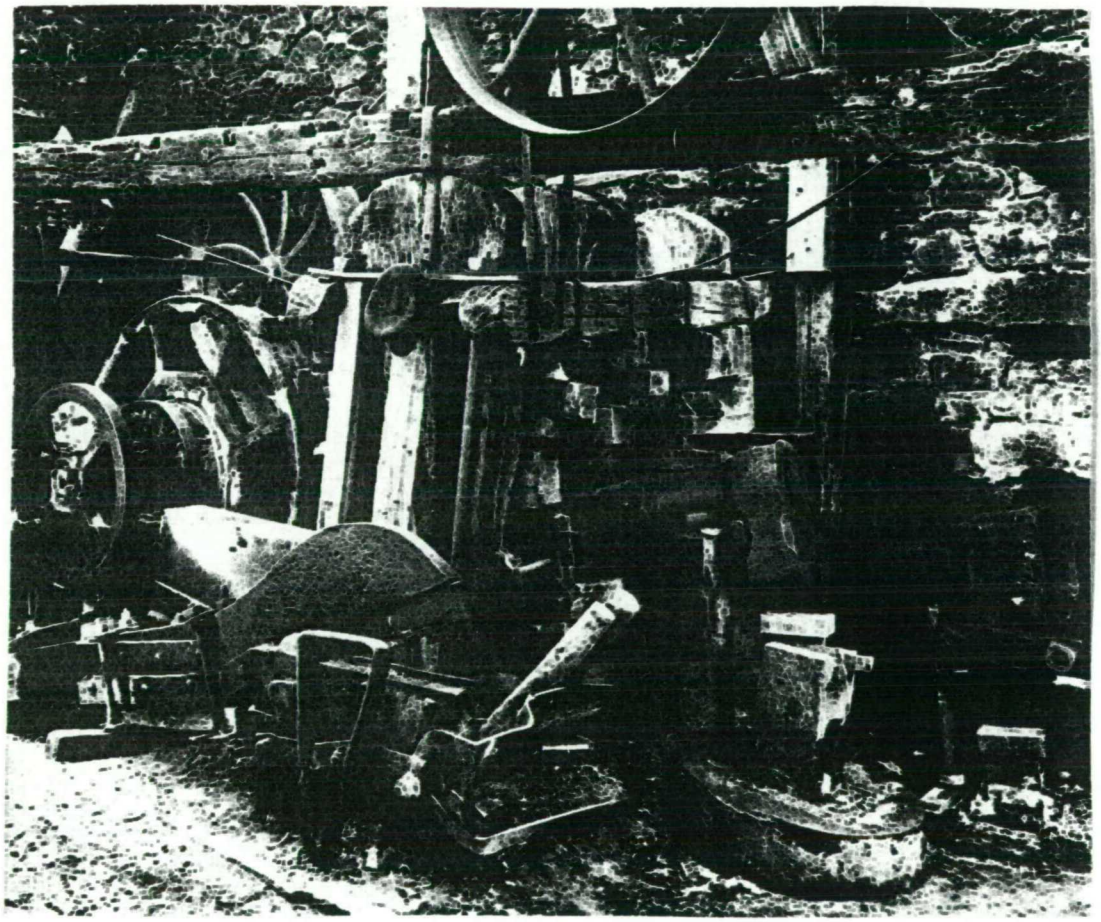


Plate 1.

The trip hammers and shears at Sticklepath Foundry.

A century and a half of operations and maintenance, of repairs, adaptations and improvements, overlain and misshapen by wear and natural decay of the timber and iron, plus the patina of age, all confuse the senses. Even the earthen floor fails to provide a true physical datum, its undulating surface reflecting generations of human presence with scale, rust and waste from the process. Imagine the further difficulties to the comprehension of function if this artefact had been abandoned for centuries and then revealed by excavation.

All of this is seen in an inoperative state. Give motion to the machinery, let it function as intended, and our understanding and experience of this single artefact is immediately and infinitely better.

The second example presents a very simple artefact having numerous similar elements but a seemingly complex function. The monoliths of Stonehenge do not immediately confuse an observer; a short walk among the stones will soon make their form and layout clear and the symmetry of their plan facilitates a speedy comprehension of the whole site, large though it is. The casual observer quickly realises the permanence of the stones and the simplicity of the monument. Many antiquaries have pondered its purpose. Artefacts that are strange and beyond our experience need all the methods of analysis that we can bring to bear upon them, and at Stonehenge it was a form of dynamic analysis that led to the 'neolithic observatory-cum-computer' theory of Gerald Hawkins.[9] Theoretical analysis supported the notion of alignments between the stones being related to the prediction of astronomical events. Rival astronomical theories now exist but it is mathematical analysis which often lends them foundation and credibility.

The other lesson which comes from Stonehenge, which the historian of technology would do well to take note of, is that our vision of its purpose has moved with the times. Christopher Chippendale has wryly noted that archaeology is an inexact science itself prone to

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9. Gerald Hawkins, Stonehenge Decoded, London, 1966, Souvenir Press.

fashion.[10] Its professional opinion can be identified with the changing visions of Stonehenge, from the Victorian druidical image through to the current technological one.

Clearly all artefacts that function by moving are best understood by functional analysis. How could a technologist do justice to the description of say, a boomerang, a toy gyroscope or a jews harp without the experience of handling and using them? Theoretical analysis is particularly well suited to those artefacts whose behaviour is predictable, especially those having mechanical functions, such as mechanisms or machines.
What do we gain by such analysis? What if a waterwheel generated (x) horsepower and the mill produced (y) kg. of wheatmeal, or double the amount? Dynamic analysis provides us with a better understanding of the machine, its function and performance, and can be used to view a machine, such as a watermill, as the interaction of several mechanisms, of integral function, to which the casual observer will be blind. The analysis may reveal functions hitherto unseen or unrecognised, or it may provide greater definition of ones already known. Speculation and supposition concerning performance tends to be reduced or removed altogether. The historian of technology uses the theory and language of physics to progress towards probability by quantifying and qualifying, by giving order and magnitude.

All artefacts contribute to the technological infrastructure of the period under consideration. This may take the form of design, skills, techniques, processes or any other technological manifestation. When an artefact is misunderstood it distorts the infrastructure and can affect our view or understanding of similar artefacts or skills, processes etc., in some small way. If an artefact remains unidentified, misinterpreted or our understanding of it undeveloped the infrastructure is the poorer for it. When an innovation or development in technology is re-assessed (in history re-discovered) its assimilation into the infrastructure causes movement, a change of view,

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10. C.Chippindale, 'Life Around Stonehenge', New Scientist, 5th April, 1984. pp.12-17.

a shift in the perspective and our understanding of history. Examples of discovery which have caused a noticeable shift in our view of ancient technology are, the Antikythera device, Roman pumps and aqueduct siphons.
A final view of the advantages of functional analysis is given by relating it to the senses. Analysis of an inoperative artefact is limited to the senses of sight and touch. Functional analysis improves the analytical mind by adding to the experience of movement the senses of hearing, smell (taste is rarely relevant) and the sixth sense of muscular effort. Thus greater consciousness of the properties of any artefact is brought about by the language of physics or physical performance.

Droysen has said that historians must know what they wish to seek; only then will they find something. One must question things correctly, then they give an answer[11]. Theoretical and operational analysis are surely the historian of technology's best diagnostic tools? Their application takes the historian towards realism and the experience of the original artisans and craftsmen, which we can approach but not reach. Reaching for reality and experience using functional analysis is the method; its effect on our knowledge and understanding of the artefact and the technological infrastructure is the result. The method ought to be fundamental to the history of technology and in this thesis the aim is to demonstrate its application to the particular and important problem of the origin of the water-mill.

C. Examples of Dynamic Analysis and Replication.

Artefacts which function by movement lend themselves readily to dynamic analysis. In this category, hand tools and hand weapons, which are relatively small and easily reproducible, are ideal for functional analysis. Working tests will help to determine their effectiveness, durability etc. It may be necessary to replicate an artefact to avoid damage or wear to the original, but providing care is

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11. J.G.Droysen, Historik, Series 4, Vol.22, 1958, pp.35-6, edit. R.Hubner, (Darmstadt).

taken to faithfully duplicate the shape, structure, materials and working conditions, bench, workshop or field tests should be fruitful.

K.D.White believes that it is disastrous to divorce the study of an implement from that of its operation[12] and points to Steensberg's work involving experiments with replicated Roman implements[13]. Sometimes, but not often, the artefact is considered workable or even expendable to the point of destruction. In the *Mary Rose* a cache of yew longbows was discovered freshly made ready for the field, in such numbers that it was possible to add to our knowledge by subjecting some to laboratory and field tests.

Occasionally an ancient tool poses the problem of how it was operated. A tomb scene at Sahu-Re at Saqqara dated c.2450 BC depicted a hand drill with a single curved handle at the top and two weights hanging from a strap at the point where the curved handle is attached to the body. The question this raised was how did it work? By wobbling or by free-hand steady cranking? This matter was re-solved by a theoretical mechanical analysis and experimentation with a simulated artefact[14]. Both forms of functional analysis were used, each complementing the other.

A similar functional analysis could have been done to establish the mode of working a rope-making whirling tool depicted in a mural in the tomb of the vizir Rehk-mi-Re (c1500 BC.).[15] The depiction is not clear enough to tell if the tool rotated in the hand or was sleeved, nor whether it was activated by true circular motion or a yo-yoing motion up and down. Replication and operation would almost certainly resolve the issues.

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12. K.D.White, Agricultural Implements of the Roman World, 1967, pp.5 and 9.

13. A.Steensberg, Ancient Harvesting Implements, trans. by W.E.Calvert, Copenhagen, 1943.

14. André Wegener Sleeswyk, 'Hand-Cranking in Egyptian Antiquity', History of Technology, Vol.6, 1981, pp.23-27.

15. Sleeswyk, as note 14.

A great number of artefacts functioned inertly, often working in conjunction with other artefacts or in association with solids, liquids or gases. The efficiency and operating problems of an ancient furnace involve much more than simply gas flow. The reconstruction and operation of a roasting furnace from the Roman iron-making site at Bardon facilitated research into the effect of inducing draught, and created a realisation that the way in which it was charged with alternate layers of ore and fuel was critical to the evenness in the degree of roasting[16]. Working replicas can change interpretations.

The Romano-British furnaces at Ashwicken were thought to be worked by natural draught until extensive trials on laboratory facsimiles proved otherwise[17]. Experimentation has also shown the ore/charcoal ratio necessary for adequate reduction and how the slag was properly tapped[18].

Our knowledge of how a typical Romano-British grain storage pit functioned was advanced when a full-scale replica was made and used at Butser Ancient Farm[19]. Gas sensors showed that the freshly stored grain created an atmosphere of carbon dioxide within the sealed pit which inhibited the activity of bacteria and preserved the crop for many months.

Artefacts such as aqueducts are much less easy to replicate due to their scale and construction. Few are in a state of preservation which will allow them to work although some have been in use for centuries after they were first built. Maintenance and repair work over the centuries, together with calcareous deposition and land movement, have tended to alter profiles and gradients.

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16. D.Strong, David Brown, edits., Roman Crafts, 1976, p.130, article by Henry Cleere.

17. Strong, as note 16, p.134.

18. Strong, as note 16, pp.134-138.

19. Information passed on to the Author by Dr. Peter Reynolds, Butser Ancient Farm Trust, East Meon, Hampshire. See P.J.Reynolds, Iron Age Farm : The Butser Experiment, 1979, pp.74-5.

Theoretical analysis can also be applied to structures to help us solve problems of design or function. It used to be thought that the triangular structure at the head of the Gallo-Roman watermill at Barbegal was a reservoir serving the two parallel headrace channels[20]. Sellin's structural analysis has demonstrated that the upstream hydrostatic pressure on the retaining wall would have caused failure[21], which means that the remains are quite simply part of the supporting fabric for the headrace bifurcation.

Among larger artefacts which functioned with movement are vehicles and it would be unjustifiable if they were examined and their effectiveness determined solely by static analysis. The reproduction of such large artefacts is costly and may prove prohibitive in comparison with the information and knowledge gained. Working tests may not be possible but an analysis embracing mechanics, power and speed according to the properties of the design would surely yield additional information. When evaluating the design and function of say, an ancient horse harness, or an ancient Greek Trireme, replication is necessary and desirable to effect functional analysis. No complete example of either has been found and even if it had it would not have been possible to put it to work.

Spruytte's experiments with early forms of shoulder-collar and breast-collar harness necessitated making full-scale Grecian, Egyptian and Chinese two-wheeled chariots.[22] This work on traction and efficiency demonstrated the failings of earlier hypotheses which lacked practical foundation. Spruytte considered that it was essential that the proper materials be used for construction and that the

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20. F.Benoît, 'L'usine de Meunerie Hydraulique de Barbegal (Arles)', Revue Archéologique, Series 6, Vol.15, 1940, pp.19-80.

21. Robert H.J.Sellin, 'The Large Roman Water Mill at Barbegal (France)', History of Technology, Vol.8, 1983, pp.91-109.

22. J. Spruytte, Early Harness Systems, 1983, London.

animals were of the size and weight corresponding to those of the periods under consideration. He rightly identified the prime requirement of replication, that of identical materials; and he was clearly aware of the second, realistic if not identical working conditions. Arguments about the speed of a Greek trireme, length of oars and their deployment has stimulated long and heated debates.[23] The Perama replica, begun in July 1985 and launched in September 1986, underwent full sea trials to help determine its performance in different conditions and evaluate its design.[24] But were the builders able to find oarsmen to match the reduced stature of our ancestors? Mechanisms, and their embodiment as machines, are ideal for these forms of analysis. Mechanisms feature in domestic, military and industrial aspects of Roman life. Many of them are simple and their function and behaviour uncomplicated and relatively easy to determine. For a few, functional analysis, probably by replication, would be beneficial, especially where developmental and evolutionary aspects are being considered. A good example of dynamic analysis being usefully applied to a mechanism is the case of the Antikythera device. Without the application of mechanical theory and the laws of motion of planetary bodies and the moon's phases, the true purpose of the mechanism might have eluded us.[25]

Dionysius of Alexandria's detailed description of a repeating arrow catapult provides a rare opportunity for reconstruction and testing. Erwin Schramm's full scale reconstruction of the catapult worked well after parts of the pull-back mechanism were replaced with modern sprockets and chains. A one-sixth scale model produced later by Tur-

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23. The Times, numerous editions during 1975.

24. The Times, 31st.July 1986, p.10. See J.S.Morrison, J.F.Coates, The Athenian Trireme : The History and Reconstruction of an Ancient Greek Warship, C.U.P., 1986. F.Welsh, Building the Trireme, Constable, 1988.

25. Derek J. de Solla Price, Gears from the Greeks, Science History Publications, New York, 1975. See pp.53-60.

ner using the same methods to overcome the pull-back problem supported the findings of Schramm. A more detailed design analysis supported by experimentation proved that the original design was functional.[26] Research showed that the pentagonal prism in the draw-back mechanism was the best shape and that to decrease or increase the number of faces resulted in disadvantages. Moreover, inefficiencies were discovered in the system - limits of operation due to friction peculiar to the design. This supported the original claim that the catapult had limited range and was inferior to a single-shot catapult. This is an excellent example of functional analysis, where replication, supported by theoretical analysis, has shown that the original description was accurate and that the mechanism and the machine itself could function perfectly.

The closest parallel to the replication of a prime-mover was the one-third scale model of the 1712 Newcomen engine, built in 1970. Although modern machine tools and processes were used to make the engine it took a further three months of experimenting and adjusting to make it work.[27] The makers found that the various problems encountered in trying to work the engine much more rewarding than those occurring during its building. They considered that their eighteenth century counterparts must have experienced very similar problems.

Of the machines which occur in the Ancient world, the watermill is surely one of the most simple in construction and yet very complicated to analyse. The horizontal watermill has only one moving part,[28] comprising waterwheel, shaft and top millstone, but its per-

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26. V.Foley, W.Soedel, J.Turner, B.Wilhoite, 'The Design of Gearing', History of Technology, Vol.7, 1982, pp.101-129.

27. R.L.Hills, 'A One-Third Scale Working Model of The Newcomen Engine of 1712', The Newcomen Society Transactions, Vol.xliv, 1971-2, pp.63-77.

28. Ignoring any vibrating device which probably existed to encourage the grain to trickle into the eye of the stone.

formance is determined by the interaction of the power generated by the wheel and the work being done by the millstones. This balance of power defies static analysis and no amount of speculation can ascertain its performance. Without dynamic analysis the remains of a 2000year-old watermill are latent and lifeless.

The vertical watermill is more complex than the horizontal, having two rotating masses whose behaviour is mechanically related via gears, which are an additional variable in the analysis. The greater mass is the waterwheel, shaft and driver gear which weigh perhaps two to three times as much as the driven gear, millstone spindle and top millstone.[29] Provided that the dimensions and construction of the major elements are known, the watermill can be subjected to dynamic analysis. The headrace can be hydraulically analysed to determine the velocity of application under certain conditions, while the wheel itself is an obvious subject for analysis to help determine the power generated at different speeds. Millstones have a complex behaviour influenced by several variables embodied in their design as well as the condition and the flow rate of the grain. Unfortunately our knowledge of millstone behaviour, especially the earlier cruder profiles and dressing styles, is very limited. In the calculation of the power necessary to drive the upper stone of a pair of millstones, the coefficient of friction, which reflects their design, is critical, having great affect upon the result. It was for this reason that the Westree millstone rig was built. This experiment provided a realistic coefficient of friction related to the use of Roman-style millstones. (See Chapter four).

However, a watermill's behaviour is the result of the interaction of two independent forces; the hydraulically generated power balanced against the power needed to drive the millstones and overcome the friction losses in the machine. It is much more fruitful to apply

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29. The Haltwhistle analysis showed the wheelshaft masses were three times the masses rotating on the vertical spindle. However the millstones probably rotated some five times faster than the waterwheel.

dynamic analysis to the whole mill and treat it as one machine rather than a series of independent mechanisms. This applies both to vertical and horizontal watermills.

To facilitate a full hydro-mechanical analysis of a vertical watermill, the archaeological or field evidence needs to provide us with- (a) bed inclination, materials and section of the headrace, (b) the diameter, width and type of application (overshot, undershot etc.,) of the waterwheel, (c) evidence of the top millstone, its diameter, thickness, inclination of the grinding face, material and density. Additional information, such as the depth of water normally flowing in the headrace, or an indication of the gear ratio, will render the analysis more accurate. Unfortunately, few ancient watermill sites provide sufficient evidence to allow a complete hydro-mechanical analysis. The Athenian Agora,[30] Haltwhistle Burn Head,[31] Barbegal[32] and the Baths of Caracalla[33] are currently the only sites where anything approaching a full analysis can be attempted.

The study of Roman watermills is essentially a twentieth century development and is to be regarded as one of the more complex as well as most important parts of ancient technology. Dynamic analysis of Roman watermills really started when the first two major sites had been published. When the works of Barbegal followed on the stimulating work of Parsons at the Athenian Agora, our knowledge of Roman

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30. Arthur W.Parsons, 'A Roman Water-Mill in the Athenian Agora', Hesperia, Journal of the American School of Classical Studies of Athens, Vol.V, No.1, 1936, pp.70-90.

31. F.G.Simpson, Watermills and Military Works on Hadrian's Wall: Excavations in Northumberland, 1907-13, edited by Grace Simpson with a contribution on watermills by Lord Wilson of High Wray, Kendal, 1976, pp.26-42.

32. See Chapter 6.

33. T.Schiφler and Ö.Wikander, 'A Roman Water-Mill in the Baths of Caracalla', Opuscula Romana, XIV:4, Stockholm, 1979, pp.47-64.

mechanical technology took a leap forward. The credit goes to Luigi Jacono for being the first, apparently, to use dynamic analysis when he applied theory to the Venafro wheel.[34] Using the admittedly limited evidence of the wheel and its headrace he nevertheless calculated a flow rate, the velocity of the water striking the wheel and the theoretical wheel speed.

At Barbegal, the only other Roman watermill site to have received any form of dynamic analysis, Sagui[35] calculated the potential power and related this to output by assuming a relationship directly proportional to the pressure provided by the topstone.[36] Twenty-five years later Sellin refined the calculations by hydraulically analysing the headrace to determine the water flow in the mill, applying a more realistic operating factor, and rejecting the principle that each waterwheel powered more than one pair of stones.[37] This showed that Sagui's figures for total power and the production rate of meal were greatly inflated. Sellin also illustrated by structural analysis that the sixteen waterwheels were not served by a reservoir at the head of the mill. But much analysis remains to be done on the Barbegal evidence and the other major Roman watermill sites. One of the principle objectives of this thesis is to make good these deficiencies by taking theoretical analysis much further.

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34. Luigi Jacono, 'La ruota idraulica di Venafro', L'ingegnere, Vol.12, 15th.Dec.1938, pp.850-853. We should note that there is some doubt regarding the date of this site. A model of this wheel is in the Technological Section of Naples Museum, Italy.

35. C.L.Sagui, 'La meunerie de Barbegal (France) et les roues hydrauliques chez les anciens et au moyen âge', Isis, Vol.38, 1948, pp.225-231.

36. Sagui based this relationship on modern figures of output and pressure. This is an imperfect method because it does not allow for the much cruder styles of dressing, together with the grinding face inclination, but it does show an attempt was made to be realistic.

37. Sellin, as note 21.

I have remarked that when the technologist chooses not to analyse (and I use the word choose deliberately being aware that many methods of analysis have been available for several decades) he is the poorer for it. It can have a marked effect on history if generation after generation of historians blindly repeat misleading, unproven or false information, or express a view or hypothesis based on such information. Two examples are provided, both related to the history of watermills.

The first illustrates how dynamic analysis can change our view and understanding of an artefact and how we have to re-adjust ourselves to the new position. The second illustrates how the failure to apply dynamic analysis can lead to a mistaken view of Roman technology generally.

Example One

No one would deny that Barbegal is very unusual, indeed unique in the archaeology of the Roman world. To the technologist, its impact is related to such factors as scale, arrangement, novelty etc., but for the socio-economic historian the language is different. Historians began to comprehend Barbegal when Sagui declared it to be capable of supporting a population of 80,000 people. To most readers of history, this is the touchstone and the figure is invariably mentioned in successive popular histories. Recently Sellin's analysis has shown that Sagui's estimates were inaccurately determined although it will take time for Sellin's findings to be assimilated into the corpus of watermill history. Further analyses have now been undertaken (see Chapter 6) so that our view of Barbegal is progressively becoming more realistic. This has resulted not from fresh evidence but rather from new interpretation of the existing evidence, and these advances have resulted from the application of dynamic analysis in one form or another.

Second example

Reynolds in his first class study of the history of the vertical waterwheel has drawn the conclusion that Roman technological knowledge in the area of hydropower may have been seriously incomplete.[38] His reasons are these:-

(a) the hub of the Venafro wheel was large and heavy so as to impair its effectiveness.
(b) the use of rims (shrouds) on undershot waterwheels.
(c) mis-setting of the Athens wheel.
(d) inefficient inclined buckets in overshot wheels.
(e) excessive wheel velocities.

All five observations appear to be subjective opinions not based on analysis. It is not possible to give here a full scale technical analysis of each of these points but everyone of them is a fruitful area for functional analysis and most of them are discussed elsewhere in this thesis. Reynolds has drawn the wrong conclusion from the features because he failed to use any form of technical analysis. His opinion that the Romans' knowledge of watermill technology may have been seriously incomplete is sadly ill-founded.

D. Problems of Replication and Retrospective Analysis.

When replicating artefacts for functional analysis it is important that they are subjected to realistic working conditions. Spruytte clearly recognised the need for this when he tested his early forms of harness with animals of the right size and weight, operating under loads at various speeds over different terrains. The operation of the Perama trireme raises some interesting questions concerning conditions. To evaluate the problems of space and the dynamics of rowing regard must surely be given to the selection of the crew. Will the boat be manned by a crew having the same stature as ancient oarsmen? Will they be fed on the same basic diet day after day?

Most historians of technology are surely cognizant of the need to replicate materials when creating artefacts. Wood, metal and stone feature prominently in most artefacts and the main problem is usually

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38. T.S.Reynolds, Stronger than a Hundred Men: A History of the Vertical Water Wheel, Baltimore, 1983, pp.43-4.

identifying them. In the Westree rig, the Roman style lava millstones were taken from the same quarry and strata that the Romans had used. Thus the material, density and porosity were duplicated to the best of our ability. But using the same materials can cause problems. In the making of the model Newcomen engine,[39] the same materials were used wherever possible but for safety reasons, the boiler was made from copper sheeting, tinned to look like lead.

In some replicas the material can be critical; for example the Roman steel-faced top die (trussel) used for hot-striking coins that was found at Trier, Germany.[40] Speculation exists concerning the number of impressions that this unusual specimen, with its iron shaft and carburized and quench-hardened face, could provide. The obvious way to obtain a reliable figure would be to reproduce the die with metallurgical precision and work it in realistic conditions.

Concerning materials, there is a well known example, sometimes quoted by historians of technology, of how a model of a Roman catapult had failed as a true replica, because the maker had not used human hair to provide the torsion. Apparently women's hair has properties which surpasses all other natural materials when used for this purpose. True or false, it is a nice story which serves to remind us that we must strive to use the same materials to authenticate function.

When replication is being considered the question of scale is important. What happens if we replicate less than full size? We have a good idea of how dynamic properties, such as power and velocity, are affected by a change of scale, but what happens to behaviour? Builders of the one-third scale working model of the Newcomen engine found that certain parts of the engine would not work, including the beam, which could not be properly balanced. There is evidence that large models of the Savery engine do not work well whilst small ones do and it is well known that model atmospheric engines are difficult to control whilst larger ones work very much better.[41]

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39. Hills, as note 27.

40. G.Becker, W.Dick, Arch. Eisenh., Vol.38, 1967, p.351.

Clearly care must be taken when making replicas otherwise some of the original functions may disappear or become distorted or changed. If possible the technologist should replicate at full-size otherwise there is a risk of creating problems or variations in functions which were not inherent in the original artefacts, unless of course it is the behaviour of those functions at scale (as distinct from design) that is the object of research. After all, scale is a factor or influence of evolutionary change, especially in such artefacts as hand implements, tools and weapons.

Another area of concern for the historian of technology, especially when replicating mechanisms or machines, is the problem of standard of manufacture. When making some of the earliest heat engines James Watt considered that he had achieved a good fit if he could not get the brim of his hat between the piston and the cylinder wall[42]. Should such inaccuracies be replicated? If they are not, how are the functions impaired? Should we not use the same methods of manufacture to ensure that the replica is made bad enough? Do we have the skills and machinery to do this?

Spruytte reconstructed a two-horse two-wheeled chariot based on the ancient rock paintings in the Tassili-n-Ajjer of the Sahara.[43] He made the vehicle using simple tools of local stone, themselves replicas of artefacts from the stone-age culture. It would be virtually impossible to make an early heat engine using the original skills, tools and machines of the period. Moreover the skills to make an artefact in the original manner are one thing; the skills required to make it work are quite another. Do we know enough to make it work?

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41. Hills, as note 27.

42. Another oral tradition has it that the test was made with the edge of a well-used coin.

43. Spruytte, as note 22.

is a question which all those involved in replication should ask themselves. But this is a question which is always worth asking in functional analysis even when replication is not undertaken.

Perhaps we should first recognise the fact that you can replicate machines and other artefacts but you cannot replicate people. Rediscovering human skills and experiences that were associated with the operation of machines and processes abandoned generations ago can prove very difficult, especially in the absence of modern parallels. An artefact which needs human skill to function and perform requires neuro-muscular co-ordination to some degree, but craft implies much more. Rupert Hall describes 'knowing how to' as mainly non-cerebral knowledge.[44] Manufacturing or operational skills are won by experience and the range and complexity of those associated with ancient technology are far greater than we think. Even in more recent times skills prevalent one or two generations ago have been lost and many are difficult to replicate - often submerged by new technology. In the North Western Museum of Science and Industry where there are many original machines maintained in working condition, the Hargreaves Spinning Jenny needed considerable skills to work it.[45] Richard Roberts' self-acting mule presented even greater problems, for none of the staff could 'doff and then spin a new cop'. Luckily they were able to get a retired operator to work it for them. As Sleeswyk noted when examining Egyptian tools, there is in the history of technology a constantly recurring process of special skills being rendered obsolete by innovation in design.[46]

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44. A.Rupert Hall, 'On Knowing, and Knowing How To', History of Technology, Vol.3, 1978, pp.91-103.

45. Richard Hills, 'Museums, History and Working Machines', History of Technology, Vol.ii, 1977, pp.157-167.

46. Sleeswyk, as note 14.

But what skills are needed by a technologist who is appraising a replicated artefact? Was Spruytte the best man for the research into ancient harness? He acknowledged that he applied to his study all the experience acquired during the course of a long professional practice in driving. His skill of working with equines and his knowledge of their structure, abilities and behaviour are beyond question. What would have been the results if a butcher or a baker had balanced on the rawhide platform and put the teams through their paces? The value of Spruytte's appraisal lies in his functional analysis based on anatomical knowledge and modern driving experience. He was a man skilled in the craft and familiar with its language, but he lacked field experience and the operational conditions of skirmish and battle. Robert Hardy's ability as a short-range and competition archer may be better than the average English or Welsh longbowman who would have drawn the yew bows of the Mary Rose. It is very doubtful if he was as experienced in terms of power, range and speed and certainly not in the field of battle.[47] And who should experiment with the replica of an early heat engine?: an engineer (millwright?), a historian of technology, or a true mechanic if one could be found?

Perhaps it comes to this. It is surely worthwhile, if possible, to have the operating skills and experience appropriate to the functions being performed and in the absence of which our appreciation and understanding would be less than complete. In all such analyses it is necessary to convey the experience to paper in the language appropriate to the craft and to translate that appraisal into normal technological language. There is a case to be made for the skills and experience of the modern operator being matched by those of the original user of the artefact. After all, we are attempting to establish the effectiveness and suitability of the artefact for the original environment. But in reality we have two insurmountable difficulties; our knowledge of an artefact's original environment is al-

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47. It must be stated however that, to be fair, his analysis was primarily concerned with the strength of the bows and the penetration and behaviour of different arrow-heads against body armour.

ways less than complete and our view of the ancient world is always liable to distortion because of the bias and prejudices deriving from modern experience.

It is very easy for the historian of technology to become so entrenched and immersed in theoretical calculations that his vision becomes impaired or lost altogether. There comes a time when he must relate his work to reality, when his findings should be identified with the social attitudes and infrastructure of the period in which he is working. For the student of Roman technology it is very difficult to establish the technological and social infrastructure of 2000 years ago. And this needs to be done and expressed in a language familiar to other disciplines otherwise his contribution will become lost and not take its rightful place in socio-economic history.

Finally, how does one assess the validity of the result achieved? We know how to do this in physics or biology or astronomy - but how in history?[48] We have seen that in this search for knowledge of ancient technology we are likely to find explanations as to why things were done and the way they were done. All of this leads to a fuller appreciation of the Roman artisan's work and skills. If we have a better understanding of their designs and the problems of maintenance and operation, it will lead to identifying the improvements and innovations which are part of technical evolution.

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48. M.I.Finley, Ancient History: Evidence and Models, London, 1985, p.56.

Chapter Three

HYDRO-MECHANICAL ANALYSIS

A. Introduction.

As declared above the aim of this thesis is to demonstrate the application of functional analysis to the problem of the origin and the development of the watermill. Functional analysis by practice is not feasible for a whole watermill. Such a project would require resources, materials, labour and finances, on a scale which would be difficult to arrange. Even if one were to model a whole mill to a smaller scale, in addition to the substantial workshop resources that would be required in the form of machine work and technician support, the practical problems of producing realistic hydraulic conditions are very difficult to realise. And so we can turn to dynamic analysis to reach our objective.

The application of mathematical theory to a watermill has great potential, for theoretical analysis is well suited to artefacts having a predictable behaviour, especially mechanical functions such as mechanisms and their embodiment as a machine. To mechanics we may add the considerable corpus of hydraulic theory which has been derived from research in water power undertaken during the eighteenth and nineteenth centuries. This conjunction of hydraulic and mechanical theory is essential to the success of this enquiry, for a watermill, or more particularly, a water-powered corn mill, is an integration of both sciences. In a watermill hydraulic power is balanced against a working machine where the mechanical function is expressed in the friction of moving parts. The analysis sequence with which we are concerned relates to vertical waterwheels, although some of the mathematics, including that associated with mechanics, would be relevant to horizontal waterwheels.

This retrospective analysis of watermills uses predominantly archaeologically derived evidence of Roman watermills. Few sites provide enough information to make a full hydro-mechanical analysis possible. Essential to such an hydro-mechanical analysis is evidence of;-

(a) the size of waterwheel (diameter, width)

(b) the arrangement of the waterwheel (horizontal; vertical- overshot, undershot etc.)

(c) head of water (gradient, materials and sections of the headrace)

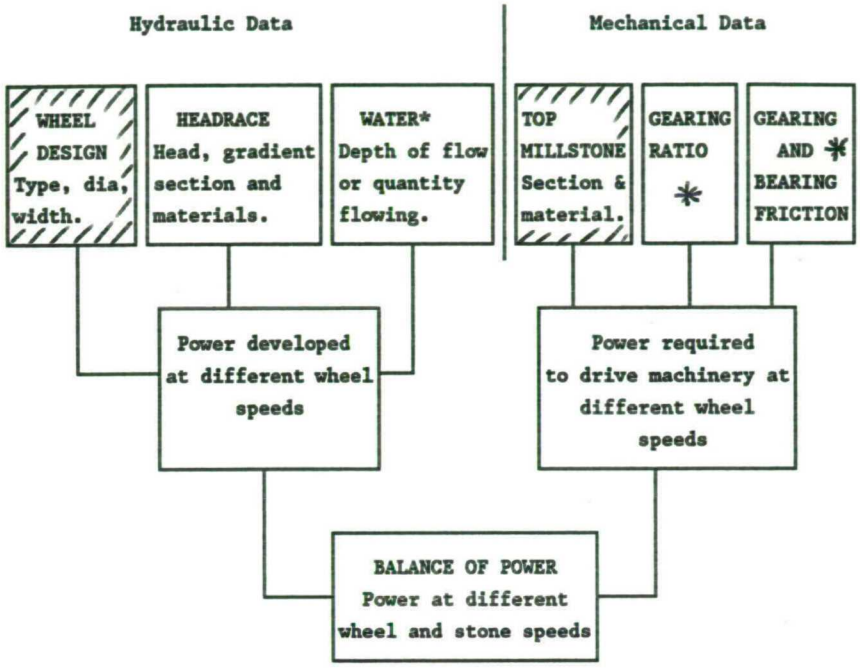
(d) the top millstone (diameters, gradient, material and weight)

With vertical waterwheels evidence of gearing would be most helpful to establish the mechanical ratio (MR) of the machine, but no evidence has yet come to light of gears within a watermill. However the unique lantern-gear and mill spindle from Zugmantel, which was most likely from a man or animal-powered machine, gives us a valuable insight into Roman gearing technology. Evidence of depth of water flow would also be helpful though only as a guide to either the depth of flow that prevailed most of the time (e.g. mineral deposits) or the maximum depth according to the section of the headrace.

Aside from the MR, for which a range of operating values can be suggested, the dominant variable in the mechanical analysis is the coefficient of friction for the millstones. Hence the primary aim of the Westree millstone rig, which was to establish a friction coefficient for Roman type millstones in operation.

The following schematic diagram shows the information which is required to conduct a hydro-mechanical analysis.

Simplified sequence of Hydro-mechanical analysis



Notes 1. Wheel design, although a mechanical feature, is placed under hydraulics because it is essential to hydraulic analysis.

2. For a river wheel a velocity of current or speed of rotation would be assumed in lieu of the headrace or water evidence.

3. For a bucket wheel, headrace evidence is not relevant unless it determines a flow rate less than the wheel's capacity.

Key ▨ Denotes primary (essential) evidence.

☐ Denotes secondary evidence.

* Reasonable assumptions can be made or a range of values used.

B. Classification of vertical waterwheels.

Modern history of technology classifies the vertical waterwheel into three broad types, the undershot, breastshot or overshot.[1] Generally

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1. Within these types there are further divisions which need not concern our analysis, e.g.,[breast] pitchback, high and low.

these types derive from the method of applying the water to the wheel but the terms are imperfect. Of the three, overshot has a clear unmistakable meaning and there are no sub-divisions. Water approaches the wheel level with the top or slightly higher so that its velocity is similar to the wheel's rim, then enters the wheel, passing over the shaft. The power of a modern overshot is due solely to weight of water, with the buckets designed to hold as much water for as long as possible.

The distinction between breast and undershot is much less clear. If we adopt the simplified method of classifying by water flow relative to the wheelshaft (datum) then the breast type is an undershot. This confusion is confirmed where the head of water approaching a wheel is much lower than the wheelshaft. When does a breast wheel become an undershot? Theory would suggest the distinction relates to how the power is generated, by weight or velocity (impulse), but the terminology of classification does not reflect this.

In Roman vertical water-wheels these modern classifications of wheel type are misleading and inappropriate. First, no examples of breast wheels have come to light; neither pitchback nor wheels where the water approaches at or near the level of the wheelshaft have been found. Secondly, and more important, we have examples of wheels where the head of water was so high above the wheel we have doubts as to whether it passed below or above the wheel-shaft, so that the classification by modern methods is difficult.

Furthermore, a classification of vertical wheels by their arrangement according to the direction of water flow tells us nothing about how the water velocity or weight is used to generate power. The following classification of types is therefore proposed for Roman vertical waterwheels.

<u>Types</u>

Low velocity undershot. [River wheels; Constrained flow.]

High velocity undershot.

High velocity high head.

Weight (bucket wheels)

B1. Low velocity undershot : River wheels

Probably the most simple type of hydraulic analysis is that arrangement which is commonly called the **river mill** where the wheel is partly immersed in a stream or river. In this type of wheel the power is generated solely by the velocity of the water pressing against radial floats. The watercourse can either be natural or man-made. In its simplest and probable original form, the river-wheel is, as the name implies, a waterwheel driven by a broad sheet of water, which is not channelled or constrained in any way. A contemporary example of this arrangement were the floating mills (boat mills) installed on the Tiber in AD 537 by Belisarius. It is most unlikely that archaeological evidence of a river mill would tell us the size of wheel, particularly the float area, so that the power generated cannot be ascertained.

This simple form of arranging a wheel was developed and improved as the advantages of constraining and controlling the application of water onto the wheel were recognised and adopted. A logical development is where the wheel operates between piers or within a masonry dam. With this arrangement the hydraulic conditions of application are different from the partly immersed river wheel, where the water is uncontrolled and can surge around and under the floats. In an emplacement the water is channelled and constrained close to the wheel so that greater pressure is applied to the floats. With this more precise and efficient application of water to the wheel the hydraulic calculations are more meaningful and accurate. Such an arrangement probably existed at Willowford Bridge[2] at Hadrian's Wall, but only the width of the wheel emplacement is known at this site, making a meaningful analysis impossible.

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2. Shaw, R.C, 'Excavations at Willowford', Cumberland and Westmorland Antiquarian and Archaeological Society, Transactions, 2nd. ser., vol.26, 1926, pp.429-506; Spain, R.J, 'Romano-British Watermills', Archaeologia Cantiana, vol.100, 1984, pp.101-128.

B2. Low velocity undershot : Constrained flow.

A rather more complex arrangement is where an undershot wheel has a low head of water, so that the calculations involve velocity and weight of water. This combination of forces is brought about by delivering the water at a low head, and constraining it with close-fitting fabric usually including a curved breast under the wheel. Archaeological evidence suggests that this arrangement existed at Martres-de-Veyre[3].

B3. High velocity undershot.

Requiring a somewhat more complex analysis is the race-fed undershot wheel. For convenience and simplification of the hydraulic calculations we can limit our enquiry to the flow rate[4] which provides the maximum effect on the wheel. This avoids repeating the equation sequence for different depths of water in the headrace.

In the hydraulic analysis of undershot race-fed wheels, it is necessary to know the size of wheel, details of the headrace, size, gradient etc., and the wheel emplacement. The theoretical power generated can then be balanced against the power necessary to drive the stones allowing for a range of gear ratios which may have existed. The perfect example of a Roman undershot race-fed wheel is the Haltwhistle Burn Head[5] mill, which was served from a man-made race sectioned and graded to produce a fast water velocity into the wheel, which ran in a close-fitting wooden trough. At Haltwhistle the evidence to effect a hydraulic analysis is such that, combined with the millstone evidence, it allows us to complete a hydro-mechanical analysis.

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3. Romeuf, A.M, 'Un moulin à eau gallo-romain aux Martres-de-Veyre (Puy-de-Dome)', Revue d'Auvergne, Tome 92, 1978, No.2, pp.23-41.

4. This will be determined by the capacity of either the headrace or the wheel.

5. Simpson, F.Gerald, Watermills and Military Works on Hadrian's Wall : Excavations in Northumberland, 1907-1913, edited by Grace Simpson with a contribution on watermills by Lord Wilson of High Wray, Kendal, 1976.

Other examples of the undershot race-fed watermill, where the water velocity determines the power, occur at Ickham, both the Early[6] and Late[7] mills, and Chesters Bridge[8] (Chollerford), but unfortunately the evidence to effect a satisfactory hydraulic analysis of these sites is not forthcoming.
Two further examples of high-velocity undershot arrangements have been identified at Lösnich[9].

B4. Weight or Bucket wheels

In bucket wheels the water is applied at negligible head and velocity so that the power is generated solely by the weight of water carried by the buckets and therefore impulse may be ignored. In the medieval and modern world bucket wheels can be overshot or, breast-shot where the water is applied below the top of the wheel. At present no evidence of a breast-shot bucket wheel has come to light in the Roman world.
In practical terms bucket wheels are invariably shrouded and designed to carry as much water for as long as possible before spilling it in the tailrace below. This calls for a shape which will maximise volume but allows the water to enter and exit easily.
An overshot weight wheel will revolve at a speed which is determined solely by its diameter. Providing there is enough water flowing to maintain motion, an increase in the amount of water laid onto the wheel will not increase its speed[10]. Several authorities and evidence

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6. Young, C.T, 'Excavations at Ickham', Archaeologia Cantiana, vol. xci, 1975, pp.190-191.

7. Spain, R.J, 'The Second-Century Romano-British Watermill at Ickham, Kent', History of Technology, vol.9, 1984, pp.143-180.

8. Clayton, J, 'The Roman Bridge of Cilurnum', Archaeologia Aeliana, vol.vi, 1861, pp.80-86.

9. Neyses, A, 'Die Getreidemühlen beim römischen Land- und Weingut von Lösnich (Kreis Bernkastel-Wittlich)', Trierer Zeitschrift, vol.46, 1983, pp.209-221.

10. It is strange that this important phenomena is difficult to find in the corpus of technical works associated with hydraulics and water power. Perhaps this is because it is primarily a fea-

from working wheels confirm the rim speed that would have existed. Within this category of gravity (bucket) wheel, at present, Barbegal[11] is the only known example from the Roman world.

B5. High velocity / High head

The remainder of the Roman watermill sites where archaeology has provided enough information to support a mathematical analysis might conveniently be described as **high-velocity high-head** wheels. The Agora, Caracalla and Venafro wheels are examples of this type[12]. The word overshot would be entirely correct for the Agora and Caracalla wheels but may not be correct for the Venafro specimen where we cannot be sure that the water passed over the shaft rather than under. Nomatter, the essential feature of this type of mill is that they were built with a head of water well above the wheel to drive a relatively fast wheel - fast certainly in comparison with medieval and modern water-powered corn mills.

With such arrangements where the potential energy of the water entering the wheel is considerable, the hydraulic analysis is an important part of the whole. To determine the velocity of the water entering the wheel it is essential to know the head and gradient of the headrace. Knowledge of the section and materials used in the water-

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ture of operational rather than theoretical behaviour, nonetheless it has great relevance to this analysis.

A simplified view of this phenomena is that once an overshot wheel is carrying enough water to produce continuous motion (assuming of course that the resistance to motion from machinery, bearings etc., is constant), then the two determinants of the wheel's velocity, the force of gravity and the wheel diameter, are constant. An increase in the weight or flow rate of water being applied to the wheel, or say passing over a waterfall, will not speed up its vertical descent. Installing a wheel within the flow retards the descent of the water by modulating the effect of gravity.

11. See Chapter Six below.

12. See Chapter Seven below.

course is desirable though reasonable assumptions can be made in their absence. The effect of different flow rates upon the velocity of the water entering the wheel needs to be determined as this will influence the power generated, especially at low flow rates. The water losses due to centrifugal force must also be calculated so that a reliable comparison can be made between the effect of radial floats versus buckets.

C. The Archaeological Evidence.

The following table is a summary of archaeological evidence of those sites which are suitable for the purposes of hydro-mechanical analysis.

Site	Information for analysis						
	Hydraulic					Mechanical	
	Headrace		Wheel			Millstone	
	Sectn & Material	Gradient & Head	Dia.	Width	Type	Dens-ity	Dia. & slope+
Agora	Y	Y	Y	Y	Y	Y	Y
Caracalla	*	Y	Y	Y	Y	?	?
Haltwhistle	Y	Y	*	*	Y	Y	Y
Ickham (Early)	N	N	Y	Y	Y	Y	Y
(Late)	N	?	N	?	Y	Y	Y
Barbegal	Y	Y	Y	Y	Y	*	Y
Venafro	N	*	Y	Y	Y	N	N
Martres-de-Veyre	?	*	*	?	Y		
Nettleton	Y	Y	Y	Y	Y	N	N
Lösnich	?	?	Y	Y	Y	N	N

Notations used in the above table;-

+ Inclination of grinding face

Y Information known

N Information unknown

? Not yet determined or dubious

* A reasonable assumption can be made

Note - at Venafro the headrace section and material are not relevant in this high-velocity, and very high-head wheel.

Outstanding for analysis are the Agora, Haltwhistle and Barbegal watermills. The power developed can be ascertained at a further four sites.

At Haltwhistle Burn Head the strength of the evidence lies in our knowledge of the hydraulic arrangement. The layout of the headrace is well recorded allowing us to undertake a detailed and exhaustive analysis of the flow rate and velocity into the wheel for different depths of flow in the race. The weakness of the evidence lies in the diameter of the wheel, which can only be ascertained by the section of the ground where the wheelside and landside bearings stood. Nonetheless, reasonable assumptions can be made which allow the necessary equations to be written down. The remains of several millstones allows the power required for milling to be determined with some confidence thus completing the mechanical analysis.

At the Athenian Agora site the archaeological evidence of the headrace, millstones and wheel is complete. Knowing the section and arrangement of the headrace, position of the wheel and the head of water, the velocity of water entering the wheel can be determined for different flow rates.

At the Baths of Caracalla two of the waterwheels are of the high-velocity high-head type, and although we are able to determine the head and the probable arrangement for bringing water to the wheels, we do not know the volume of water flowing. The primary determinant of the power of these wheels, knowing their diameter and width, is therefore the depth of float. This hydraulic analysis is therefore expressed in terms of float depth, and whilst the resulting power is

generally proportional to the float area, the speed of the wheel varies much less. As in the Agora and Barbegal analyses the balance of power is expressed in terms of different millstone thicknesses.

The remains of the Barbegal 'factory' provide us with ample evidence of the arrangement and sizes of the sixteen overshot bucket waterwheels that existed. Benoît provides us with the drawing of a lower millstone that was found which gives us the diameters and slope of the grinding face to complete our mechanical analysis.

The older Ickham watermill has been reconstructed theoretically so that we have rough dimensions for the undershot wheel that existed together with numerous millstone specimens. Unfortunately the gradient, materials and section of the headrace are unknown which means that we are unable to complete a worthwhile hydraulic analysis.

The archaeological evidence relating to the later Ickham watermill has not yet been released for analysis by the archaeologists but provisional observations suggest that we are dealing with at least one undershot wheel served by a close-boarded lined headrace. Whilst the gradient of the headrace is probably known the size of the wheel may not be. Various millstones were found at this site.

The evidence from Martres-de-Veyre of the size of the waterwheel is very limited, making the hydraulic calculations of little value. At Nettleton[13], the wheel dimensions and headrace channel arrangement are very clear so that the hydraulic calculations are more meaningful, but unfortunately no evidence of the millstones (was it a cornmill?) have come to light.

At Lösnich archaeologists have suggested that an undershot wheel operating within a curved breast was fed by a steep headrace so that the water entering the wheel was at a high velocity. A short distance downstream another smaller undershot was located. Unfortunately our knowledge of the wheel size and the way in which the water was constrained in front of and at the wheel, is lacking.

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13. Wedlake, W.J, The Excavation of the Shrine of Apollo at Nettleton, Wilts, (1956-71), Society of Antiquaries, London, 1982. Reports of the Research Committee, no. XL, pp.95-98.

The design of the unusual Venafro wheel is very clear from the archaeological evidence, and although we know the head of water we have no knowledge of the headrace or gradient and unfortunately the millstones have been lost.

D. Hydraulic Analysis.

D1. High Velocity - Impulse Wheels.

In high-velocity high-head wheels, a hydraulic analysis must first attempt to establish if the wheel had buckets or radial floats. This analysis has to be done for such wheels as the Agora specimen and the two wheels in the Baths of Caracalla.

At the Agora the power generated for different wheel speeds has to be calculated for different flow conditions. Resolution by graphical methods is the only practical way of analysing this so that full account is taken of the varying loads that occur in the moving buckets and the water losses, due to centrifugal force[14]. This gives us the power generated by weight of water for both the bucket and radial float design.

It should be noted that with shrouded wheels, which very likely existed in the Agora and Baths of Caracalla, the radial floats would have carried a small amount of water, thus deriving a small proportion of their power from weight. When we examine the power generation curves, weight plus impulse, for the different flow rates, the conclusion that we reach is that these wheels most likely had radial floats and not buckets. The high velocity of the water entering, combined with the great amount of splashing that must have occurred, supports this conclusion. Let us assume therefore that these high-head high-velocity wheels are impulse wheels; so too are the high-velocity, undershot wheels and the methods of hydraulic analysis is the same for each type.

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14. J.Weisbach, A Manual of the Mechanics of Engineering and of the Construction of Machines, Vol.II, pp.214,215, New York, 1880. Trans. by A.J.Du Bois.

Calculations to determine the power from impulse are well known and suitable equations can be found in most text books devoted to hydraulics.[15] Essentially impulse power is related to change in the velocity of the water, that is, the difference between the velocity entering and leaving the wheel. A typical formula is,

Torque = 2.0193 (Ve. Cosϕ - Vl) Vl. Q. ft.lbs.

where, Ve=velocity of water entering the wheel ft/sec.

ϕ =angle of water with tangent of the wheel rim.

Vl=velocity of water leaving the wheel (at mid-float)

Q =flow cubic feet/sec.

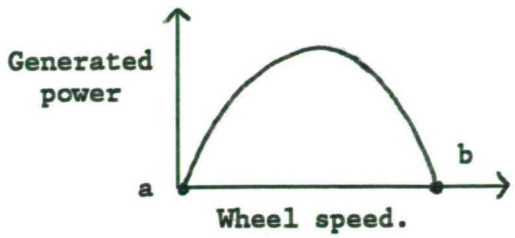
Having determined the torque we may then, knowing the wheel speed, find the horsepower.[16]

With high velocity wheels, e.g.,the Haltwhistle and Agora, the impulse effect (pressure), is greatest when the wheel is stationary and the water fastest. But when this occurs the speed of the wheel is zero, and so too is the horsepower, which is proportional to N x T. Correspondingly, when the wheel speed reaches the water speed the pressure becomes zero and again, so too does the horsepower. So we have, whether under or overshot, the following relationship between power and wheel speed, at a given constant water flow rate. See Fig.1.

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15. Lea, Hydraulics for Engineers and Engineering Students, 3rd. Edition, London, 1916, p.268.; Weisbach, as note 14, p.205.

16. In the equation the constant of 2.0193 is determined from the weight of a cubic foot of water divided by the force of gravity and appears to be in error. The true figure should be 1.941. Q should be the flow of water taken by the wheel, i.e. directed onto the floats. In the Haltwhistle undershot wheel, care had to be taken to relate Q to the maximum float area; if a greater flow i.e., a stream with a greater cross-section area was applied to the floats, the impulse effect would not increase because the float area had not increased. When the float area is completely covered by the water striking it, the impulse effect can only alter by changes to the velocity differential between the water and float. For the Agora analysis more care was needed in the problem of ensuring that the flow rate (Q) used in the equation represented the water which struck the wheel.



a = wheel stopped

b = wheel and water speed are equal.

Fig.1 - Generated Power and Wheel Speed.

For each wheel speed generation curves can be produced, if necessary a different one for each flow rate. These calculations for power have to provide a complete curve over the full impulse range of minimum (wheel speed very slow) to maximum power and then at higher wheel speeds until the power approaches zero again.

D2. Weight or Bucket Wheels.

At Barbegal, the hydraulic analysis requires a different approach to that used for the Agora and Haltwhistle wheels. Hitherto we have been concerned with either high velocity undershot or high-head high-velocity impulse wheels, whereas at Barbegal the water was laid onto the overshot wheels with negligible head so that only the weight of water was used to create power and therefore impulse was of no consequence.

This hydraulic analysis is limited to calculating by drawing, the weight of water carried by each bucket, its torque and the determination of water losses due to centrifugal force. Wheel power is related to the summation of the torque elements and the wheel speed. This drawing will also confirm the flow rate that is necessary to fill the wheel i.e., that associated with the maximum wheel power. With a wheel that has constant speed the power generated at different millstone speeds is constant also; thus on the power generated/millstone speed graph the power resulting from a particular flow rate is represented by a horizontal line. To effect these calculations the size of the wheel needs to be known.

In these circumstances there is no need to consider the design of the headrace and its effect on the water flow unless it provides less flow than the wheels capacity or, there is evidence of the actual flow rate. The effect on power generated due to variations in the

flow rate can be calculated without recourse to any hydraulic formulae, and so the whole analysis is limited simply to the application of mechanics.

E. Mechanical Analysis.

E1. Millstone Power.

In the mechanical analysis of a watermill, especially those of the Roman period, the greatest part of the power necessary to maintain the machinery in motion, was absorbed by the millstones. The friction of gearing, especially the crude rudimentary types, was the second greatest resistance to the motion of an early watermill, though very much less than the friction between the moving millstones.
When calculating the power absorbed by the friction between the surfaces, a coefficient of friction is used which varies depending on the materials of the surfaces and the lubricity between them. When the friction between moving surfaces is to be minimised, such as in bearings, lubricants are introduced, and in later technologies the use of balls and rollers are incorporated. However, in this analysis the surfaces can be considered as dry, but are separated by corn meal upon which the stones are working. The power absorbed by the millstones is caused by the work done in the cracking and reduction of the grain. The term 'friction', which relates to the interaction between two surfaces, is considered ill-fitted for the purposes of this analysis and the term 'coefficient of grinding' is therefore used.

It is strange that there appears to be no established theory for the behaviour of working millstones. Even when the corn milling industry reached its peak, when the energy forms of water, wind and steam power were widespread and much in evidence to the enquiring minds of Victorian engineers, the subject of the performance and power of millstones appears to have been more or less ignored. Corn-milling was a craft sustained far more by oral tradition and custom than written works; a mystique often jealously guarded in both the urban and rural industries.

The dynamics of working millstones may be described briefly as follows.

In disc millstones, rotation of the topstone produces several forces which act upon the grain and meal[17]. These are centrifugal force, the shearing action of the furrows, friction between the grist and stones, and air movement through the stones.

When rotation occurs, centrifugal force is applied to the topstone and the grist which is moving between the stones. Centrifugal force varies as the square of the velocity so that the grist is subject to an increasing force as it moves from the eye to the rim of the stones. The application of furrows to each stone helps to crack and reduce the grain and when they are large enough to act as airways they provide ventilation and help keep the grist cool. Whatever the pattern of the furrows on the stone faces (straight, spiral, circular arc etc.) they are arranged to produce a scissor action which pushes the grist outwards to the rim. This force is a maximum close to the eye and a minimum at the rim.

When the grist carries part or all of the weight of the topstone friction occurs between the grist and the stones. This form of energy manifests itself in reduction of the grist, wearing of the grinding faces and in heating the grist and stones.

If the furrows are large enough to act as airways the centrifugal force produces an outward flowing current of air which removes heat and helps to transport the finer fraction of the grist. When the furrows are relatively small, such as those used in the Westree stones, or alternatively the grist flow rate approaches the capacity of the stones, then the furrows become full and air movement ceases.

Of these forces which occur within millstones, the centrifugal force is dominant in producing movement outwards and no further encouragement is necessary, either in the form of furrows or inclination of the grinding faces. Modern rotary millstones are flat, but in earlier periods they were sloped, usually the earlier their date the steeper the slope. Although there are exceptions, generally Roman millstones

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17. It is convenient to use the term grist for the corn products between the stones; (grist = grain intended to be or that has been ground).

have slopes steeper than medieval stones. Whether or not this was because they considered it necessary that gravity should help the grist through the stones, or that the slope was an evolutionary relic from rotary querns, is unclear. An alternative explanation is that they considered a slope necessary to keep the topstone in place, but this is fallacious, because a neck seal, necessary to stop grain from falling through the bedstone eye, would have acted as a bearing, albeit crude.

There are apparently no published values for the friction coefficient of grinding although it is possible to derive values from tests where the power necessary to drive particular millstones has been established[18].

The absence of established theory for millstone behaviour means that predicting the performance of Roman or other early style millstones is very difficult. However, the study of the power absorbed by millstones is facilitated by using formulae associated with clutches, where the surfaces under consideration occupy an annulus. Where the surfaces are inclined to a plane normal to the axis of rotation, as in Roman millstones and querns, the formula derived for cone clutches is particularly relevant. Using this formula it is possible to determine the coefficient of grinding for millstones. This allows the development of a relationship between the torque (or power), speed, weight and angle or inclination of the surfaces, with a coefficient of grinding.

It is worth noting that a similar approach to establish the torque necessary to drive millstones was taken by Fabré as quoted by d'Aubuisson[19].

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18. John Sutcliffe in Treatise on Canals and Reservoirs, 1816, states that a 30 h.p. engine will power five pairs of constantly working French burr stones, four foot eight inches in diameter (p.384) at a speed of 95-100 rpm when the grain is moderately dry (p.285). Making assumptions concerning stone thickness, density etc., this equates to a coefficient of grinding of 0.069. Kozmin also states 1/20 to 1/22. Peter A Kozmin, Flour Milling, London, 1921, p.193.

19. Fabré, form his work upon the mills of Provence, estimated the resistance for milling wheat, supposing it to act at two-thirds of the radius of the runner stone, as 1/22 or 0.045 of its

The clutch formula can be expressed in one of two ways. The first, has been derived on the basis that constant wear occurs across the friction faces, and the second method is based on constant pressure existing across the friction faces.

These are;

for constant wear, $T = \mu W/2 \times (R_1 + R_2)$ Cosec ϕ

for constant pressure, $T = 2/3 \times \mu W \dfrac{(R_1^3 - R_2^3)}{(R_1^2 - R_2^2)}$ Cosec ϕ

Where Cosec ϕ = 1/Sine ϕ and ϕ = inclination from the horizontal.

T = torque ft. lbs.

R_1 = radius of millstone rim in ft.

R_2 = radius of millstone eye in ft.

W = weight of the top millstone in lbs.

μ = coefficient of grinding.

In practice the formula for constant pressure produces a higher power figure than the constant wear method. The question as to whether or not working millstones suffer constant pressure or constant wear, or some other mode of mechanical behaviour, is most difficult to resolve. A brief discussion on this issue follows.

First let us assume that;-

(a) the millstone material is homogeneous and that hardness is constant between and across all grinding faces.

(b) the product between the grinding faces is not homogeneous; it varies from whole grains at the eye of the stone to meal at the skirt. Moreover its moisture content and temperature will vary.

(c) a steady state condition exists when the stones are working under load, i.e., constant feed rate and quality, input equals output, at constant speed.

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weight. See J.F.d'Aubuisson de Voisins, A Treatise on Hydraulics, for the use of Engineers, trans. Joseph Bennett, Boston, 1852, p.447.

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What is meant by constant wear? Presumably that the thickness of material removed from the millstone is constant across the faces. If the wear at any given radius is the same for both the top and bottom stones, then the inclination of the profile will not alter[20].
If, because of an un-homogeneous product, we assume unequal wear, and greater wear did occur at a given radius, then the pressure would reduce at that radius but increase simultaneously elsewhere (total weight being constant). This increase in pressure would automatically cause an increase in wear so that there is a natural tendency for the wear and pressure variations to be self-regulating and to balance out across the faces. However, theory tells us that the constant wear condition requires more power and therefore it follows that the two conditions cannot co-exist.

One other approach to this problem is to view the product flow as a fluid. Assuming that steady state conditions exist in the working millstone, gravity, centrifugal force and the action of the furrows induce a constant flow through the stone from eye to rim. The grain and meal moves and responds to the forces to which it is subjected, tending to move away from high pressure areas to low pressure areas. In a closed system a fluid has constant pressure throughout but in the millstone it is an open system. Nonetheless this theory supports the notion that the product, when flowing, responds to pressure differences and therefore tends to create constant pressure[21].

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20. With a homogeneous stone it is difficult to imagine that wear could be unequal between the bottom and top stones at any given radius with the exception that the bottom grinding face takes the weight of the grain and meal, an infinitesimal increase in pressure compared with the top grinding face. Nonetheless this pressure difference at opposite points on the stone faces can be assumed to be, for our purposes, more or less constant across the radius of the stone.

21. Pressure differences would occur if meal was returned to the stones to be re-ground because the centre of the stones would not grind the meal, being open at the eye to receive whole grains. It follows that wear would not be constant.

If the gradient of the face does not alter (there is no difference in the wear between the faces at any given radius) then the wear must be constant. In support of this is the fact that the miller dresses his stones so that the wear occurs right across the faces from the moment grain enters the stones. When the stones are re-dressed, he deepens the furrows, takes off any high spots and literally 'chases' the work profile.

To summarise, it can be seen that the question of whether or not constant pressure or constant wear occurs between working millstones is unclear. Let us therefore develop both formula and see how the results compare.

Both formula express that $T \propto R\mu W \operatorname{Cosec} \phi$ where R is a relationship of R_1 and R_2. When R_1 (the millstone rim radius) is significantly greater than R_2 (the eye radius) their relationship within the formula becomes insensitive to the result of T. For example, let us assume that $R_1 = 6R_2$, which is a typical relationship, then,

$$T \text{ (for constant wear)} = \mu W/2 \times 7/6R_1 \operatorname{Cosec} \phi = 0.58\ R_1 \mu W \operatorname{Cosec} \phi$$

$$\text{and } T \text{ (for constant pressure)} = 2/3\ \mu W\ (R_1^3 - R_1^3/216) \operatorname{Cosec} \phi$$

$$\overline{\qquad\qquad\qquad\qquad}$$

$$(R_1^2 - R_1^2/36)$$

$$= 0.667\ \mu W R_1 \operatorname{Cosec} \phi$$

These results, for constant wear and constant pressure, are relatively close and it is considered reasonable that they can be averaged at 0.6235, which is within 7% of the two extremes. For convenience it is suggested that the formula can be simplified to $T = 5/8\ \mu W R_1 \operatorname{Cosec} \phi$.

When torque for the millstone is established, this can be related to power by using the formula,

$$\text{Power (h.p.)} = \frac{2.\pi.N.T}{33000}$$

Where, T = torque ft.lbs.
N = rpm of the stones.

Substituting the average value for T we have,

$$H.P. = \frac{2.\pi.N.5/8.\mu WR_1 \text{ Cosec } \phi}{33000}$$

Therefore H.P. α NμWR Cosec ϕ and, for a given pair of millstones whose diameter, coefficient of grinding and surface inclination are constant,

H.P. α speed x weight.

If we substitute from chapter four below the determined values of horsepower, speed, weight etc., from the Westree millstone experiment, (see chapter four below), we have,

$$HP = 0.51 = \frac{2 \times 3.142 \times 84.6}{33{,}000} \times (5/8 \times 0.984)\ \mu \times 143 \times 1.011$$

Therefore μ, the coefficient of grinding, = 0.356 or 5/14.

It is interesting to compare this figure with the results of friction tests undertaken by the writer using Mayen lava stones in a non-rotary mode[22]. This experiment, using furrowed fragments of Roman millstones, showed that the coefficient of grinding for grain was 0.231 and for meal 0.532. This suggests that the friction between rotating millstones varies across the surface, being a minimum at the eye and a maximum at the rim or skirt of the stones. The coefficient produced by the Westree results, must be viewed as an average, not only of the constant pressure/wear calculations, but also of the con-

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22. Tests undertaken in March 1976 using a standard friction bed with free running pulleys and weights, with the stones arranged to produce a 'scissor' action on the furrows and loaded to simulate a topstone thickness of 4 inches.

ditions which exist across the grinding faces. The Westree coefficient of 0.356 for rotary work, appears to relate well to the non-rotary grinding coefficients, which ranged from 0.231 to 0.532.

The Westree experiment described in Chapter Four has provided a coefficient of grinding for lava millstones dressed in the Roman style, using one set of variables including slope, dress, diameter, weight, speed and grain type. How confident can we be about the extrapolation of the results to other situations?

In determining the coefficient of grinding in laboratory conditions neither the weight of the body nor its velocity, after motion has begun, has an effect on the result. The slope of the surface does have an effect on the result, but as this relationship can be determined by trigonometry, it can be expressed in any of the power formulae involving friction. The effect of varying slope is integrated within the friction formula for cone clutches and represented by the variable Cosec ϕ. To summarize, variation of the weight and speed of the top millstone theoretically has no effect on the friction value determined by the rig experiment and different slopes are automatically covered by the torque formula when the power to drive them is calculated.

The grinding coefficient determined by the experiment (0.356) is substantially greater than those for modern wheat stones as suggested by Sutcliffe[23] (0.069), Kozmin[24] (0.045), and Belidor[25] (0.0286). Although the figures produced by these authorities range widely by a factor of over two, the Westree figure is much greater. Why is this?

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23. John Sutcliffe, as note 18.

24. Kozmin, as note 18.

25. J.F.d'Aubuisson de Voisins, as note 19, quoting Belidor & Navier.

The answer surely lies in the differences of material and dress of the grinding surfaces and the physical properties of the material being ground. The obvious difference lies in comparing lava millstones with French burr millstones, which was the material invariably favoured for wheat milling by modern millers.

In lava stone it is the gas cavities which provide the cutting and reducing edges necessary to effect the milling process, with each cavity offering resistance to motion. With non-porous millstones, such as French burr, the miller has to resort to very fine furrows or 'stitching' to produce wheatmeal. The natural efficiency of lava stone, of the right porosity, for grinding is reflected in the fact that many Roman lava stones are without furrows, confirming that a reasonable product can still be obtained without additional cavities in the grinding faces.

The dressing of modern wheat stones developed during the last two centuries to become a practice requiring great skill and precision. Many different forms of dress appeared, each with its own design of furrows, stitching and profile, and each having their exponents and supporters. Very little of this was published and the methods and skills relating to millstone dressing was communicated almost entirely by practice, custom and oral tradition. The styles varied greatly, not only among the millers themselves but also between areas and countries. This range of modern millstone dressing styles tends to cloud any attempt at comparison with the Westree stones. However, a simplified view is that modern stones were clearly developed to produce a more refined product and in persuing this objective, millers sought the material best suited to carry and maintain accurate and fine profiles for flour milling. Lava stones could not provide this.

In support of this theory we should take note that the coefficient of grinding for the lava millstones at Barbegal was approximately 0.35, using the power formula established above[26]. Wulff's examination of modern horizontal watermills in Persia suggests that a coefficient of

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26. Taking the HP as 2.4, millstone speed 47 rpm. and a millstone weight of 834 lbs.

grinding in the order of 0.24 occurred using millstones which were clearly not french burrs and therefore unlikely to have been dressed in the modern style to produce refined products[27].
The writer concludes that it is the physical properties of modern millstones combined with the fineness and accuracy of their dressing which produces a grinding coefficient much lower than that from the Westree experiment.

In the making of the Westree rig, resources, time and cost influenced its scale, particularly the size of the millstones. The size of millstones chosen was at the bottom end of the range for water-powered Roman millstones and this raises the question, would the grinding coefficient have been different with larger diameter stones? During the Westree grinding experiments a sample of the meal which had been passed through the stones twice showed that no further refinement had taken place, suggesting that the stones had reached the limit of reduction. If this is correct, it also suggests that if the stones had been larger, the product would have been the same. In other words, refinement is not dependent on size of stone but material and dress. Thus we come to the conclusion of lava stones producing a meal which is coarse by modern standards; in other words they are unable to produce fine flour. We can also conclude that if a much larger pair of stones produced the same coarseness of product at the rim, the average coefficient of grinding would be the same as for a smaller pair, such as used in the Westree experiment.
On the subject of wheat type, it would have been appropriate to have conducted the milling experiments using the unique strains of Emmer and Spelt wheat grown and harvested at Butser Ancient Farm Trust, but this was not possible. What difference this might have made to the results, and the relevance which these wheats have to that which was harvested in the Roman corn lands is not clear.

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27. Hans.E.Wulff, 'A Postscipt to Reti's Notes on Juanelo Turriano's Water Mills', Technology and Culture, Vol. VII, No.3, 1966, pp.398-401.

How are feed rate and grinding friction related? From the power formula discussed earlier in this chapter, theory tells us that provided there is always meal between the stones' faces, and the diameter, speed, dress, weight and other factors remain constant, then the amount of power required is also constant. Under these conditions the work being done at the stone faces on the grain or meal does not change, and greater throughput simply means that the thickness between the stones is greater, and the product spends less time in contact with the stone resulting in a coarser meal.

Thus the same power can be used to produce greater throughput of less refined meal. A pair of millstones running at constant speed can grind twice the quantity of corn if it is produced as coarse meal for animal food rather than meal containing fine flour[28]. For this to happen, and the relationship Power α NW to hold true, means that the throughput (Q) is directly related to the fineness (f) or particle size of the product i.e., an increase in coarseness would facilitate an increase in throughput.

A particular pair of millstones, such as the Westree lava stones, will produce a meal whose fineness is <u>limited</u> by the inherent grinding properties of the stone and its dress, but <u>determined</u> by the throughput flow rate within limits[29]. The meal issuing from millstones has a range of particle size, from fine to coarse, and if throughput is increased with all other factors constant, the product will become generally coarser. For a given pair of millstones the fractions of product (e.g., flour, middlings, bran etc.) can therefore be varied within limits but the finest particles cannot be reduced further. Neither weight, speed or area of grinding surfaces can bring about further fineness or reduction; only a change of stone material can do this.

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28. <u>Industrial Archaeology of Watermills and Waterpower</u>, Project Technology Handbook, No. 11, p.35. Heinemann Educational Books/Schools Council.

29. There is clearly a minimum flow limit, to keep the stone faces apart, and a maximum flow limit when the capacity of the stones is exceeded and proper grinding action ceases to take place.

So the coefficient of grinding is not a function of product fineness or flow rate, but a property of the stones relating to work done upon the product. A change in grain type or, say moisture content, should be viewed as affecting the flow rate rather than the coefficient of grinding, i.e, a higher moisture content would require more power and therefore the production/h.p. hr. would reduce.

Within the Westree experiments the effect of the grains' moisture content on the power requirements has not been determined. Although the 16% moisture content of the Westree wheat is slightly high by modern standards it can probably be compared to the moisture content of grain coming straight from the field or storage. When corn drying was practised, the power requirements would have been somewhat less, though by how much is unknown. As Moritz suggests, for climatic reasons, Roman wheat probably contained less moisture than English wheat[30].

In conclusion the writer considers that taking all things into account, it would be prudent to view the coefficient of grinding provided by the lava stones of the Westree rig as being of the right magnitude, but not necessarily very accurate. The writer therefore proposes that the coefficient of grinding of 5/14 for lava stones should be taken as having an accuracy of, say, plus or minus 20%.

Using this coefficient of grinding the power necessary to drive the millstones at different speeds can be determined, using the formula given above, with each set of mechanical ratio power lines being unique to the pair of millstones being considered. At each mill site consideration must therefore be given to having a thicker top-stone, especially at the Agora, where all the stones found were remarkably thin. Clearly it would be misleading to limit a power analysis to a millstone that was at or near the end of its useful life. For example, the Agora top-stones finished up at approximately two inches thick and started life perhaps three times as thick and heavy when

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30. L.A.Moritz, Grain-Mills and Flour in Classical Antiquity, Oxford, 1958, p.222, Note U.

the power required would have been much greater. To illustrate such a range of power for the life of a stone one need only to illustrate two sets of mechanical ratios (MR's), one for the thin condition and one for a thickness relating to a near-new condition. Our interpretation of the resulting graph and the conclusions concerning the probable gearing ratios and flow rates must therefore reflect millstone life.

E2. Power for Bearings and Gears.

A watermill, like any other machine, suffers from friction losses when in motion. In addition to the millstones these losses occur at the journal bearings at each end of the wheelshaft (no Roman evidence of overhung gears or wheels), the footstep bearing at the bottom of the millstone spindle and the friction between the gears.

In the Haltwhistle analysis these bearing losses have been calculated with great care to the extent of designing the entire wheel (both clasp-armed and radial), shaft, spindle and lantern in order to get realistic bearing reactions. Allowances for different moisture contents of the wheel and shaft, and alternative materials for journal (bronze, iron) and bearings (wood, stone) were considered. The losses in the bearings represent some 3 to 4% of the total power generated. Gear losses are expressed as a proportion of the power being transmitted. All bearing and gear losses are then expressed in terms of wheel speed at different gearing ratios.

F. Balance of Power - Mill Speeds.

All friction losses for the millstone, gearing and bearings are then summated and calculated for different wheel speeds for a range of gearing ratios. Allowance has to be made for the effect of mechanical ratio where higher rotational speeds occur in parts of the machine. All of these losses are directly proportional to speed and can therefore be related to wheel speed, represented by a straight line on the power/wheel speed graph.

The total power consumed by the mill for each different gearing ratio is calculated and can be represented by a series of straight lines, radiating from the zero co-ordinates on the power graph, thus, see Fig. 2.

Generally the higher the MR, the higher the power required. Where intersection occurs, the power generated balances the power necessary for all friction losses.

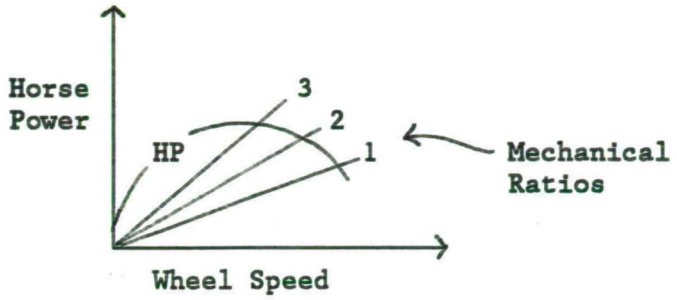


Fig.2. - Friction Power and Wheel Speed.

With high speed impulse wheels, this balance seems to occur somewhere between the maximum power and the higher wheel speeds. A simplified view of this is that if the mill is over-powered, as at the Agora with its thin millstones, then the balance will occur near the speed limit of the wheel, whereas if the power demand is close to the maximum of the wheel, the balance will occur close to half the wheel's maximum speed.

The balance of power graph for the Haltwhistle Burn Head watermill analysis is shown in Fig. 3.

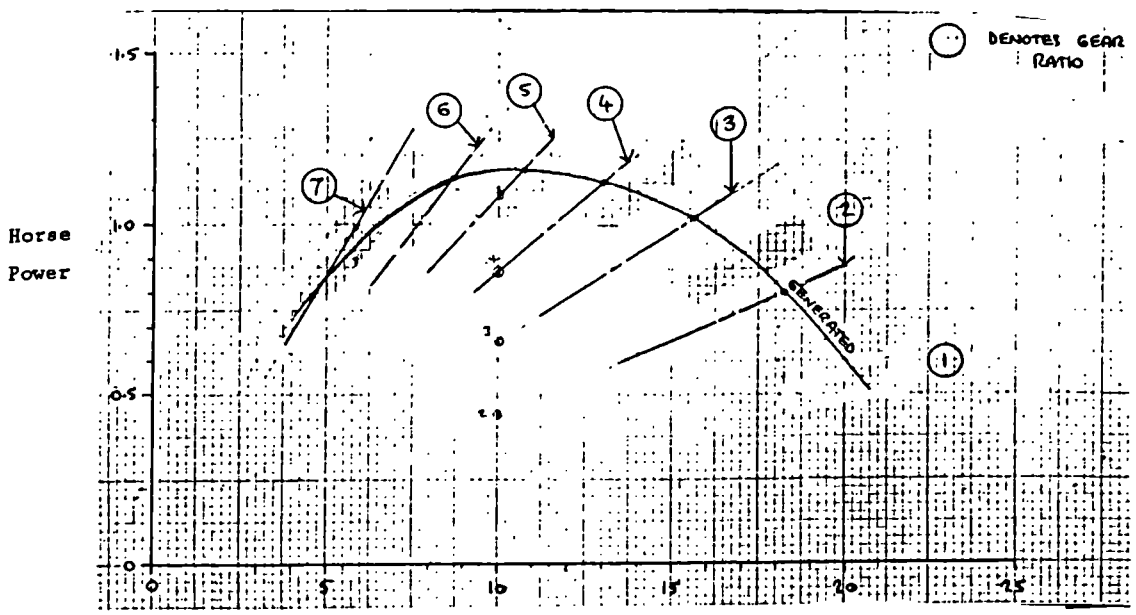
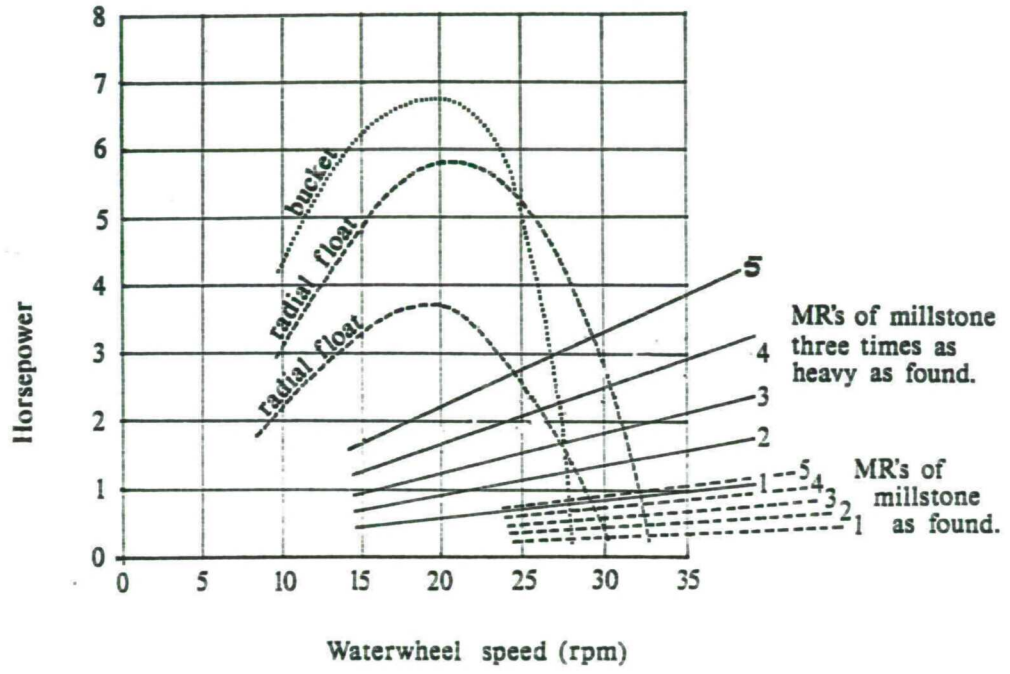


Fig.3.- Haltwhistle Burnhead Mill - The Balance of Power.
(Using top stone no. one.)

In the Agora power graph (see Fig.4.) the opportunity has been taken to show the effect of having different depths of water in the headrace and superimposed on these are a range of MR values from 1-5, both for thin and thick stones. With this information we can begin to suggest what gearing ratios existed and gain an insight into the effect of having different headrace water depths.

Fig. 4

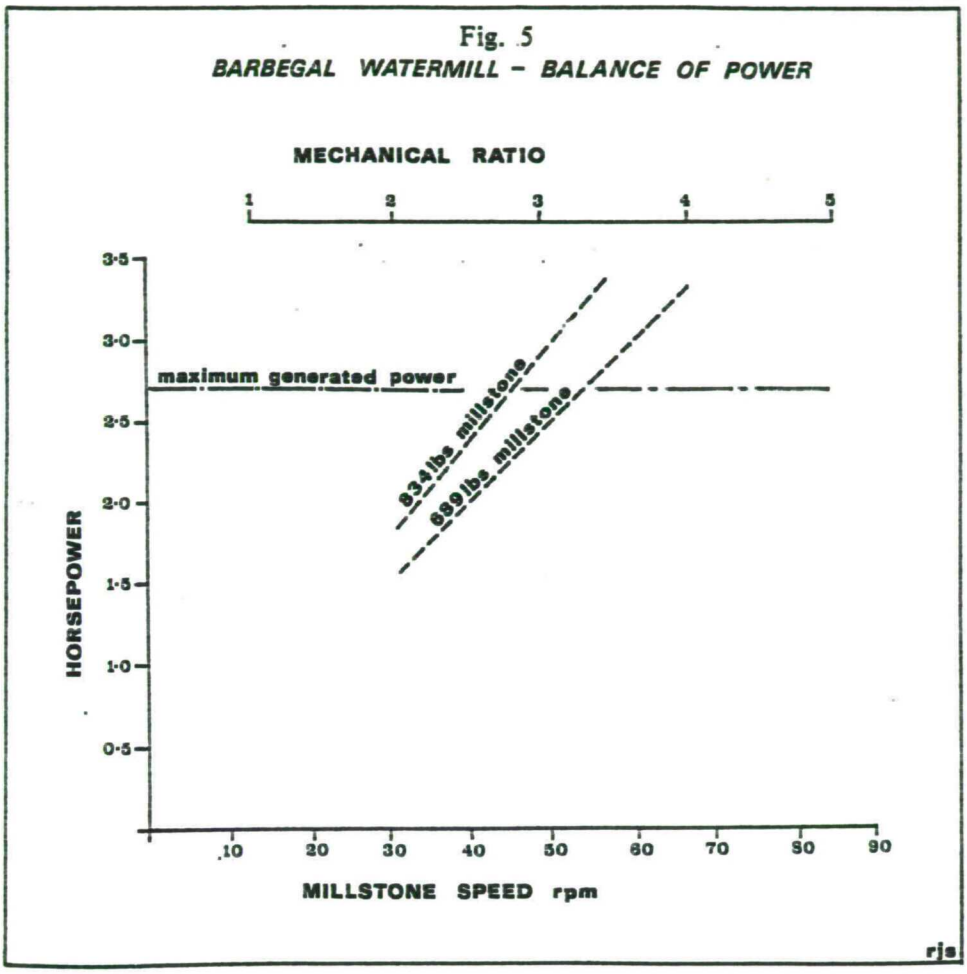
ATHENIAN AGORA WATERMILL - BALANCE OF POWER



The Barbegal power graph is simple, where the maximum generated power (determined by a full aqueduct) can be represented by a horizontal line across the graph. See Fig. 5.

Fig. 5

BARBEGAL WATERMILL - BALANCE OF POWER



Onto this can be superimposed the power lines which relate to different millstone thicknesses, one for each. As the wheel runs at a constant speed the lower axis of the graph can be millstone speed. The total power required to drive the millstone and overcome all other friction can be established for any speed, the point plotted and a straight line drawn between it and the zero of co-ordinates. As before, the intersection of power lines are positions where the balance of power occurs.

The graph provides a view of the relationship between stone thickness (or weight) and MR against a base of millstone speed. It shows, of course, that as the stone gets lighter the wheel has surplus power that could, with a change in MR (increase) drive the stone faster.

G. Equation Sequences.

Examples of the equation sequence used in the analysis are given in Appendix A. The first given is Haltwhistle Burn Head, a race-fed undershot waterwheel; the second is the Agora specimen, an example of a high-velocity high-head wheel; and finally the third, Barbegal where overshot bucket-type wheels existed.

Appendix A

Haltwhistle Burn Head Watermill - Equation Sequence.

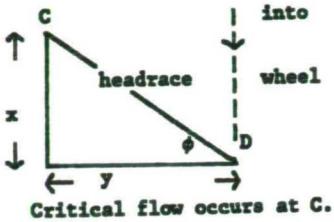
References

Constants and variables

d_c = depth of water at c(ft)
Q = volume flowing(ft^3/sec)
g = 32.2ft/sec^2
b = width of channel(ft)
V = average velocity(ft/sec)
A = c.s.a. of flow(ft^2)
E = specific energy(ft)

1.0 Objective - to determine the velocity of the water entering the wheel

Data required - gradient, length and sections of the headrace.



Critical flow occurs at C.

Assumptions are made concerning water behaviour at the wheel (D) which predetermines a theoretical depth at D. This figure is confirmed by stage 1.4 of the equation sequence.

1.1 Using $d_c^3 = \frac{Q^2}{gb^2}$ where $Q = V_c.A_c$

See W.J.Duncan, A.S.Thom, A.D.Young, An Elementary Treatise on the Mechanics of Fluids, 1960, pp.424-427.

1.2 and $E_c = d_c.\cos^2\phi + \frac{V_c^2}{2g}$

Stage 1.1 has been derived from ;-

$$\frac{Q^2}{g} = \frac{A_c^3}{b_c}$$

1.3 $x + E_c = E_D$

1.4 $E_D = d_D.\cos^2\phi + \frac{Q^2}{2g.A_D^2}$

Critical flow is a change from laminar to non-laminar condition where the law of resistance changes (relationship between head and velocity).

By putting A in terms of d, and by trial and error, a value for d_D is established.

Using $A_D = d_D.b_D$

1.5 $V_D.A_D = Q$

Where V_D is velocity of water into the wheel.

2.0 Objective - to determine the effect of headrace friction on water velocity.

Data required - headrace material and section.

Using Manning's equation where

2.1 $$s = \frac{n^2 . V^2}{2.22\ R^{4/3}}$$

2.2 s.y = friction loss $_{C-D}$

2.3 new E_D = original E_D - friction loss$_{C-D}$

2.4 loop back into 1.4 to get revised V_D.

s = energy slope
V = average velocity
$= \frac{V_A + V_B}{2}$
n = roughness coefficient
R = average hydraulic radius
$= \frac{\text{c.s.a.}}{\text{wet perimeter}}$

3.0 Objective - to determine the scouring velocity where the headrace was cut into sand and gravel to see if revetment of the banks was necessary. A single post hole was found in a position which suggested that revetment probably existed.
Data required - length, section and gradient.

M.Bazin, Annales des Ponts et Chaussees, 1897, vol.IV, p.20. See F.C.Lea, Hydraulics, 1908, pp.182-190.

For Chezy's formula see W.J.Duncan, A.S.Thom, A.D.Young, An Elementary Treatise on the Mechanics of Fluids, 1960, pp.424-427.

Using Bazin's formula, where

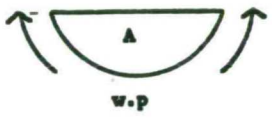
3.1 $$C = \frac{157.5}{1 + \frac{\Omega}{\sqrt{m}}}$$

Ω = coefficient for earthen channels.

C = coefficient
m = R = hydraulic mean depth.
$= \frac{\text{c.s.a.}}{\text{wet perimeter}} = \frac{A}{w.p}$

Using Chezy's formula

3.2 $V = C\sqrt{m.i}$.



V = mean velocity(ft/sec) of the water.
i = hydraulic gradient of water (in uniform flow is equal to the bed gradient).

3.3 Using Q = A.V where Q is known from 1.1 above.

Then combining 3.1, 3.2 with 3.3 and expressing m in terms of A/w.p., and assuming a depth of 0.9ft., a value for m is established. Substituting this value of m into Bazin's formula in 3.1, then into Chezy's formula in 3.2 gives a velocity.

An alternative and simpler method is using Q = V.A. where A is based on the assumed depth of 0.9ft., confirmed by the equation above.

Using information coming from Du Buat as quoted by Rankine, this velocity can cause erosion of pebbles 1.5 inches diameter, so that revetment was theoretically necessary.

4.0 Objective - To determine the power generated by the wheel at the flow rate equivalent to the maximum capacity of the wheel (Q from 1.1 above).
Two alternative methods can be used,-
(a) kinetic energy x wheel efficiency
(b) using the torque generated by the force of the water, calculate the HP less an allowance for friction, leaks and splashing.

(a) Using the kinetic energy method;
Data required, volume and velocity of water flowing.

4.1 $$K.E. = \frac{V^2.Q.62.5}{2.g.550} = h.p.$$

4.2 Power generated = $\cap$ x h.

(b) Using torque method;
Data required, volume flowing, wheel and water velocities, float area and cross section of water entering wheel.

4.3 $$\text{Force } P = \frac{Q\varepsilon(V-v)-[\ 0.5h_o^2.b.\varepsilon-0.5t^2.b\varepsilon\ ]}{g}$$

4.4 Torque T = force(P) x radius(ft)

4.5 $$H.P. = \frac{2.\pi.T.N}{33000}$$

Where $$N = \frac{60 \times v}{\pi \times \text{wheel dia. at mid-float}}$$

$$v = V_W \times 0.425$$

4.6 power at driven gear = H.P less friction, leaks and splashing.
This result of this method, using torque, compares reasonably well with the K.E. method used in 4.2 above.

5.0 Objective - to determined the power generated at different wheel speeds, assuming that the efficiency of application will follow the theory -

K.E. = kinetic energy in h.p.

Q = volume flowing($ft.^3$/sec) See 1.1 above.

V = V_W = velocity of water entering wheel. See 1.5 above.

$\cap$ = wheel efficiency.

P = force acting on floats(lbs)

Q = volume flowing($ft.^3$/sec)

ε = density of water(lbs/ft^3)

V = V_W = velocity of water entering the wheel(ft/sec)

v = mean float velocity(ft/sec)

h_o = depth of water at the wheel (ft)

b = width of wheel(ft)

0.425 = depth of water before the wheel [see pp.12, 13 of the author's analysis.]

N = rpm of wheel

5.1 Efficiency $= \frac{2.v(V_W - v)}{V_W^2}$

5.2 Entering various values of v and V_W, and allowing for the 0.425 factor and the power generated (from 4.6, 4.2) at a certain wheel speed (N), a curve of power generated against wheel speed is produced.

6.0 Objective - to determine the power necessary to overcome the friction of the bearings and gears.
Data required - bearing loads, velocities and coefficients of friction.

An assumption is made that the power loss for the gears is 5% of the total.

6.1 Bearing loads have been calculated by reconstructing the wheel, shaft, gears and millstone spindle, allowing for different wood densities due to moisture content and exploring the differences between a clasp-armed wheel and a radial armed wheel design.

6.2 Journal velocities and pressures have been calculated having regard to extant Roman specimens [drainage wheels and water-wheel bearing blocks], and work by General Morin, Tredgold and Buchanan.

6.3 Bearing materials of stone and hardwood have been considered, influenced by extant evidence at Barbegal and Ickham, together with the works of Rankine, Hunter, Palmer and Wailes. Journal material of Bronze and wrought iron are influenced by Roman mill-spindle evidence and drainage wheel shafts [Davies, Palmer].

6.4 Coefficients of friction for bearings have been influenced by Morin, Wailes, Thurston and Wheeler.

6.5 The power to overcome friction of bearings and gears is expressed in terms of the wheel shaft speed, which relates to item 5 above.

7.0 Objective - to determine the power necessary to drive the millstones.
Data required - the weight, material and diameters of the upper millstone(s), and the coefficient of grinding.

7.1 The torque necessary to rotate a millstone can be determined by using a formula normally applied to cone clutches, where-with pressure constant,

$$T_P = \frac{2\mu\, W.r_1^3 - r_2^3 \text{ cosec } \phi}{3 \quad r_1^2 - r_2^2}$$

or, alternatively, for constant wear,

$$T_W = \frac{\mu.\ W\ (r_1 + r_2) \text{ cosec } \phi}{2}$$

An average of these two methods has been used where,

$$T = 5/8\ \mu W r_1 \text{ Cosec } \phi$$

T_P or T_W = torque with constant pressure or wear (ft.lbs).

μ = coefficient of sliding friction.

W = weight of upper millstone(lbs)

r_1 = outer radius of upper millstone.(ft.)

r_2 = inner radius of upper millstone.(ft.)

ϕ = inclination of grinding face.

7.2 A value for μ can be established by using values for W, H.P, N, ϕ and r_1 as determined in the Westree experiment. This produces o coefficient of grinding of $\mu = 0.356$.

The coefficient of grinding used for lava stones was determined by the Westree experiments.

7.3 Using,

$$H.P. = \frac{2.\pi.N.T.}{33000}$$

the power absorbed by the millstones can be determined for different speeds.



8.0 Objective - To determine the power to drive the whole mill at different speeds. This is found by summating the power for bearings and gears [see 6.5] and millstones [see 7.3] in terms of wheelshaft speed N. Allowing for different gear ratios, a graph can be constructed of power against water-wheel speed.

9.0 Objective - To determine the balance of power that occurs at different mill speeds. This is achieved by superimposing the power generated curve [5.2] onto the power required to drive the mill using different gear ratios [8.0] employing a common base scale of wheel speed.

9.1 From the graph the millstone speed for different gear ratios can be determined. For the particular top stone chosen, a maximum speed range can be identified which relates approximately to the greatest generated power.

9.2 A summary of the Haltwhistle analysis is provided in the table below.

Balance of Power			
MR	Wheel speed (rpm)	Stone Speed (rpm)	H.P.
2	18.3	36.6	0.78
3	15.6	46.8	1.00
4	13.0	52.0	1.11
5	10.7	53.5	1.14
6	8.7	52.2	1.12
7	5.9	41.3	0.88

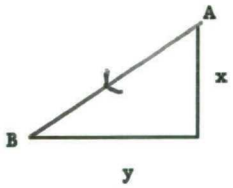
The conditions which apply to these figures are (a) velocity of water into wheel 14.76 ft/sec. (b) quantity of water to fill wheel 11.2 $ft.^3$/sec. (c) top millstone weight 363.7 lbs.

9.3 Finally the effect on the mill's behaviour of an ageing top stone, and other different size and weight top stones has to be debated, including the implications on gear ratios and mill throughput.

Athenian Agora Watermill - Equation Sequence.

1.0 Objective - To determine the velocity of the water entering the wheel, without friction.

Data required - gradient, length and section of headrace.



1.1 Using $D^3 = \frac{Q^2}{gb^2}$ find Q

1.2 Then using $Q = V_A.A$ find V_A

1.3 Using $B_E = B_D.\cos^2 + \frac{V_B^2}{2g}$

by putting A in terms of d, and by trial and error, a value for B_D is established.

1.4 Using $A_B = B_D.B$ find A_B

Assumptions (a) that critical flow occurs at the top of the steeply inclined trough above the wheel (point A). (b) width of trough same as the stone lined headrace upstream. (c) different depths of water are taken at A.

D = depth of water at A(ft)

Q = volume flowing(ft^3/sec.)

g = 32.2(ft/sec^2)

b = width of trough(ft)

V = average velocity(ft/sec)

A = c.s.a. of flow(ft^2)

E = specific energy(ft)

Then using $V_B.A_B = Q$ find V_B

The above sequence is repeated for different depths of water in the headrace.

2.0 Objective - To determine the effect of headrace friction on water velocity.
Data required - headrace material and section.

2.1 Using Manning's equation, where find S

$$S = \frac{n^2.v^2}{2.22\ R^{4/3}}$$

Then losses due to friction between A and B are y x S. Energy at B (B_E) is therefore revised.

2.2 Substitute new value for B_E into 1.3 and re-calculate 1.4 for final velocity at B.

3.0 Objective - determine additional velocity of water due to free fall from end of trough into the wheel.
Data required - height of fall.

3.1 Using $V^2 = U^2 + 2vs$.
Find V and add to V_B above in 2.2 to give final velocity into wheel.

4.0 Objective - to determine the power generated by the wheel using buckets.
Data required - design of buckets and wheel

4.1 The method of analysis is to generate drawings of the wheel and calculate the volume of water that each bucket holds, allowing for rate of flow and loss of water due to centrifugal force. For each bucket the torque created by the impulse caused by the velocity change and the water striking the edge of the buckets is calculated and summated for the whole wheel. This is then used to find the generated shaft horsepower This is done for different wheel speeds and flow rates and shown on a power/wheel speed graph.

5.0 Objective - To determine the power generated by the wheel using radial floats.
Data required - Design of the floats and wheel.

Assumption - (a) material of trough (b) roughness.

S = energy slope

v = average velocity = $\frac{v_A + v_B}{2}$

n = roughness coefficient
R = hydraulic radius
= $\frac{\text{c.s.a.}}{\text{wet perimeter}}$

Assumptions - position of end of trough relative to crown of wheel.
V = final velocity(ft/sec)
U = initial velocity(ft/sec)
s = drop(ft)
f = 32.2(ft/sec^2)

Assumptions - number of buckets, their depth and configuration.

Assumptions - number of floats and their depth.

5.1 The same analysis and resolution as described in 4.1 is used, and the inform -action displayed on the same power/speed graph. For a radial float wheel the power due to impulse and weight of water carried is separately calculated at all speeds.

5.2 The work done due to impulse is given by the formulae used in the Haltwhistle sequence 4.3 - 4.5.

6.0 Objective - To determine the power necessary to drive (a) a typical millstone as found (b) a thicker, newer, same diameter millstone.
Data required - Diameters, weight and coefficient of grinding for the stones.

6.1 The same calculations are used as in the Haltwhistle sequence [see 7.0 - 7.3].

6.2 The power necessary to drive the stones at different MR's can be shown on the power /wheel speed graph. (See Fig.4).

7.0 Objective - To discuss the likelihood of whether the Agora wheel was a bucket or radial float design.

7.1 The power generated/wheel speed graph shows us that the bucket wheel losses are considerable due to centrifugal force at wheel speeds over 18rpm. Moreover, the power necessary to drive fairly thick millstones at speeds in excess of 120rpm, was easily provided by a headrace at least half full of water.

7.2 The graph suggests that the balance of power would have occurred at a wheel-speed of approximately 26-32rpm and that it was therefore unlikely that the Agora wheel had buckets.

TABLE ONE

Water velocity into wheel (ft/sec)	Depth of water in headrace (inches)	Flow rate (ft^3/sec)
19.2	15	10.9
17.7	12	7.8
17.1	9	5.1
12.1	6	2.75

TABLE TWO (Radial Float Wheel)		
Wheel speed (rpm)	Horse power developed	
	12inch. depth at 7.8ft^3/sec	15inch. depth at 10.9ft^3/sec
5	0.93	1.19
10	2.26	3.13
15	3.2	4.84
17.5	3.48	5.48
20	3.46	5.81
22.5	3.13	5.69
25	2.59	5.35
27.5	1.74	4.41
30	0.42	2.98
32.5	0	0.95
35.0	0	0

TABLE THREE Radial float wheel.				
Millstone thickness	Balance of power (HP)	MR	Speeds rpm with 12-15ins. depth flow	
			Millstone	Waterwheel
Six inches	2.8-3.2	5	120-145	24-29
	2.1-2.6	4	104-124	26-31
	1.75	3	81-96	27-32
	1.2	2	56-64	28-32
As found two inches	less than one HP	5 4 3 2	between 58-165	between 29-33

Barbegal Watermill - Equation Sequence

The equations used in this analysis are the same as those employed in the Haltwhistle and Agora analyses. For brevity, only the objectives and methods are listed here together with a summary of the results.

1.0 Objective - To calculate the theoretical power generated by a typical waterwheel.
Data required - wheel diameter, width, and bucket/float design.

Method - Establish by drawing the volume of water carried in the buckets, radius and torque; summate to get the total power due weight of water. Then determine the power due to impulse for the same range of wheel speeds. Summate power from weight and impulse. Check the flow rate of the wheel with the aqueducts capacity.

2.0 Objective - To determine speed of overshot wheel.

Method - Using Fairbairn, Bradley, Busquet, and Buchanan figures, agree an average rim velocity for the fall and calculate rpm.

3.0 Objective - Calculate power needed to drive typical topstone at different speeds.

Data required - stone diameters, gradient, material and coefficient of grinding.

Method - calculate for different thickness stones, volume then weight, torque (average of constant wear and pressure) then HP.

4.0 Objective - Calculate power losses for journals, footstep bearings and gears.

Method - Assume gear loss to be 5% of power transmitted; bearing losses based on Halt-whistle analysis.

5.0 Objective - Determine balance of power for certain size stones and then related gearing ratios.

The millstone diameter and surface inclination are according to Benoît.

Method - Determine by graph intersection of power lines.

6.0 Objective - Determine production rate of factory and number of people served.

Method - Using product/power ratio of Westree rig and Sellin's load factor and meal consumption rate.

Balance of power 2.625HP wheel 15.3rpm.

Weight [lbs]	Thickness at eye [inches]	MR	Millstone speed
834	6	2.74	42
689	4	3.33	51

Factory output

Allowing that each pair of millstones absorbs 2.4HP then the production from each pair is;-

$$\frac{2.4\ HP \times 117.[lbs/hr]}{2.2046} = 127\ kg/hr$$

With 16 pairs of stones at 60% load factor then the total output per day is;-

$$16 \times 127 \times 24 \times 60\% = 29{,}261\ kg.$$

If we assume 90% of the product was for consumption, at 900g/person per day then,

$$\frac{0.9 \times 29{,}261}{0.90} = 29{,}261\ people.$$

For further discussion on the load factor and human consumption see chapter 6.

Water flow

The flow required to fill each waterwheel is 6.25 ft^3/sec. Therefore with two series of parallel waterwheels the aqueduct flow has to be at least 12.5 ft^3/sec. Average velocity in headrace is 3.125 ft/sec. (Sellin's is 1m/sec.)

Chapter Four

THE WESTREE MILLSTONE RIG

A. Introduction.

We have seen from Chapter Three above, that in the theoretical hydro-mechanical analysis of a watermill, the calculations require that a value be put to the coefficient of friction for grinding between millstones. (See page 49 above) This coefficient is important because it has great effect on the power necessary to overcome the resistance of the mill machinery to motion.[1]

A few years ago the author undertook friction tests using fragments of lava millstones in non-rotary experiments with wheat grain and meal.[2] The crude nature of these tests and the limitations imposed by the fragments of stone left much to be desired. The coefficients produced by these experiments appeared to be rather high compared with the figures related to the modern power tests which involved stones with a more advanced design of furrows (with furrow patterns, sharper and more efficient profiles) in association with fine 'stitching' or grooves. Moreover there is a danger that a coefficient derived from linear friction tests may be inherently different from rotary friction.

The author therefore resolved to undertake a more refined laboratory test using 600mm diameter rotary lava millstones, either original or replicas designed to match typical Roman stones. Such an experiment might also provide experience associated with the design, building and operation of a corn mill.

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1. The friction of gearing, especially the crude rudimentary types, was the second greatest resistance to the motion of an early watermill, though very much less than the friction between the moving millstones.

2. Experiments conducted at Mid-Kent College of Further and Higher Education during March 1976.

B. Design.

B1. The Millstones.

To determine a friction value it was essential for the millstones to be made of a material and design typical of the Roman period. Throughout the Empire millstones and querns tended to be made either from local stones, if satisfactory stone was available, or lava stone. Because it has suitable hardness, tenacity and porosity, lava stone is a first class material for grinding grain. Before the discovery of quartzose stones in the La-Ferte-Sous-Jouare region of the Department of the Seine, these lava stones were considered to be the best available. It is also homogeneous and therefore monolithic millstones can be made from it. The ancient lava fields which the Romans exploited for centuries were in Germany, in the Rhine valley, west of Coblenz near Mayen.[3] In later periods this quarry and others in the area continued to provide millstones and querns for English corn mills. The grey/black lava stone became known as 'Cullin' stone after Cologne. At Mayen, millstones and querns were made to be transported all over the Empire. Lava was the only stone which had such 'currency' throughout the Empire, and it was for this reason that the author decided that lava stones should be used in the millstone rig.

During the early part of 1985, the author attempted to find a pair of Romano-British lava millstones that would suit the purpose of the experiment. An advert was placed in the *Museums' Gazette* but this appeal proved fruitless, and so the author resolved to have a pair of stones made at Mayen.[4]

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3. See J.Röder,'Die Mühlsteinbrüche von Mayen', Geländedenkmäler einer vor- und früuhgeschichtlichen Grossindustrie, Sonderdruk aus Bonner Universitätsblätter, 1972, pp.35-46; O.G.S.Crawford et.al., The Quern Quarries of Mayen in the Eifel, Antiquity, 1955, vol.29, pp.68-75. Millstones of volcanic origin were also made from the lava at Mount Etna and part of Hungary (Bars Geletnek) where trachyte stones were obtained, though probably not in Roman times.

4. The author was most fortunate in gaining the help of Frau Röder, wife of the late Dr.Röder, an acknowledged expert on the history and development of the Mayen lava quarries. At Mayen the porosity of the lava varies according to the depth and position of the deposits; generally the

For the purpose of establishing a friction coefficient it was felt that small full-size millstones, somewhat larger than querns, should be used. The employment of large millstones would have meant substantially higher manufacturing and transport costs combined with greater labour and more materials for the making of the rig. A diameter of 600mm was chosen for the millstones which is comparable to the largest extant querns and the smallest of the 'Saalburg' type of Roman millstones[5].

It was important that the design of the grinding faces typified Roman dressing, especially the inclination of the faces and the layout of the furrows, and in these respects the author was greatly influenced by extant Romano-British and Saalburg specimens. The furrows of Roman millstones are usually laid out in harps like modern stones, where each segment of the face contains a set of parallel furrows having an alignment arranged to promote a 'scissor' action towards the rim of the stones when they are in motion.[6]

Of those Roman millstones which bear evidence of furrows, the accuracy of the layout can vary, some harps being larger than others on the same face, sometimes with furrows having a negative[7] lead. In

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deeper the deposits the less the porosity and the smaller the gas cavities become. Frau Röder was able to direct the German masons to ensure that the right type of stone was quarried - from the same strata that the Romans used - and to oversee the making of the millstones according to the design. The millstones were quarried and shaped by Mayko of Mayen at a cost of £250. During August 1985 the author visited the manufacturers at Mayen in company with Frau Röder to agree the final dressing details of the grinding faces.

5. Named after a collection of small Roman millstones which exist in the Saalburg Museum.

6. A few Roman millstones have been found with curved or sickle furrows, but these are greatly outnumbered by the number of extant stones having evidence of sets of parallel furrows within harps.

7. Where the scissor action of the furrows in the top and bottom stones theoretically moves the grain and meal towards the eye of the stone rather than the rim.

some lava stones the accuracy of design and execution of dressing is of remarkably high quality, for instance, the large stones in the Museum of London and some of the small Saalburg specimens. We should recognise the difficulties of laying out these designs and cutting them into curved surfaces, unlike modern stones, which have near-enough flat grinding faces. With few exceptions, the sections of Roman furrows are roughly semi-circular and symmetrical.

In the centre of the millstones, at the eye, the grinding faces need to be separated by some 3-4mm. to allow the entry of the wheat grains. This was incorporated in the Westree stones with the gap reducing to zero one third of the way towards the rims. The furrow design was modelled on extant Roman stones, each made 6mm. wide by 3-4mm. deep, running in sets parallel to the lead furrow in each of the ten equal area harps. See Fig.6.

Evidence of the gap between Roman millstones which ran together (top and bottom as a working pair) is rare. The dressing of millstones to produce the gap or profile between the grinding faces has probably varied throughout history and from place to place. In modern millstones the dressing was undertaken by each miller or millstone-dresser and it varied according to custom and practice, treated by some as a craft secret. What effect these slight variations in dress had on product fractions is unknown, although the writer believes them to be largely the result of modern flour milling techniques when efficiency and refinement were the objectives[8].

In Roman millstones the inclination of the grinding faces can vary considerably from stone to stone, from being quite shallow to over 10 degrees from the horizontal, although there seems to be a preponderance of examples between 6-10 degrees. Historians suggest that millstones have become shallower over time and when comparing the evidence from historic periods such as Roman, Medieval and Modern this appears to be generally the case[9]. However, this hypothesis has

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8. See pages 53-54 above for further discussion on this subject.

9. There are exceptions, for example, the unusually thin Agora specimens, almost flat in profile which occurred late in the Roman period.

yet to be developed within the Roman period itself.

The thickness of the replica stones, especially the upper, was adopted to reflect newer stones rather than older. It also provided an adequate thickness of stone to allow numerous regenerations of the grinding faces to facilitate more work and experimentation should it be necessary.

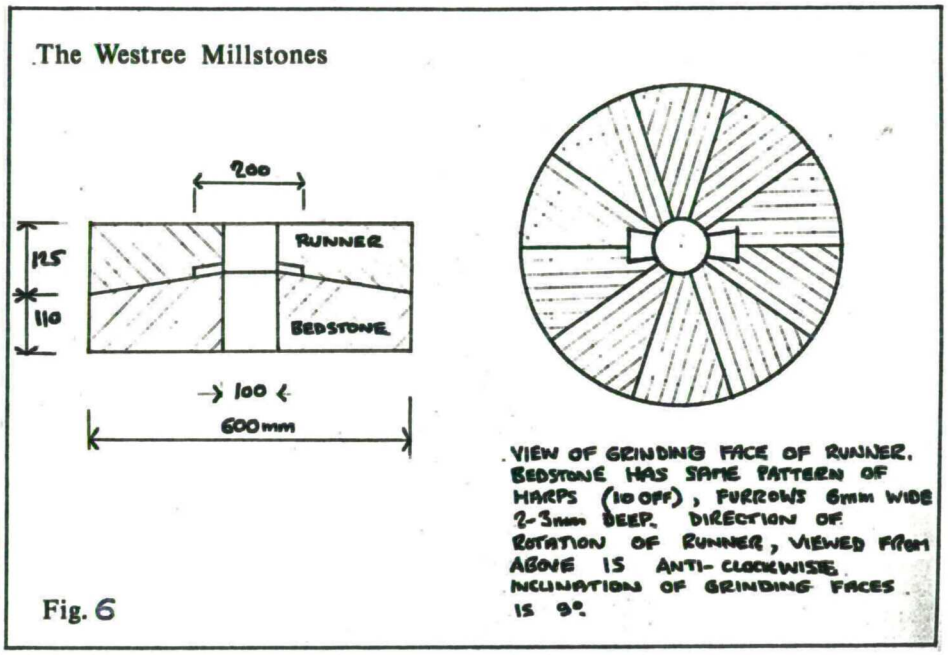


Fig. 6

B2. The Rig Table

A redundant science laboratory bench of heavy proportions was used as a rig-frame, which had to have sufficient strength and rigidity to support working millstones and be of a size which would take the motor, gearbox and other driving components.

The relatively large driven gear was the most difficult item to fit into the bench frame. This was achieved by widening the bench by 150mm, by inserting additional timbers into the thick hardwood top and lengthening the horizontal frame elements mortised into the legs.

B3. The Driven (Lantern) Gear, Millstone Spindle and Rynd.

As far as possible, this was based on the unique Zugmantel specimen. The model had the same number and size of iron staves (pitch, diameter and length) and oak discs of the same diameter and thickness. The method of securing the staves and clamping the gear on the millstone spindle was, however, different. On the Roman specimen the staves were slightly tapered at both ends, and so the oak discs were probably driven onto the staves.[10] See Fig. 7.

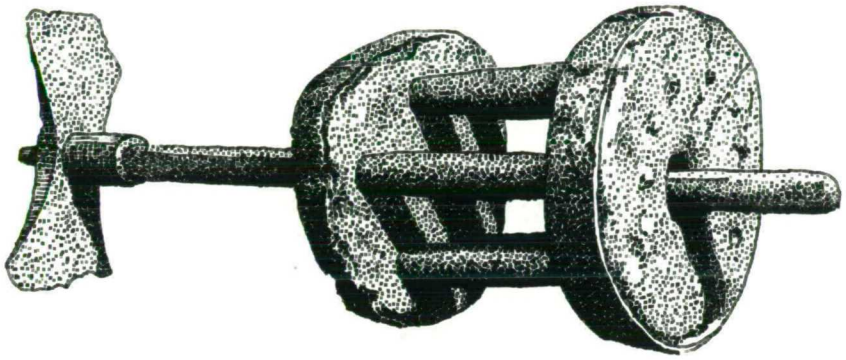


Fig. 7. The Zugmantel Roman lantern gear.

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The ends of the iron staves were flush with the outside faces of the oak discs. The Roman specimen appears to have two sets of stave holes in the oak discs - one presumably an earlier set of positions with a later set re-cut between them. Most likely the best fit would have been achieved by heating the stave ends, driving them into the oak discs and quenching. On the Roman discs wrought iron rings or hoops were placed for strength, probably heat welded; on the replica identical iron hoops, welded, were hot shrunk onto the discs.

The Zugmantel lantern gear has six staves, each with a maximum diameter of 28mm, on a pitch circle of 129.5mm diameter. The oak discs were some 50mm thick, 203mm diameter with 38 x 3.5mm thick iron

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10. R.J.Spain, 'Romano-British Watermills', Archaeologia Cantiana, vol.100, 1984, p.125, Fig II; see also Jacobi, 'Römische Getreidemühlen', Saalburg Jahrbuch, 3, 1912, Taf xvii.

bands driven or shrunk on. In the replica the rungs were not tapered and at the ends they were reduced to a half inch diameter and threaded, to pass through the oak discs which were bored to take the turned down spigots so that the discs were clamped onto the staves by nuts, washers and locknuts. See Fig. 8. The gear was clamped onto the millstone spindle to achieve a positive drive. This arrangement also allowed movement in two planes in order to get the gear rotating on an axis central to the rotating staves.

With high mechanical ratios combined with a gear having relatively few cogs or staves the wear on the small gear is greater than the wear on the larger gear, in direct proportion to the mechanical ratio. When such a ratio combines with a small gear, for example a lantern gear, the wear and stress is much worse because of the geometry of the engagement, the fewer the staves the worse it becomes. When the number of cogs or staves reduces from say 8 to 7, to 6, the small gear theoretically suffers a variation in angular velocity as each stave passes through engagement. With five staves the change in angular velocity becomes very marked, especially at low speed, and the stresses in the cogs and staves increases considerably. With four staves the engagement fails. At higher speeds these variations in angular velocity are 'dampened' or reduced by the flywheel effect of the top millstone. Six staves is probably the least number that can be adopted to produce acceptable running conditions.

The wear characteristics of higher mechanical ratios demands harder and more durable materials in the smaller gear. In this development hard woods would be replaced eventually with wrought iron, which is the obvious material for the Romans to have used.

It seems likely that the Zugmantel gear, having six iron staves, represents a developed form of driven gear.

The few extant Roman millstone spindles all have roughly square section shafts and the Westree spindle followed this pattern. A square spindle facilitates better mounting and driving of the lantern gear and mill rynd.

Square section iron of 32mm was used for the spindle, its lower end tapered with a rounded end seated in the footstep brass. This pressure area was made to be similar to extant Roman footstep bearing

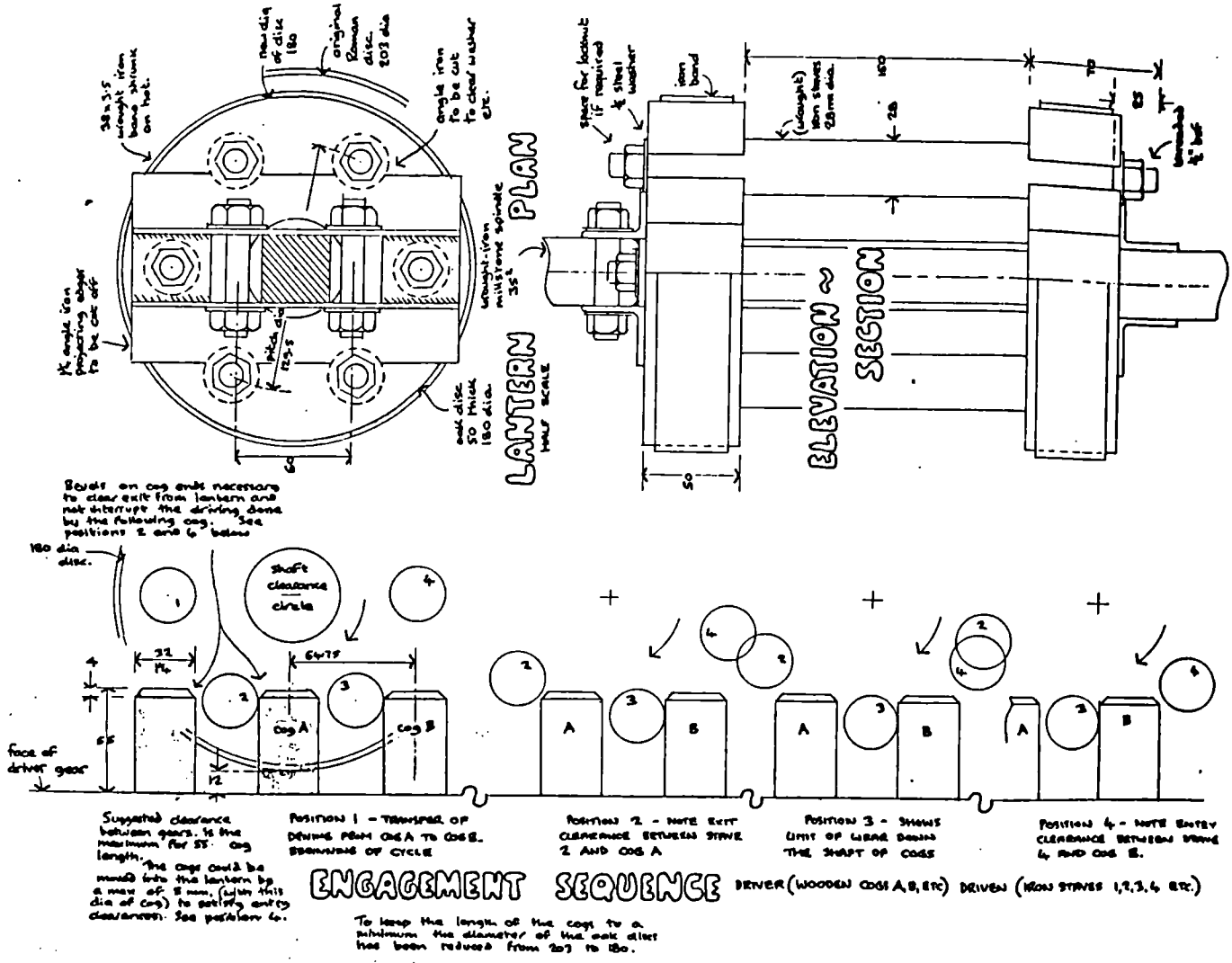


Fig. 8. Lantern construction and engagement sequence.

stone cavities, being hemispherical, generated by a radius of approximately 3mm., and with a depth of 3-4mm. In the middle of the bedstone, where the neck seal was positioned, the spindle was reduced so as to create a circular section of 25mm diameter.
It was considered fairly important to create the typical butterfly type of Roman mill rynd. As the stones wear away the cavity needs deepening otherwise the underside of the wings scores the top face of the bedstone. It follows that (a) the pressure, and therefore wear of the faces is much less with a broad wing and (b) the shallower the wings and cavities, the longer the topstone will last before the cavities weaken it. Hence the shape of the rynd.

Modern methods of driving and supporting the top millstone involve mechanisms mounted on top of the spindle which allow the stone to take its own level on the bedstone. The centre of gravity of the top stone is always below the axis of suspension. In these arrangements metal to metal bearings are used whereas in ancient millstones the rynd bears against the stone. Some querns have rynds that are leaded in, showing that the rynd was fixed with the stone, but this arrangement does not appear to have existed with millstones. No traces of lead have been found in millstone rynd cavities.
Rynd cavities in abandoned Roman millstones usually show clear signs of wear on the leading edges and the roof. They become shallow as the grinding face wears away and a loose fit develops. Examples have been found in which a pair of cavities have been abandoned and fresh ones cut between the old ones at opposite sides of the eye.
The leading edge of the rynd wings drives the stone. The rynd needs to start off as a good fit because the imperfections of the gears in transmitting motion combined with the torque reaction will tend to cause wear and movement of the rynd in the cavity. The rynd cavity, which has a depth of 12mm, lies parallel to the grinding surface so that the wings of the cavity have the same inclination as the grinding face.
The rynd was made from 12mm thick mild steel stock and machined by milling to fit the cavity. It was shaped to provide the best possible fit to the cavity, on the basis that the better the fit, the less movement and wear would occur. To minimise pressure the top face of

each wing was machined to the same inclination as the cavity roof. The eye of the rynd was machined out to create a sliding fit on the 38mm. square shaft of the millstone spindle. Metal was left around the square bore for strength.

When machining was completed all corners of the rynd were smoothed off by file so as not to have sharp corners acting on the stone and the rynd was then tried in the cavity. It was found that one of the alternative positions for the rynd was better than the other in that the leading edges fitted the cavity walls so as to provide pressure all along the faces. In this position the rynd was found to rock in the cavity and so the stone was chiselled out until the rynd rested firmly in its place.[11]

When the cavity had been made to fit the rynd, the rynd was welded to the spindle. The few Roman millstone spindles found all appear to have a fixed iron rynd. These may have been tapered driven fits but it is more likely that they were heat welded onto the spindles to provide a firm and secure arrangement. X-rays of the spindles might confirm this.

B4. The Driver Gear

The large driver gear was made from two oak discs, cross-grained and bonded together with a strong wood adhesive to produce a thickness of 65mm The cog design was given considerable thought. The first question that had to be resolved was whether to adopt a pin type of cog or a rectangular tooth type.

In Jacobi's reconstruction of the Zugmantel gear rig he shows the driver as having rectangular cogs engaging the lantern gear. No Roman specimens have survived to shed light upon this question. Clearly the

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11. This cold chisel work was most interesting because it revealed the strength and nature of the lava stone. The hardened and tempered chisel, 12mm. wide, held its edge very well. The lava stone was very hard with an unusual quality of 'yielding' before the chisel. A slightly spongy texture was felt when working across the face of the stone and the chisel left whitish marks where the stone had suffered compression. Close examination of the surface worked by the chisel revealed lines of compression, pale by comparison with the surrounding porous stone. The stone felt hard and somewhat gritty as the chisel progressed.

pin type is cruder, and probably pre-dates the rectangular tooth form. Both forms can be found in use in irrigation traditions throughout the Mediterranean and the Middle East.

The pin cog is not difficult to make for it can be turned on a simple lathe. Moreover it can be easily mortised into the gear with the aid of an auger or wood bit. Pin cogs have the advantage of wearing-in quickly, and, depending on how they are secured (taper and driven, nailed, dowelled, wedged etc.), they may be rotated in their sockets to present a new rubbing surface.

The rectangular form of tooth or cog requires much more labour and skill to shape and fit into the gear, but has the distinct advantage of greater strength and longer life. A rectangular or square mortise needs to be cut, on a radial axis and the cog finally shaped in position to ensure that it runs sweetly in engagement.

The Zugmantel lantern gear with its tapered wrought iron staves could have been driven either by pin or rectangular cogs. A pin cog would follow the curved surface of the iron stave during its engagement but a rectangular tooth would need to be slightly curved on its leading flank to run smoothly. But such considerations become too speculative. We cannot attribute such knowledge to the Roman millwright in the absence of any evidence of wooden gear teeth. Providing a pin cog was strong enough to do the job, there was no need to adopt the more complex rectangular form.[12]

In the Zugmantel gear the ample height of the lantern staves suggests that the diameter of the driver gear was not large. With a large diameter gear the cogs produce a shallow trajectory as they pass through the lantern, allowing the lantern oak discs to be set closer together. Some allowance must also be made for the vertical movement of the lantern and spindle to facilitate the raising of the runner stone. An obvious response to this observation concerning the height of the Zugmantel lantern would be that it may have been driven by

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12. The engagement analysis of the Zugmantel gear shows that the maximum diameter of the pins was close to 32mm, allowing some 5mm for clearance and backlash which, if made of hard wood should be of ample strength to take the torque for driving the smaller Zugmantel millstones.

rectangular cogs. But in this discussion of the cog form we must remember that the Westree rig is not necessarily attempting to reconstruct the Zugmantel mill, only its lantern gear. It is a coincidence that the Westree millstones, although very similar to the small Saalburg type, were not modelled on them, rather they reflected general Roman millstone design especially British practice, with which the author is more familiar. See Fig.9.

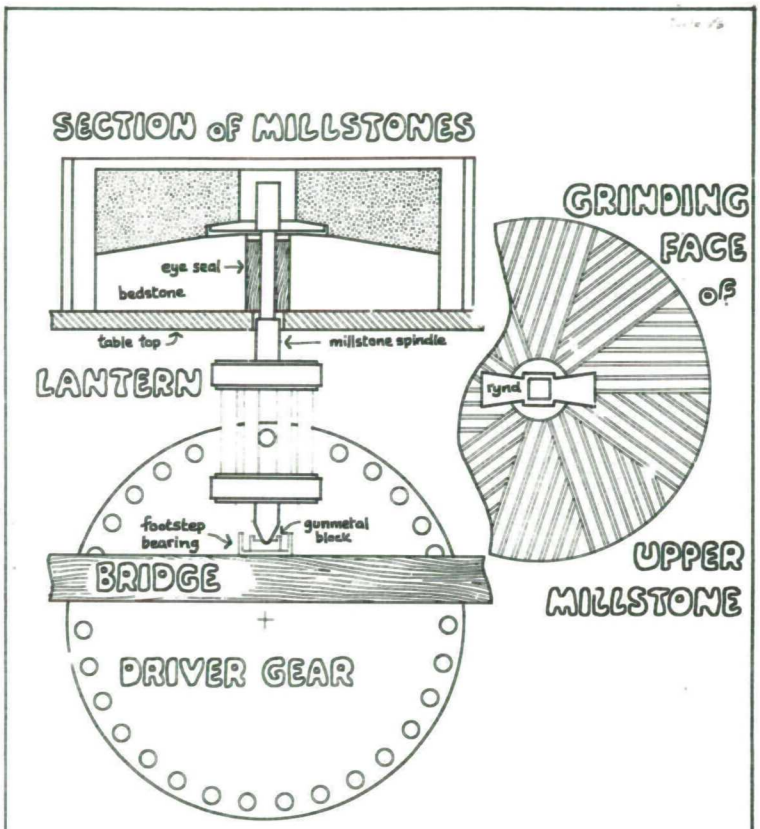


Fig. 9
GENERAL ARRANGEMENT OF GEARS

To achieve maximum strength it was decided to introduce into the oak pegs a steel core. This took the form of a bolt which was a tight push fit, having a head recessed into the cog end. Each cog was made of old oak (table legs), well seasoned, mature and stable without stresses etc., and reduced in diameter where mortised into the oak disc to create a narrow shoulder on which to clamp. See Fig.10.

The bolts were made of 32mm diameter steel stock with machined heads welded on. Each head was slotted to allow a large screwdriver to provide purchase to tighten the bolt if required. Large diameter steel washers were made and positioned at the back of the gear to reduce compression of the wood. On the driver the pitch circle was marked and then, using dividers and centre punch, the correct number of cogs was found[13]. A pilot hole was drilled in each position and then bored out using a special wood bit. Each cog was driven into the gear, drawn up by the bolt and 'rung' with a mallet to confirm rigidity and tightness. A hunting cog was fitted to give a ratio of 31:6 and to create a cyclic wearing pattern of 186 cog engagements. It was decided to determine the pin characteristics by generating the engagement cycle.

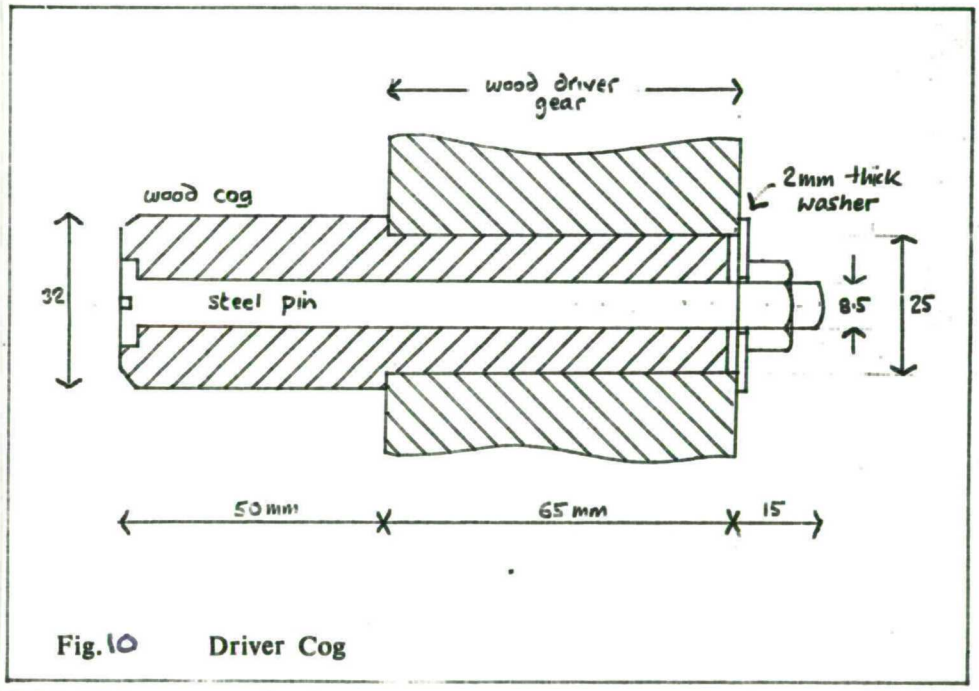


Fig. 10 Driver Cog

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13. The pitch of the teeth, that is the distance from centre to centre of two contiguous teeth, can be measured two different ways, along the curved pitch line (arc method) or the straight line (chord method). In the past, engineers have adopted one or other and in gears of roughly the same size there is little difference in result. However, when a small gear or pinion engages a large gear or rack a slight error occurs with the chord method. But such theory is more applicable to machine-cut metal gears with developed tooth forms. These are either epicycloid or involute forms having generated curved flanks which provide perfect uniformity of motion.

B5. The Gear Engagement Sequence

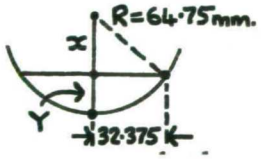
The adoption of the Zugmantel lantern replica within the rig necessitates gear engagement studies to determine the geometry of a suitable driver gear. An engagement sequence analysis helps to identify the options of cog length and diameter and by this process, we are discovering something about the design of the original gear which drove the Zugmantel lantern and others like it. Without such an analysis, the gear design would be entirely hit and miss, with the likelihood of considerable resources and time being expended to achieve satisfactory results. Moreover there is the risk of damage and set-backs which cog breakage would bring.

The first development when considering the engagement sequence was the realisation that the pitch diameter of the staves and the diameter of the oak discs and iron bands affected the length of the cogs. With a solid face driver gear the 'overhang' of the driven discs means that the cogs have to be lengthened to produce engagement.

The overhang on the Zugmantel gear is 24.5mm. and the minimum cog length to begin and terminate engagement can be seen in Fig. 8.

(a) Position One in the sequence

In this position cog A has started to disengage from stave 2 and simultaneously cog B has started to engage stave 3. This engagement cycle is repeated as the lantern rotates through 60 degrees and each cog travels through its pitch of 64.75mm. At this point in the sequence the staves in contact with the driver gear are the same distance from its face, and as motion continues they approach the gear face by the distance Y, where X + Y = 64.75.



$$(64.75^2) = x^2 + 32.375^2$$

$$x = 56.08\text{mm}$$

and $$Y = 64.75 - 56.08 = 8.67\text{mm}$$

It is suggested that there would probably need to be a gap of, say, 12mm between the outer face of the iron band on the lantern gear and the face of the driven gear ie., running clearance. This would be needed to allow for irregularities in the rotating elements of the

gears, distortion of the wood and misalignment of the gears on their axes etc. Allowing for this running clearance, the minimum length of cog for the Zugmantel driver gear would be,

= lantern radius - stave pitch dia./2 + Y + 12mm

= 105 - 64.75 + 8.67 + 12mm = 60.92mm.

The diameter of discs in the rig's lantern gear has been reduced to 180mm, compared with the Zugmantel specimens of 203mm, in order to reduce the amount of overhang and thus the length of cogs. This produces less leverage on the cogs and less likelihood of breakage occurring. The length of cog is 55mm. including a chamfer of 4mm at the ends for engagement clearance.

Continuing with the engagement sequence;-

(b) Position Two

As cog B continues engagement with stave 3, cog A requires end chamfer to ensure non-engagement and clearance to allow its unimpeded movement behind stave 2.

(c) Position Three

This shows the maximum travel of the stave down the side of the cog ie., the limits of wear. This length of wear is equal to y = 8.67mm.

(d) Position Four

While B continues to drive stave 3, the approach of stave 4 shows that it requires clearance from B to allow 4 to make contact at the optimum moment.

Having analysed the engagement sequence it is now possible to determine the maximum diameter of the cogs.

An obvious suggestion would be to make the cog diameter equal to the gap between the staves 2 and 3 in position 1.

Now cog pitch = stave pitch = 64.75mm

Thus the maximum clearance that occurs is 64.75 - 28 = 36.75mm.

However this gap reduces as the staves move towards and away from their perigee with the gear face. For example position 4 shows the 'projected' gap P has increased noticeably approaching the diameter of cog B. At position 3, the projected gap between 3 and 4 is less than the diameter of B. This changing geometry determines the

relationship between the diameter and length of the cogs - short and fat or long and thin - with a series of alternatives between the extremes.

This engagement geometry is peculiar to the six stave lantern gear. If the number of staves were reduced to less than six, the angular velocity of the lantern becomes unsteady, fluctuating as each stave passes through the engagement sequence. Of course the rotating masses of the millstone act as a flywheel and tend to dampen the variation in angular velocity and torque, but the cog stresses caused by this imperfect drive of fewer staves becomes greater as does the likelihood of breakage.

The major factor in choosing between these options is that the shorter and fatter the cog, the stronger it is and the longer its life would be. A cog diameter of 32mm was adopted which gives a clearance (backlash) of 36.75 - 32 = 4.75mm for the stave between the cogs.

What diameter to make the driver gear was influenced by several factors. Obviously when conducting a friction test the speed of the millstones is not critical. Clearly too high a velocity might cause overheating of the stones and meal, more power would be required and the danger of disintegration from a fault in the millstones would be higher. We should remember that the style of face dress used by Roman millers gave poor ventilation compared with modern stones.

There is obviously a lower limit for speed, which is so slow that the production rate would be poor. A rough guide is to assume that the stones should revolve at least as fast as a quern, say 60rpm[14].

The mechanical ratio of the drive arrangement was determined by the following design sequence.

First, the lantern gear was a replica of the Zugmantel specimen, having six staves.

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14. Since the Eighteenth Century, millstones of, say, 1200mm. diameter would be expected to turn at 100-120rpm depending on the material and style of dress. But this speed relates to well dressed, ventilated and balanced stones.

Second, the pitch of the driver gear was predetermined by the lantern gear and its diameter was made as small as possible within the constraints of,

(a) not being overhung[15].

(b) being able to be mounted within the rig frame.

Third, the millstone speed was chosen to lie between 80-90 rpm. This range was influenced by the following,

(a) there was no useful purpose in approaching speeds in excess of 100rpm such as are associated with modern milling experience,

(b) the millstones' speed should be noticeably greater than a rotary quern, say 60 rpm.

Fourth, to locate and mount within the rig a suitable motor and gearbox.

Fifth, mechanical ratio of the pulleys was predetermined by the mechanical properties of the driver/driven gear, motor and gearbox, and the speed range of the millstone, all as described in items 1-4 above. See Fig.11.

B6. Motor and Gearbox

Whilst the rig was being modified for the millstones, the search was made for a suitable motor to power the drive. One and a half horsepower was considered to be ample for powering the millstones at the intended speed. A redundant motor with an integral gearbox was located, inspected, tested and found to be in satisfactory working condition. The gearbox was drained and filled with new oil.

The specification on the manufacturer's plates were as follows;-

Motor - power 1.5 horse power
speed 1410rpm
3 phases 415cycles/second.
2.5 Amps.

Gearbox - Input 1430rpm
Output 25rpm.

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15. An unsatisfactory arrangement which often results in greater bearing thrust, a more massive shaft and a less compact hurst frame.

The mechanical ratio of the gearbox is 1430/25 or 57.2 to one. With a 1410rpm motor attached the output speed of the gearbox driving the rig is 1410/57.2 = 24.65rpm.

Slide rails were provided so that the motor could be adjusted in its position to ensure that its axis was parallel to the layshaft and to allow belt adjustment and tensioning.

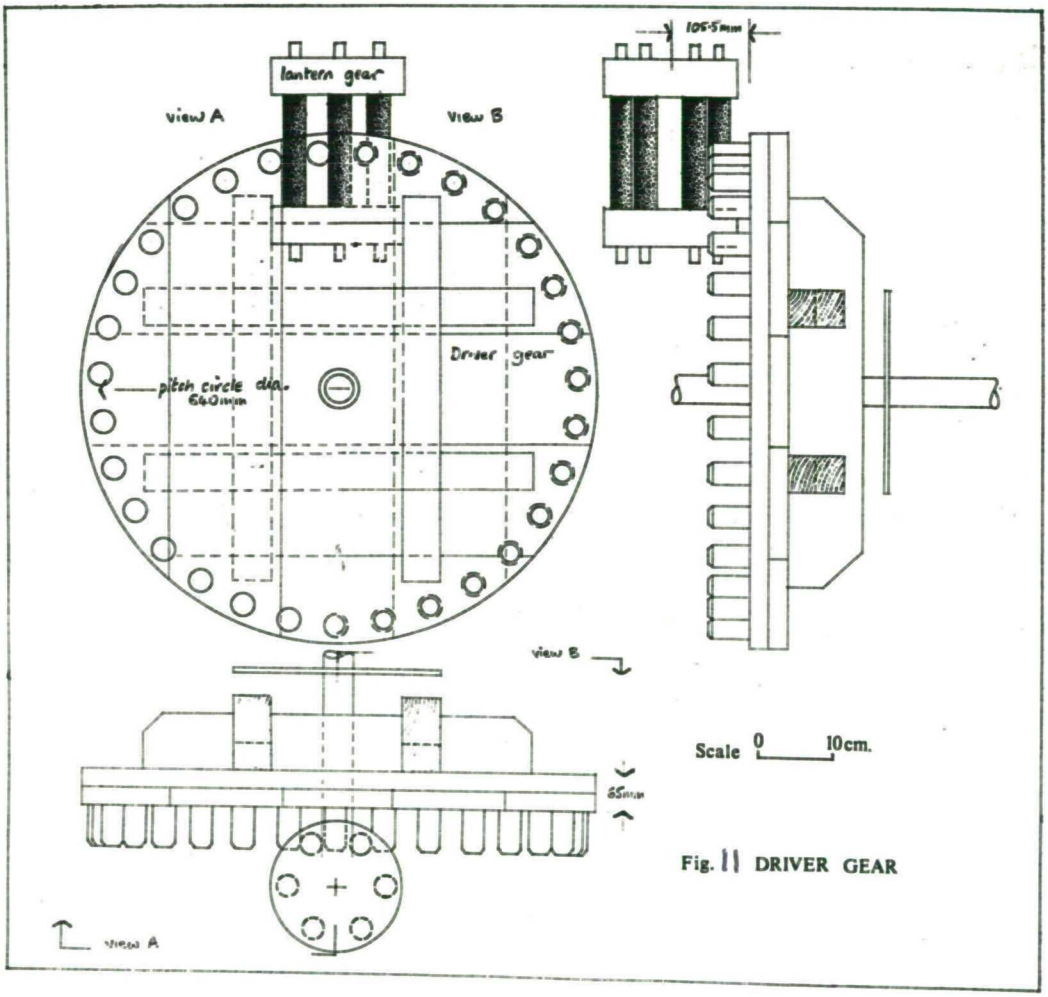


Fig. 11 DRIVER GEAR

B7. Footstep Bearing

Only stone footstep bearings have been found associated with water-mills of the ancient world. All of these display the unmistakable circular emplacements created by a rotating spindle end. Some of these bearing stones show more than one cavity, where the stone has been moved to present a new surface because the cavity became too deep. Such a move might have been prompted by the cavity becoming so deep that

(a) it created a noticeable drag to the rotating machinery, but this is unlikely, or,

(b) it became increasingly difficult to control the gap between the stones i.e., the bearing stone could not be raised enough to allow for the increase in depth of the cavity. This seems unlikely also because it would have been a simple matter to provide either packing beneath the stone, or, alternatively, adjust the leverage on the bridge tree.,

(c) there was a risk that the bearing stone would split, or,

(d) the cavity became too large in diameter and allowed the millstone spindle to vibrate while rotating or, finally,

(e) the cavity became of a depth that allowed the rynd to mark the bedstone.

There are two alternative views concerning the operating techniques of millstones. The first technique assumes that the gap between the stones is adjusted to create optimum milling conditions. We might call this variable or controlled gap milling. Modern milling practice includes this technique which shows that with heavy (i.e. thick) well-balanced millstones it is necessary to adjust the gap (at a particular feed rate) to produce the quality of product wanted. Ancient millstones were not balanced in the modern meaning of the word and were generally much lighter (i.e., worked at lower pressure) than modern stones.

The Westree tests showed that a second and alternative method of determining the optimum milling condition was to let the full weight of the top stone be taken by the bedstone and then determine the maximum flow rate for the grain according to the quality of the product. In other words the flow rate did not exceed the capacity of the

stones which at constant speed, is determined by the factors of pressure and dress, (draught, stone quality, grain quality, inclination, furrows, lead, etc.,). Capacity is the constant and flow rate variable.

There is also a pressure limit which must not be exceeded. With modern stones, thicker and able to take much greater pressure, the balance of flow rate and gap is used to control quality. The Westree rig used the full weight method and increased the flow to the limits of quality.

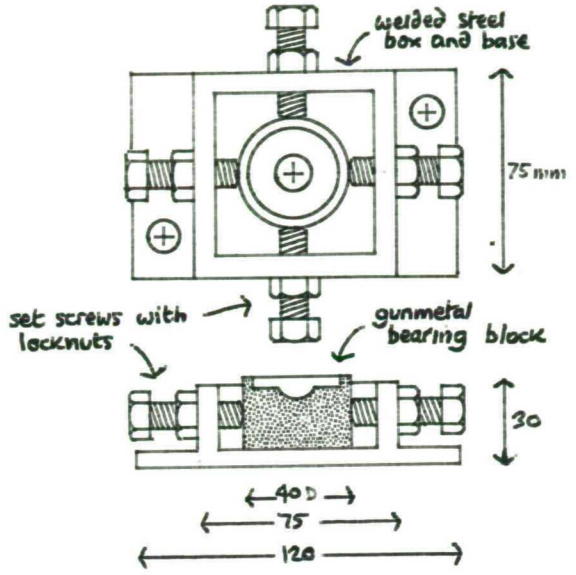
With the full weight method the footstep bearing takes only the weight of the spindle and gear, i.e., it is lowered until the topstone is carried by the bedstone. If the bearing were lowered further the rotating mill rynd would touch the bedstone causing wear and the footstep bearing would then move downwards and away from the spindle end.

The footstep bearing must also act as a steady so that the side thrust caused by the gears does not throw the millstone spindle over. Thus the footstep cavity must have depth; it is not merely to support the spindle and stone. Even in modern stones, using the controlled gap method, most of the weight of the topstone must be carried by the meal and thus the bedstone. With minimum vertical load the effect of a continuous side thrust must result in an enlargement in the diameter of the footstep cavity. This could mean, especially with a lantern gear with few staves, that the bottom of the spindle vibrates or rocks from side to side due to the imperfect engagement of the cogs and stones.

For the Westree experiment it was decided to use a gunmetal footstep bearing with a hemispherical seat, provided with an edge wall so that the bearing could operate flooded with oil. See Fig.12. An open square box to house the bearing was fabricated from steel plate and welded together, each side wall drilled and threaded to receive a setscrew

so that the bearing could be adjusted and locked in position. The brass bearing block was given flats on two opposite sides to prevent rotation.

Fig. 12 Footstep Bearing



B8. Pulleys and Belts

The type of endless V rope selected was 'B' class 16.5mm. wide x 11mm. deep. Determination of basic horsepower related to rope speed was taken directly from the manufacturer's selection graph. It was decided that two ropes should be used because the velocity was so slow.

The sizes of the pulleys were determined by considering (i) the minimum recommended diameter for the 'B' type of V belt, (ii) the need to produce approximately 80-90rpm at the stones and (iii) the need to make the drive ratio as near to unity as possible to maximise the arc of contact on both pulleys.

One pulley, 178mm. diameter and 51mm. thick, was to be bolted onto the 165 x 11mm thick face plate keyed onto the output shaft of the gearbox. The other was 267mm. in diameter complete with boss, which was bored, keyed and mounted on the 38mm. diameter layshaft. See Fig.13. Both pulleys were made of cast aluminium and had machined profiles.

The top millstone speed was therefore-

Gearbox output x [pulley dias.] driver/driven

x [gear teeth] driver cogs/driven lantern staves

= 84.6rpm.

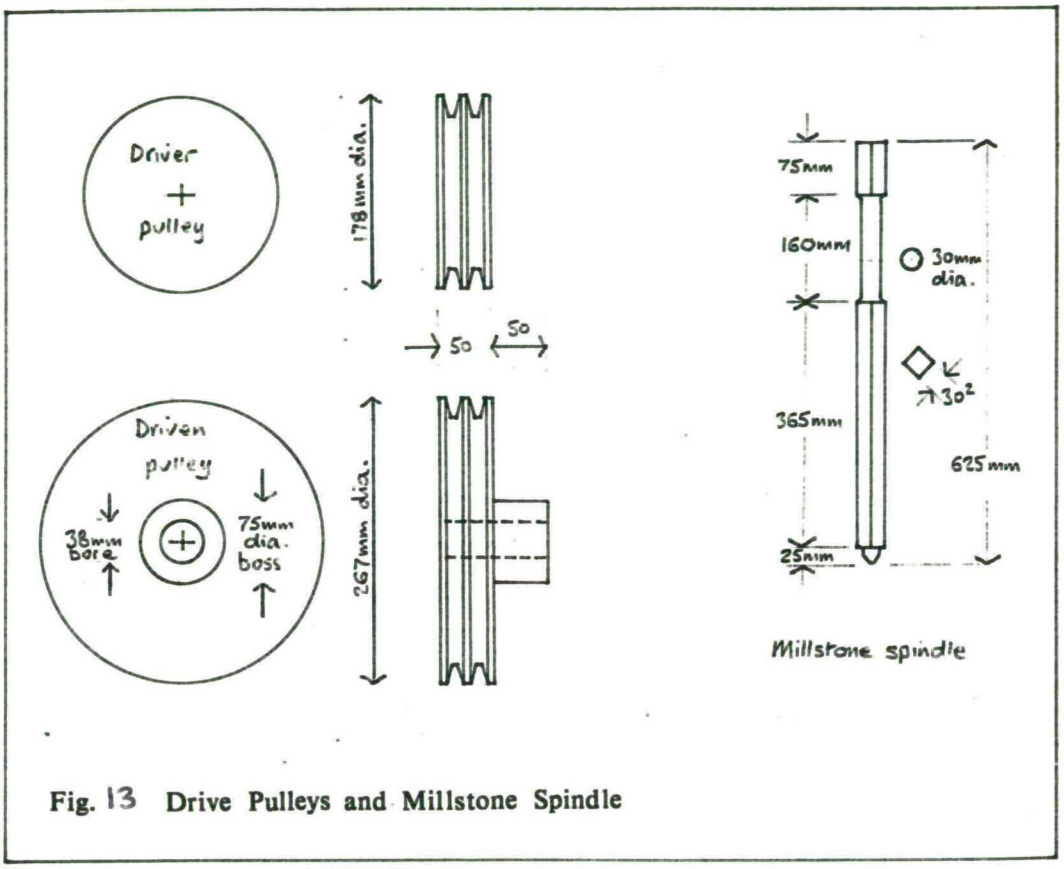


Fig. 13 Drive Pulleys and Millstone Spindle

B9. Lay Shaft

It was considered easier to make a mild steel shaft rather than a wooden one. The question of replication does not enter into this item; replication only concerns the gears, millstones and spindle. The plummer blocks had to be fairly tall where they sat on the cross frame members. This was to ensure floor clearance for the driver gear. Oil holes were provided in the tops of the plummer blocks for lubrication.

B10. The Eye Seal

When millstones are working it is necessary to stop the grain from falling through the eye of the bed stone. In the Westree Rig this was achieved by placing around the spindle a turned elm wood collar. The

millstone spindle was turned down over a length of 160mm to facilitate rotation within the neck collar. To allow easy installation and removal the neck collar was cut into halves from top to bottom. The collar was bored to be a free running fit on the spindle and turned on the outside to be a loose fit in the millstone eye. When running it was packed around the outside with strips of soft rag. This allowed the wood collar to move and thus allow the millstone spindle to oscillate about an axis off centre from its machining. This was considered necessary in case the axis of rotation generated by the grinding faces was different from the axis of rotation for the rynd and spindle. The length of the collar was such that it could sit on the bench with its top just below the upper surface of the bedstone.

The neck seal can also act as a 'steady'. A simplified diagram of the spindle is given in Fig.13. Depending on how well the rynd fits in its cavity, the spindle may be thrown against the neck seal by the side thrust of the gears. There is always some movement in the rynd, which gets steadily worse as time passes. This must mean that the neck seal takes progressively more thrust itself.

There seem to be two options concerning this matter:

(a) The neck seal is designed to take side thrust, and therefore to yield only a minimum amount. This requires the axis of the seal to be on the axis between the footstep bearing and the top millstone.

(b) The seal is not solid/rigid but flexible and does not act as a steady. In this case the only requirement is that grain must not fall through, which is easily achieved with rags, dry grasses, heather etc.

The advantage of the flexible seal is that it can readily take up any oscillation of the spindle as it rotates (imperfections in its axis, section etc.,) and it has negligible resistance. Its disadvantage is that the rynd suffers much more from the side thrust from the gears, which must surely accelerate the wear occurring between the rynd and the stone. Such an arrangement also allows the side thrust of the gear (with a footstep bearing which does not move in a horizontal plane) to act on the top stone. Providing the grinding surfaces are dished or inclined, this would not adversely affect operation. However, as the inclination becomes shallower, the rotating stone is

less able to withstand side thrust without moving. On flat or near flat grinding surfaces the neck seal must therefore act as a steady. With a bedstone firmly anchored to the milling frame (hursting) and a solid neck seal the gear thrusts would not affect the rotation and the grinding operation. This also requires the axes to be well aligned.

B11. The Bridge Tree

Whether the 'fixed gap' or 'full load' mode of operation is employed it is desirable to be able to adjust the height of the top stone in relation to the bedstone. This is because;-

(a) It provides the facility to lift the top stone if a foreign object enters between the stones and damage occurs or is likely to occur.

(b) It can provide gap adjustment to allow for different types of grain or pulse.

(c) It can be used to lighten the load on the machine for an easy start.

(d) When the rynd can float up and down in its emplacement the adjustment will allow the rynd to drive but not carry the stone and keep it clear of the bottom stone. As the topstone wears the adjustment will allow the rynd to keep the same optimum position i.e., chase the wear.

(e) It will help to raise the topstone in readiness for lifting off the rynd for cleaning, dressing, changing, inspection etc.

It follows that the lantern gear is ideal for this vertical movement without adversely affecting the engagement. It allows power transmission to continue as it is raised or lowered.

Modern watermills invariably employ a compound lever arrangement for raising and lowering the bridge-tree. We have no evidence of how tentering was achieved in ancient watermills (Roman) although it is reasonable to suggest that a simple lever arrangement was used. The Westree Rig was adapted to provide a simple practical solution; it was not intended to necessarily re-create the modern or ancient method of adjustment. See Fig.14.

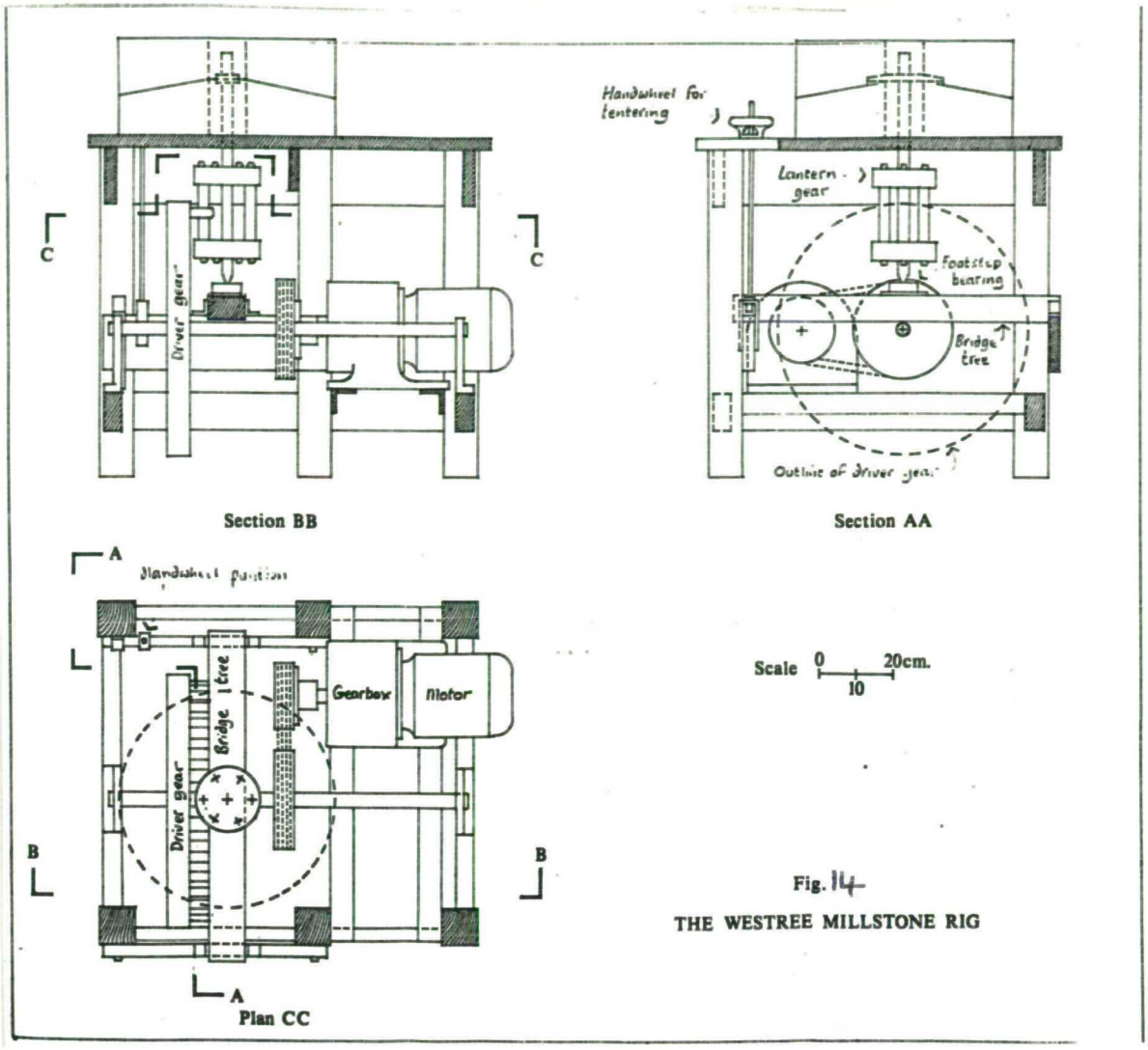


Fig. 14
THE WESTREE MILLSTONE RIG

The leverage was arranged such that when the stones just touch, the side lever is more or less level. When the lever moves up or down the bridge-tree is no longer stable where it rests on the lever (because it is a beam with a flat surface). This could have been overcome if this end of the bridge-tree was made as a knife-edge support. To stabilise the bridge-tree, each end was constrained in angle brackets giving a sliding clearance.

B12. The Tun Case

It was decided to make an octagonal wooden tun to surround the stones to provide (a) protection for the operator, (b) a method of collecting the meal, and (c) a means of reducing the migration of meal dust.

The tun was made of soft wood planks screwed together and made to stand slightly higher than the millstones. Most modern tuns have their tops covered to contain the dust but in the rig, it was left open to allow the sides of the stones to be seen so that their operation and meal discharge pattern could be observed. The annular gap created by the tun around the stones varies from approximately 25-50mm. It was originally intended to collect the meal by the modern method of attaching a small 'sweep' to the upper millstone projecting down inside the casing to push the meal out through a slot in the table top. This slot is about 12mm. wide and about 80mm. long with leads on the ends to help the meal enter the slot. However no sweep or paddle was fitted because it was decided that collection could be made by brushing the meal down the hole after each batch was processed. A plastic bag was suspended below the hole and it was found that a fairly large sample could be contained inside the tun, quite ample for experimental purposes.

To provide a positive register and also to ensure that the lower stone did not move, the gap between the tun case and the bedstone was laid with 6mm. thick wooden laths which were glued down to the top of the table.

B13. Assembly of the Rig.

The gearbox and motor were mounted on the guide-rails, then the lay shaft and bearings roughly positioned with the pulleys and belts in place. The axis of the layshaft had to be parallel to the side of the rig and lie under the centre of the millstones. The layshaft was bolted in position and the table top bored to receive the millstone spindle. Next the bedstone was positioned, then the tun, and the laths laid and glued between the two. The side lever and bridge tree were bolted in position complete with the angle brackets.

To install the lantern gear it was necessary to pass the spindle from above through the bedstone and table top, sliding the lantern gear up the spindle as it was lowered through the bedstone. The footstep bearing was positioned simply by making the spindle vertical with a spirit level whilst the bridge-tree was horizontal. The height of the bridge-tree was largely predetermined by the position of the mill rynd and the top millstone. Careful measurement was needed to ensure

that when the millstones were just touching, the bridge-tree was approximately mid-range in its vertical adjustment. This was needed so as to allow the topstone to be lifted (raising of the bridge-tree) and also allow for wear taking place between the millstones (lowering of the bridge-tree). The gunmetal footstep bearing had already been positioned centrally in the box with its set screws.
The driver gear was moved along the layshaft until the gears were correctly engaged with the minimum of clearance. This was confirmed by running them together and moving the driver as close as possible to the lantern without the lantern rim touching the driver face. All pulleys and gears were then locked on their shafts.

C. Operations.

C1. The Grain

Two 25kg. sacks of British wheat were used for the grinding experiments. Just prior to the start of the experiments, which were spread over several days, the moisture content of the grain was tested and found to be 16%. English wheat cannot be stored in bulk above a moisture content of 16%, or in sacks above 18% without a risk of overheating and mould occurring.[16]
It was originally planned to use grain from Butser Ancient Farm Trust where grain from unique strains of Emmer and Spelt wheat is harvested. However, the wheat was not forthcoming.
Jasny, in his study of Roman milling techniques[17], considers that the preparation of wheat for milling during the Roman period was negligible. Cleaning by coarse sieving may have occurred, but washing, according to Galen[18], was practised only in Asian cities. The moisten-

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16. N.Owen Simmons, Compound Milling, London, 1955, p.101.

17. N.Jasny, 'Wheat Prices and Milling Costs in Classical Rome', Wheat Studies of the Food Research Institute, vol.xx, part 4, March 1944, pp.135-170.

18. Claudii Galeni Opera Omnia, edit. by D.C.G.Kuhn (Medicorum Graecorum Opera quae Exstant, Leipzig, 1829) vol. XVIII, Pt.1, Ch. 41, pp.470-71. Galen was a physician who lived in the second century AD.

ing of wheat, although mentioned by Pliny[19], Jasny considers uncommon at the time, and drying was probably non-existent in the provinces surrounding the Mediterranean. This conclusion is strengthened by the fact that no reference to drying occurs in the writings or sculpture evidence from the period. But perhaps this is not surprising in view of the fact that the granaries of the Empire, Africa, Sicily, South Gaul, Egypt etc., that were servicing Rome, the major cities and the military markets, were areas of hotter climate. Away from the Mediterranean, in the cooler and wetter frontier provinces the story was probably different.

Numerous corn-drying ovens have been found in Romano-British towns, villages and villas, varying from the simple single-flue type to the single and double T-type ovens which are associated with the 4th. century AD and later[20]. There is evidence that they were carefully designed having double hollow floors so that the corn was dried or parched rather than roasted. Some of these ovens may have been used for malting.[21]

Where corn drying was practised, it may not have been necessary throughout the whole of the year. Modern milling experience tells us that drying kilns were common in the northern and western wetter areas of Britain, whereas in the south, kilns in association with corn mills were rare.

The effect of moisture content on the power needed by the millstones has not been determined.

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19. Pliny, Naturalis Historiae Libri xxxvii, (Bibliotheca Scriptorum Graecorum et Romanorum Teabneriana), Leipzig, 1892, Book 18, Ch.10, sec.89, p.166; Ch.9, secs.86-87, p.166.

20. R.G.Goodchild, 'T-shaped Corn-drying Ovens in Roman Britain', Antiquaries Journal, vol. xxiii, July-Oct. 1943, pp.147-153; vol. xliv, 1964, pp.38-40.

21. P.J.Reynolds and J.K.Langley, 'Roman-British Corn drying Ovens : an Experiment', Archaeological Journal, 156, 1979, pp.27-42.

C2. Feeding the Grain.

The traditional way of feeding and controlling the flow of grain into the stones is through a hopper with an orifice at the bottom, often feeding into an inclined chute (shoe) which delivers the grain into the eye of the top stone. Invariably the chute (and sometimes the hopper) is vibrated to keep the grain flowing, otherwise there is a risk that the grain will hang up. The orifice is usually controlled by a small wooden slide or gate which is adjusted to create a hole to suit the flow conditions.

Tests were undertaken using a genuine hopper[22] to establish the best method of providing the grain flow rates required. As a very rough guide the 600mm diameter stones running at 80rpm were expected to process approximately 120-210 lbs/hr of grain. This is related to typical production rates for nineteenth century millstones which would have grinding faces much superior to Roman millstones.

The gate at the bottom of the hopper was slightly inclined and measured 78mm in width with a variable opening of 28mm to 8mm. It was soon found that even with vibrating by hand, the slowest feed rate with the gate closed as far as possible (without interrupting the flow with hang ups) was 328 lbs/hr. An aluminium orifice plate was then made of aluminium and the smallest opening without hang-ups occurring gave 180 lbs/hr. This was not low enough for experimentation purposes, nor did this method of control by gate, give a consistent rate of flow. No experimentation was done on automatic vibration techniques; when hang-ups occurred the side of the hopper was banged with a mallet.

It was decided that the best method of grain feeding was to measure the grain being put into the eye and deliver it at a pulsed or timed rate. Various tests were done to establish the flow rate over a period of time and equate this to the use of various sizes of measuring scoops or spoons. Considerable accuracy was soon established using the two variables of spoon size and frequency of use. The best timing method proved to be a metronome which gave an unmistakable signal and could be varied over a wide range of frequencies.

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22. A wooden hopper and shoe were borrowed from Mr.Uren of Chegworth Mill, near Leeds, Kent.

Controlling the grain feed by this method appeared to be entirely satisfactory. Although feeding the grain into the hopper might be thought to produce a pulsing or fluctuation in the flow passing into the eye, none could be discerned. Clearly some advantage was gained by throwing the grain into the hopper from the spoon, for this action scattered the grain so that it passed through the gate over a short period of time rather than all at once. Furthermore the frequency of feeding by spoon was never allowed to be so slow that pulsing or surging resulted within the stones.

If the feeding of grain was stopped while the runner stone was rotating and under load, the stones quickly changed their noise as the meal worked out of the stones and the grinding faces worked against each other. Within a few seconds, the soft rumble of stones working on the fibrous and powdered meal became increasingly harsh as the hard lava faces ran together. Only a few seconds of this working condition could be tolerated for fear of damaging the stones by friction and heat.

This problem of failing to achieve a satisfactory automatic method of regulating grain flow is not considered serious. Numerous alternative methods are employed in water and wind-powered corn mills throughout Europe to achieve a trickle flow of grain into the eye of the millstone.[23] All of these utilised the rotation of the top stone, or a projection of the millstone spindle to cause vibration. The Romans undoubtedly used similar methods although evidence is scant.[24] In the Westree experiment the method of feed was unimportant as this was not an object of study. What was needed was an accurate and measurable method of grain feed which was achieved, albeit laboriously, by the method described.

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23. See for instance the fascinating variations that existed in Portugal, J.Dias, E.Veiga de Oliveira, F.Galhano, Sistemas Primitivos de Moagem em Portugal, Porto, 1959, pp.86-91.

24. Hoppers are clearly evident in contemporary sculptures depicting milling scenes confirming that automatic feeding existed. White describes some Pompeiian type mills having perforated metal plates in the necks of the catillus which were surely intended for regulating grain flow. See K.D.White, 1984.

C3. Grinding.

When grain was falling into the revolving stones a few grains did not fall into the eye but struck the top face, scattered across it and fell into the tun. This was particularly noticeable when high flow rates were attempted. It is likely that this could have been stopped by adding deflectors or a chute below the hopper gate. However a simpler solution was found. A coil of soft rag was placed around the rim of the eye, and all the grain fell into the eye thereafter.

During the grinding work the maximum flow rate for the stones was found by gorging the eye i.e.,increasing the feed until the grain built up in the eye. Maximum flow occurred when the level of grain within the eye remained at a constant high level. This proved to be at 119 lbs/hr. In this operating condition the meal coming from the stones was very rough; indeed the word meal is mis-applied. The output was nearly all whole grains, bruised and cut with hardly any reduction, and with very little flour present.

One other operating condition that can occur is when grinding ceases altogether in choked conditions and the topstone 'rolls' on the grain. This is determined by the amount of grain outside the throat of the stones. With sufficient grain, each taking part of the runners weight, the pressure is insufficient for crushing and the ball bearing effect occurs.

C4. Problems and Solutions.

Perhaps the most difficult problem met with during the experiment was the slippage that occurred on the driving belts. In an attempt to overcome this a tension jockey pulley was installed, mounted on a lever so that the operator could push it down in the event of slippage occurring. This increase in belt tension together with applications of viscous paste on the belts helped considerably although slippage still occurred on start-up. Obviously maximum torque occurs as the top stone begins to move from rest. Two additional methods were employed which appeared to eradicate the problem. On start-up the top stone was lifted slightly by raising the bridge tree in the traditional manner, and to help matters further, the top stone was 'thrown' by hand, to overcome the friction of rest.

During the friction tests, the revolutions of the top stone were counted and related to the duration of each test to ensure that a speed of 84rpm had occurred. Using these methods no slippage was recorded during the tests.[25]

On one or two occasions the spindle was found to have jumped out of the footstep cavity, coming to rest on the bearing block. This was undoubtedly caused by the reaction between the gears, most likely at start-up. It was fortunate that the lip of the bearing block caught the spindle end, otherwise damage might have occurred to the gears and the rynd would have scored the face of the bedstone. To reduce the likelihood of this occurring the cavity was deepened slightly and for most of the start-ups the topstone was turned by hand to reduce the gear reaction and belt-slip.

When the millstones were grinding, the lay shaft oscillated to and fro along its axis by several millimetres. Clearly the tall plummer blocks bolted to the cross-beams were not stable enough to stop this movement. The oscillations appeared to be set up by the rotation of the lantern, which, because of its geometry involving only six staves, probably caused fluctuations in the torque. To stop this end movement of the shaft a wooden cross-brace was bolted to the ends of the rig, positioned to pass across the end of the shaft.

D. Results.

D1. Analysis of Samples.

Initially, four samples of meal were produced, each the product of a different feeding rate (29, 35, 43 and 57lbs/hr). While grinding these samples the gap between the stones was not regulated so that the full weight of the topstone was taken by the wheat/meal; thus any difference in granularity or coarseness was the result of different

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25. The obvious answer to overcome this problem would be to change the belt drive for a chain drive. It is suggested that this should be the subject of the first major design modification to the rig.

feed rate only. Throughout all of these grinding experiments the speed of the stones was constant at 84rpm. Later three further samples were taken at higher feed rates (75, 105 and 117lbs/hr).
The analysis of each of the samples was undertaken by Dr.Simon Hook, Principal Scientific Officer of the Flour Milling and Baking Research Association at Chorleywood, Hertfordshire. The following results were found;-

	% PRODUCT		
	Flour [Dunst & Flour]	Middlings [Semolina & Fine Middlings]	Bran+Pollard [Bran & Weatings]
Sieve Apertures microns	>180 <180	>500 >300	>1000 >850
Flow Rate lbs/hr			
29	51.6	35.8	12.6
35	50.7	36.4	12.9
43	52.1	35.4	12.5
43x2	52.1	35.4	12.5
57	52.4	36.2	11.4
75	38.0	37.3	24.7
105	34.8	38.8	26.4
119	24.1	35.7	40.2

* The modern classification of products are shown in brackets.

Note that the second 43lbs/hr results were related to a sample put through the stones twice. The sieves were nested in the order shown and the weight of material retained by each was recorded. Hence a value quoted as >850 refers to material that passed through a 1000 micron aperture sleeve but was retained by a 850 micron sieve.
It is interesting to note that the twice-ground sample failed to significantly reduce the general coarseness of the product which suggests that the stones have a natural limit on the fineness of product and that the ancient product was much coarser than the modern one.

The analyst suggested that to get finer material the flow rate should be reduced. However when the feed rate was dropped below 29.0lbs/hr the noise of the stones suggested that they were running together and

defacing each other. Moreover a glance at the above table of product analysis suggests that reducing the flow rate will not reduce the coarseness of the wholemeal product; there seems to be a fairly constant proportional pattern of gradings for the four lowest flow rates even when one is ground twice.

When the above table of product refinement is shown in graphical form it is much easier to see what happens with different flow rates. See Fig.15.

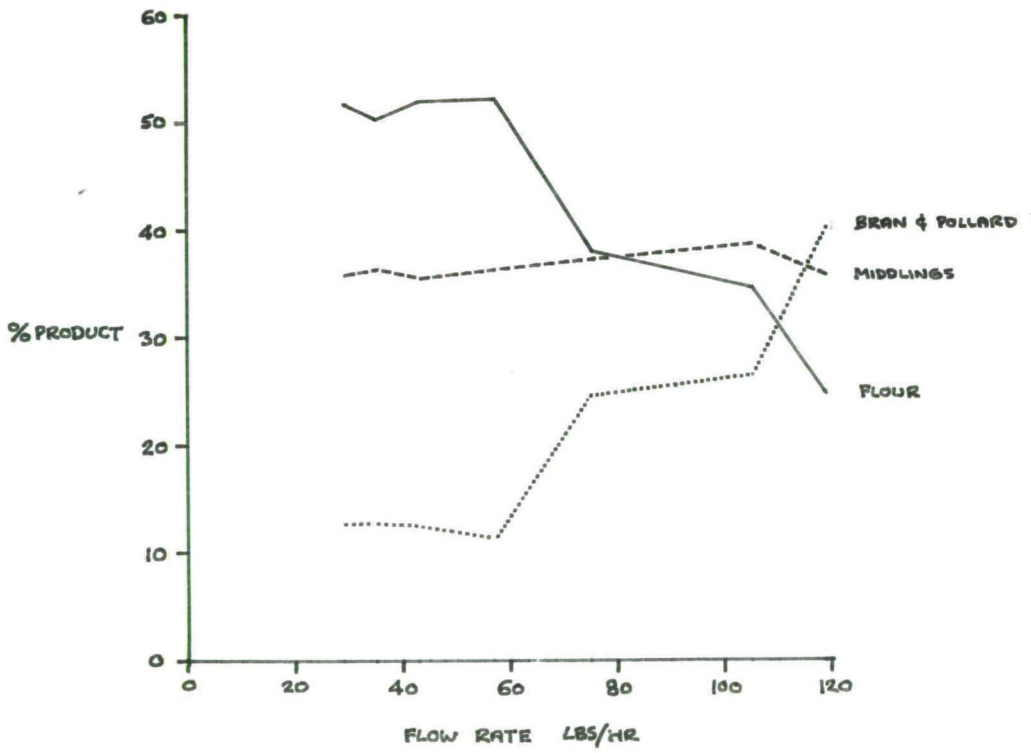


Fig. 15 Product fractions at different flow rates

One would expect the coarseness of the product to increase with greater flow rates, which the graph shows, but the rate at which it occurs is surprising. Up to a flow rate of 60 lbs/hr. the various proportions represented by the refinements are very steady, but when the feed rate exceeds 60 lbs/hr, there is a rapid change as the meal becomes coarser. Middlings appears to hold steady at some 35-40% of the output, while the flour fraction decreases at the same rate that bran and pollards increase. As the flow rate increases further, first middlings becomes the major refinement and then, as the maximum flow rate is approached (119 lbs/hr for the fixed stone speed of 84rpm), the three refinements become reversed to the original order of magnitude. The greater part of the output was now coarse.

The graph suggests that there is another range of flow rates, above 60lbs/hr where the product fractions are relatively constant from 75 to 105lbs/hr. The fractions appear stable, but at 105lbs/hr, their proportions move rapidly towards coarser meal. At a flow rate of 105lbs/hr, the flour production is at a maximum of 36.5lbs/hr compared with 30lbs/hr at a grain flow rate of 60lbs/hr. However to achieve this greater flour production the millstones have to process almost twice as much grain, and, of course, there is a corresponding increase in the production of coarser products including the offals. In the Roman period, if the flour had been sieved out, some advantage would have been gained by passing the remainder through the millstones again to obtain further flour. In the Westree experiment, the double grind on the 43lbs/hr sample suggested that the dress on the stones needed to achieve further reduction was different from that required for wheat grain. With the normal dress the throat of the stone, which is used to crack and reduce grain, would have no effect on meal. If the coarser fractions were put through millstones again, then the stones needed to be a different pair, dressed accordingly. We may suggest therefore, that in those corn milling establishments having more than one set of millstones, that sieving followed by further grinding of the coarser products may have occurred.

When interpreting this graph of product fractions for different flow rates we must not forget that the sieving standards used by the Roman millers may have been quite different from those adopted in the

Westree experiments. If, for instance, the Roman flour was coarser than the flour defined above, [<300 microns] then the modern fractions would appear differently on the graph. The line for flour would appear higher and the remaining products would be correspondingly less in total. The 'critical' flow rate as shown by the change in gradient of the line would still occur although its value might shift slightly from 60lbs/hr.

The natural capacity for these stones, running at 84.6 rpm and absorbing 0.51 h.p. is 60 lbs/hr; this could be recognised as their critical or optimum flow rate above which the product becomes rapidly coarser.

The following table provides a comparison of typical modern products;-

PROCESS (Wheat)	% PRODUCT		
	Flour	Middlings	Bran & Pollard
Modern Stoneground Wholemeal (English)	75.7	15.7	8.6
Modern Roller Mill Wholemeal (English & Canadian)	83.5	12.5	4.0
Roman style millstones (English)	52.4	36.2	11.4

This comparison shows that the meal coming from the Roman type lava stones is much coarser than modern millstone products.

The wheatmeal coming from Roman millstones was undoubtedly coarse and probably not returned to the stones for refinement, a conclusion supported by the coarseness of the sieves used and the lack of evidence of grinding more than once[26]. As Jasny points out, repeated grinding

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26. Jasny, as note 17, pp.150, 151.

is far too important not to have been mentioned by many. Jasny reasons with conviction that the grades of product given by Pliny were uncommon, indeed rare, probably found only in the largest cities, and that the dominant product was whole wheatmeal, perhaps even in Rome itself[27]. Although Jasny has derived the probable proportions of the various millstone products from Pliny's extraction rates for the two common forms of wheat, the writer considers that it would be valueless to make comparisons with the Westree products - products which are classified by modern standards and which, therefore, have no relevance to ancient milling and baking practice.

D2. Power Tests.

A laboratory wattmeter was connected into the power circuit so that induction tests could be undertaken on the motor, which has a rating of 415V, 3ph, 2.5A and 1.5h.p. During these tests the speed of the millstone was visually checked by counting its revolutions over a marked period of time. This was done to ensure that the drive belt was not slipping.

A no-load test was measured which gave 420V, 1.4A, 260W and 0.27 power factor lag when the output speed of the shaft was 88rpm. During the no-load test the top millstone was raised so that friction between the stones was non-existent. In this operating mode the friction between the gears still occurs and the footstep bearing also has a power loss. This has the disadvantage that the footstep bearing is taking the full weight of the top millstone, which does not occur during full running conditions. It is considered that this test arrangement is a better alternative than dismounting the runner stone, which would have the disadvantage of making the no-load power losses much less due to the absence of rotating masses and their effect on gear and bearing losses.

A test of the circuit under load gave 420V, 1.7A, 680W, and a power factor lag of 0.79 with an output shaft speed of 84rpm. The resistance between the terminals was 9.03 Ohms.

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27. Jasny, as note 17, pp.151, 155, 138.

Power calculations.

The output power on load = input power - (fixed losses + extra stator 'copper' loss + rotor 'copper' loss)

Input power = 680W

Fixed loss = 260W

Extra stator copper loss = 3/2 x 9.03 x [(1.7x1.7) - (1.4x1.4)]
= 12.5W

Rotor copper loss[28] = slip x rotor input
= 6/90 x (680-260-12.5) = 26.5W

Hence output power of shaft = 680 - (260 + 12.5 + 26.5)
= 381W = 0.51h.p.

D3. Product/Power Ratios.

If we accept that the natural capacity for the Westree lava millstones is 60lbs/hr. when absorbing 0.51 h.p., then their product/power ratio is 117.01bs/h.p. hr.

It is interesting to compare the production/power ratio for the Westree Rig against modern millstone arrangements. The following information, which relates to the stone milling of wheat, is associated with experiments undertaken by millers of different nationalities, nearly all during the nineteenth century. For most of these experiments the operating conditions are not declared, and such information as, type of wheat, moisture content, fineness of product, millstone speed dress and sizes are invariably not given. The use of these figures for comparison purposes must be done with great caution. The type of stone, except in one or two instances, is not declared. However, the customary stone used for wheat throughout this period, confirmed by many of the texts in which these figures feature, was French burr.

A summary of these comparisons is given in the following table.

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28. Assuming 90rpm as synchronous speed.

PRODUCTION/POWER RATIOS (Water-powered stones unless stated)		
Source	lbs/hp.hour	Conditions if known
Westree Rig	117.0	
d'Aubuisson de Voisins[29]	55.1	Wheelshaft power
" " "	over 82.7	Power at millstones
Freese[30] (England)	16.8	Windmill; gross power
Belidor & Navier[31]	108.4	
M.Hashette[32] (Nr. Paris)	73.2	Wheelshaft power
Tardy & Piobert[33] (Toulouse)	5.6 - 59.1	Power at millstones
M.Egen[34] (Westphalia)	46.5	
Kozmin[35] (Russia)	94.5 - 126.0	From 35-56 ins.dia.
Buissan[36]	30.3	Burrs, no exhaust.
Dedrick[37]	51 .0 - 78.5	Power at millstones.
Farey[38]	approx. 59.0	Steam:grindg & dressg

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29. J.F.d'Aubuisson de Voisins, A Treatise on Hydraulics for the use of Engineers, trans. Joseph Bennett, Boston, 1852, p.448.

30. Stanley Freese, Windmills and Millwrighting, Cambridge, 1971, p.111.

31. d'Aubuisson, as note 29, p.464, quoting Belidor & Navier, Architecture hydraulique etc., vol.I, Paris, 1819, p.464.

32. d'Aubuisson, as note 29, p.448.

33. d'Aubuisson, as note 29, p.448.

34. d'Aubuisson, as note 29, p.448.

35. P.A.Kozmin, Flour Milling, London, 1921, p.190.

36. Kozmin, as note 35, p.190.

37. B.W.Dedrick, Practical Milling, Chicago, 1924, p.309. Derived from a modern mill power requirement varying between 0.26 - 0.40 h.p. per 196 lbs in 24 hrs. and allowing that 40% of the power is needed by the millstones. The author disagrees with Jasny's calculations using Dedrick's figures; see Jasny, as note 17, p.157.

Where the power ratio is related to the windshaft or the wheelshaft the production/power ratio for the millstones will be greater, because the gross power will include not only bearing and gear friction losses, but also ancillary machinery including bolting and dressing machines, elevators and conveyors.

The proportion of wheelshaft power taken by millstones will vary from mill to mill and most certainly through time as more and more machinery appeared during the nineteenth century to help millers to produce increasingly refined products. In the hey-day of flour milling, say from approximately AD 1870 onwards, a typical well-fitted flour mill would have perhaps one half or less of the wheelshaft power devoted to the millstones, particularly in large mills. We must remember also that the few writers which addressed the subject of flour milling were often describing exemplary examples of best practice which the greater number of mills, especially rural wind, water and steam powered, were striving to match. The figure given by Freese, which probably relates to a production/power ratio at the millstone spindle of, say, 25 lbs/h.p.hr, could be said to represent flour milling at its peak.

This low production/power ratio is supported by the evidence from a miller who operated 1067mm. diameter wheatstones earlier this century which could process 168 lbs. of wheat in an hour[39]. How interesting to see that other twentieth century authorities, such as Dedrick, give a figure between two and three times that declared by Freese, and Kozmin even more.

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38. Farey describes several trials, made between the years 1806 and 1811, made with steam engines powering millstones (in most cases declared as French burrs) dressing wheat. In nearly all cases Farey adopts a power rating of one bushel of wheat (59 lbs) an hour per horse power, rather than the declared nominal rating of the engines. See John Farey, A Treatise on the Steam Engine, Historical, Practical and Descriptive, London, 1827, Vol.2, David and Charles, 1971, pp.73-75.

39. Not more than 4h.p., 5 at the most, which equates to 42 - 33 lbs/h.p. R.J.Spain and M.J.Fuller, Watermills: Kent and the Sussex Borders, Maidstone, 1986, Memories of Wally Nye, p.166.

Earlier, nineteenth century writers, also give wide ranging production/power ratios; those of Farey approaching the Westree figure, allowing for the power needed for dressing, and those of Hashette and d'Aubuisson, again allowing for ancilliary dressing and transporting machinery, approaching and perhaps exceeding the Westree figure.

One other comparison for the Westree results is provided by Wulff[40] who declares product/power ratios ranging from 29.7 to 33 lbs/h.p.hr. for relatively modern Persian arubah-style horizontal mills. Wulff's figures are based on data from site observations of working water-mills but assume an efficiency of application[41] and a theoretical relationship between jet orifice and water flow rate. The product/power ratios which he uses are derived from the potential power within the water-jet and no account is taken of the power required for the grinding. Wulff's figure of 10 h.p. for a pair of 1.2m diameter stones moving at 164 rpm is much greater than that which modern milling experience would suggest; so too is the rim velocity, which is one third greater than the modern limit used to avoid the burning of the meal. Moreover, in the data the throughput of the mills is more than doubled with only a slight increase in speed. No information is given concerning the type of grain used, the stone material, weight or dressing, nor how the coarseness of the product varied with the changes in throughput. With a doubling of throughput the coarseness of product would increase, as shown by the Westree

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40. Hans.E.Wulff, 'A Postscript to Reti's Notes on Juanelo Turriano's Water Mills', Technology and Culture, Vol.VII, No.3, 1966, pp.398-401.

41. Throughout his calculations Wulff uses a constant coefficient of efficiency of 0.75 [Wulff p.400] which he applies to all three watermills that he examines, where in each mill the water flow rate varies by a factor of at least two to one. This variation in flow is achieved by changing the size of the clay nozzles whilst the waterwheel remains unchanged. The writer questions whether or not a constant coefficient of application or efficiency can be used in these circumstances.

results. If this occurred in the Persian mills, as seems likely, the product/power ratio should increase, but Wulff's figures remain remarkably constant.
Using the potential power of the jet with crudely applied efficiency coefficients Wulff has probably overrated the power required by the stones, so that his figures should be used with caution.

To summarise, the Westree production/power ratio is generally much higher than modern ratios, although some authorities, especially early nineteenth century, are comparable. This comparison appears to confirm that the ratio is directly related to the coarseness of product, the Westree lava stones requiring much less power to produce the same flow rate as modern french burr wheatstones.

E. Conclusions.

We have seen that the production/power ratio is considerably higher than that related to modern millstones, which is a reflection of the coarseness of the product. This relationship between power and coarseness of product is disproportionate, so that for an increase in coarseness the power required is proportionally much less, a phenomenon recognised earlier this century[42]. Thus we may conclude that power required for grinding is proportional to Q (quality)/ f (fineness of particle size).
What then of the production/power ratio? What factors influence its accuracy and its application to other Roman mills?
The most obvious influence on the production/power ratio is the flow rate itself. From Fig.15, which shows the product fractions at different flow rates, we have identified what appears to be a natural capacity, a flow rate limit, up to which the fractions are more or less constant. Above this there is another range of flow rates, from

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42. Anon, Annales Institut National Agronomique, 1910, 2nd. Series, lx, pp.309-310.

75-105lbs/hr, where the fractions remain more or less constant, but where the product is very much more coarse. This variation in flow relates to a production/power ratio of 147-206 lbs/h.p.hr.
Although the change from the lower flow rate to the greater would be very noticeable to a miller by virtue of the sudden increase in the coarseness of the meal issuing from the stones, we cannot take for granted that the product refinement associated with the lower flow rate was generally adopted.
For the purposes of this study the production/power ratio of 117 lbs/h.p.hr. has been adopted for lava stones, but if a very much coarser product was accepted then the production could have been increased by up to 75% using the same power.
The other influence on the production/power ratio is the coefficient of grinding. Having concluded that its accuracy is in the order of plus or minus 20%, then this same tolerance must be applied to the ratio, because of the direct relationship between power of the stones and the friction between their faces.

The Westree experiment has provided us with a production/power ratio relating to Roman lava millstones. This allows us to estimate the production rate of those Roman mills where it has been possible to determine the probable working conditions - the power being absorbed by the millstones. Additionally in Chapter Three above it was established that millstone power is proportional to a product of speed (N) weight (W) and radius (R) (see page 52 above) where the coefficient of grinding and inclination of the face[43] can be assumed constant. This provides an alternative method of determining production by comparison with the Westree rig. For example, using power α NWR the throughput of the Haltwhistle mill can be determined as,

$$= \text{Westree throughput} \times \frac{\text{Haltwhistle NWR}}{\text{Westree NWR}}$$

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43. Cosec ϕ, which relates to the inclination of the faces, for these purposes can be assumed constant at unity.

$$= 60 \text{ (lbs/hr)} \times \frac{53.5 \times 363.7 \times 38.1}{84 \times 143 \times 30} \times 0.4536 \text{ (kg/lb.)}$$

= 56.0 kg/hr.

Alternatively, using the production/power ratio method,

throughput = 117 lbs/h.p.hr. x 1.086 hp. x 0.4536

= 57.6 kg/hr.

The following table provides the results of these calculations for three Roman watermills.

ROMAN WATERMILL PRODUCTION (kg/hr.)		
	Production/power	Power α NWR
Haltwhistle	57.6	56.0
Agora	141.5	134.2
Barbegal (single mill)	127.4	133.2

The close relationship between the two alternative <u>independent</u> methods of calculating output shows that the Westree results can be transposed to other lava millstones and confirms the relationship between the components of millstone power.

The Westree experiment attempts to replicate a pair of working Roman millstones: only the geometry and the operating mechanics of the stones, the lantern gear and the driver gear[44] have relevance to his-

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44. The replication of the Zugmantel lantern geometry and the mating driver gear with its pin-type oak cogs, has not been fully exploited. It should be possible to determine the power loss and thus the efficiency of this early and basic type of gearing, but this has not been done. There is a great deal more that could also be learnt from further tests with the millstones, but all beyond the terms of reference of this thesis. The preservation of the rig will afford future

toric authenticity - in other words the dynamic properties of the rig. The power source and transmission arrangements are irrelevant to this attempt at replication. So too are the problems associated with them which occurred during the experiment.

The primary object of the Westree Rig was to mount and drive a pair of lava millstones, designed to a typical Roman style and being capable of adjustment between the grinding faces. This object was achieved in spite of teething problems associated with the commissioning of the rig. Arrangements for tentering of the runner stone and brigging of the spindle were based on the well-proven methods found in modern corn mills. Advantage was also taken of modern technology to power the rig, but in the power drive the gearing design was greatly influenced by the inclusion of a replica of the Zugmantel lantern gear. Working the gears, the spindle and the millstones, appears to be without problems, although we must recognise that the total number of operating hours to date is very low.

The Westree experiment has provided a coefficient of grinding for lava millstones dressed with furrows in the Roman style. For the few Roman watermills where a hydro-mechanical analysis can be applied, the coefficient will allow a more accurate calculation of the balance of power to be made. The determination of probable millstone speeds combined with the product/power ratio coming from the Westree experiment, will facilitate more realistic grain processing figures. Production from single millstone watermills or factory complexes such as Barbegal, can now be re-assessed with greater confidence.

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research students the opportunity for other studies into the operation of Roman style lava millstones.

Chapter Five

THE WATERMILLS OF BRITANNIA

A. Introduction.

At the turn of the last century, when Bennett and Elton were busy producing their impressive study concerning the history of corn milling,[1] Romano-British watermill sites were unknown in these islands. Apart from a dubious suggestion by an eighteenth century historian, that a conduit discovered at Knott Mill near Manchester, may have been the race of a Roman watermill,[2] no archaeological evidence had been identified to support their existence. Even Clayton's excavation work during the 1860's, which revealed a millrace and millstones associated with the tower of a bridge abutment where Hadrian's Wall crossed the River North Tyne, was not identified as a possible watermill.[3]

Many millstones were being discovered in Roman contexts and horizons throughout the nineteenth century and later, but these were rarely recorded and invariably cast aside and often lost, many museum specimens being unprovenanced. Querns were even more common as a staple artefact of most domestic, military and industrial sites. Unfortunately, the distinction between millstones and querns has always caused problems for the archaeologists, and still does, especially when fragmented and degraded.[4]

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1. R.Bennett and J.Elton, History of Corn Milling, 4 vols, London, 1898-1904.

2. Whitaker, History of Manchester, ii, 1771, p.216.

3. Archaeologia Aeliana, 2, vi, 1865, p.86; J.C.Bruce, Roman Wall, 1867, p.148.

4. In this context the word degradation means the mechanical detrition by man involving the obliteration in part or whole of the original working surfaces by subsequent, different functions, e.g., rotary milling to reciprocating milling to whetting.

Perhaps understandably then, these artefacts were largely ignored in site reports, lost among the volumes of minutiae devoted to the drawings and identification of sherds and other artefacts. The difficulties of interpreting milling artefacts together with the lack of understanding of associated hydraulic and mechanical technologies have inevitably retarded studies of watermills in the Roman landscape.

But it would be wrong to arraign earlier and more recent archaeologists of being blind or insensitive to the technological content of their discoveries. The historian of technology is a recent animal to emerge in the evolution of disciplines and specialisms associated with the study of history. Even when a Victorian archaeologist realised that he had uncovered a watermill, it had little relevance to his classical interests; only recently has engineering and the sciences of the industrial arts [technology] been accepted as an expression of intellectual development.

The professional or amateur archaeologist, who overviews the changing English landscape, very often finds that his site is threatened and faced with limited life and resources. In such circumstances he must make the right decisions as to where to dig, be aware of what to look for and understand the relevance of what is being uncovered. Often time does not allow him to utilise the knowledge of other disciplines, so that the contribution of the historian of technology is post-excavation, and the full potential of the site is not realised. At the moment of recording, the quality and potential of the evidence is reflected by the methods, skills and sciences which create the record; thereafter its value decreases relatively as our knowledge, archaeological methods and skills steadily improve. When a site is wholly preserved, successive generations of historians can re-assess the evidence, but when, as in Britain, perhaps a half of the sites are lost shortly after discovery, the process is irreversible. Only recently has it been suggested that the interpretation of primary site evidence for the purpose of engineering analysis is the preroga-

tive of the engineer.[5] But until this is widely recognised by archaeologists of the Roman period, a fruitful reciprocal relationship with engineering historians will not occur.

And so the Roman watermill corpus has as one of its potential sources, in addition to the publications devoted to present-day archaeology, the historical works of excavation. In England and Wales almost every County has its archaeological Society or similar medium of publication, long-established in many cases, so that searching extant records for possible Romano-British watermill sites is never-ending. Doubtless this could be extended to other parts of the Empire, but few provinces are as rich in records or have the same intensity of archaeology, both professional and amateur, as Britannia enjoys.

For the historian of Roman technology, more particularly the student of waterpower, this tremendous volume of archaeological and related historical works presents two problems, both of them an inevitable and direct consequence of England's long-standing prominence in the archaeological world.

All earlier archaeological reports being, to a greater or lesser degree, deficient by present-day standards in terms of accuracy, interpretation, dating and recognition etc., present the student with doubts as to what was found or had existed. Thus it becomes essential to the study that the degree of certainty or *probability* must be established. This concept of probability requires that the evidence for each potential watermill site is assessed for acceptance before being included in the corpus. The criteria of probability are discussed later.

The very nature of the Britannia evidence, provides the student of Roman waterpower with, not only a surprisingly high proportion of the total extant evidence, but also a number of sites having a degree of probability associated with them. Herein lies the second problem. When first examined, the Britannia evidence cannot be interpreted by analogy from elsewhere, and the elemental probabilities which exist

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5. R.J.Spain, 'Romano-British Watermills', Archaeologia Cantiana, vol.100, 1984, pp.101-128, pp.101ff.

must be incorporated into an appraisal of the whole Roman province. A somewhat more difficult task follows, of assimilating the Britannia evidence into the Empire context.

Transcending all of these difficulties we must not lose sight of the paucity of evidence that we are dealing with, and should recognise that it is bad practice to write history with so much evidence still to come. This also makes the objective assessment of new evidence very difficult.

B. The Archaeological Evidence.

B1. The Criteria of Acceptance.

In Romano-British watermills, usually nothing remains above the original floor and ground levels, so that the *in-situ* evidence is limited to foundations and watercourses. Scattered artefacts provide dating evidence, occupation patterns and information concerning the effect of the natural forces of decay, erosion and deposition. In the absence of machinery remains or telling evidence embodied in the building fabric, we have of necessity, to look to other forms of evidence to confirm the existence of a watermill. Such questions as, How was the water brought to and taken from the wheel? What mode of application and methods of water control were used? can have great influence on deciding if a watermill existed.

Of all the criteria of acceptance, dating is surely the most important. Without dating, the evidence has no datum and cannot be related to the historical context. The foundation date has particular relevance, for this was when the original design was committed to fabric. Secondly, the duration and occupation periods of the site are also important because continuity of operation, opportunity for change and technical development are greatly affected by the life of the mill. Having undated evidence, when considering technological evolution, is the same as having unprovenanced evidence when considering technological diffusion; one is invalidated because it is unrelated in time, the other in space.

The primary evidence of a watermill is unmistakable, a building with a watercourse passing through or alongside it, in conjunction with millstones,[6] usually fragmented, found within the mill or its environs. Such evidence, although essential for the case to be made, is not *per-se*, conclusive; the millstone may have been powered by animate sources, and the watercourse used to wash grain. Such evidence was found in a second-century AD site near Littlecote Park villa at Ramsbury in Wiltshire between 1978-81. A large timber building was found 10m by 30m containing a corn drier, oak-lined tanks, quern-stone fragments and ovens, suggesting that a bakery existed there.[7] Outside the building another fragment of a very large quern (millstone?) was found, and in the adjacent stream part of a millstone. The scale of operation combined with the proximity of a large stream makes this a potential watermill site but, as yet, no direct and conclusive evidence of water-power generation has come to light.[8] What is missing in all of this is evidence of the machine itself, the wheel, wheelshaft, gearing and horizontal bearings, or evidence of the hydraulic arrangement necessary for water application.

One other example of discovery and interpretation is particularly relevant. During 1988, a third century AD threatened site was uncovered at Boxted Wood near Great Dunmow in Essex. The site had been thoroughly stripped in the Roman period of all building fabric including sole plates, but enough evidence remained to suggest that a watermill had existed here. Foundations of three kilns and at least two buildings could be traced together with numerous waterways and ditches criss-crossing the site, which occupies a prime position in the loop of a stream.[9] As more evidence emerged, including several

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6. As distinct from querns, although we should note that these have been found alongside millstones in a number of Roman watermills.

7. Britannia, xiii, 1982, pp.387-8; xii, 1981, p.360, Fig.16; x, 1979, p.329, Fig.17.

8. I thank Mr.B.Phillips for his patience and the care which he gave to my lengthy communications.

millstone fragments and a man-made watercourse which passed alongside one of the buildings, the probability that this was a water-powered site increased. The total absence of any building fabric or machinery evidence brought the focus of attention onto the watercourse beside the building.

If the excavation had been arrested or lost at this point, or the archaeologist had not seen fit to bring in far more resources, Boxted Wood would have entered the history records as a high-probability Romano-British watermill site. To the credit of the archaeologists, a historian of technology was invited to take an overview of the work from the early stages and it was this combined discipline approach which accelerated the development and technical interpretation of the site.

Further excavation of the 'V' shaped supposed millrace revealed the following evidence-

(a) It had not been lined either with clay or wood.[10]

(b) No alluvial deposits were found and the sides of the channel were remarkably clean.

(c) It had little or no gradient.

(d) Beside the building, the optimum position for a wheel, there were no signs of a sole plate or post holes on the 'landside' bank to support the outside wheelshaft bearing.

(e) Some two metres past the building the watercourse abruptly ended in a 'sink' or 'sump'.

(f) No bypass arrangement or water control evidence, separate or integrated with this channel, could be found.

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9. I am indebted to Chris Going for bringing this excavation to my notice during the early stages of discovery, and to Mr. Owen Bedwin, Deputy County Archaeologist for Essex for giving me access and involving me in the ineterpretation and planning of the work.

10. No post holes for revetment work were found and its curvature on plan was too great for planking.

The inevitable conclusion of this evidence is that the water channel had not been used to generate power; its purpose is something of a mystery.

The lesson to be learnt from these examples is twofold. First, there is clearly a type of Romano-British site where watercourse, millstones and buildings occur in juxtaposition but waterpower was not employed. In the absence of above-ground[11] proof of the existence of a watermill, the archaeologist must search, interpret and record the hydraulic evidence to the point of conclusion whatever the result.

In Britain, where presently the type of landscape and the archaeological interests combine to produce a higher incidence of uncertain watermill sites, more than anywhere else, the concept of *probability* needs to be applied. Experience of the Littlecote Park villa and Boxted Wood examples show that we must ensure that, when we assess probability, the criteria that we use must include not only for evidence found (positive) but should also reflect where the absence of evidence could <u>not</u> be proved (negative). What the archaeologist failed to find could be as important as that which he discovered. But to be able to say what was not there the archaeologist must know what he is looking for, which in many of these sites requires a knowledge of Roman hydro-mechanical technology. However, ignorance is only one of several reasons why an archaeologist may not realise the sites' full potential of evidence; so often the historian of technology, who assesses the probability, will have his task clouded with uncertainty. Nevertheless he must attempt to gauge the comprehensiveness and interpretational qualities of the work, for these can greatly affect the unknown elements of probability. But before we develop further the concept of probability, let us summarise the criteria of acceptance in order of importance, and having done this, subject the Romano-British evidence to the test, identify and reject that which fails.

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11. The Roman ground level.

Mandatory First, having identified that dating is critical for acceptance, all material which is attributed to a date by circumstantial evidence should be regarded most dubiously and considered for rejection.

Proven Second, convincing evidence of the machinery (water-wheel, wheelshaft, gears) or its position (horizontal journal bearings, wheel or gear pits).

Probability Third, in absence of the second criteria there must be evidence of a suitable watercourse, which can be viewed as providing the opportunity to generate power.

Probability Fourth, evidence of millstones (not querns), whose existence can be taken as proof of demand for power.

Probability Fifth, evidence of a building.

B2. Evidence to be Excluded from the Corpus of Watermill Sites.

(a) Millstones. There is in existence a great number of millstones, provenanced and unprovenanced, which have come from Romano-British sites. Only those stones which can be related to possible or proven watermill sites can be included in the corpus; all others may have been powered by animal, man or water. The possible incidence of watermills is discussed later.

(b) Millstone spindles. Two millstone spindles have been identified in Romano-British iron hoards[12] which cannot be related to known watermill sites. The Great Chesterford specimen, complete with mill-rynd attached is most probably related to an under-driven arrangement which is surely therefore of watermill origin.

However, the much larger Silchester spindle, without rynd, although probably under-driven, could be over-driven, which if correct is unlikely to have been water-powered. Although we cannot include them in the corpus of sites, the spindles are valuable examples of milling machinery.

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12. One was found in a hoard of iron-work at Great Chesterford in Cambridgeshire, see Archaeological Journal, xiii, 1856, 9, 13, no.28; the other specimen was found with a hoard of iron-work in a well at Silchester. See.W.H.Manning, 'A Mill Pivot from Silchester', Antiquaries Journal, xliv, 1964, pp.38-40; J.Evans, Archaeologia, liv, 1895, p.141, Fig.2.

(c) The supposed waterwheel hub from Chesters Fort and Lincoln.
Close to Chesters Fort, where Hadrian's Wall crosses the River North Tyne, an unusual barrel-shaped stone with equi-spaced mortices around its girth was found. Its proximity to the probable watermill site in the east abutment of the Roman bridge no doubt prompted the suggestion that this was a waterwheel hub. Clearly it was not intended for this purpose, nor was the similar stone found at Lincoln in 1950 beneath the east side of the High Bridge.[13] This is an example of where a false interpretation was accepted and repeated by subsequent historians, apparently without further consideration, thus becoming part of history.

(d) The Nettleton site. In 1968, when a tropical storm caused the rivers of north Somerset to flood, deposit and denude their banks, an unusual water-wheel emplacement came to light east of a Romano-British settlement, near Nettleton Scrubs, Wiltshire.[14] The waterwheel site, which lays just 300ft. to the east of where the Fosse Way crosses the Broadmead Brook, was in the south bank of the river against an outcrop of oolite limestone at the foot of a hillside. Dressed limestone blocks formed the wheel-pit, inlet channel and parts of the tail-race, and adjacent to the wheel position in the river bank was a dry-stone platform probably intended for access. Opposite the wheel emplacement, the river broadens in a semi-circular area contained by a raised bank with evidence of stone revetment work, and in mid-stream, in times of spate only, there is a raised area. Apart from some blue pennant roof tiles found in the water channel, no datable evidence was discovered on this site. However the archaeologist suggested that the limestone work was parallel to the nearby Roman work dated at before AD230.

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13. I.A.Richmond, Roman Britain, 1955, p.171; J.Liversidge, Britain in the Roman Empire, 1968, p.184; S.Holmes, Proceedings of the Society of Newcastle-upon Tyne, 2, ii, pp.178ff; Proceedings of the Society of Newcastle-upon Tyne, 3, ii, p.283; J.C.Bruce and I.A.Richmond, Handbook to the Roman Wall, 1947, p.79.

14. W.J.Wedlake, The Excavation of the Shrine of Apollo at Nettleton, Wilts. (1956-71), Society of Antiquaries, London, 1982, Reports of the Research Committee, no.XL, pp.95-8.

Understandably, with the discovery of this site, and perhaps excited by some of its unusual features, historians tended to quickly accept this as an additional specimen for the corpus. But before we adopt the archaeologists opinion of the age of the site we should see if it meets the criteria of acceptance which we have established above. We might also examine the technological implications of the evidence, and briefly, the effect on synthesis within the corpus that this would have.

At present, the Nettleton evidence has the following features which are unparalleled within the archaeology of Roman watermills. First the building work;-

(1) The approach channel and wheel-pit are made of large cut and dressed stones (varying from 1.143m to 1.575m long), with those forming the lower part of the channel cut from one piece.

(2) A splayed inlet shaped in the stones.

(3) Slots cut in the stones just in front of the waterwheel for an inclined water-control sluice.

(4) The water-wheel pit has a curved breast of dressed stone.

Secondly, we should note the unique features of the river works, which the waterwheel clearly relates to, which are;-

(5) The river has a substantial deflection of over 12.19m. opposite the water-wheel, contained within a man-made raised bank, semi-circular in plan, with stone revetment work.

(6) Between the river deflection and the water-wheel the river bed has a raised area, which must be the remains of some water control construction.

The above delineated features, when integrated and considered as a whole, represents a peculiar contribution to the Roman watermill world, so unusual, that analogy to other evidence is impossible, and synthesis is beyond question. The evidence is rather odd in other respects; if all of these works were intended to generate power within the Roman period, why make a major diversion to the river if the throughput of the wheel is such a minuscule part of the whole

flow? The diversion is not needed to create a head of water, nor to create a bypass to the wheel which could have been effected beside the wheel. Why then divert the river?

In other respects this would be an unusual Roman watermill. As a river-mill, it seems to be reasonable that the foundations are of stone, and we can identify others in Britannia that are similarly constructed. However, none of them are so well made of cut and dressed stone, not even those which form part of the much greater and important works of Hadrian's Wall. With a mill site such as at Nettleton, which is remote from the nearby settlement and has no apparent military connection, this seems incongruous.

Finally, we should note that the archaeologists make no attempt to reconcile this wheel site with the course of the river during the Roman period, which is clearly shown on their general plan of the whole area. It would be very difficult to join up the straight Roman river course shown on the plan with the waterwheel site. More obviously, why should the river have shifted so much from its Roman canalised course in this region and not moved from the 'Roman' wheel site? During such dramatic and natural changes to its course, how could the river landscape close by the 'mill' remain unchanged since Roman times?

Although we have doubt concerning its Roman origins, this wheel was clearly intended to generate power, but its purpose is unknown at present. Perhaps the waterwheel was an eighteenth century construction for river control or part of a landscape feature. Whatever its origin, it has been dated solely by inference, by circumstantial evidence from the nearby Romano-British site. For this reason, we should not include it within the Britannia corpus. Further excavation work should be undertaken within the envirions of the wheel emplacement, and the raised bank should be sectioned. Additionally the course of the canalised Roman river should be traced into Castle Comb valley to see if it positively moves towards the wheel site and, in so doing, their respective levels should be determined to prove the possibility of bed gradients.

B3. The Concept and Determination of Probability.

Earlier discussions have suggested that the probability of a watermill having existed can be determined by subjecting the archaeological evidence to the following criteria of acceptance.

DETERMINATION OF PROBABILITY : CRITERIA OF ACCEPTANCE		
Evidence	Examples	Condition
Date:site must be Roman.	Dating by coins, pottery, dendrochronology etc.	Site must meet this criterion.
Water-power generating machinery.	(a)*machinery*; waterwheel, wheelshaft, driver gear, journal bearings.[15] (b)*building fabric*;emplacements, support fabric or friction marks of above. (c)*control of water flow*; head, gradient, constrained /accelerated flow, sluices.	If this evidence is found, the site is proven.
Water courses. [opportunity to generate]	Natural or man-made, head-race/tail-race, bypass/ bifurcation.	Must be able to carry sufficient flow.
Millstones.[16] [demand for power]	Fragments or whole stones.	Not querns.[17]
Building.[18]	Foundations (post holes, sole plates etc.)	

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15. Millstone spindle and/or gear by themselves are not proof; they may have been powered by animate sources.

16. Currently all known Roman watermill sites relate to corn milling. We should not forget that there were probably other industries which used water-power.

17. Querns have been found on watermill sites. If millstones exist it would be assumming too much that a building existed at the same place without evidence.

18. It follows that if there is evidence of both watercourse and building, there must not be evidence that they were not in juxtaposition.

Probability of existence can be expressed as either positive evidence (artefacts or other evidence of actual existence) or negative evidence (proof that the artefacts etc., did not exist). In this concept positive evidence creates or increases probability whilst negative evidence decreases or destroys probability. Negative evidence rarely occurs in archaeological reports of possible watermill sites, for the archaeologists, who are rarely fully aware of what they are seeking, will not knowingly confirm or prove its absence. To make matters more difficult, the excavation has to be exhaustive for negative evidence - with proof of it being taken to the limits, otherwise it is inconclusive.

An example of negative evidence was provided at Boxted Wood, where the watercourse was proved, beyond doubt, not to have been used for water-power generation.

Now let us attempt to determine the probability of existence of the Romano-British watermills, including only those which have been positively dated to the Roman period[19].

SITE	EVIDENCE[20]	PROBABILITY	STATUS
Halt-whistle[21]	Building beside watercourse; Machinery(control of flow to the wheel); Millstones.	100%	Site covered
Ickham[22]	Watercourse thro' building;	100%	Site

19. For a general discussion of all Romano-British evidence see Spain, as note 5. See additionally Stanwick, Current Archaeology, vol.xi, 2, Nov. 1990, p.122.

20. Primary criteria underlined.

21. Proceedings of the Society of Newcastle-upon Tyne, 'Discoveries per Lineam Valli', 3, iv, p.167; F.G.Simpson, Watermills and Military Works on Hadrian's Wall : Excavations in Northumberland, 1907-13, (Ed.) Grace Simpson, with a contribution on watermills by Lord Wilson of High Wray 1976.

22. Robert J. Spain, 'The Second-Century Romano-British Watermill at Ickham, Kent', History of Technology, vol.9, 1984, Ed. N.A.F.Smith, pp.143-180.

(Early)	machinery (conjectured support frames);millstones.		destroyed
Ickham[23] (Late)	Building beside watercourse; machinery (control of flow?, journal bearings, bypass sluice);millstones.	100%	Site destroyed (yet to be analysed)
Fullerton[24]	Building beside watercourse; (bypass channel); millstones.	70%	Site destroyed?
Leeds[25]	Watercourse; millstone.	50%	Partially destroyed.
Ardleigh[26]	Watercourse; millstones.	50%	Partly dug
Chesters[27]	Watercourse thro' building; millstones.	60%	Foundation exists.
Willow-ford[28]	Watercourse thro' building; millstone; control of flow?	60%	Ditto.

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23. C.J.Young, 'Excavations at Ickham', Archaeologia Cantiana, xci, 1975, pp.190-1.

24. Journal of Roman Studies, vol.lv, 1965, p.217.

25. Excavated by Newbury and Grove in 1975/6. There are no published records of this archaeological work.

26. I am indebted to Mrs.Dean Hughes (nee Pettit) for bringing to my notice the information concerning this mill site. A report of the excavation work and finds does not appear to have been published.

27. J.Clayton, 'The Roman Bridge of Cilurnum', Archaeologia Aeliana, 2, vi, 1861, pp.80-85; J.C.Bruce and I.A.Richmond 1947, as note 13, p.166; L.A.Moritz, Grain-Mills and Flour in classical Antiquity, 1958, p.136.

28. R.J.Spain, as note 5, pp.109-111; see also R.C.Shaw, 'Excavations at Willowford', Cumberland and Westmorland Antiquarian and Archaeological Society, Transactions, 2, xxvi, 1926, pp.429-506.

For those sites which have been destroyed the probability of existence is unlikely to change, although there is a slight possibility that as our knowledge of Roman watermills increases, our interpretation of the evidence may change. However, for those sites where the evidence remains, the potential for changing the probability is largely determined by the thoroughness of the excavation. For instance at Chesters and Willowford we are unlikely to learn any more evidence which will advance the probability, whereas at Ardleigh and Leeds, we can be fairly certain that further excavation work would bear fruit, (negative or positive evidence).

B4. Physical Environs of the Sites : Location and Arrangement.

The environs of watermills are always worth studying, for they may indicate why the builder chose the site and how the landscape was altered to bring water to and from the wheel. The table below gives a summary of their locations.

NAME	WATER SOURCE	ENVIRONS
Haltwhistle	6-12m wide Burn.	In the bend of a river; military road adjacent; headrace cut through rock.
Ardleigh	Small stream	4.8km from the sea and Colchester
Chesters	30-45m.wide R.North Tyne	Within tower, part of bridge abutment; military road adjacent.
Willowford	R.Irthing	Between sluices and piers of bridge; military road adjacent.
Fullerton	4.6m.wide ancient stream.	Bifurcation,1.5m.wide headrace; 4km from Roman road; in an area of Celtic fields.
Ickham (Early)	Ancient course of Lesser Stour.	Low lying, marshy, esturine land; navigable water and Roman road close by.
Ickham (Late)	Ditto.	As above but less wet.
Leeds	Small stream	Steep ravine-like valley;4.8km from known Roman road.

All of the above waterwheels, where known, were undershot vertical wheels, and lay close to Roman roads and/or navigable water. No evidence of water storage in the form of a pond, lake or river dam or weir has come to light, which may be a reflection of the relatively small flow rates which the wheels required. This may also partly explain the wide ranging type of site, which varies from the very small stream to large rivers, suggesting that there would have been literally thousands of potential sites all over Britain. This is confirmed by the Domesday Survey, for although we have no archaeological evidence as to whether or not they were vertical or horizontal, it does indicate the potential diffusion of water power sites in the landscape.

At Willowford the flow to the wheel was controlled partly by the adjacent sluices and very likely by other piers and water-gates upstream. With a wheel in such a vulnerable position receiving the open current, at least some protection would have been needed to stop floating debris (branches, weeds etc.,) from smashing the wheel especially following storms. A strong wide grille made of wood or iron was necessary upstream of the wheel, preferably some distance so that its clogging would have less effect upon the operation of the wheel. Without this upstream protection the operation and maintenance of the waterwheel would have been very difficult. In the light of other evidence from elsewhere in the Empire, it is likely that the wheel occupied the middle channel, the driver gear the other adjacent narrow channel, (closed at the downstream end by another abutment), with the sluice gates in the wider channel.[29]

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29. A less likely arrangement had the wheel in the wide channel. See Spain as note 5, pp.109-111. See also Bidwell, P.T, and N.Holbrook, Hadrian's Wall Bridges, English Heritage, Archaeological Report 9, 1989. Bidwell and Holbrook are unconvinced that a watermill existed here. In absence of a race or channel downstream from the sluices, they believe them to be for pressure relief but admit them to be too near the end of the abutment to be effective. They fail to explain satisfactorily the reason for three different width channels in close proximity and why they would expect to find a channel downstream from the sluices in a river mill situation.

Apart from Chesters and Willowford mills, whose positions and arrangements were predetermined by other building works, the other sites, where it has been possible to ascertain, appear to have had the water brought to them in a man-made headrace. At Leeds and Ardleigh we do not know the arrangements, but at Haltwhistle and both Ickham mills, this was clearly the case, whilst at Fullerton we can readily identify the advantages in taking the water to the wheel. At the early Ickham mill, where the building straddled the watercourse, it was much easier for the builder to bring the water to the mill on whatever line was most suitable, with the wheel-pit constructed to suit the wheel. This was surely done at the later Ickham mill where the headrace was lined with planks fixed to uprights and stretchers for some 28m of its length. If construction had taken place over an existing natural water channel, the banks and bed close to and within the mill would have required revetment and consolidation. At Haltwhistle, the mill was carefully sited in a loop of the river, all within the *vallum* of the frontier, and positioned so that the headrace length and gradient provided a high velocity application to the wheel. The sides of the headrace were revetted nearer to the mill with rough stonework and bratticing, probably with hurdles, for the water velocity was considerable as it approached the wheel, capable of moving small pebbles. Without protection the banks would have been quickly eroded. As the race approached the wheel its gradient increased and the builders cut through bedrock to achieve the slope, and the velocity that they wanted. Nearly all of the millstream was taken up by the headrace, with the tailrace kept short and graded to ensure that the water readily cleared the wheel to avoid backwater.

At Chesters it is not possible to determine how the headrace was taken from the river, but we can speculate that there may have been a weir or some similar arrangement to deflect or encourage the water into the race, most likely incorporating a sluice gate. However the line of both head and tail races is easily seen although the original gradients are difficult to ascertain. The siting and arrangement of this mill invites two main criticisms. First, the headrace does not align with the tower as it approaches, and within the tower, its course is skewed, almost diagonally across the chamber. Inside the

tower the waterwheel and other machinery would have been supported entirely by cross beams from the walls, and no separate foundations need have been built within the walls. It follows that the axis of the wheel and wheelshaft would have probably laid parallel to the tower walls but with this arrangement the axes of water flow and wheel rotation were misaligned. Even if we were to assume that within the confines of the tower the watercourse was re-aligned by changes of direction so that the water was applied normal to the floats of the wheel, the effect on the flow and the water velocity would have greatly reduced the efficiency of application.

The alternative to this was for the wheel to have been skewed to align with the watercourse which would have required its support beams to have been similarly aligned. At a slightly higher level would have been the bridge-trees supporting the millstone spindle. Whichever of these arrangements existed, they seem imperfect and ill-planned, though both possible[30].

The second criticism, which is an equally obvious one to the site visitor, is that the builders had chosen a site which must have become increasingly difficult to use as the river slowly but surely shifted its course away from the mill and its headrace. A glance on site or at a map shows the mill to be on an inside bank of a bend, and coincident with the forces of the current scouring and eroding the opposite bank would be the deposition occurring adjacent to the mill. Here, where the current slowed, the material carried in suspension would have settled out in deposits creating shallows and banks, especially just downstream of the bridge piers and abutments. These would have tended to choke the entrance to the headrace and make it increasingly difficult for the race to receive its water.

Over the centuries nature has taken its course and the river is now some 25m away from the mill. On this problem of river movement the builders would surely not have allowed the river to undermine the

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30. Following recent work at the site, Bidwell and Holbrook think that the channel probably served as a mill race but consider it far less probable that the tower housed the wheel. They do not discuss the alignment problem, nor the possibility that the tower floor could have been removed when a waterwheel was installed. Bidwell, as note 29.

foundations of the bridge. Both here and at Willowford, extensive stone pavements exist showing the efforts taken to combat erosion and undermining, and we can assume therefore that a considerable effort was made to maintain the water margins including, no doubt, the mill and mill-race.

Our criticisms of the position and the arrangement of Chester's mill need to be put into a different light and tempered if it is suggested that at this frontier river crossing there was an additional tower on the bridge, at the west end. On reflection this seems to have been an obvious and sensible arrangement, both from the military and water-generation point of view. With a bridge 58m. between abutments it would have required a tower at each end to command the bridge, the Wall and the military way. If a watermill also existed within the west tower it would have enjoyed a superior position. Being on the outside bank of the river bend, it would have received a strong water current, which would have provided a good flow condition through the mill and been relatively free of shoals and banks. We can conclude with some confidence that the west tower probably existed and it seems likely therefore, that it contained a watermill.

B5. <u>The Machinery of the Watermills.</u>

We have already identified that the major cause for the need to adopt the concept of probability is the paucity of Romano-British evidence found above Roman horizons in our archaeological sites. In Britannia no *in-situ* evidence of watermill machinery has come to light comparable with the outstanding Continental examples at the Agora[31], Barbegal[32] and the Baths of Caracalla[33]. At these three sites the machinery evidence is embodied within the remains of the building fabric, which, being stone and brick, has preserved wheel and gear pits, bearing emplacements and the scoring of rotating gears and

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31. See chapter 7.

32. See chapter 6.

33. See chapter 7.

water-wheels. Different climate and durable building fabric has largely contributed to the greater technological content of the Mediterranean sites compared with Britannia. These advantages are balanced partly by the results of a greater intensity of archaeological enquiry and partly by the rewards of more recent work.

The following table provides a summary of all evidence of machinery associated with the Romano-British sites, including two unprovenanced millstone spindles. The limited specification of the millstones, where known, has been given in the following order as first whether top stone(M^t) bottom stone (M^b), or both (M^{tb}), then diameter in cms, then weight of the complete stone in kg. Thus a stone may be defined as M^t,30,364.

EVIDENCE OF WATERMILL MACHINERY		
Site	Hydraulic	Mechanical
Haltwhistle	Remains of wooden trough. Headrace and tailrace.	M^t,76,165;M^t,64;M^t,74; M^t,79;Footstep bearing.
Fullerton	Headrace and bypass.	M + M - details unknown.
Leeds	None so far discovered	M,63.
Ardleigh	None so far discovered	M,64.5;M,54;M,41.
Chesters	Headrace and tailrace.	M?
Willowford	Emplacements for wheel, and sluices.	M? Emplacement for driver gear.
Ickham (Early)	None	Several millstones; foundations for the m/cy support frame.
Ickham (Late)	Headrace and tailrace.	M^{tb},86,121;M^t,86,123.8; M^b,88,130.9;M^b,92,96.7; M^t,56,44.7;M^b,78,157.8; M^t,103,207;M^t,56,97; M^b,75,64.2;M^t73;M^{tb},71, 28.7;M^b,73,29.5;M^t,82.5; M^b,67;M^b,64;M^t,62: 3 jrnl. bearing stones; iron hammer head[34].

34. This important find must soon be studied and published.

Great Chesterford	[unprovenanced]	Millstone spindle with 3 bladed rynd.
Silchester	[unprovenanced]	Millstone spindle.

No other journal bearing stones, other than those listed above, have been found in the whole of the Empire. Their journal cavities prove that the wheelshafts had metal journals, probably either bronze or wrought iron. Similar cavities which can be seen beneath bearing stone emplacements (not the bearings themselves) in the Baths of Caracalla, support the same conclusion. The millstone collections from Haltwhistle and Ickham show that native stones were used almost exclusively, and, at each site, different sized stones had been employed. This suggests two things; first, the miller may have used the stones for different purposes and/or, less likely, for different speeds; second, a more simple reason is that he had less control over the diameter of new stones in that they were produced by different craftsmen, at different times, and certainly in many cases, in different quarries. Clearly there were no standard sizes as suggested by the 'small' Saalburg type.

The Ickham collection of millstones, which appears to be the largest known from a single Roman watermill site, tells us a great deal more about milling technology with regard to styles of dress and stone wear, but it is beyond the aims and needs of this study to examine and speculate upon them in greater detail[35].

In contrast to the Continental sites, the Britannia watermills have produced little evidence to support hydro-mechanical analysis. Only at two sites can we attempt to estimate the flow rate through the wheel. At Haltwhistle the maximum was close to 0.31 cubic metres/sec, and at the older Ickham Mill a very similar flow rate may have existed. For the Haltwhistle site, where the headrace design is known and a reasonably reliable reconstruction of the waterwheel can be combined with the millstone evidence, a full hydro-mechanical

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35. R.J.Spain, An Analysis of the Millstone and Quern Fragments from Ickham, Kent, 1977, an unpublished report.

analysis can be made. Elsewhere the machinery evidence is fragmentary and analysis is limited to determining the power necessary to drive the millstones at different speeds.

Probably the most significant feature of the Haltwhistle watermill is the headrace, which analysis shows to have been constructed to give the water a progressively faster velocity as it approached the wheel. This acceleration was achieved in spite of the fact that the builders had to cut the final section through bed-rock. An unusually high velocity of application was gained at the wheel which increased the potential power of the headrace perhaps by three to four times. This feature of accelerated flow has not yet been found elsewhere in Britain, and, although we have only a single example, we should identify it as a progressive development; a positive indication of an improved and more effective design.

It is just possible that the evidence from the Late Ickham mill might support a hydro-mechanical analysis; provisional drawings of the headrace indicated that a meaningful study of the flow conditions could be undertaken but, what is not yet clear is whether or not we can determine the size of the waterwheel, particularly its diameter. Without this the calculations cannot be completed to give generated power, which in turn thwarts us from determining the balance of power expressed in terms of gear ratios and speeds. Time will tell. There is a greater likelihood that this evidence will shed light on the development of earth-fast, timber-framed structures. Provisional observations of the unfinished drawings suggests that there is a noticeable difference between this fourth-century mill building and the older mill downstream.

B6. <u>Building Technology.</u>

At Haltwhistle, Simpson found the mill building to be roughly rectangular in plan, though a slight parallelogram, having walls 0.83m thick faced on both sides with well-squared stones. Up to 3-5 courses were *in-situ* above a footing course. Beside the wheel the end of the building was built on bed-rock but elsewhere the walls rested on gravel with the ground level rising steeply, perhaps by as much as 1.2m, to the wall furthest from the water. A single door existed at the corner furthest from the stream and the remains of a clay floor

and a hearth were found. The clay floor would have been in the south-east half or two-thirds of the mill, with a wooden platform at the other end over the machinery and supporting the millstones.

The wheel-pit was cut out of solid rock some 1.7m. wide and 0.91m. deep, and opposite and parallel to the mill several large blocks of basalt were used to act as a wall. A few feet inside the mill on the line of the wheelshaft, Simpson's site photographs show stones which appear to be *in-situ* and are probably foundations for the inside wheelshaft bearing. Wilson[36] thought that the building was built of timber on low stone walls, perhaps because of the absence of stones found in the excavation, but this could be explained by robbing. It seems just as likely that the walls could have been built wholly of stone, which would have been more durable and weatherproof as an envelope.

Both at Chesters and Willowford, the watermills are integrated with frontier works, the foundations of which are all stone. At Willowford, the Roman bridge was built apparently to incorporate the emplacements of the wheel, driver gear and adjacent sluices, as we have already noted, extensive stone pavements were built on the river bed both upstream and downstream of the bridge, and through the bottom of the watercourses under the bridge.

Above these foundations, the arrangement of the mill is open to speculation although it was essentially determined by the Wall and military way passing above. The mill may have spanned the abutment and parallel pier, but until we have some idea of the pedestrian and vehicular level of the bridge, there is little point in suggesting the layout or area that it commanded.

At Chesters, the whole mill was contained in the bottom of the east tower, which is entirely made of stone. Recent excavations within the tower has shown that there are no foundations between the walls, confirming that any machinery was carried by beams and floors suspended between the walls.

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36. Simpson, as note 21.

In lowland Britain, at Fullerton and Ickham, timber-framed earth-fast constructions were used. There did not appear to be any sole plates for the building at the late Ickham mill and there certainly were not at the older Ickham site. The ground of the older Ickham mill appears to have had a wooden floor with the later extension having a flint cover probably floored over. At Fullerton the floor was a flinty rubble platform.

At Ickham (Early site) the building machinery support frames were carried by a considerable number of substantial square-section posts that had been dug in with the machinery support frame partly integrated within the building frame. Structural analysis has suggested that the mill was extended on one side, then later on the opposite side. The later work has been identified with a higher proportion of posts having unsymmetrical sections. Probably not more than a few decades after the mill was built the frame settled and moved so that the miller had to insert additional support posts. The poor symmetry of the frame, the choice of scantling in relation to their function, the irregularity of section, all seem to suggest that this structure was built by native craftsmen rather than military. This conclusion is supported by the fact that timber frame was the traditional Celtic building method.

With regard to the machinery support structure the wheelshaft was supported on parallel transverse beams with the spindle supported by a transverse bridge carried on parallel longitudinal beams. The four horizontal beams were supported by separate posts at each end, making a total of 8 posts. The millstone platform was carried above the wheelshaft and bridgetree by transverse beams, one carried by two of the bridge posts, and others carried by separate posts. In modern English mills all four of the bridge-tree posts rise to support the stones and platform, so that the Ickham frame is not identical to traditional hursting because the support function of the bridge-trees and millstone platform are not completely integrated.

There are considerable inaccuracies in the plan of the Ickham mill, even allowing for the additions that have been identified for extensions and strengthening. We must remind ourselves that space frames do not need to be set precisely because the final position of the

machinery is not dependent on the planes being perfectly normal to each other. This is something to bear in mind when considering the wheel and watercourse arrangement within the tower at Chesters.

C. Watermills in the Landscape and Settlement of Britannia.

C1. The Limes of Ostorius.

A glance at the O.S. map of Roman Britain[37] shows that as much as 90% of the civilian population as represented by the Cantonal capitals, other walled towns, major and minor settlements and villas, lie south and east of a line from the Severn to the Trent, excluding Cornwall and Devon. Is it coincidence that this was the line of the first frontier drawn up by Ostorius Scapula, Governor in AD47? The whole of Wales and its borders, the Pennines and the northern counties lie almost bare of settlements of purely civilian origin. In these same areas the military sites dominate, mirroring the civilian distribution.

The map shows that seven-eighths of all known auxiliary forts (not fortlets), excluding the southern uplands of Scotland, were to the north and west of the *Limes* of Ostorius. A substantial number of these forts and camps were temporarily garrisoned, in association with the formative years of occupation and subjugation. The majority of the cohorts making up the three legions and their auxiliaries that were present in Britannia for most of the occupation period were garrisoned in the legionary fortresses and the auxilliary forts of the northern frontier, including the outpost forts. On the northern frontier a tremendous palimpsest of military works exist especially in the Hadrian's Wall zone. But this purely cartographic view of the evidence is misleading and does not convey the changes of the period, nor reflect the military and civilian developments. During the late first century and most of the second century AD there is some justification for seeing the province in terms of separate military and civilian areas with the army largely concentrated in the highlands of Wales and the North and, elsewhere, almost entirely open settlements

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37. Third Series. A revised and updated Fourth Series was published late in 1988.

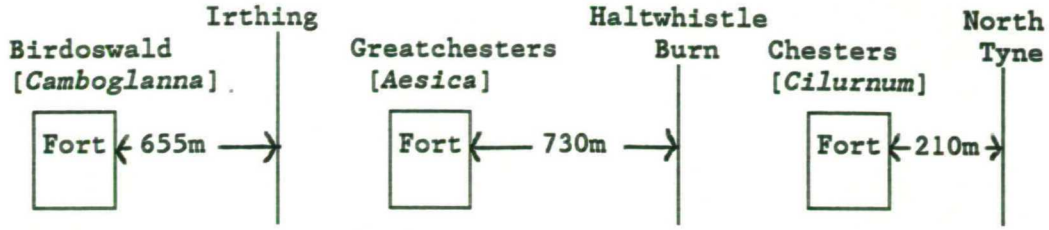
of civil character. In the third and fourth centuries, the difference between these two areas became less marked, though still obvious, with growth occurring within the military area of civilian settlements, mainly attached to forts, and in the south the military presence grew as the defence strategy of the province changed to include the Saxon Shore forts.

C2. Military Watermills.

When seeking to classify the sites of Romano-British watermills the most obvious group to take our attention in the hope of having some common relationship with each other are the three specimens associated with the Hadrian frontier. In some ways it is not surprising that the largest, best known and most durable of all Roman works in Britain should have provided us with the first three watermills to be found.

At Willowford and Chesters the mills are associated with the bridges which carry the frontier, (the Wall and military way) over major rivers, and are therefore military works. By comparison the Haltwhistle mill lies between the *vallum* and the Wall itself, and this strip of land is now recognised as a military zone. Within this zone or *limes*, in which a military road ran behind the wall to facilitate both defensive and offensive troop movements, civilians were banned. Where the Haltwhistle Burn passes through the frontier, the *vallum* and the Wall come to within 60-90m. of each other. A detailed map of the area shows that although there were other suitable positions on the Burn for a watermill, our attention should be taken by the fact that the mill was built within this narrow military zone at the nearest position to the Great Chesters [*Aesica*] fort 730m. away. Haltwhistle mill must therefore have been a military foundation.

At Willowford and Chesters, there are also auxilliary forts within a very short distance of the bridges, clearly positioned to protect and command the river crossings and the valleys through which they pass. And so we have three watermills each in proximity to a fort, thus;-



In the vicinity of these three forts it is possible there were other watermills. We have already determined that there was probably another tower at the west end of the Roman bridge over the North Tyne, and that it would have been a much superior position for a mill. At Haltwhistle, there must have been a bridge taking the wall over the water, but no trace of it remains. This would have been an ideal position to integrate a watermill into the stonework of the bridge, but here the Burn is much narrower than the broad rivers of the Irthing and North Tyne; perhaps only a single wheel with its associated sluices existed.

These three auxilliary forts, each within half a mile of a watermill, were each capable of housing either a *quingenary ala* of cavalry[38] or cohort of 480 men (6 centuries) or a *milliary* cohort of 800 men (10 centuries).

What of the other forts along the wall? How are they placed in relation to the rivers which break through the frontier? Surely there can be no place within Roman Britain that we have a greater probability of finding a watermill than along this frontier. This *limes* is a veritable *via aquatilum*[39], along which lies the conjunction of demand, as represented by the forts, with natural sources of power, the rivers and streams which pass through. It is not difficult to find possible sites for our attention. At Carvoran fort [*Magnis*] the Tipalt Burn passes between the wall and vallum only 760m away. At *Vindolanda* fort the Brackies Burn and the Bradley Burn come together at the north-west corner of the site, creating the Chainley Burn which then flows southward down the east side of the fort. Almost as

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38. As at Chesters fort.

39. 'Way of the watermills' or perhaps, via molarum, 'way of the mills'.

close is the Knag Burn to Housesteads [*Vercovicium*] on the wall. Several of the outpost forts to the north of the wall, deep in the territory of the *Selgovae* and *Votadini* tribes, appear to have suitable rivers or streams close by. At High Rochester [*Bremenium*] there are two streams, including the Sills Burn, within 305m. of its walls, and at Risingham [*Habitancum*], the fort is close to the river Rede. Similar juxtapositions occur with Newstead [*Trimontium*] and the River Tweed, and Netherby [*Castra Exploratorum*] and the River Esk.

All of the three watermill sites on the wall are thought to be third century constructions which means that they were not part of the original wall works, nor built with those sections which were converted from turf to stone by AD 163. Early in the third century some parts of the wall were rebuilt by Septimius Severus (AD 193-211) and shortly after AD 211 Caracalla withdrew all Roman garrisons back to the wall and equipped the outpost forts with semi-mobile units. In AD c197 the Pennine forts were reconstructed by Virius Lupus. Thereafter, during the middle and late third century, Roman Britain went through a relatively peaceful and settled period.

We might imagine that at the northern frontier, that if the permanent garrison *limitanei* [troops of the frontier provinces], included engineering corps and technical resources, they would be utilised in providing a supporting infrastructure of buildings, roads, bridges and of course, watermills.

Elsewhere in the military-dominated highlands, the army appeared to have more of a patrolling function. In Wales, Leintwardine fort was occupied constantly from the time of its building in AD c160 until the second half of the fourth century. In contrast, Prof. Jarrett has suggested that the Welsh garrison was gradually run down from the time of the first Antonine occupation of Scotland[40].

It has been suggested that late in the third century there is evidence of a lightly held northern frontier, perhaps regarded as safe because of the preceding settled period, and in about AD 296 the wall appears to have been stripped of its troops and possibly overrun by the outlying tribes. Ironically this was preceded by a substantial

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40. M.G.Jarrett (ed), V.A.Nash-Williams, Roman Frontier, Figs.4-11.

increase in the size of the army, estimated at twice that at the beginning of the third century, which would have brought about a simultaneous expansion of the supporting state-run factories. Early in the fourth century the wall garrisons were partially restored and the inland forts re-occupied.

Among the watermills of the south-east there is one, the fourth century Ickham site, which shows evidence of being an industrial site with military connections. In addition to the presence of numerous quern and millstone fragments relating to corn milling, there was considerable evidence of metal-based industrial activity, including large quantities of pewter, iron and bronze. Some of this material was in the form of belt buckles and fittings, *ballista* bolts and lead seals, which has prompted the theory that this site was an official depot or works associated with the Roman forts of Reculver and Richborough, situated at either end of the nearby Wantsum Channel. Amongst this evidence was a large iron hammer head with deformation on one face suggesting that it was from a mechanical trip-hammer. The inclination to suggest that this machine may have been water-powered is strong, bearing in mind that we have literature evidence that the Romans used water-power for non-milling purposes[41]. Moreover, a provisional view of the Ickham evidence suggests that more than one water-wheel may have worked there.

On the northern frontier, the creation and maintenance of a military zone, complete with its watermills, from which civilians were positively discouraged, indicates a positive geographic segregation of military and civilian functions. In an active military theatre this appears common-sense, but did this policy extend to such places as manufacturing and works depots, and collection depots for the corn tax?

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41. For a late fourth-century AD reference to water-power saws for cutting marble see Ausonius, trans. H.G.Evelyn-White, 1919, 1:253, bk.10, Mosella, lines 361-64; See also Vitruvius, On Architecture, trans. F.Granger, Book x, chapter v, (Loeb Classical Library), London, 1962, pp.304-307.

At the late Ickham site all of the industrial evidence, including corn milling, appears to be contemporaneous as far as we can tell, and was found in close geographic proximity. Moreover the number of millstones found suggests that corn-milling was more or less continuous for the life of the site.

If more than one prime-mover existed here, it was surely necessary to have single corporate management to avoid disputation concerning water control and rights. And with military weapons and equipment being made, it is inconceivable that any influence or interruption to production would be tolerated from a civilian industry occupying part of the site. On balance therefore it seems that this watermill was founded and managed by the military.

The late Ickham mill site should also be viewed in a wider context, and its occupation and operation related to military events occurring in the south-east of the province.

Early in the third-century Saxon raids began on the east coast which called for an increasing military presence. A major re-deployment of the army occurred and new forts appeared including Reculver at the north end of the Wantsum Channel. This was an eight acre stone fort, built AD c212-225, approximately half way through the life of the early Ickham corn mill which has been dated to AD 150-280. At Reculver fort there is a marked absence of late fourth-century coins which seem to end at Magnentius suggesting that the fort was in decline during this period. This may have been partly caused by the building of Richborough fort at the south end of the Wantsum channel in AD 275-285, one of six new forts which formed a new defence against continuing Saxon incursions. These works have been identified as the second stage of a defence system known as the Saxon Shore.[42]

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42. The Roman name 'Litus Saxonicum' (Saxon Shore) is preserved only in Notitia Dignitatum OCC XXVIII, dated to AD c395. How much earler we can use this name is uncertain. See O.Seeck, Berlin, 1876.

The metal work for the late Ickham mill commences from AD 330 at which time Reculver was in decline whereas at Richborough there was increasing military activity until the beginning of the fifth century. The latest date of the Ickham metalwork is AD c410 which coincides with the withdrawal of the Roman army from Britannia.

Towards the end of the fourth century the defence of Britannia became precarious as the numerous enemies of Rome assaulted the Empires frontiers. Magnus Maximus took troops from the province to fight in Gaul in AD 383-4 and Stilicho withdrew a legion at the turn of the fifth century, as recorded by Claudian as coming from the north in AD 401-2. By AD 400, many of the watermills which had been processing corn from the granaries of the army ceased to work. Six years later, when Britannia declared her independence of Rome, we may assume that all the working watermills were in public or private hands.

C3. Civilian Watermills.

We have limited evidence suggesting that civilian adoption of water-power for corn-milling may have occurred earlier than its use by the military. At present Leeds and the Early Ickham mills pre-date the military watermills with their predominantly third-century AD building dates. We can put greater reliance on the dating of the Early Ickham mill from the analysis of the abundant coins found which give a building date of AD 150. But at Leeds the evidence does not admit of such close dating, being derived from sherds to the 1st. and 2nd. centuries AD. Just as we have related the military demands for water-powered corn-milling to forts, so too can we identify concentrated civilian demands in cantonal capitals and larger settlements.

Any settlement having at least, say 100-200 people, would have provided stable custom and trade for an early watermill, so that a demand for corn milling was most certainly present throughout most parts of lowland Britain. How early this was satisfied by water-power, and what proportion continued to be met by the labours of men and animals, we cannot yet tell.

At present we have no examples of a watermill within a Romano-British settlement, but the Spring Valley site, some 6.4km. from Colchester can be suggested as possibly receiving town trade. Leeds mill might

also be put in this category. But this is stretching the imagination, for the number of potential watermill sites was such that literally all settlements, certainly all of the larger ones, could have been served by a local mill. King William's survey of 1086 confirms the potential of the English landscape for waterwheel sites, as does the exploitation for water-power in later centuries.

Away from the towns and larger settlements there were two apparently disparate forms of land exploitation, the villa estates and the native farmsteads. North of the *limes* of Ostorius villa estates are rare and native farmsteads occur in most highland areas. We know too little of the Romano-British villas and native farms to ascertain what social structures existed. Some villas have evidence of corn production on a large scale, which prompts the suggestion of slave-run estates managed by freedmen.[43] The Fullerton watermill was close to a villa, suggesting that the mill probably served local demands rather than Winchester 14.5km away, although we have no knowledge of the size or nature of the Fullerton villa estate.

The analysis of the Early Ickham mill has suggested that it was civilian built most likely by native craftsmen. Although only 10.5km from Canterbury the abundance of potential sites precludes that this mill served the town and we must assume therefore that the mill served local people. Whether it was associated with a particular villa or a group of farms is not known.

But the building of a watermill needed resources and skills not available to all social classes, and we can envisage that either an entrepreneurial or landowner initiative was required. In nearly all settlements and estates where a land-based economy existed and the resources were labour intensive, a landowner or manager could gain considerable advantages by satisfying the collective demands of animal and human foodstuffs from a water-powered corn mill. Although there is a danger in presuming that the Romano-British had a notion of efficiency in the modern sense as applied to resources, the very existence of watermills in both the military and civilian scene, confirms their willingness to adopt new technology for the advantages

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43. I.A.Richmond, as note 13, p.118.

that it brought them. What these advantages were, in both qualitative and quantitative terms, remains to be determined. A freeing of either human or animal resources for other agricultural or husbandry work would be an advantage to whoever commanded such resources, added to which would be the income or rent in cash or kind. It is not difficult to see the origin of milling soke in the Romanised lowlands for several of the socio-economic conditions which probably existed were repeated later in the medieval period, when watermills gravitated to landlord control as valuable sources of income. In the rural scene it would be the landlord who provided the artisans to build the mill and thereafter maintain its fabric, machinery and waterways.

Were any watermills state controlled? The official who controlled the central treasury, the *thesaurus*, was also responsible for the state factories of weaving, dyeing and transport, and the councils of the civitates were responsible for the leases of state-owned corn-stores, depots, mines, factories etc. Apart from supplying the army with corn-meal and other derivatives, a demand which was satisfied by the industry of watermills local to forts, there does not appear to have been the need for the state to control watermills serving the public. Whilst other industries, such as cloth, dyeing and mining, produced durable products which do not suffer from storage and travel, corn-meal, by its very nature had to be produced close to its customers. Meal, unlike grain, cannot travel or be kept. There is also a dissimilarity between meal and other staple products in their relative importance to the state; all metals were essential to the state economy - iron, lead, gold, silver, copper etc., and important for political, military and civil development and well-being; cloth-making, dyeing and leather were staple products for the army; all of these lent themselves to strategic administration and control. With the army controlling its own corn-milling, public or civilian demand could be met by private enterprise. This was surely the situation in the rural areas, while in the larger settlements, there might have been a corporate approach. Councils of the civitates may have been enterprising and have seen the same advantages as a private entrepreneur.[44]

Amongst the civilian settlements we must count the *vici* attached to the forts, which attained a considerable size and prosperity. In both these and the *coloniae*, the settlements for retired legionary soldiers (e.g., Lincoln, Colchester.), there would be an awareness and knowledge of the military watermills.

D. The Significance of the Britannia Evidence.

With regard to the incidence of waterpower, consideration must be given to animate power sources, both man and animal, in an attempt to determine their significance in the socio-economic conditions of Roman Britain.

We have already recognised the difficulty in classifying millstones and querns because of their obvious similarities which exist when they are of disc form within a range of diameters; when the artefacts are incomplete, which is so often the case, the problem is far worse. Luckily only large querns match the diameter of small millstones, the majority, including the typical military quern carried by soldiers, are smaller than any millstones. But identifying an artefact as a millstone is one thing; it is quite another to show that it was water-powered. At present only the Pompeian style millstones can be positively claimed as being none-waterpowered[45], whereas disc millstones, could be man, animal or waterpowered. Only three fragments of Pompeian style millstones have been found in Roman Britain, which suggests that the incidence of this type of animal mill was

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44. Throughout the 3rd century AD a great many cantonal capitals and other towns improved their defences by building stone walls which would have required a corporate initiative on the part of the councils or town elders.

45. Of the numerous milling establishments using Pompeian-style stones, none have been water-powered and all of the depictions dating from the Roman period show animal-powered arrangements.

very rare, undoubtedly due to a combination of the native stones being unsuitable for this large monolithic type of stone and the high costs of transporting these lava stones from abroad.

For all provenanced millstones it is the archaeological context which determines the power source, for at present there appear to be no technological features which help to solve this question[46]. Animate-powered disc millstone sites have been found at Kenchester in Herefordshire[47], Orton Hall Farm at Peterborough[48], and at Silchester[49], but what proportion of all millstones were water-powered cannot be ascertained; not enough evidence has yet been found to allow a meaningful assessment to be undertaken.

A rough indication of the reliance which was given to querns is provided by the great number of extant Romano-British specimens in comparison to millstones. It has been estimated that there are from 8-10000 pre-Saxon querns in the north of England[50], the great majority of which are clearly Roman military specimens. In this same area the number of millstones is more difficult to estimate, perhaps 2-400, but this quantitative comparison has little meaning unless we reconcile it with the following questions. First, we do not know the date or provenance of the great majority of these stones. Second, the

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46. Even the rare over-driven stone which uses a mill rynd on the top of the upper stone could be water-powered. Over-driven stones were apparently used in parts of Barbegal and at least one specimen has been found in England.

47. S.P.Rahtz and A.R.Wilmott, 'An Iron Age and Romano-British Settlement outside Kenchester (Magnis), Herefordshire: Excavations 1977-79', Trans. Woolhope Naturalists Field Club, for 1983 or 1984.

48. Report by R.J.Spain to the Nene Valley Research Committee dated August 1981.

49. G.C.Boon, Silchester: The Roman Town of Calleva, 1974, p.289.

50. Information from Adam T. Welfare, University of Newcastle-upon-Tyne, in correspondence with the author.

output of a pair of millstones should be compared with many pairs of querns. The Haltwhistle mill would have provided daily, enough meal for over 461 men in addition to the offals for animal feed[51]. Third, if we assume that there was a reliance on water-power for corn milling, querns must have continued in use all the time there was a military presence, especially on the frontier. A continuing demand for querns would have come from,

(a) all army units on the move.

(b) small garrisons which patrolled beyond the reach of watermill suppies.

(c) fortlets and temporary camps.

(d) garrisons well away from watercourses, although it is difficult to find examples of this.

Even for those forts which had their own watermill, a garrison could never discard its querns; they would have been called into use on all occasions of mechanical failure in the watermill, water-shortage or maintenance work, or any other event which brought about an interruption in the mill's production, including being over-run by the enemy. Whilst the army could never permanently abandon its querns, civilians were in a position to put much greater reliance upon the watermill. However, some of the lower social classes may not have been able to afford, in money or kind, the miller's services, and there were others whose lives were bound to hand-labour, including no doubt, quern work.

And so the question of incidence of water-power versus animate sources is complex and fraught with imponderable influences. Nonetheless, we can readily identify very positive advantages for its adoption, especially for the military. If we accept that one watermill could provide the daily demands of approximately 460 men, then the miller's work would free them from the quern labours that they would

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51. Allowing that the mill produces 57.6 Kg./hr. of meal; 90% for human consumption; 8hr. day, 7 days/wk; 900gr/day per person. The proportion for human consumption is very speculative. See N.Jasny, 'Wheat Prices and Milling Costs in Classical Rome', Wheat Studies of the Food Research Institute, vol. xx, no.4, March 1944, pp.135-170.

have otherwise have done. As every section of eight soldiers was normally equiped with a quern, this equates to the daily quern work of 460/8 = 57.5 men, whatever that may have been. Such were the advantages of technology.

Why then, did they not use water-power on such sites as Boxted Wood? Clearly the site was chosen, in the loop of a stream, to provide ready access for water, perhaps for washing and conditioning the grain. Even more obvious, the builder could have used the water for powering the stones, but for some reason, unfathomable to the modern mind, he did not[52]. What it does tell us quite positively, is that in the third century, animate power sources were used on sites where water-power was available. The significance of this will be determined partly by the incidence of animate-powered corn-milling sites found in the future, and partly by the socio-economic context of the occupiers, users and the industry that took place on them.

We have been able to identify, with some success, the two classifications of military and civilian, with regard to the building and operation of Romano-British watermills. Unfortunately, the paucity of evidence has brought about a very cautious attribution of their individual constructions to particular events or closely dated periods. Against this background the question of their incidence and diffusion can only be approached in a prudent and generalised manner.

Once built, watermills are not liable to periods of disuse during their lives, because without use, their decay is very rapid and damaging to their function. Modern experience tells us that the wood and iron of waterwheels, gearing, shafts and other machinery, quickly becomes unusable when abandoned, and a Romano-British miller would have suffered an identical experience. Millers would come and go, breakdowns and flood damage would occur, new roofs required etc., but all the time there was an assured local market for milling products, there would always be an income or labour-saving for the army or some enterprising investor or land-owner. If operations lapsed, for

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52. What was the ritualistic relevance of the horse-burial, and beneath it, the headless chicken and timber structure?

whatever reason, the uncontrolled effects of nature in the form of storm, flood, deposition, erosion and the advances of water-plants, scrub and trees, would render a watermill irretrievable within a few years. When this occurred, the unsophisticated building technologies and less-labour intensive building techniques of the Romano-British would have made it worthwhile re-building a mill on a fresh site.

Where were the skills to be found for such technology? The skilled technicians of the army were primarily to be found in the legions, although we should recognise that many of the artisan skills associated with corn milling must have been present in the auxilliary units of *quingenary* or *milliary* cohort size. It is interesting to note that in AD 297 Constantius drew from Britain a large number of skilled men [*artifices*] for work elsewhere in the Empire. Apparently Britannia was one of 'those provinces [which] had a surplus of them'.[53] The requisite artisan skills of carpentry and smithy work would have also been present in most of the established civilian settlements including the *vici* and *coloniae* where there would have been a substantial social and commercial intercourse between the military and civilian elements. We have no evidence that millers were able to collectively control and regulate their trade by guild or fraternity although we know of five *collegia* or associations in Britain who may have been merchants or craftsmen, one of them being a guild of smiths.[54] Even if they had combined, its effect would probably have been limited to the larger towns, for it would not have stopped the general public's awareness of the advantages of water-power and the skills required to support it.

One reason identified to support the notion of watermills being close to their customers is that meal has limited life and therefore cannot travel far in the ancient landscape. More telling is that land carriage was expensive in Roman times. Diocletian's edict on maximum prices implies that a 1200 pound wagon-load of wheat would double in price in 300 miles, whereas carrying it the length of the Mediter-

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53. Pan.Lat.Vet. VIII, (v), xxi, 2.

54. G.Clark (edit), Oxford History of England, Roman Britain, Oxford, 1981 by P.Salway, p.559.

ranean would cost less. Only the army, the wealthy and most privileged could afford long distances of land carriage. Towns were therefore heavily reliant on their hinterland for food production unless they had direct access to waterways.[55] As in more recent periods water-power corn mills were never far from their customers and in the Roman period this was surely the case; the closer a miller was to the demand, the greater his trade and custom and the lower the costs of carrying the products, whether borne by him or his customers.

Our knowledge of Romano-British watermills, coming from eight known sites, is sadly weak on dating and in terms of machinery, being limited almost entirely to wheel arrangements, waterways and millstones. To identify any technological or diffussional developments with such little evidence is virtually impossible. There are however two observations which can be made, both speculative to a greater or lesser degree, but worthy of consideration if only for the future when they can be reviewed and developed as more evidence comes to light.

The first is that two of the civilian mills, Ickham and Leeds, predate all of the known military examples. Does this reflect a military policy, of adoption only when there was a permanency of presence, on established *limes* and associated outpost forts? Such conditions were probably present in areas of the Welsh garrison and the Pennines during the late first and second centuries. And surely the agent of diffusion of such technology would have been the Roman army and its administration? And so we can expect earlier examples of military watermills to exist in Britain.

The second observation springs from a general view of the evidence, which shows that the sites and buildings display a wide variation of type. They range from small streams to broad rivers, earth-fast timber frames to stone-walled buildings, and have widely differing geographic settings. Moreover the standard of building ranges from the crude work of the native artisan in the early Ickham mill, to the well planned work of the military *artifices* embodied in the

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55. M.I.Finley, The Ancient Economy, 1973, paperback 1975, p.126f.

Haltwhistle wheel arrangement and headrace. If these few examples as found by the archaeologists are random discoveries, which they must be, then the variation we have in them are indicative of the ability of the builders, both military and civilian, to adapt to almost any geographic situation of marsh, downland or highlands and using local materials, to generate water-power. We have therefore a corpus, spread over three centuries, whose paucity denies us evidence of technological development *per se*, but instead, shows us the adaption of technology to the environment; the application of building and water-power technologies to the numerous different faces of the English landscape.

What is the significance of the British evidence in the context of the Empire?

The outstanding contribution of the Britannia evidence is its intensity, having more known or possible watermill sites than any other province of the Empire. Indeed, there have been times during the last decade when the Britannia evidence represented a surprisingly high proportion of all known Roman watermill sites. Currently this numeric significance is that Britain has approximately half of all known archaeological sites. The reason for this has already been identified as a reflection of archaeological intensity and quality rather than any distribution factors. There is no evidence that this province should have had a greater intensity of watermills than any other, nor should we expect any. Although there were three legions present in Britannia for most of the Roman period, Gaul and other frontier provinces had similar sized army garrisons. More obviously the land areas of Gaul, Italy and the Iberian peninsular are vast compared with Britannia, being ten times the size. We can see no reason why these Roman provinces, with their flourishing towns and cities could not have taken advantage of water-power for corn milling, and yet only three possible sites have been identified in Gaul and none in Iberia! The archaeological potential of such landscapes, in terms of water-power technology, must be tremendous, though at present there is no sign that this will be realised.

One very interesting fact emerging from the Britannia evidence is that all of the known watermill arrangements are undershot whereas several of the continental Roman watermills were overshot. Although the Athens, Barbegal and Caracalla specimens were served by aqueducts or other above ground watercourses, this does not explain *per se* why the overshot principle could not have been used in Britain. In chapter 8 an evolutionary model is proposed for the vertical water-wheel which suggests that overshot modes developed from the undershot arrangements. We have far too little evidence at present to tell if this model is realistic.

Chapter Six

THE BARBEGAL ENIGMA

A. Introduction.

Long since the first antiquary recognised these ruins near le Grand Barbegal as being a place of Roman industry, the historian of technology has realised that water-powered corn-milling existed here on a scale not repeated by western civilisation until more than one and a half millennia had passed. The Janiculum complex[1] and the Ephesos complex[2] suggests that Barbegal may not have been unique in the Empire, but it is the only example known to us. Its limestone walls and aqueducts, hewn from ancient quarries in the nearby *Chaine des Alpilles*, have withstood the kind Provencal climate and the stone-robbing of man to leave us with indisputable evidence of its former glory, enough to allow a theoretical reconstruction of its building and machinery fabric.

The sheer scale of Barbegal has, understandably, invited estimates of its throughput and the number of people which it served, but to the technologist these socio-economic considerations are ancillary to the solving of more significant questions. Who built Barbegal and why here? Was the aqueduct built for the mill and if so what are the implications of resources being committed to water-power on this scale? Where does Barbegal feature in the evolution of water-power and what effect did it have?

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1. We owe this knowledge to Roman historians and writers and not to modern archaeologists, whose efforts to relate the discoveries of aqueducts and millstones with the mills which worked on the Janiculum slopes, remain unconfirmed.

2. Hermann Vetters, 'Ephesos. Vorläufiger Grabungsbericht 1980', Anzeiger der Phil.-hist. Klasse der Österreichischen Akademie der Wissenschaften, 118, 1981, pp.137-168. Remains of a series of at least six mills at Ephesos, Asia Minor, dated to the 7th century AD.

Fernand Benoît's publication of his survey of Barbegal[3], made in the late 1930's, gave students of Roman technology, another outstanding watermill site following closely upon Parsons account of the Agora mill. Since then a succession of archaeologists, historians and technologists have examined the problems posed by Barbegal including Sagui[4], Grenier[5], Sellin[6], Smith[7], Roos[8] and Hodge[9].

As our archaeologically-derived corpus of Roman water-power grows, the historian of technology is able to view the contribution which Barbegal provides with an increasing enlightenment. Our analytical techniques are strengthened by more new and improved methods and approaches so that a periodic review is often fruitful.

Observations made by technologists during recent visits to the Barbegal site has brought additional evidence to light and confirmed that archaeologists have just revealed new features. All of these

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3. Fernand Benoît, 'L'usine de meunerie hydraulique de Barbegal (Arles)', Revue archéologique, 6th. ser. 15, 1940, pp.19-80.

4. Sagui, C.L, 'La meunerie de Barbegal (France) et les roues hydraulique chez les anciens et au moyen âge', Isis, vol.38, 1948, pp.225-231.

5. Grenier, A, La Gaule Romaine, New York, 1959, vol.VI(I), p.72.

6. Sellin, R.H.J, 'Le grand moulin à eau romain de Barbegal', La Houille Blanche, no.6, 1981, pp.413-426.

7. Smith, Norman A.F, 'The Origins of Water Power : A Problem of Evidence and Expectation', Transactions of The Newcomen Society, vol.55, 1983-84, pp.67-84.

8. Roos, P, 'For the Fiftieth Anniversary of the Excavation of the Water-Mill at Barbegal : A Correction of a Long-Lived Mistake', Revue Archéologique, 1986, vol.2, pp.327-333.

9. Hodge, A.T, 'A Roman Factory', Scientific American, New York, November 1990, vol.263, no.5, pp.58-64.

fresh developments are associted with the aqueducts which has prompted a review of our traditional views and consideration to new interpretations of the function and chronology of the aqueducts.

B. Aqueduct Studies.

At Barbegal, two aqueducts converge some 300m north of the mill. One comes from the east over a distance of approximately 17km and the other, much longer, comes from the west.

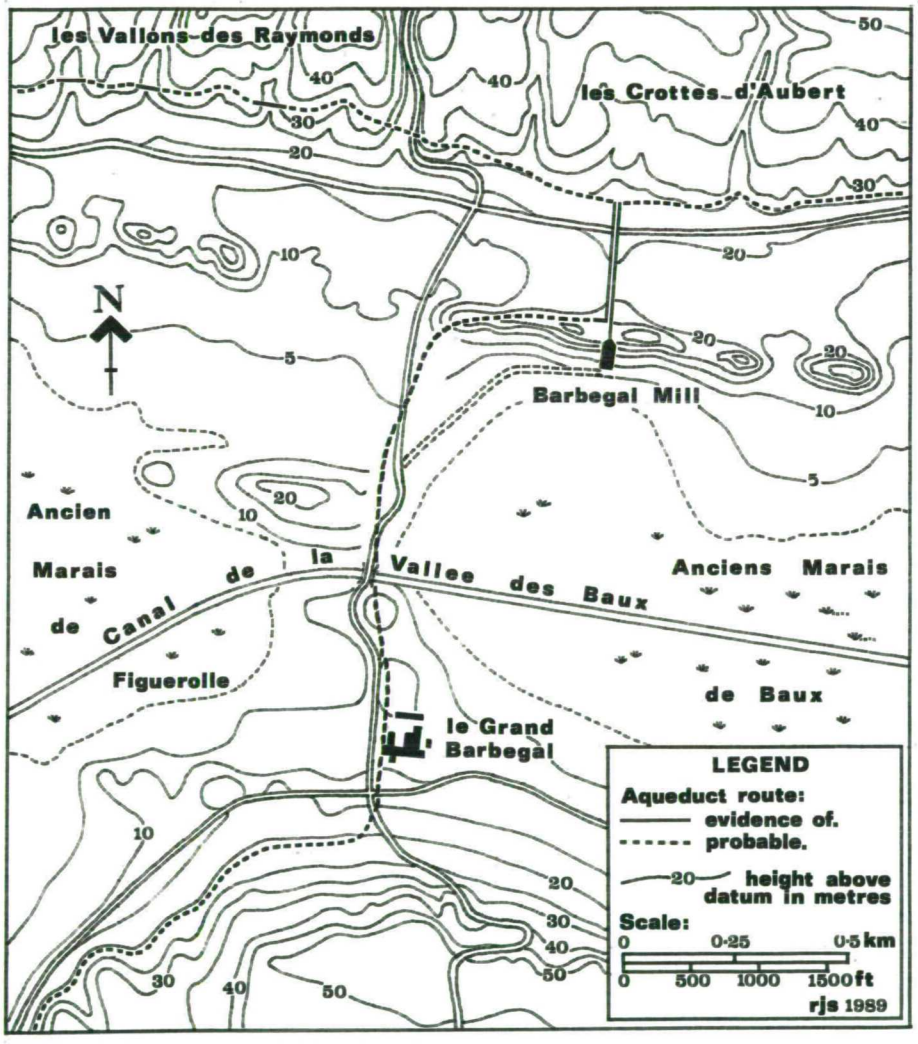


Fig.16. Physical environs of Barbegal Mill.

Where they come together, in the scarp slope of the lês Crottes d'Aubert, they turn southwards towards the mill crossing a shallow valley on separate structures side by side. From here the eastern aqueduct serves the mill whilst the other watercourse diverts westwards just before the mill then passes south to la Grand Barbegal then on to Arles.

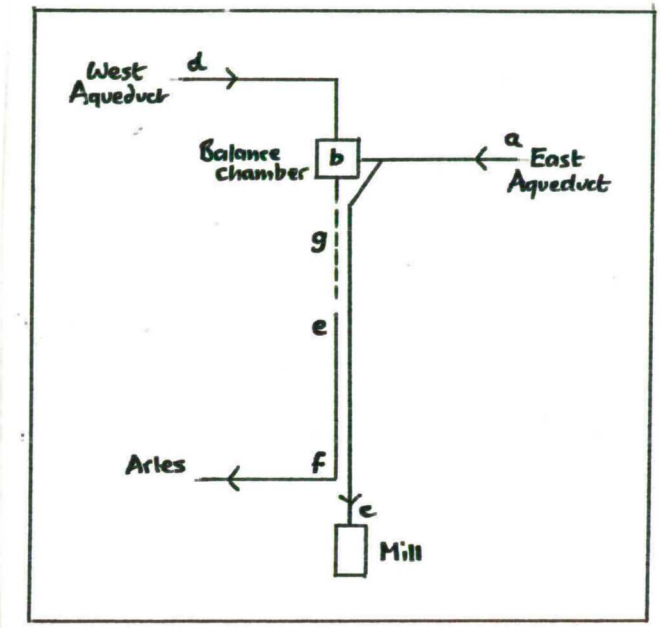


Fig.17. Schematic plan of the aqueducts.

The east aqueduct appears to follow the contours of the landscape for most of its length. On the IGN's carte topographique 1:25000[10] (see map in the pocket) it is possible to trace the aqueduct as an extant watercourse around *les Defends de Sousteyran*, picking up the *Canal de la Vallee* below *le Grand Mejan*, then northwards to the same origin shown by Grenier in the *vallon d'Entreconque*. Grenier's map of the aqueduct lacks detail[11] and suggests that the route cut across *la Burlande* in the valley to the west of *Paradou*. Even though Grenier indicates that across this valley there was evidence of the aqueduct,

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10. Sheet 3043 ouest, St.Martin-de-Crau, Fontvielle 1984.

11. Scale approximately 1km = 6mm.

the writer considers that the true route followed the contours along the *Canal de la Vallee*. To cross this valley would have needed an arcaded structure reaching to a height of at least 25m. and a kilometre in length which could have been avoided by skirting the head of the valley and digging into the hillside for a distance of 3.5km.
Measurement of the length of the east aqueduct is greatly influenced by the scale of the map used. Grenier's map suggests a length of 12.5km including a 1km tributary into the *d'Arcoule valley*. A far more realistic measure is provided by the 1:25000 scale map which reveals the true length as at least 17km including the *Font de l'Arcoule*.

A glance at the route of this aqueduct, shows that the builders took every advantage of the natural landscape to reduce the materials and associated labour as much as possible. Providing the aqueduct's gradient could be maintained to the destination, the builders could gain great savings in resources by following a course whose gradient more or less coincided with that of the aqueduct, and at the same time keeping the aqueduct as low as possible to the ground[12] . The surveyors would have sought a route involving minimal building resources, that line which balances the resources of excavation with those of construction above ground.[13] Obviously the nature of the ground will have some effect on this balance, but on the Provence landscape the minimal resource route surely lay very close to the natural ground level.

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12. An aqueduct say 10m above ground might have required as much as a quantum increase in resources in comparison with the same duct at ground level remembering that we must allow for (i) foundations, (ii) the formwork of arches, (iii) the additional resources necessary for building high above ground including scaffolding, cranes etc.

13. A parallel can be drawn with the 19th century English railway builders where the surveyors were influenced greatly, within the bounds of gradient and curvature, by the search for minimal resources in balancing cuttings, embankments, cut and cover, and tunnelling.

The ground levels close to the mill (See Fig. 16) show that as the aqueducts approached the mill they followed a shallow natural ridge existing between the hills to the north and the Barbegal ridge running parallel to the south. The section running along the foot of the hills appears to be almost wholly at ground level cut into the ground in an open(?) channel with superstructures only used to traverse the small valleys which break the scarp face of the hills[14]. When it was built the east channel may have captured some of the springs and streams issuing from these slopes to augment the main flow coming from the east.

It is interesting to reflect on the resources necessary to build the mill itself compared with those for the 400m long arcaded headrace. If for simplicity, we equate resources to the volume of building fabric[15], summating masonry, cement, timber and tiling[16], then the mill is equivalent to the building of an aqueduct 4m high, 2.2m wide and two-thirds of a kilometre long.
To complete this view of resources we should also reconcile the resources relating to the building of the open-channel ground level aqueduct with those of the above-ground structure. Opinions on this resource ratio will remain speculative because our assessment does not have a full knowledge of ancient methods and skills. However,

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14. Examples of where the east aqueduct is carried over these valleys occur between 3 and 5km upstream of the mill on the south-facing slopes of the Defends de Sousteyran, where the scarp is higher and more precipitous. Similar valley bridges occurred in the western aqueduct between 1 and 2km above the mill on the scarp slopes of Vallons des Raymonds.

15. An assumption that relates labour with different materials, and ignores any differences in constructions, skills or manufacture. Its strength lies in the fact that 95% of the material is masonry.

16. Allowing also that the volume of any excavation into the natural rock equates to the resources necessary for creating the same volume of building fabric above ground.

putting such weaknesses aside, a unit length of 4m high aqueduct is thought to equate to the resources necessary to build 4 to 5 times the length of open channel ground-level aqueduct construction.

Grenier shows the Arles aqueduct as passing south of *Mas de Ste-Marthe* some three and a half kilometres downstream of the mill. A detailed survey map suggests that the level of the aqueduct as it enters the building lies between 23 and 28m above datum, whereas Grenier's line of the aqueduct to the south west of *Mas de Ste-Marthe* passes over ground 35m above datum. This would have necessitated a cutting or tunnel at least 11.5m deep below ground allowing for the shallowest gradient of 0.001. Unless the ground levels have changed to this extent since Roman times, the builders would not have taken this route, but skirted north of *Mas Barracan*, following the contours.

The gradients of the west and east aqueducts are given in Fig.18.

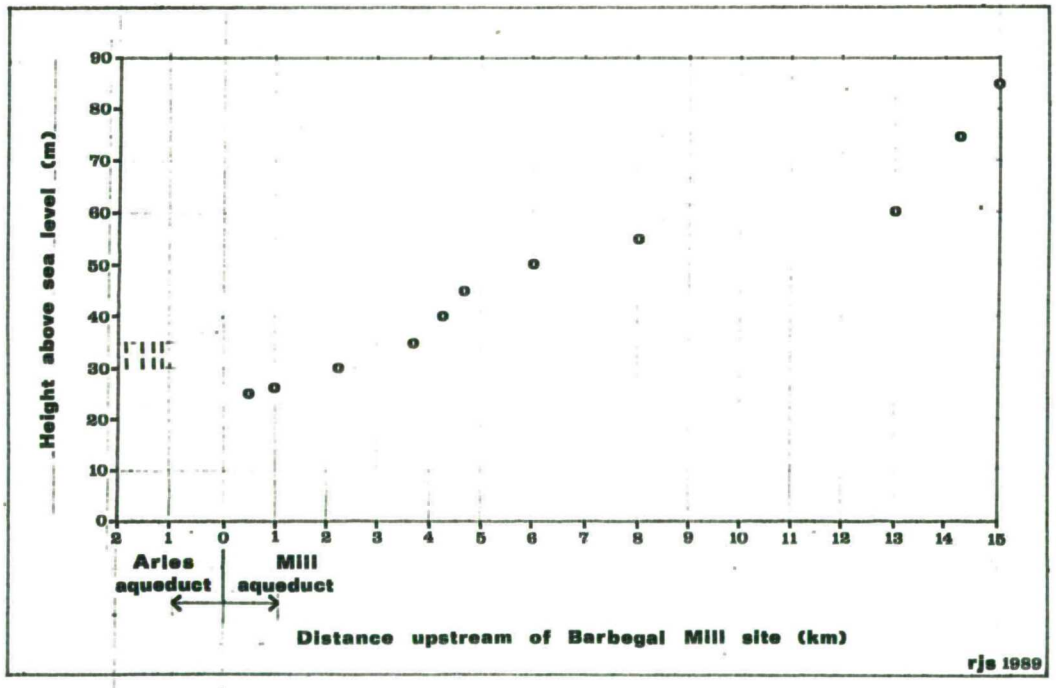


Fig.18. Gradients of the aqueducts.

Upstream from the mill the gradient of the east aqueduct can be generated by plotting where it crosses the 5m contour levels on the 1:25000 map. In the *vallon d'Entreconque* the aqueduct is at its steepest, and shallowest just before it turns southwards across the shallow valley towards the mill. Over most of its length the gradient is .004 but it reduces to .003 closer to the mill. Within the hills the aqueduct may have required a steeper bed to counteract the effect that its twisting course had on the velocity. Where the contours have less influence and the landscape is flatter the bed gradient could be reduced without too much effect on velocity and flow rate. As one example, for the Arles aqueduct to arrive at the city with a minimum head of, say 5m. above datum, the average gradient for the 9km travelled would have to be;-

26.5-5.0/9000 = .0024

If 10m head, 26.5-10.0/9000 = .0018

It is not possible to determine the gradient of the west aqueduct upstream of the mill due to lack of site evidence. The position of the aqueduct bridges on the scarp slope of the *Vallons des Raymonds*, within one to two kilometres upstream of the mill, are shown on the graph as bars spanning adjacent contours. A detailed survey of the aqueduct course would probably give greater definition to levels in this area.

The mill aqueduct near *b* (see Fig.17.) seems to be close to a level of 25m. The road at the south end of the mill lies between levels 5m and 10m. Allowing, according to Benoit's section of the mill, that the head of the mill race is 18m above the road, this puts the headrace at the top of the mill at a level of between 23 and 28m. This is comparable with an estimated level of 25m at *b*.

Grenier states the levels of the aqueducts, presumably above some datum, where they run next to each other as[17] -

d'Eygalieres (Arles)	60m 50cm
Caperon (East)	59m 85cm
Difference	0m 65cm

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17. Grenier, as note 5.

This must be a mistake for whilst the difference agrees with site observation and measurement, the heights above the datum are wrong because they cannot be reconciled with the IGN survey[18]. The summit of the scarp, not far from the *peiro troucado*, is 37m, and the crude analysis of the levels shown in Fig.18 suggests that the water levels where the aqueducts run side by side must be close to 25m. This error in levels is compounded by Grenier's suggested route.

Sellin has confidently suggested that the aqueduct which can be seen serving the mill, was constructed specially for that purpose, presumably built at the same time as the mill itself[19]. He went on to support the idea that the Arles aqueduct was built first[20], but the reason put forward for this, the misalignment between the axes of the mill and its aqueduct, is not conclusive. Scrutiny of a detailed map shows that both aqueducts took a straight line across the shallow valley above the mill where the 20m contour lines come closest together, on opposite flanks of the valley. This alignment minimised the resources necessary to build both aqueducts. The alignment of the mill was unrelated to the valley above, being determined by the orientation of the scarp slope of the hillside on which it was built[21]. However, recent discoveries on site do not support Sellin's hypothesis.

If Sellin had been right about the aqueduct being built for the mill, then our appraisal of Barbegal would have to embrace the fact that the Romans supported the outstanding scale of the factory with the commitment of considerable resources in the form of a 17km long aqueduct. Such scale of commitment for water supplies is not uncommon in the Roman world but to a watermill is new to us. The significance of this, which is discussed later, adds considerable importance to

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18. The altitude origins are based on mean sea level at Marseille.

19. Sellin, as note 6, p.414.

20. Sellin, as note 6, p.419.

21. For further discussion on this point see pp.174-175 below.

the Barbegal problem, such that any further analysis that can be applied to shed light on the aqueduct question is certainly worth the effort.

For further resolution of the building sequence of the aqueducts, our attention must surely be given to the area where they are in proximity, north of the mill.

Figure 19 shows the section of the two aqueducts where they run beside each other just north of the mill.

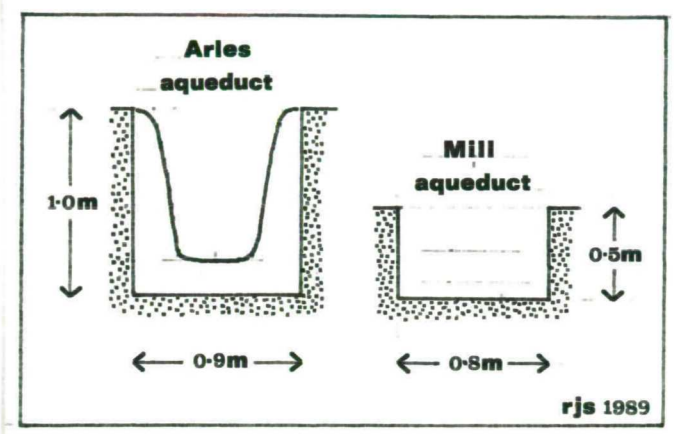


Fig.19. Sections of the aqueducts.

The mill headrace measures close to 0.8m wide but its depth is more difficult to ascertain. Close to the balance tank (See *b* in Fig.17) the depth of deposits has been measured as 0.56m by Lewis[22] which compares with Sagui's figure of 0.5m based on deposits which he saw.[23] The Arles aqueduct varies considerably in section depending on where the measurement is taken. Above the arcades 60m north of the '*piero troucado*' rock cutting, the section is very rectangular inside of the cement lining which is approximately 0.9m wide. Sellin estimates that the depth of flow was close to 1.0m[24]. Downstream where

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22. I am indebted to Dr. Michael Lewis for his measurements of this tank and its connecting water channels recently discovered and cleared by French archaeologists.

23. Sagui, as note 4, p.226.

the aqueduct is cut out of the rock face and just past the point where it changes direction to flow due westwards, the existing section inside deposits is some 0.8m deep with the width tapering from 0.4m at the bottom to some 0.7m at the top. The deposits appear to be some 10cm. thick at the top of the walls.

A more detailed site observation, where both aqueducts run beside each other across the valley above the mill has revealed some interesting features[25].

The first is that there are the remains of pier foundations on the axis of the Arles aqueduct (see Fig.17, *g*) which have approximately the same width as the extant stretches of the Arles aqueduct approaching the mill, but differ in one significant respect; they contain massive monolithic voussoirs which are quite unlike the arcaded structure near the mill where the piers arches and faces are made almost entirely of smaller square or rectilinear coursed stone blocks. The obvious suggestion is that these voussoirs are the remnants of an older aqueduct having an early Empire style of building.

The second feature is the bridging that exists between the aqueducts in three places, and the third feature is the evidence that exists within the channel of the Arles aqueduct of the raising of its bed between *e* and *f* in Fig.17. This was first taken to be blocking of the channel but Bardell's examination of the remains proves that a length of the channel bed was raised. This higher bed has clearly been placed on the top of an older working bed but when this occurred and its significance is not easy to ascertain.

More recently, archaeologists have discovered the existance of what appears to be a balance tank at a junction of the east and west aqueducts. See Fig.20.

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24. Sellin, as note 6, p.418.

25. I am indebted to Dr.N.A.F.Smith of Imperial College and Dr.P.Bardell for bringing these to my attention.

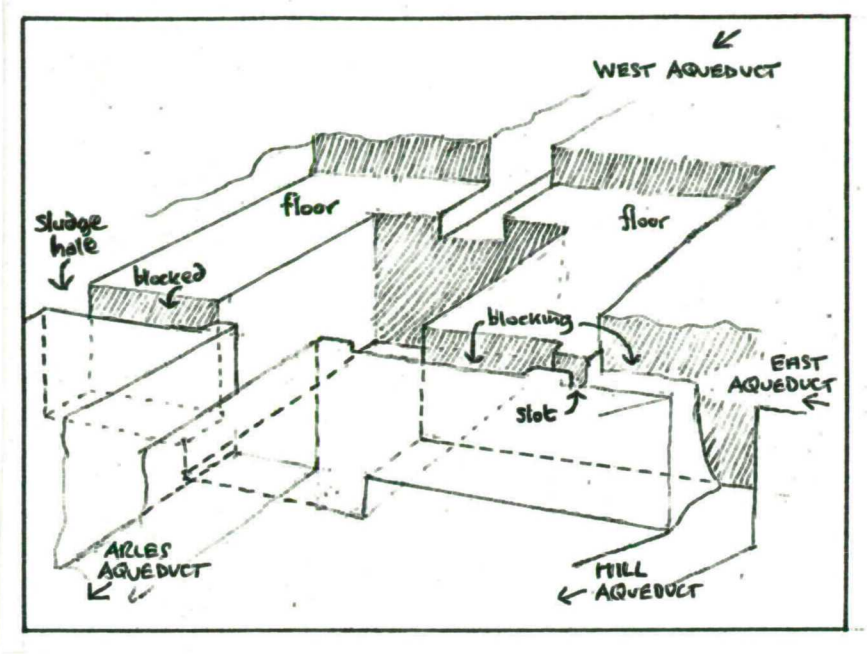


Fig.20. Isometric view of the balance tank.

Here the east aqueduct and the channel leaving the tank southwards (the Arles aqueduct) have the same bed level, but the west aqueduct, which enters the tank on the north side, is 0.76m higher. Within the tank there is evidence of subsequent blocking of the east aqueduct in conjunction with an overflow sill, which is probably contemporary with the insertion of the mill headrace into the east aqueduct, some 7m from the axis of the Arles aqueduct.

The remains of the aqueducts in the area north of the mill are most difficult to interpret. However, there are two facts of which we can be fairly certain. The first is that we are clearly looking at two aqueducts (coming from the east and west) which at some time interacted with each other, and, each has been re-routed and modified, probably as a result of the building of the mill.
The second certainty is that we clearly do not have a full knowledge of the site evidence. At the time of writing excavation work remains unfinished and accurate measurements of the evidence, especially levels and gradients, has yet to be established. Moreover, we should not forget that there may well be additional building features and other evidence remaining to be discovered.

Accepting the view that we are at an interim stage of discovery, it would be foolhardy to attempt anything more than a rudimentary and simplified view of what sequence of developments may have occurred with the aqueducts. Some tentative suggestions can be made. These are;-

[1] A suggestion has been made that the mill aqueduct may originally have cut through the *'peiro troucado'* and run onwards to Arles, presumably turning westwards and running along the south slope on which Barbegal is built. But the effort in cutting through the ridge would have been wasted and could be avoided, furthermore, there is no evidence in the rock of the scarp face to show that this occurred. This draws us to the conclusion that the length of mill aqueduct which runs beside the Arles aqueduct, was built solely for the mill.

[2] The first aqueduct to be built in this area, served the city of Arles, approached Barbegal from the east and followed the course *a,b,g,e* and *f*. At *g* the remains of massive voussoirs are part of the original structure. There is evidence to suggest, that as time passed, the flow in this aqueduct diminished.

[3] Some time later a new aqueduct was built approaching Barbegal from the west which joined the east aqueduct at *b*. At this junction the west aqueduct was higher than the east aqueduct and to facilitate level and velocity differences a balance chamber was built which incorporated a settlement pit.

[4] Barbegal Mill was built and its headrace was inserted into the east aqueduct.

[5] The introduction of a new water source from the west was surely caused by either a depletion of the flow from the east which then gave the opportunity for excess water to be used for corn-milling, or, by the desire to build the mill which required additional water to be found.

[6] At some later date the Arles and mill aqueducts, where they ran parallel beside each other, were braced by infilling in at least three places. The reasons for this must surely relate to structural stability and the only apparent explanation was that one or both of the aqueducts became unstable and moved towards or away from each other. Installation of the braces must obviously have occurred when at least one of the aqueducts was still working, though not necessarily when both were in use[26].

C. Building Analysis.

Let us attempt to establish how the builders set about constructing this factory and identify the sequence that they may have followed. By the time they had brought the headrace across the dip-slope of this escarpment and cut through the ridge, the decision had been made to have two parallel sets of consecutive waterwheels. We can safely assume that the aqueduct was built up to the ridge before work on the mill building itself had begun. For an essential pre-requisite for the construction of the watermills was that the level of the headrace(s) entering the building had to be established. Moreover, until they had cut through the ridge, to a depth of some 5m at least, they could not easily position the building to align with the watercourse(s).

Immediately upon bringing the headrace out of the scarp slope face, it was bifurcated, but each branch did not deflect the same angle from the axis of the aqueduct. The eastern branch deflected 29 degrees whilst the western headrace was 39 degrees from its original course, and the reason for this is simply that the axes of the building and the aqueduct are misaligned. This slight change of direction

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26. If the mill aqueduct had shown instability whilst the Arles aqueduct was in use, the municipal authority would surely not have allowed the bridges to be installed to bear upon their structure unless it too was also demonstrably unstable. Tha alternative situation which would prompt their approval of bridging, was if the building of the mill aqueduct had produced a demonstrably adverse affect on the Arles aqueduct, even though it remained stable and sound.

was made to allow the building to follow the slope of the hillside. If the builders had not done this there would have been a noticeable difference in the heights of the east and west flanks of the whole structure; the east flight of waterwheels would have required a greater number of subterranean chambers than the west flight which might have been all above ground. And so the builders understandably chose to give the construction rough symmetry of shape by following the slope.

According to Benoît's plan the axis of the aqueduct strikes exactly the north wall of the building in the middle of the central stairway, but the corners of the building are not equi-distant from this point. The difference can be seen in the widths, east to west, of the northern-most chambers, the east one being noticeably smaller than the west chamber. The surveyors [*agrimensores*] who laid out the diverging headraces assumed that the axes of the headrace and building coincided at the point of bifurcation, whereas the north end of the central stairway (i.e., its two side walls) was apparently set out on the assumption that the axes pivoted at the north end of the building. See Fig. 21.

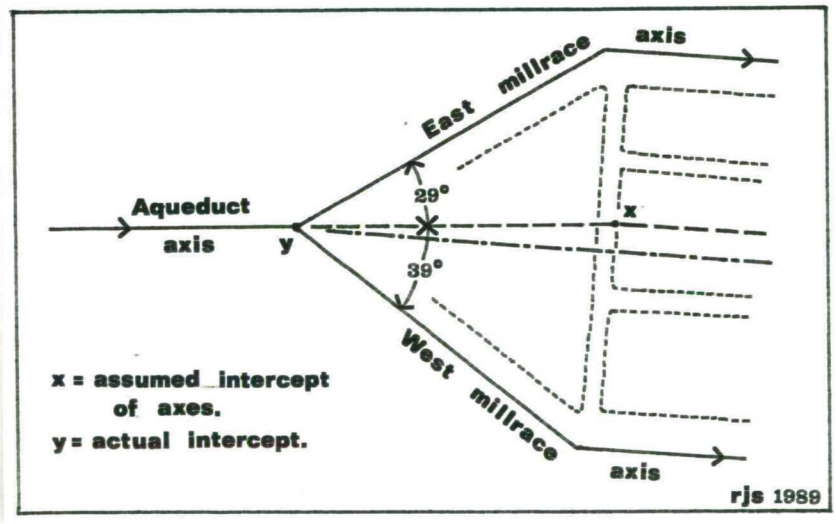


Fig.21. Building axis.

Following bifurcation of the aqueduct, the line of each headrace was continued out over the hillside until the distance between them was the width of the intended building. The builders appear to have know-

ingly placed the highest and first waterwheel in each series well above ground level. It would have been easy for them to have made the enclosed angle of bifurcation more obtuse[27] and in so doing the wheels could have been closer to the ground and the foundation of the wheel chambers and access stairs could have been much reduced. But they chose not to do this, and the reasons are obscure[28].

In our attempt to understand the layout of Barbegal it is very convenient that Benoît's section through the structure should pass through the rooms in the eastern half of the remains. The east side is by far the best preserved, both in terms of building foundations and the chambers, pits, apertures etc., for the machinery. It is on the lower slopes where the mill machinery, in both the east and west series of waterwheels, was necessarily placed in chambers cut out of the rock. See Fig. 22.

Elsewhere on the site the ravages of man and nature have taken effect to make the interpretation of the remains most difficult, but in the south-east and south-west corners of the building, the underground works provide the historian of technology with evidence to facilitate a reconstruction of the machinery. As Benoît found, the analysis of these lower mills gives us confidence in our reconstruction and helps us to visualise the probable arrangement of the upper mills and the rooms housing them.
The builders of Barbegal must have begun the foundation works of the walls and wheel chambers at the top of the hill-side and proceeded downwards. No other general direction of working is possible for the

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27. With a mean water velocity no more than 1.0m/s this was quite possible; note the 90 degree change of direction in the Arles aqueduct on the north face of the ridge. Balancing of the flow rates in the headraces would not have been a problem.

28. It cannot have been their original intention to have larger waterwheels, or to have over-driven stones; neither of these suggestions can be sustained.

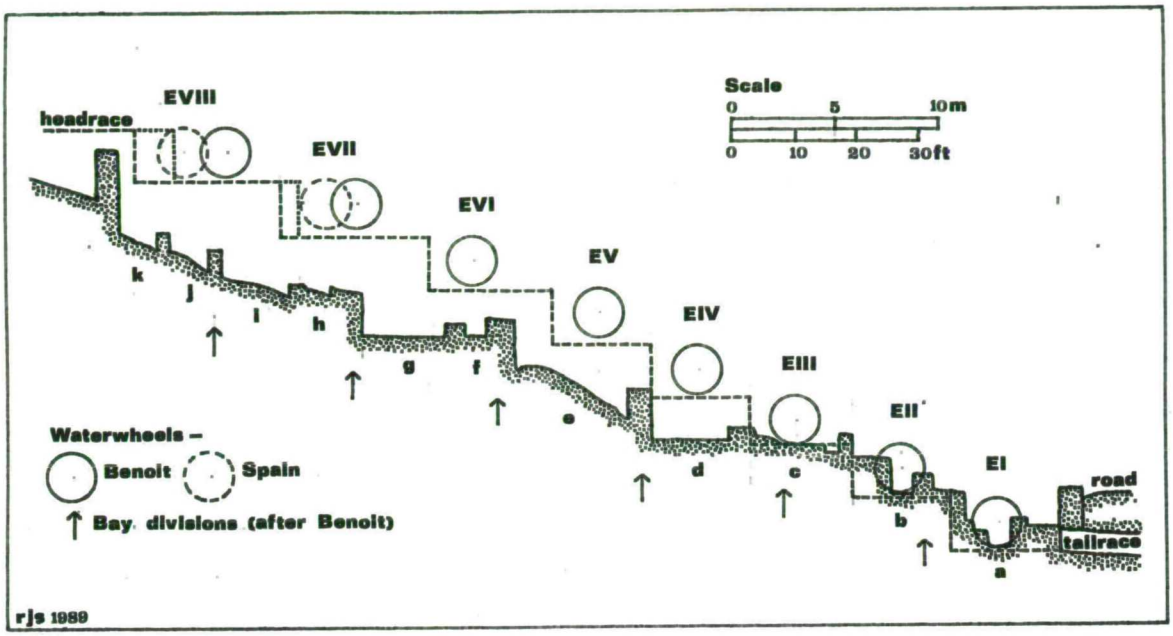


Fig.22. Section through the building.

fabric which relates to the wheel series, where the layout depends so much on the water levels of the successive head and tail races. The only variation to this sequence that can be contemplated is -

(a) that one half of the whole site, east or west, could have been progressed in advance of the other, and

(b) once the levels of one series of wheels had been established (i.e., the gradient of their chambers), work on the lower foundations could have proceeded in advance of higher foundations. But this would have been very limiting, as the analysis below suggests.

Clearly the ground-level layout of a broad central access corridor with rooms down each side was adopted from the outset. So too must have been the sizes of the waterwheels which determined the widths and 'steps' of their emplacements down the hillside. At this stage of the works the builders would have tended to follow the natural gradient of the hillside to help determine the slope of the wheel 'steps'.

The writer considers it likely that the north faces of the top wheel chambers (EVIII and WVIII) would have been closer to the corners of the building where the races changed direction. There was no need for the races to travel another 12 feet or so before entering the wheel chambers as Benoît shows, for the additional height above the ground which this gave is superfluous. If we adopt this suggestion, the slope for the top three wheels, EVI-EVIII, determined by the evidence of the north corner of EVI tailrace, is shallower than Benoît's, and relates closely to the slope of the hillside[29]. See Fig. 23.

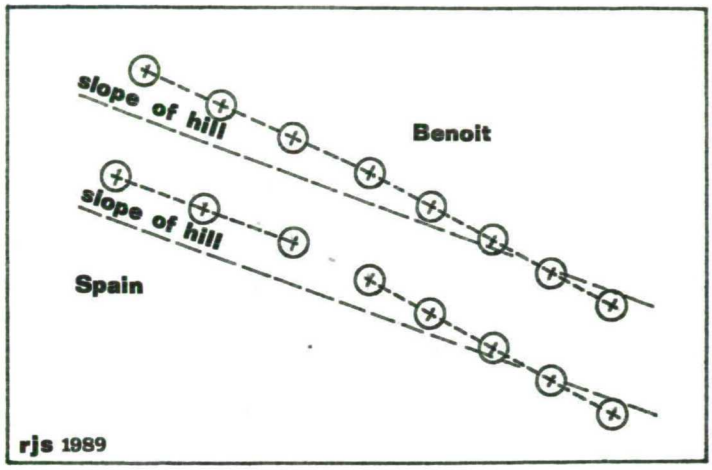


Fig.23. Slope of the waterwheel series.

And so it is suggested the top three wheel chambers were designed and built as the first phase of the works. Then something happened which prompted them to change the slope of the wheel series, for the line of the lower wheels, EI-EV, is steeper than those above. Being steeper than the hillside itself, the lower the wheel is in the series, the closer it is to the ground, with the bottom two mills EI and EII, having their wheel and gear pits cut into the rock face of the hillside. Why was this done? Why did they choose not to continue on the same gradient?

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29. Historians should not be confused by Benoît's slope of 30%, mistaken by some as 30 degrees. See Roos, Paavo, as note 8, pp.327-333.

There appear to be five possible reasons -

(1) The builders found the length of the wheel chambers was unnecessarily long, in that the water falling from a wheel became a steady usable flow without turbulence well before it reached the next wheel, or,

(2) The builders wished to install as many waterwheels as possible. If they had continued to install wheels at the same slope as the hillside, or even at the slightly steeper slope that Benoit shows for the top four wheels, the lowest wheel would have been above the level of the road at the south end of the building. By increasing the slope of the wheels, the builders were able to install an eighth wheel and run the tailrace in a culvert beneath the road, or,

(3) By increasing the slope of the wheels the builders would greatly reduce the foundation masses of the wheel-pits and the adjacent access stairways.

(4) That in each of these higher mills, access to the wheel chambers was across the tailrace from a doorway in the mill room. The builders subsequently realised that this plurality of entrances was unnecessary and that the space saved allowed a shortening of the tailraces.

(5) That during the building works there came a person of different expertise whose influence affected a change to the design. The mistakes made early in the layout of the foundation of the north-south walls, high on the hillside, may have precipitated this.

For the first reason given above to be realised it was necessary for the top three wheels to be built and run to establish the operating conditions. There would have been clear advantages in checking their design before they built the whole series, to see, for instance, how the tailrace of one wheel acted as the headrace of the next, or how effectively the water could be diverted from any wheel. We should not lose sight of the possibility that this cascade of wheels may have been unique in the Roman world, or at least, new to the experience of the builders.

To have tested the first few wheels in this way would have needed at least one headrace completed to bring water to the top of the series; it also assumes that the wheels, shafts, bearings and water control devices were being made whilst the general building works were

proceeding. Such tests need not have taken long, even allowing for development and modification work to be done; meanwhile the masons and their labourers had much to do as the ground works progressed steadily downhill. See Fig. 24. Once the site had been surveyed and the plan established, the foundation for the wheel chambers, stairways and their containing walls *vw*, and *xy*, could have been established down the hillside some distance ahead of the completed chambers. One wonders just how far ahead they progressed with their works before the decision to change the design was made.

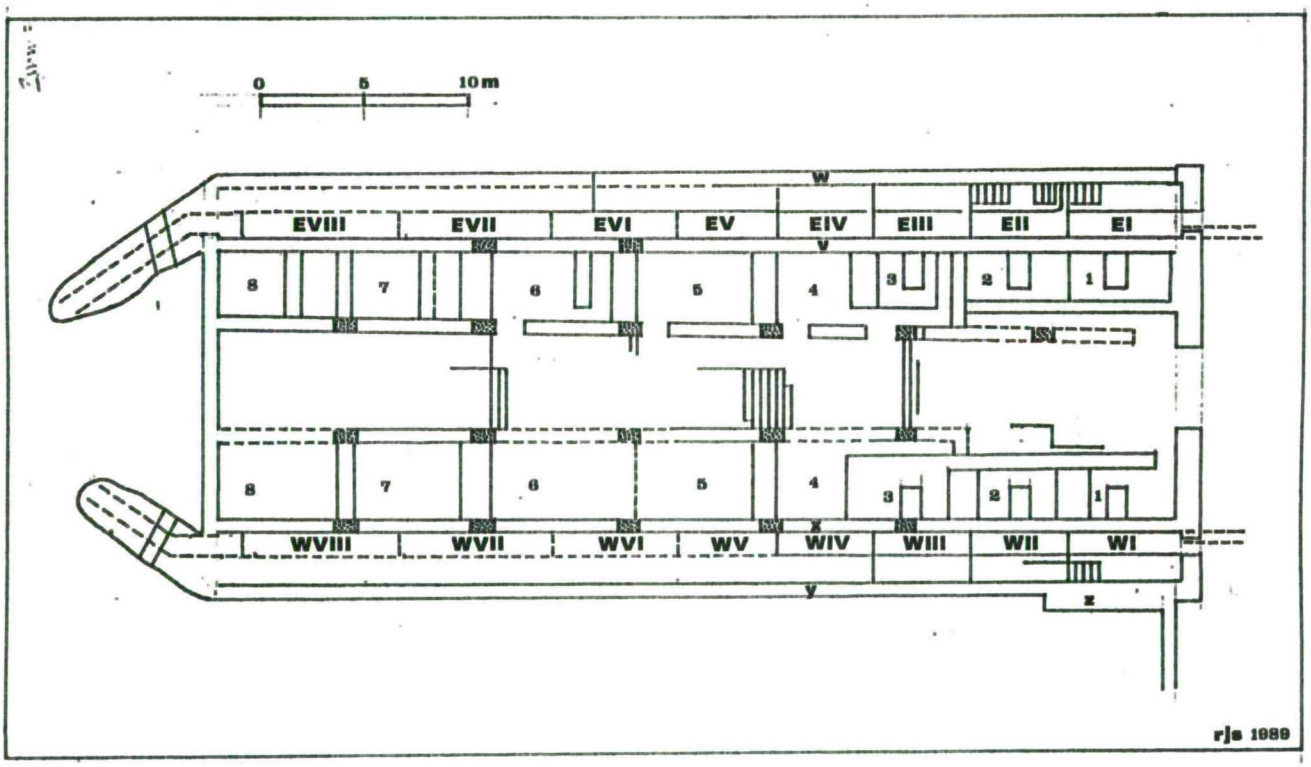


Fig.24. Plan of Barbegal Mill.

To increase the number of waterwheels was the most likely cause for their change in design, for this was in sympathy with the whole concept of Barbegal, of production on a grand scale. And so the wheels EI to EV were placed closer together, in a line which was steeper than the top three wheels, such that the bottom two chambers, their wheel and gear pits, were cut out of the bedrock on the hillside. By doing this the full potential head of the water from the top, north end of the building, to the tailrace culvert was utilised. The depth of the tailrace culverts beneath the road would have been greater than would have been required with seven wheels in the series.
We can assume that the layout of the wheels on the west side of the building, was the same as the east series, for the chambers of the lower four, WI to WIV, appear to be identical to EI to EIV in layout. If both wheel series had a 'double' gradient then they were clearly built more or less at the same time and from top to bottom.

With each of the mills in the series at a different level, an average of 2.6m (8.5ft) apart, we can suggest that the floors of the building were similarly spaced. Even if the mill machinery occupied a series of platforms or mezzanine floors, the advantages of having constant floor height throughout the factory were obvious. This invites the question, did the floor heights dictate the diameter of the waterwheels?

On the lower slopes, where the builders cut into the hillside to create the emplacements for the machinery, the arrangement of the mill chambers is not difficult to ascertain. See Fig. 25.
But on the upper slopes, where the machinery was well above the ground level inside the building, up to at least 5m at EVII and EVIII, there is no evidence of the mill chambers themselves. In absence of superstructure it is entirely reasonable to look to the remains of the substructure or foundations to learn all we can of what might have existed above. Benoît did this, but unfortunately in his keenness to relate the building fabric with the watermills, has drawn false conclusions on the layouts that existed. This appears to

stem from a single assumption made early in the analysis, that the positions of the waterwheels related to the rooms which can still be seen in the east and west sides of the building.

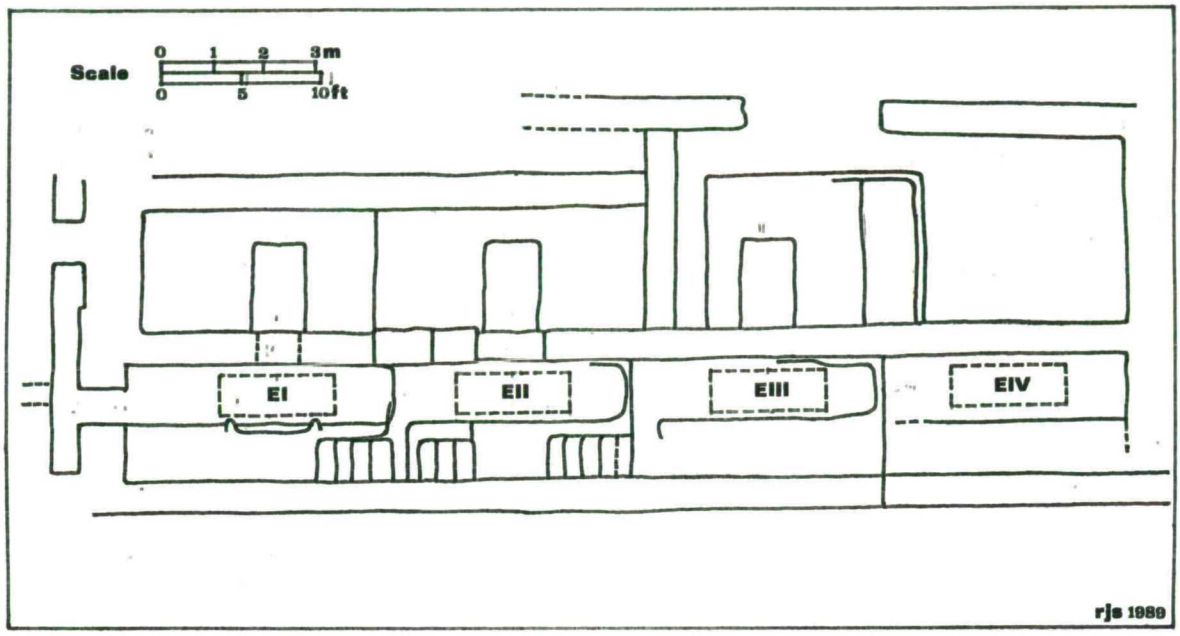


Fig.25. Plan of Mills EI-EIV.

In the lower floors, this relationship is patently obvious, because the mills are, *per se*, the rooms themselves. How can it be otherwise? But this gave Benoît a false start, for having identified that eight waterwheels had probably existed, and then found that eight rooms had existed, (the west side shows this much clearer) he assumed that they related to each other, that the room series were the mill chambers. In fact the two series are disparate as the writer will proceed to demonstrate, although why this should be, is much more difficult to explain.

Ignoring the watermills for the moment, the building appears to have seven distinct bays from north to south as Benoît has identified. See Fig 24. The upper four bays are divided by cross walls *de*, *ef*, *gh*, and *ij*, (See Fig. 22.) and on each division line Benoît has suggested that four support positions existed coinciding with the four north-south walls of the building. On the lower slope the remaining three

bays can be identified by some of the support positions; those cross walls that can be seen do not appear to relate to the bays but rather to the mills themselves. All seven bays have very similar spacing of 6.7m, even on the lower slope, but here the evidence of an accurate grid, supporting the notion of pre-conceived and accurately laid out plans, ceases. Why is this?

Let us first list the obvious features which show either lack of accuracy or poor symmetry in plan,

(a) the wall to the east of the central corridor is not parallel to the other three major north-south walls.

(b) the lower six mill chambers are all different in area and are haphazardly arranged within the building.

(c) the main entrance off the road is not central to the building.

(d) the ground level within the chambers is very irregular - some are level and others, bare undressed rock.

(e) the wheel chambers vary in length, shorter on the lower slopes and longer on the upper.

The seven bay theory fits the evidence very well, especially on the eastern slopes where the bay divisions are coincident with major cross walls. However, Benoît's theory of supporting pillars on the bay divisions makes little sense because,

(i) These were not necessary for roof supports as suggested. The internal north-south walls surely continued up through the floors above to help support the grain storage areas. If pillars did exist they would only occur on the top floor below roof level and no trace of them would occur in the foundations.

(ii) Several of these support positions occur in the external walls and are coincident or close to crosswalls. Once again the suggestion of support pillars is negated by the existence of walls which would have been continuous from ground to roof. Obviously the walls supported the roof.

There is another flaw in the bay theory. Although we have some doubt concerning the exact position of the top three waterwheels, it is quite clear that bay divisions *ij*, *gh*, and *ef*, must have coincided or been very close to their wheelshafts. This is particularly relevant

for mills EVII and EVI where the cross-walls were massive. We should remember that not only does the wheelshaft have to pass through the external wall but there has to be space to position and operate the gears and millstones. If we assumed that the millstones required rather more clearance than the gearing, an absolute minimum would be say 0.75m between the face of the wall and axis of the millstones. If these no-go zones are overlaid on the section it will be seen that in mills EVI-EVIII the position of the wheels with the emplacements shown by Benoît becomes impossible!

Of course, the same space limitations apply to the other cross walls in chambers 6, 7 and 8 which brings us to the inevitable conclusion that these bay division walls could not have passed up through the mill chambers above. The suggestion has been made that they supported the mill machinery but this was surely not so because,

(a) wall *ij* would have been approximately 5m high, and,

(b) walls *gh* and *ef* are unnecessarily thick, and finally,

(c) the floor loading of the machinery was probably much less than that which must have existed in the grain storage areas of the building.

In other words, all of the floors within this building could have been supported by cross beams carried by the four north-south walls of the building. One final point to make is that the floor support beams would surely be aligned east-west, so why have massive bay walls?

So the division bay theory seems to fall apart when we attempt to develop the reconstruction of the building.

Let us now examine the foundation of the cross walls to establish what relationship they might have with the mills. For this purpose the spaces <u>between</u> the foundations have been indexed on the section (See Fig. 22.) through the east half of the building starting in mill EI with *a*, EII *b* etc., to *k*. Starting at the low end of the building, we can confidently identify rooms *a*, *b* and *c* as mills EI, EII and EIII respectively. Their plans confirm that they were restricted and did not extend as far as the central corridor.

Benoît and Sellin identify these main rooms (nos. 4-8 inclusive, both on the west and east sides of the plan) as 'mill chambers'. This is in error and the reasons for this are fairly obvious,-

(a) Benoît's 'chambers' do not relate to the mills above, with the exception of space *d* (Benoît 4) all of the spaces are out of phase; the higher up the hillside, the more unrelated they become.

(b) Space *e* has an impossible floor level. It may be part of the face of the natural hillside. Even if a floor had been placed over this area, it would be very close to the floor of mill EV.

(c) We have determined that the mill machinery could have been contained on a floor or platform adjacent to each wheel so that the space requirements did not extend to the central corridor

(d) The floors of spaces such as *i* and *j* are between 16-20ft below the nearest mill machinery above. This height suggests there would have been an intermediate floor.

(e) The width of the spaces (north-south) from *d* to *k* vary and appear to be entirely random.

The triangular space which existed between the foundations of the two diverging headraces measures 14m wide at the south end, and its height above the ground to the top of the stone walls of the races, perhaps no more than a metre at the north end and at the south end 5m. Benoît's section of the mill suggests that the rock face of the hillside within this triangular area had been roughly smoothed. As the building was constructed progressing down the hillside, this space would have offered an area that could have been utilised as a store and roofed over. If the builders had not roofed this area over, they would have needed a drainage tunnel to allow rain water to get away.[30] The most obvious entry into this space is from the top of the central stairway and corridor and the absence of a room here suggests that access into the triangular space probably existed at this point. How would they light such a space? Obviously by light shafts through the flank walls where they stand high, one through the east wall aligned literally true east to get the early morning sun, the other in the west flank, arranged in symmetry to the other light. In the

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30. Sellin makes this point.

summer they would have provided ventilation through the ground floor corridor with the doors open at the top and bottom, a pleasant air movement which would have provided a welcome air change in the large dark dusty interior. The difference in level between the open lights beneath the headraces and the large main entrance doors beside the road, some 18m, would have provided a natural draught (the stack effect) up through the steeply inclined rock-hewn stairs of the building.

The central access corridor was the main thoroughfare in the factory and communicated with the upper rooms in the higher floor levels, on each side. One can imagine that the numerous workers within this factory, millers and their assistants, artificers, and those labourers moving grain and meal about, would have needed ample corridors, passageways and stairways to facilitate their movement throughout the numerous floor levels that existed in this hillside building. Vertical transport of the sacks of grain and meal would have been greatly assisted by central lifting 'wells' passing up through the centre of the building where pulleys and ropes would have been used to great advantage.

It was the practice of the army to keep the granaries (*horrea*) of their forts stacked with one years supply of grain. Our modern experience in both wind and watermills shows that it was the custom and practice to store one year's supply of grain at harvest time then work the stock down throughout the year. Without such a store the miller would need to buy more grain during the winter or spring when the price was higher. The builders of Barbegal had the choice of creating storage within the mill itself, or use other buildings, preferably close by. If the grain was stored in the factory itself, this avoided double handling and transporting at times of year when the weather may have been more inclement. Moreover it gave the miller(s) the advantage of having the stores at hand. Such advantages suggest that most, if not all of a year's supply of grain would have been stored in the mill. We might take as supporting evidence the size of the building, particularly its width and the great strength of the cross walls.

The popular image of the factory, with its cascading headraces and flights of wheels, is founded on the visual impact of the waterwheels being seen from outside the building. Sagui captured this effectively in his delightful small sketch of the reconstructed building looking from the west. This arrangement has become part of the historian's image of Barbegal, and a traditional feature in the public's appreciation of the site. But the evidence for this reconstruction is not convincing, and an alternative arrangement can be suggested from an analysis of the site.

We might first look to the massive foundations that exist for the wheel chambers above ground level. The parallel walls each side of the chambers become integrated with the fabric of the wheel emplacements and adjacent maintenance stairway, creating a foundation some three and a half metres wide. Further up the hillside the water channels and stairways become more elevated above ground and a vertical section through the side of the building, say on the centreline of any of the higher wheels, (see Fig. 26) shows that the outer wall has great stability and strength. All previous reconstructions of this building have suggested that the external walls on the east and west sides were those lying between the wheel pits and machinery chambers.

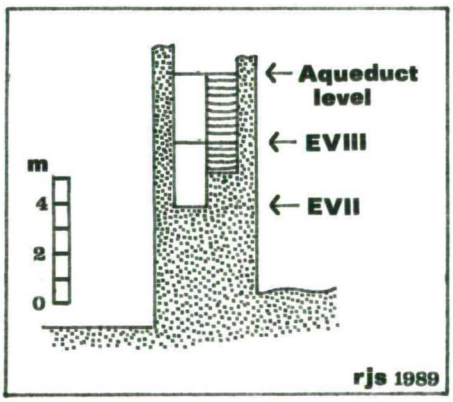


Fig.26. Section through the eastern external wall.

An alternative and rather obvious suggestion to make is that the walls next to the steps were the outside walls of the building. In other words the wheels and access stairs were either roofed over or the upper floors extended over them. What evidence do we have to support this proposition? The following is suggested;-

(a) The foundation masses favour wall *w* rather than the inner wall *v* for this function. See Fig.24.

(b) The south wall of the building, which is at least 0.9m thick, continues outwards to join walls *w* and *y* at the lower corners of the site[31]. This surely indicates that the south wall at the ends of the wheel chambers continued to the same height as the rest of the building, whatever that was. Otherwise why close off the ends of the chambers, especially if they were open to the outside?

(c) If the wheels were outside, why were there not doorways through the south wall in line with the bottom of the stairways? This surely proves that access to the stairway was from inside the building and therefore the wheels were enclosed by walls *w* and *y*.

(d) What is the significance of foundation *z*? Does this not suggest that wall *y* was not solely a boundary or enclosure wall, especially beside the subterranean wheels of WI and EI. Wall *z* surely relates to a higher structure above the level of the mills.

In addition to the above evidence we should note that space for grain storage would be greatly enhanced by extending the upper floors out to walls *w* and *y*. In the light of this the writer favours the wheels being floored over rather than roofed over. With this arrangement natural lights would have been required above the stairways in walls *w* and *y*, which might have taken the form of low arcades or colonnades, to introduce daylight into the wheel chambers. Fig.27. is an artist's view within the east wheel chamber.

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31. The south wall is pierced by the tail races and the water control gates above, but the mass of the wall clearly continues to the corners of the building.

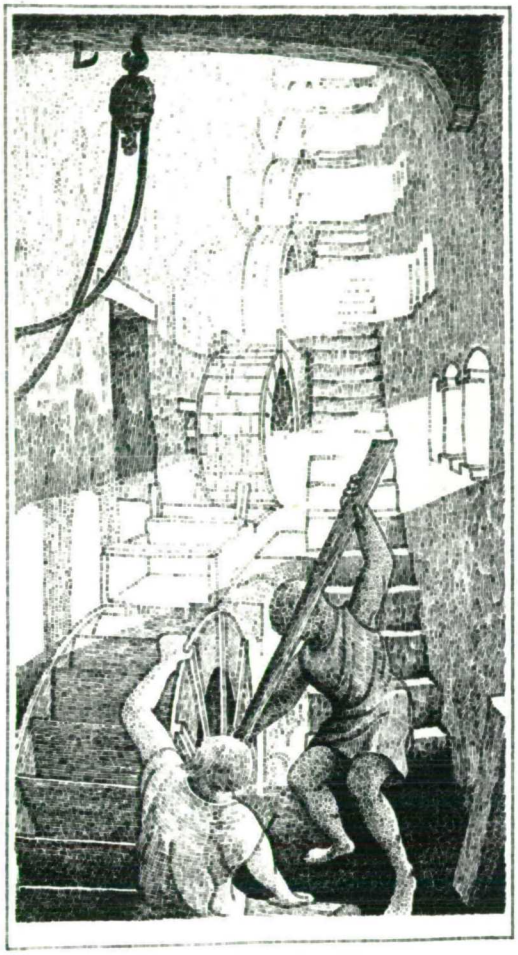


Fig.27. Artists view of the east wheel chamber.

If one year's supply of grain was stored at Barbegal, and we assume that the upper floors extended out over the wheel chambers, then at least two additional floors would have been needed above the millstone floors. The remains of massive cross-walls seen at ground level support this notion of the *horrea* being integrated within the factory as does the absence of evidence of other buildings in the vicinity of Barbegal. Fig. 28. is an artist's view of Barbegal looking from the west, a reconstruction which assumes internal water-wheels.



Fig.28. Artist's view of Barbegal Mill from the west.

D. Hydro-Mechanical Analysis.

The site evidence at Barbegal allows us to estimate the volume of water entering each of the headraces and, knowing the size of the waterwheels, the power generated can then be determined. Allowing for bearing and gear losses, the power available for the millstones can then be related to output using the Westree power/output factor. Knowing the diameter and shape of the millstones, various options of MR and millstone speeds can be postulated.

A survey of the extant wheel chambers confirms that the diameter of 2.2m and width of 0.7m proposed by Benoît[32] for the waterwheels fits the evidence well[33]. Benoît's waterwheel width of 0.7m, presumably

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32. Benoît, as note 3, p.50.

33. Sellin suggests that a diameter of 2.1m is more appropriate, but the author favours 2.2m; the difference is not important.

outside the structure, fits easily within the chambers, and Sellin and the writer favour this width as being more appropriate for the width inside the rims. See Appendix A for the Table of Critical Dimensions.

A theoretical reconstruction of the wheel, assuming a bucket depth of 0.25m facilitates the production of a capacity diagram which determines the total torque generated by a fully loaded wheel[34]. If we assume the $0.4m^2$ aqueduct carried $0.33m^3/sec$,[35] then using the maximum bucket capacity we can calculate that this flow rate equates to a wheel speed of 15.3rpm[36]. At any speed less than this the water being applied exceeds the wheel's capacity, and at any faster speed the buckets are not being filled. At a wheel speed of 15.3rpm the power generated is 2.625 hp and allowing for gearing and bearing losses, some 2.4hp is available for the millstones.

Fig.29 shows the power diagram for a typical waterwheel. As the speed increases above 15.3rpm, the volume of the water carried by the wheel reduces because its equivalent flow rate is greater than the aqueduct can provide. The increase in speed balances the decrease in torque, so that the power is constant[37].

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34. Varying the design of the buckets does not make a significant difference to the wheel capacity.

35. 0.8m wide by 0.5m deep, average velocity 0.825m/s. Flow rate assumes that 0.3 cubic metres/sec serves both sets of waterwheels, (i.e., 0.15 to each series) plus an additional 10% for splashing etc.

36. This is a rim velocity of 6ft/sec.

37. In reality centrifugal forces would affect capacity at higher speeds, so that the power would drop away, following a lower power line such as x on the diagram.

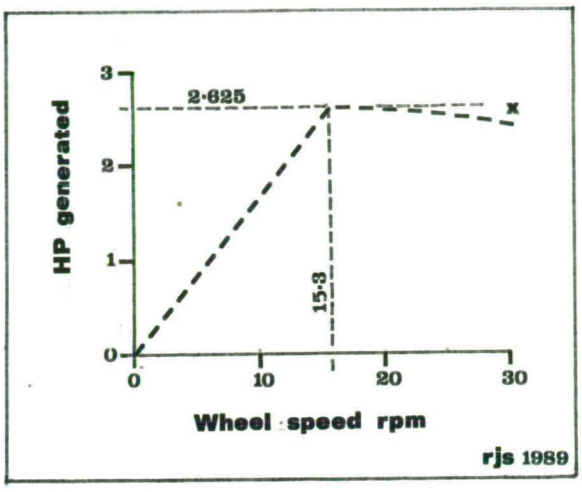


Fig.29. Power diagram for a typical waterwheel.

This power analysis is particularly sensitive to two variables within it, the average velocity of the water in the aqueduct and the depth of the buckets. For both of these variables the power can be assumed as being directly proportional to changes made to either of them, but as we have seen above, they can inter-act[38]. Generally they should increase or decrease together, otherwise the combined effect will be a tendency to move towards either (a) slow wheel and high MR's or (b) very fast wheel and low MR's.

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38. If Q is increased the power graph would move to some higher point P_2 (See Fig 30.), if decreased, a lower point say P_3. When the bucket depth is altered, say reduced, (assuming Q as before) then the power generated at 15.3rpm will be less, thus a new power slope is produced xN. However the speed at which the wheel becomes full must be greater than 15.3rpm, so that the line xN must extend to some higher point. And so these two variables can be given a whole range of values which affect the power/speed graph. The values which have been adopted in this analysis are considered as being realistic.

With 2.4hp available for the millstones, the speed of the thinnest top stone, say two inches thick at the eye[39], would be 72rpm. If we assume that a new top stone was six inches thick at the eye, then 2.4hp would produce a stone speed of 47rpm.[40] as it became thinner and its

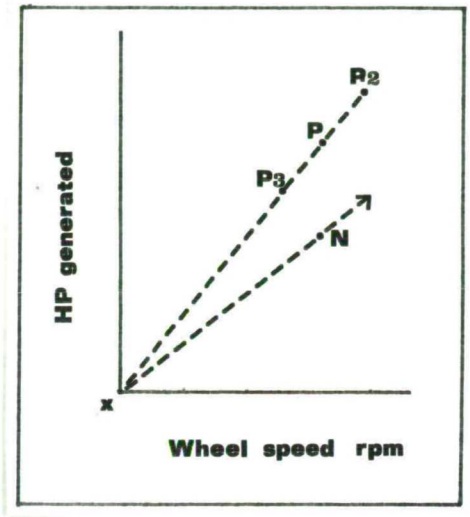


Fig.30.

weight reduced, the application of 2.4HP would make it speed up. To ensure that the power available to the stones never dropped below 2.4hp, (i.e. the wheel never slows below 15.3rpm.) an MR of 3.1 would be required. With a new top stone this would have a wheel speed of 15.3rpm and as it became thinner the wheel would speed up to 23.2rpm. We have no way of telling if the builders were aware of these relationships between load variation and speed. If the designers did not have this operating experience, then they may have inadvertently adopted a gearing ratio which would limit the power being applied to the stones. An MR substantially greater or less than 3.1 to 1.0 would

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39. The thickness has to allow for a mill-rynd on the underside in an under-driven mill.

40. Sellin says that the Barbegal stones of 0.9m diameter, needed 3.6kw for 53rpm. This is a higher figure than his waterwheel could have developed, and, the thickness or weight of stone is not declared. The 53rpm appears to come from Sagui quoting Belidor, but how the power of 3.6kw has been derived is obscure.

do this. But some consideration ought to be given to the operation of sixteen mills over many decades which would have greatly increased their understanding of the behaviour of these machines. See Appendix B for a brief discussion concerning the throughput of a typical mill.

E. Factory Output.

A hydro-mechanical analysis of a typical Barbegal watermill has suggested that the maximum power generated by the waterwheel was 2.625h.p. Allowing for gearing and bearing friction losses means that approximately 2.4h.p. was available for driving the millstones. Using the output power factor of 117lbs/hr per horse power for Roman style lava stones, as derived by the Westree experiments, indicates that each pair of Barbegal millstones could produce 127kg/hour [281lbs] of operation. If we assume that 90% of the product was used for human consumption[41] and that the consumption per person was 900 gr/day[42] the following table provides a comparison of the basic factors of production according to the three different analyses.

AUTHOR	Sagui (1948)	Sellin (1981)	Spain (1989)
Aqueduct flow rate (cubic m/s)	1.0	0.3	0.33[43]
Mean water velocity (m/s)	2.5	0.8	0.825
Pairs of millstones per waterwheel	2	1	1
24hrs factory production (tonnes)	28[44]	9	48.77
Consumption per person (gr/day)	350	350	900
Population supported on full output	80,000	25,700	48,768
Output- one pair of stones/hr (kg)	45[45]	-	127[46]

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41. See footnote 51 on page 155.

42. I am grateful to Dr.M.Lewis for this figure, based on rations for slaves, soldiers and plebs given by Cato, Seneca, Polybius and various ancient legal codes and laws.

43. Assumes 10% excess to the wheel for splashing etc.

44. The writer is unable to reconcile this figure with the output of 45kg at 60rpm for each pair of stones.

Sellin considers that Sagui's theoretical flow rate and velocity for the mill aqueduct is excessive, supporting the view with practical experience and a telling, albeit crude, calculation of a waterwheel's capacity.[47] Sellin modifies Sagui's estimate of potential power in light of the revised flow rates and proceeds to reduce the mill output accordingly, accepting in the process Sagui's estimates of these millstones' power and output. Sellin is clearly justified in rejecting the idea of each waterwheel powering two pairs of millstones, an erroneous conclusion drawn by Sagui, which historians of technology must now abandon. Appendix B provides a brief discussion of other factors which have been considered in this analysis.

Sellin mistakenly uses Sagui's figure of 45kg/hr for each pair of the Barbegal stones, which he then modifies according to the corrections he makes. The figure of 45kg/hr Sagui apparently relates to modern millstones providing a pressure of 850kg/m^2 with ventilation fan, although he also relates it closely to Belidor[48] who provides an early eighteenth century example. In either event, if the pressure quoted were related to the diameters of the Barbegal specimens, it would re-

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45. Based on a stone speed of 60rpm but Sagui's text is confusing; elsewhere he suggests 44kg output apparently relating to 53rpm.

46. Based on a wheel speed of not less than 15rpm. A comparison with Sagui's stone output is to be avoided; whilst the difference between basis can be partly explained in terms of gear ratio, the calculations and assumptions made by both Sagui and the writer in leading to these figures are irreconcilable.

47. Sellin's adoption of a wheel speed of 10rpm is misleading, for there is no doubt that an overshot wheel of this diameter would probably have a rim velocity between 6-7 ft/sec. (See Fairbairn, Bradley, Buchanan etc.) which equates to 16.6-19.4 rpm. The author's detailed wheel analysis shows that a wheel speed of approximately 15rpm matches a headrace flow of 0.15 cubic metres/sec.

48. Belidor, Architecture Hydraulique vol.1, L. II, p.283, Paris, 1737.

quire an average thickness of 1.4ft and a weight of 1183 lbs. Such a stone would be extremely heavy and with 2.4hp being applied would only revolve at 33rpm.

By far the most influential factor in the comparison of these three analyses, aside from Sagui's false assumption which was identified by Sellin, is the writer's retrospective analysis involving mathematical analysis of the hydro-mechanics, together with the full-size grinding experiments using replicated lava millstones. This method has provided an agreement on output from two different approaches, (i) production/power ratio and (ii) comparison of different millstones by using the power relationship of their speed weight and size. These have combined to give greater realism in the analysis of the output at Barbegal.

However these calculations relate to optimum output of the machinery, a condition which, when considering the factory's throughput over any period of time, is unrealistic. The writer views the factors which affect production rather differently from Sellin who combines maintenance, supplies (water and grain), management and labour disruptions, into a single load factor of 50%. This is not unreasonable in light of the numerous variables which have to be taken into account, for even if we can ascribe accurate values to some, it is the product of them all with which we are concerned.

An alternative view of these variables is to express them in terms of the two major factors of production, which are,

(a) the number of pairs of millstones capable of being used. This would allow for the effect of all building and machinery maintenance e.g repairs to wheels, races, gears, bearings etc., and the redressing of the millstones faces.

(b) the average hours of operation per day for those millstones capable of work. This can be viewed as the working day, say 12, 16 or even 24hrs/day continuous operation.

Let us examine each of these factors in more depth.

Interruption in the flow of water was probably rare for it is difficult to imagine a blockage occurring in an aqueduct that was regularly surveyed. Moreover any blockage that did occur would be known of immediately and action taken. Using spring water sources silt deposition was non-existent but mineral deposits were a very real problem. The existing aqueducts show that mineral deposits reduced the channel dimensions by a substantial amount. The build up of these deposits was a slow affair, but we can imagine that after some decades of working the miller(s) at Barbegal would have found the diminution of flow affecting operations. Labour gangs with hammers and chisels would have needed a dry aqueduct to work in and so it seems likely that there may have been shut-down periods when the aqueduct flow would have been diverted well upstream near source. These shut-down periods were probably limited to the storage time of meal so that a surplus of production could continue to satisfy the customers demands. Water leaks that occurred could also have been dealt with at the same time.

If we remind ourselves of the scale of the Barbegal project, and of all the resources necessary to build sixteen separate watermills on a single site, it is inconceivable that they would not have taken advantage of operating the mills as much as possible. Some sort of shift working or rotation of labour would have avoided idle millstones and the whole complex working under capacity. The writer favours the vision of the factory working the whole time, in other words sufficient labour to operate and maintain the mills subject to the incidence of machinery repair and replacement and millstone dressing. In nineteenth century England, in the heyday of water-powered corn milling using horizontal millstones, a typical four-pair mill might have one pair down for dressing all of the time. Some allowance must also be made for interruptions to work caused by machinery repairs and renewals, which in a single pair mill would shut down that particular mill.
Site evidence suggests that all of the waterwheels, millstones and probably gears, were of the same size[49], which would have facilitated

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49. Different MR's and stone speeds may have existed for the processing of different types of

holding spares ready for quick replacement. For instance, spare millstones could have been dressed ready for replacing those that became damaged or worn. This would have been easy in an establishment the size of Barbegal.

The suggested figure for operating hours/day can be made with far more confidence than that for the pairs of stones in use. For the former the writer favours 24hrs/day continuous, whereas the number of stones in use is more speculative. A figure of twelve is suggested but the following graph allows the reader to explore the effects of varying both of these factors. These two factors, the operation of the factory (hours/day) and the pairs of stones in use, can be represented on a common graph to illustrate their combined effect on the number of people served by the Barbegal production. (See Fig. 31).

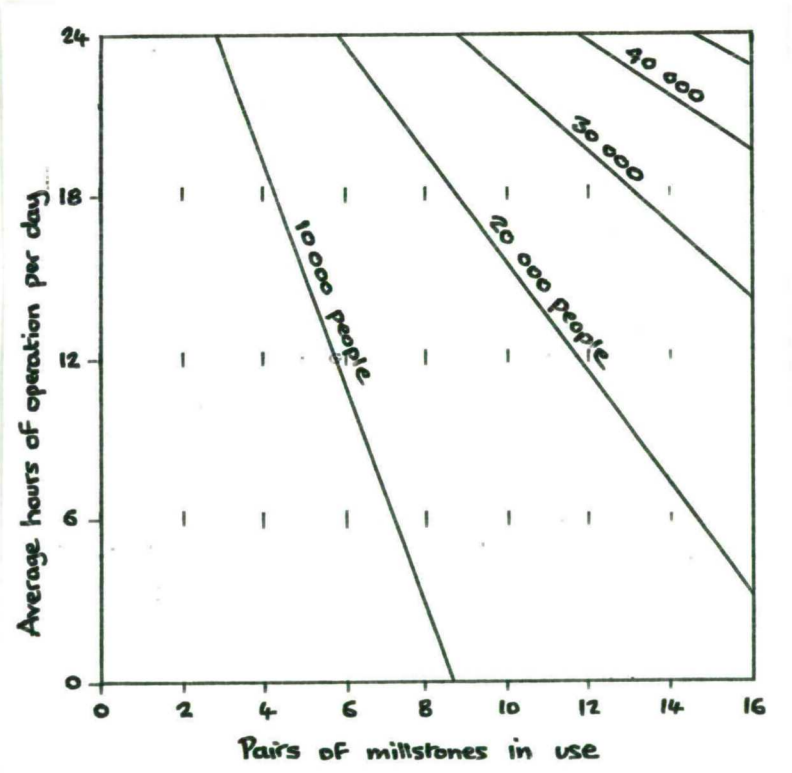


Fig.31. Factory output.

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corn.

As stated above the writer believes that the factory would have been operated 24hrs/day subject to the supply and interruption of those factors of production which would have affected the whole place e.g., water, grain and labour. Perhaps an operational period equivalent to 90% of a twenty four hour day is realistic. If we assume that on average two thirds of the mills were working, the combined effect of the two factors is 90% x 66% = 60%. This is to be compared with Sellin's figure of 50% for a single overall load factor. 60% would equate to a production capable of supporting a population of 29,261.

F. Problems and the Significance of Barbegal.

Applebaum has suggested that in Roman Britain corn production was probably in the order of 20 bushels per acre (1.4 tonnes/hectare)[50] If we accept for the purpose of this study the same yield for Provence[51], then the area of land needed to support a factory production serving 29,261 people was 95.36 square km (36.8 sq.miles)[52]. This area of farmland probably remains realistic, or at least comparable to Provence, if we considered that Barbegal's grain originated from another corn-growing area of the Empire. But we should remember that in places such as Lyon, the mountainous hinterland would have been hard-put to provide wheat on this scale.
It is perfectly possible that the output from Barbegal could have served the population of Arles or nearby cities of similar size. Lyon, which was one of the Empires largest cities, had a demand which could probably have taken most, if not all, of Barbegal's output,

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50. S.Applebaum, Britannia, 6, 1975, 121f. Reynolds experiment at Butser with Emmer wheat, the traditional bread wheat of the Roman army, suggested an average yield of 2 tonnes per hectare. See P.J.Reynolds, Iron Age Farm : The Butser Experiment, 1979, p.61.

51. The effect of differences in climate, soils and farming methods is unknown.

52. Based on a single crop of wheat per year, no crop rotation and allowing that 20% of the farm land was lost to roads, paths, headlands, water, buildings etc. The Butser yield would require 30% less land.

but it lies some 180km upstream of Arles so that the meal would have had either to be taken by road or more likely, trans-shipped to barges and towed upstream.

The transport implications of Barbegal's output are worthy of closer attention because of the influence this may have had on the siting of the factory and the light this may give to our determination of where the customers were. The throughput of Barbegal has been estimated at 29 tonnes of wheat per day which equates to a daily intake of 38.5 cubic metres of grain. When wheat is ground there is a 60% increase in the volume of product, and allowing for compaction with the stacking of sacks of meal[53], Barbegal's production must have been at least 60 cubic metres per day. Transporting this by road, which must have occurred at least as far as Arles, would have needed a considerable number of carts or wagons, with the number proportional to the distance or time taken. For instance, if the product was taken to Lyon by road, a return journey of some 350miles, the number of vehicles on the road at any one time would have been very great. Land transportation was costly, and as pointed out by Hodge[54] it made Barbegal's mass production more difficult to justify.
Water transport was far more effective for carrying bulky products over distance[55] so that if the meal was taken to Lyon, the obvious method would have been to use the Rhone. The meal could have been transferred to barges at Arles then the boats towed upstream. Whilst the journey would have been slower, the capacity of the barges would have been equal to many carts, and the journey would still be within the six weeks life of the meal.

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53. I am indebted to Dr.Hook of the Flour Milling and Baking Research Association that advised a wheatmeal density at 450kg/ cubic metre and 10% volumetric compaction.

54. Hodge, see note 9.

55. This was true for several periods of history, given that the technology existed; the English canal era is a good example.

Was Barbegal fed by imported grain? Provence was an exporter of grain in the Empire and helped to feed the capacious granaries [*horrea*] of Rome. Under these circumstances it is difficult to imagine economic conditions which would warrant importing grain into the province to be ground at Barbegal. The ergonomics are weak. Why not use local grain at Barbegal and send the displaced imported grain direct to Rome?

If the produce of Barbegal served Lyon the great weakness of the imported grain suggestion is that surely there would be a suitable site for a similar factory in the mountains around Lyon? Other advantages would include;-

(a) having a longer life product, perhaps as much as two weeks, within reach of the customers.

(b) transporting up the Rhône valley a less bulky product and one which is less affected by inclement weather.

(c) if the grain was imported it could reduce the long carriage journey between the river and the factory if the Lyon factory was within 12km of the city.

Whilst we cannot rule out Barbegal serving Lyon this is considered less likely to have occurred in view of the alternatives discussed below.

Where were the mills whose trade was affected by the building of Barbegal? Were they water or muscle powered?

Before we answer this we must first recognise that the economies of scale provided by the physical integration of 16 watermills under one roof must have equated, in terms of throughput, to a greater number of separate similar-sized watermills. This is a most effective measure illustrating the efficiency of combining the factors of production at Barbegal. However, we need not be too concerned about accuracy on this point as it is the order of magnitude of the number that we are interested in.

The writer suggests that to have matched the throughput of Barbegal, at least twice as many separate and individual watermills would have been required, and an even greater number of muscle-powered mills.

Of course the simple, but unhelpful answer, is that the mills whose work was affected or replaced by Barbegal, were very likely, though not certainly, in the area where Barbegal's product was consumed.

Let us approach the question by first recognising that Barbegal's output was surely intended for urban consumption, not rural. If the custom lay in one or more cities then we can be fairly safe in assuming that nearly all potable water sources in those cities were not available for powering millstones; this is to assume that generally corn milling was either powered by streams and rivers or the muscles of men and animals. Mills powered by aqueducts (synonymous with potable water) were rare simply because within the urban environment the head of water was a valuable and inviolable quality of the service. To introduce a watermill into a city's water supply without adversely affecting consumers was only possible if either the natural gradients facilitated this, as in the Janiculum, or, it received water that was waste or rejected and had already served its purpose, such as at the Baths of Caracalla. Such opportunities must have been rare. Wikander has drawn the conclusion, and demonstrated by a convincing analysis, that in Rome, water-power corn-milling was far from dominant during the first four centuries AD, even after the Janiculum complex became established.

If this pattern was repeated throughout the largest cities of the Empire, or, as may be more likely, the adoption and incidence of this more efficient technology was rather less than in Rome, then most of Barbegal's production affected extant animal mills. If this was true, then it could be viewed as simply technological progression, a shift from muscle power towards water power. In economic terms, less efficient production units were being replaced with more efficient. For example, one of the Janiculum mills would have been many times more efficient than animal powered Pompeian-type mills which required much greater animal, labour and land resources in proportion to the output. The natural forces of supply and demand, not only for wheatmeal, but resources for production, including labour and land within a city would have stimulated the exploitation and adoption of more efficient technology.

In Caligula's time there were 250 bakeries [*pistrina*] in Rome, nearly all of which had draught animals providing the milling work. These animal mills were controlled by the bakers who had become a powerful organisation [*collegium pistorum*] that worked actively against the introduction of watermills in Rome[56]. It seems likely that this monopolistic situation occurred in other large cities of the Mediterranean, given that it was a sypmtomatic product of lack of suitable water-power sites combined with growing population.

With the considerable advantage that water-power had over muscle-powered corn mills[57] it was only a matter of time before the opportunities to exploit such economic advantages came about. The monopolies based on the old technology would have been tested and eventually broken by the emerging corporation of *molendinarii*. Those bakers who did not have their own mills would have bought corn meal coming from the watermills either direct or through middlemen (meal factors) in the market place.

When the Janiculum factory was built it must have had a noticeable effect on Rome's meal market; its production was surely large[58] and the price would have reflected the efficiency of overshot application. Such advantages of technology and scale would have been obvious and invited replication. Barbegal can be viewed as a manifestation of these economic forces.

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56. R.J.Forbes, Studies in Ancient Technology, vol.II, Leiden, 1955, p.94.

57. One of the Barbegal mills would have been ten times as productive per/hour as a Pompeian-mill. Even allowing for the difference in capital, running resources and overheads, this must have been reflected in a cheaper price.

58. Aside from the statements of contemporary writers we have only two indications of its scale (1) the crest of the Janiculum hills stood some 60m above the Tiber and (2) when its aqueduct was cut production was maintained by floating mills moored in pairs, one after the other in a long line.

In late antiquity, c500AD, the whole of the province of *Narbonensis*, particularly the lower Rhône valley and coastal regions from Narbonne [*Narbo*] to Marseille [*Massilia*] and the via domitia was an area dominated by large wealthy cities such as Arles [*Arelate*], Avignon [*Avenio*], Nîmes [*Nemausus*], Béziers [*Baeterrae*] and Aix-en-Provence [*Aquae Sextiae*]. Such cities created great markets and those on the Rhône, especially Lyon [*Lugdunum*], and the coast would have been readily accessible to water transport coming out of Arles.

Provence was a corn-growing province of the Empire and studies of the corn supply of ancient Rome have revealed that Arles was an exporting centre, and that the shippers [*navicularii marini*] had offices in Ostia[59]. Moreover, there was a *procurator annonae* in residence at Arles, possibly to coordinate supplies for the Roman market[60]. However there seems to be no evidence that this trade, especially to Rome, dealt with meal rather than corn. Wheatmeal has a shelf life of six weeks, by which time oxidation of the germ oil has caused rancidity that is intolerable to the human palate. Grain ships could have given part of their load over to meal and easily reached Rome in two or three days with favourable winds,[61] in time to sell well within its shelf life. Larger meal shipments from Barbegal, say a typical 300 tonnes cargo boat[62], would necessarily have taken some meal at least two weeks old, which would have reduced the life of the meal at its destination. This does not preclude Rome as being the source of the demands for Barbegal's product but the nearby coastal cities and towns would appear to have been equally, if not more, attractive markets.

Who built Barbegal? Was it the army?

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59. G.Rickman, Corn Supply of Ancient Rome, 1980, p.113.

60. Meiggs, Roman Ostia, p.286; also Corpus Inscriptionum Latinorum, 12, 672.

61. Narbo to Ostia normally took three days.

62. Some Roman cargo boats could carry 1000 tonnes.

Throughout the period with which we are concerned southern Gaul was a peaceful province and the army had no need of a presence. There were no legions within the southern three-quarters of Gaul which might have suggested a demand for the Barbegal product. Even if there were, a full strength legion of 5500 men represents only one sixth of full output.

Historians are aware that there existed throughout the Empire six state-owned and run cloth factories. This prompts the question was Barbegal an initiative of the state? These cloth factories would have served the army, where the demands justified factors of production being integrated on a large scale. Cloth was a commodity which, although bulky, was easily transportable and could be stored for long periods. Meal could not. Because of its limited life, meal had to be produced within a reasonable distance of its customers.

And so we are not able to justify the existence of Barbegal as supporting military demands. In fact it is probably easier to suggest the opposite view, that this badly planned building, with its poor symmetry, was not the product of military resources. If this conclusion is reached, then we have greatly simplified the remaining options. In essence there are two and they could both be described as being entrepreneurial initiatives.

In asking ourselves who built Barbegal, we might also pose the question who built the Janiculum complex?

With some confidence we can suggest that the Janiculum initiative was probably taken by either the state or private enterprise; it is unlikely to have been the army. Although Roman life was very much state organised, more or less divorced from the countryside, with a full or heavily subsidised food supply, their urban proletariat exploited every means of making money through industry and commerce. There are two other types of people who may have been involved with the building of Barbegal. The first is obvious and easily dealt with. In the Roman world there were a great many rich people, large landowners in the main, who would have wider information and substantial resources at their command. Such people were invariably well travelled for their estates were often scattered over many provinces. To those who lived in or visited Rome the Janiculum mills would have been a

familiar sight. Their successful operation, so evident in the edicts, codes and other contemporary writings, would have been the talk of Rome and the provinces.
If Wikander is correct in his dating of the Janiculum mills to a construction date in the last third of the third century AD[63], then the Janiculum watermill complex would have provided a perfect example for the entrepreneur to replicate.

The third possibility is that Barbegal was built by a commercial organisation. We know that the *molendinarii* eventually formed their own corporation but we do not know when, neither do we know the part the millers may have played in the market place. The influence of any such corporation may have been limited within a single chartered Roman city, where it was founded and incorporated. The same questions apply to the *collegium pistorum*, and once again we have no evidence that suggests that they could have initiated and controlled the Barbegal factory from a remote city or province.
Of course, this invites the suggestion that if Barbegal was in the Arles *territorium* then the millers or bakers of that city might have initiated the project. But it is unlikely that they could have provided the financial resources; Arles was surely not large enough to have fostered such a rich corporation.
It is far more likely that a group of merchants, perhaps a *conventus*[64], recognised the great potential of Barbegal for we should remember that in the lower Rhone valley there were numerous provincial colonial settlements, *coloniae*, during this period. The whole venture required a certain amount of 'horizontal' integration of millers, carriers, merchants and perhaps bakers, so that a consortium of interests may have been involved with Barbegal, if not in its

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63. Wikander,Ö.J, 'Watermills in Ancient Rome', Opuscula Romana, 12, 1979, pp.13-36. See pp.21-25, 34.

64. A group of Roman citizens, often residing together forming an expatriate organisation.

building, then its management and marketing of product. The wealthy landowners on whose estates the grain was produced could have formed such a consortium.

The permission to build an aqueduct was apparently determined by the city council and so the change of use embodied in the Arles aqueduct, if this occurred, would have required approval by the Arles council. What part the colonia of Arles played in the building or diversion of the mill aqueduct is difficult to say. If the mill aqueduct originally served Arles, then the city would have had control of its future. In all chartered Roman cities, four magistrates elected by the council were responsible for a wide range of local services including tax collection (local and state), and all public works such as baths, theatres, circuses, public temples, roads and water supplies. By 340 AD Constantine II had insisted that all expenses for public works came out of the pockets of the *curiales* (members of the council) so that Arles council would have seen a value in the defunct aqueduct if only for its building materials. Alternatively they may have retained an interest in the operation of the mill as an income source. We might also ask, if, in the event, the aqueduct had been built for the mill and within the *territorium* of Arles, how their responsibilities for public works were affected by others undertaking the works. Moreover was there a division of responsibility where the aqueducts were bridged together?
Such questions invite the answer that the colonia of Arles may have been partly or wholly responsible for the building and operation of the mill, whether or not the aqueduct had been built for the mill.

We have seen that, when the Romans wished to build a very large meal factory, they did so by building numerous replicas of the same watermill. Did this stimulate or inhibit the evolution of waterpower technology?
In building numerous identical units in a relatively short period, parts of the building design were committed in fabric which would have tended to prohibit future changes and development. The experience of building Barbegal preceded operation and maintenance[65] so

that any developments which affected the design of the building may have been impossible or difficult to implement. This could be seen as a lost opportunity for technological progress.

On the other hand, the operation of sixteen identical watermills may have accelerated technological development in other ways. Two examples will suffice. After a few decades of operation the millers of Barbegal would have found the top millstones throughout the factory to vary in thickness. The slight differences in hours of operation, maintenance problems, operating skills etc., would have produced over the years, appreciable differences in the machinery, especially the millstones. The top stones in some mills would have been worn thin or broken and been replaced by new ones before others.

At the time when the mills were built, all of the top millstones would have been new and thick. As a runner stone wore away, the power needed to drive it reduced, so that a fully loaded waterwheel would have tended to drive it faster. The balance of power between the wheel and the millstone would be influenced by the gear ratio and the limits of speed that an overshot wheel of this size could reach. With a much lighter millstone a higher MR could be adopted with advantage, to avoid the inefficiencies of a very fast wheel, thus a higher output would result.

The operation and maintenance of this number of machines with their slight differences, would have accelerated the learning and experience of the millers and artificers at Barbegal. It seems likely that those developments which are spawned by comparative work, such as more effective gear ratios, would have appeared in Barbegal much quicker than in single watermills scattered elsewhere in the landscape[66].

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65. A suggestion has been made that some of the mills may have been operated for a short while before all of the mills had been built.

66. A natural development of this would be that certain mills may have higher gear ratios, which could have worked with those millstones which had become thinner and lighter.

One other example of technological development that was almost certainly present in Barbegal was the standardisation and interchangeability of machinery parts. With sixteen identical watermills, the opportunity to take advantage of mass production and interchangeable parts was obvious. This would reduce down time of the mills considerably. Similar advantages must have occurred in extensive mines where identical sets of drainage wheels were pre-made, then erected and maintained underground.

And so we can conclude that Barbegal, on balance, must have provided a working environment which tended to stimulate the development of waterpower technology, particularly in mechanical engineering.

Appendix A - Table of Critical Dimensions

TABLE OF CRITICAL DIMENSIONS (cms)					
Mill	Wheel Pit			Gear Pit	
	Width	Length	Height	Width	Length
EI	111	526	?	105	170
EII	121	479	265	115	174
EIII	123	490	242	110	170
EIV	128	480	264	does not exist	
EV		474	264	" "	"
EVI	121	588	?	" "	"
WI	unable to measure				
WII	120	470	256	104	167
WIII	120	476	?	?	181

Fig. 32 is a typical section through one of the mills EIV to EVII.

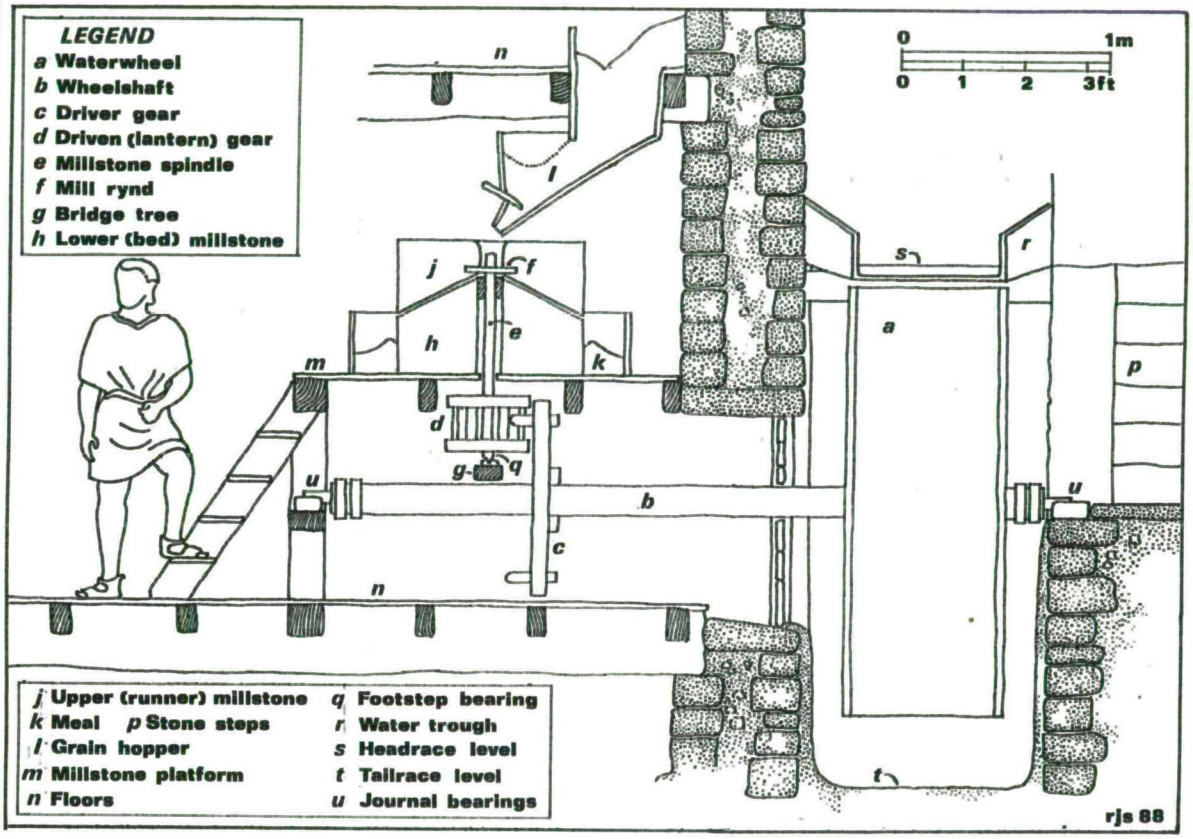


Fig.32. Typical section through mills EIV to EVII.

Appendix B - Theoretical Assumptions.

The following assumptions apply to the calculations of throughput;-

(i) The feeding rate into each pair of stones would tend to be a maximum above which the coarseness of the product increases. In the Westree experiments the flow rate at which this occurred was dramati-

cally obvious. It represents that condition where the weight of the stone is insufficient to do the work of reduction; greater flow rates would lift the stone.

(ii) Throughput of these stones is directly related to the weight of the top millstone, all other factors being constant. As the top stone wears away and gets lighter its capacity reduces. The graph Fig.29 has been based on a stone weighing 689 lbs, having a thickness at the eye of 4inches and at the rim 12inches which can be taken as a half-life condition.

(iii) A fully loaded waterwheel has to be capable of driving a new thick top stone. Assuming an eye thickness of 6inches and a rim thickness of 14inches, the weight is 834lbs, which when absorbing 2.4H.P. would rotate at 47rpm.

(iv) Using the product/power ratio derived from the Westree experiment the average output of a pair of Barbegal stones would be 127kg/hr.

This relationship between output, weight and speed of a top millstone is found within the formula for power. If we accept for the purposes of this study that power can be directly related to output, then with all other factors being constant, the formula for torque tells us that power is directly proportional to the product of weight and speed. This relationship applies to any particular pair of stones and cannot be transposed to other pairs where the variables of dress, material etc., may differ.

(v) As a millstone wears away and becomes lighter the power needed to drive it at constant speed reduces. The excess power generated could be applied to increase the speed, and thus the output, by changing the gear ratio by the same proportion that the weight reduces. To match the generated power, theoretically the MR would need to be regularly increased, which is an impractical solution. What might have been done is to either,

(a) change the MR to a higher value, say, half-way through a stones' life, which could have been achieved by installing either a new lantern gear with fewer staves or, a larger driver gear, or,

(b) move the millstones to another mill where the MR was higher.

But this is pure speculation.

Chapter Seven

THE ACCELERATED HEADRACE MILLS OF THE EMPIRE

Among the watermills of the Roman world there are several sites where the wheels were designed and arranged to run fast, that is, to run at a high speed by driving them with a fast-moving stream of water rather than a sluggish flow or by weight only. We know of at least four Roman watermills that received water from a level high above the crown of the wheel and another where the headrace was purposefully accelerated into the underside of the wheel.

Technological evolution of the vertical waterwheel is the subject of the following chapter in which a general theory is outlined and proposed. Within this theory the writer will proceed to demonstrate that these accelerated headraces can be related within a proposed evolutionary phase of water power development. This particular feature can be found within several well known watermill sites of the Empire, which are here given a general examination.

What name do we give to this type of wheel and of what significance is the arrangement? Why did they build fast wheels?

In both overshot and breast wheels where the water is carried in buckets, their velocities derive wholly from the weight of water carried, and the potential energy relating to velocity is inefficiently harnessed by the buckets. In such wheels the velocity of application is similar to the rim speed, for if it is increased much above this speed, turbulence and splashing occurs, and their volumetric efficiency decreases. Waterwheel design and practice over the last few centuries bears this out, with the water being applied at a velocity to more or less match the speed of the passing buckets. Twentieth century molinological experience and literature suggests that under normal loads overshot and breast wheels invariably have a rim velocity approaching two metres per second whilst undershot wheels are usually considered as having roughly half the water velocity. Under conditions of lighter load all types of wheels would revolve faster according to the balance of power.

Within the classification of vertical waterwheels the terms overshot and undershot have been long established as primary genera. They relate to the passage of the water through the wheel and the meaning of the words 'over' and 'under' are at once both obvious and simple. They refer to how the water passes the wheel when moving from the headrace to the tailrace. Some molinologists prefer to use the wheelshaft as a datum rather than the whole wheel, but it matters not to the result.

Another more simplistic view has the term overshot involving water being applied from above and undershot from below, but these are imperfect and misleading interpretations.[1]

Although the term undershot theoretically covers all non-overshot types, modern practice tends to treat breast-shot wheels as a separate classification and limits the use of the term undershot to wheels with very low heads of water.[2] The Venafro specimen, where the head is very high, illustrates the inadequacy of these modern terms of overshot and undershot rather well. The archaeological evidence from Venafro has failed to identify how the water was applied to the wheel, that is, whether it passed over or under the wheel. Furthermore we do not know the direction of flow of the head and tail races, which raises the question, if they take different directions, can we still use the term over or under-shot? Let us suppose that in plan view the direction of the headrace is normal to the tail-race and that neither race passes over or under the wheelshaft. This is quite possible with a high-head wheel especially when the headrace approaches in an aqueduct or other man-made course whose direction may be influenced by quite different factors to those relating to the tailrace direction. In the arrangement described the terms overshot and undershot have no meaning.

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1. For example, some pitchback wheels receive water from above which then passes below the shaft.

2. Say as a guide not more than a sixth of the wheel diameter.

So when the head is greatly increased, how should we then classify water-wheels? The names that we can consider for this type of wheel are *fast*, *radial floats wheel*, *high-head*, *impulse*, and finally, *accelerated headrace*.

The most obvious name for consideration is surely *fast*, but classification would not be easy. When does a wheel become fast? The adoption of a theoretical speed cannot provide total confidence where the limits of definition are arbitrarily chosen. Moreover, the inevitable incompleteness of the archaeological evidence and the consequential assumptions that have to be made produce a more theoretical and speculative result. These difficulties highlight the advantages of adopting a classification which relates to a definite feature easily identified and often occurring in the archaeological evidence.

A term which is worthy of our consideration is *radial float* wheels. We can confidently suggest that radial floats relate to both fast overshot and undershot wheels, so why not use it as a category? There are two reasons why this is not suitable. The first is simply that the remains of waterwheels or evidence of their existence is very rare[3], making the identification of radial floats most unlikely, and secondly radial floats were used in all undershot-wheels including river wheels.

When the head of water is greatly increased above a wheel to create what might be called a *high-head* wheel, the term overshot may be inappropriate. The term high-head has the same disadvantage as the term *fast*, in that it relies on arbitrary criteria for definition. However it does have the advantage of relating to linear rather than dynamic or potential energy criteria, which the archaeological evidence is far more likely to provide.

Why not use the term *impulse wheel*?

The greater the acceleration of the headrace the greater the proportion of generated power due to impulse rather than gravity. But the balance between the two can vary not only from wheel to wheel but in

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3. The Venafro evidence, where nature provided a mould or cast of the wheel construction must be considered very rare.

the behaviour of the same wheel. Some wheels use both gravity and impulse in generating power, such as the Agora specimen, where the hydro-mechanical analysis has shown that at slower speeds the gravity effect was dominant and as the wheel increased in speed the impulse effect took over. It is therefore not desirable to use the term impulse as a main category. The theoretical analysis was used to help decide whether or not buckets or floats existed, bringing focus on the question as to whether a radial float wheel would have been shrouded and soled.

Analysis shows that in such wheels as those in the Baths of Caracalla, the division between power caused by weight and reaction is velocity related. As the head is increased above a wheel the velocity of application causes the wheel to rotate at higher speeds, increasing the centrifugal forces and diminishing the water being carried by the buckets. Although the slope of the headrace and its roughness influence the velocity, their effect, especially in an overshot wheel with a wooden headrace, is slight.

It is recommended that the type of wheel we are considering should be known as an *accelerated headrace* wheel. Such a term has a singular and outstanding advantage which more or less predetermines its adoption, which is that the archaeological evidence of a site will invariably yield facts concerning the head of water, the headrace, and usually, the diameter of the waterwheel. Such evidence makes the identification of an accelerated application straight forward. Like the long-standing terms of undershot and overshot, accelerated headrace relates to arrangement rather than result, but has the additional advantage of being without ambiguity and is readily identifiable.

For purposes of analysis we are concerned with that portion of the race nearest the wheel between the point where critical flow[4] occurs

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4. Where the conditions of flow change usually from laminar to non-laminar and the relationship between head and velocity (law of resistance) changes; critical flow usually occurs at the point where the water accelerates.

and deceleration occurs at the tangential intercept. This provides us with the final velocity of application into the wheel and allows for specific energy in the headrace, resistance to flow and acceleration due to free drop between the trough and wheel.

For simplification and to make identification easy we could limit our view to the inclined trough, after all the existence of a substantial head is usually very obvious and analysis is unnecessary to confirm a fast application. However an accelerated headrace is not singular in the sense that it can be undershot or undershot but analysis can be revealing. The point at which critical flow occurs may not be obvious and furthermore, acceleration may begin much higher upstream as was the case at Haltwhistle. Such changes to the bed gradient approaching the position of critical flow should be noted because they probably indicate an awareness and therefore intended design on the part of the builders.

So much for theory; but such refined analysis is irrelevant to the general idea that if a Roman millwright wanted fast water into the wheel he simply brought the water down a steep flume.

All accelerated headraces have inclined beds whose inclination can either be uniform gradient [as in the Baths of Caracalla and the Agora] or variable gradient [as at Lösnich and Haltwhistle].

Acceleration of a headrace occurs up to the position of application, during which the flow is directed, thereafter retardation occurs as the energy of the water is transferred to the wheel. Downstream of the point where the headrace is at maximum speed the water can be constrained by rims, shrouds, a curved breast or trough. This increases the efficiency of application by maximising and prolonging the action of the water upon the wheel.

When high velocity water is applied to the lower parts of a wheel there are advantages to be gained in using a trough. Not only can it be used to deliver the water, but if the wheel runs inside the trough, it can be adjusted to reduce water escaping under the wheel. A trough helps to generate laminar flow conditions up to the wheel and constrains the water as it passes through the wheel. In this way

it duplicates the functions of shrouds, so that they can be omitted, although radial floats would still need to be stable and strong to endure their working conditions.

When fast water is applied to higher parts of a wheel the constraining function, provided by the sides of the trough, ceases when the water strikes the wheel unless either;-

(a) the wheel runs in a close fitting pit, or,

(b) the radial floats are shrouded.

Faced with this choice it is easier to add shrouds to a wheel than to build a close-fitting wheel-pit which would require far more resources (materials and skills). Additionally the fit of a wheel within a pit is adversely affected by lime deposits and bearing movement; and, moreover, the wheel can also be easily damaged by debris floating into the wheel.

The writer now examines the Haltwhistle, Agora, Caracalla, Lösnich and Venafro arrangements in turn. In the case of Lösnich and Venafro, it has been necessary to examine and interpret the evidence in some detail because extant publications fail to do this.

A. Haltwhistle Burn Head Watermill.

Within Roman Britain there is only one site which shows unmistakable evidence of having an accelerated headrace. This is the Haltwhistle Burn Head mill on Hadrian's Wall. This watermill is described in more detail in chapter 5 above.

A hydraulic analysis has shown that the headrace, a man-made watercourse cut across a loop in the river, was purposely graded to accelerate the water into an undershot waterwheel. The gradient of the race was increased as it approached the wheel and cut through solid bedrock to provide a velocity of application of approximately 15ft/second. The stream was applied to the wheel low down, at roughly five o'clock (clockwise rotation) and constrained by a wooden trough in which the wheel ran.

Of the accelerated headrace sites this is the only one having evidence which supports the notion of the wheel being without shrouds[5]. The evidence for this was the remains of a trough which was found in the bottom of the wheel pit.

B. Athenian Agora Watermill.

By far the best known Roman watermill having an accelerated headrace is the specimen that was found in the Athenian Agora in 1933 and interpreted by Parsons[6]. Parsons' outstanding analysis has remained an exemplar in spite of other splendid examples of Roman watermills which have been examined and published. He cleverly illustrated and supported his analysis by comparison with Vitruvius' well known description of a watermill.

Parsons' interpretation of the evidence provides us with the only example of a watermill geared-down in the manner which he believed to agree with the Vitruvian text. The writer has suggested an alternative interpretation which supports the existence of a fast wheel driving geared-up millstones.[7] This hydro-mechanical analysis also includes a re-appraisal of the water control methods, the wheel-shaft journals' alignment and the millstones. In the Agora mill the diameter and position of the waterwheel is confirmed by the scoring which its rim made in the lime deposits on the wheel-pit wall. The wheel chamber, which was cut some 3m deep into bedrock, was clearly made to allow the wheel to be set low and create a high head, allowing for an underside clearance of 0.6m. The headrace approaches from the south and takes a straight course directly towards the wheel over the last 20m, Unfortunately, although the foundation wall of the race can be seen, the remains of the water channel on the top disappears 13m from the edge of the wheel pit.

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5. At Lösnich the suggestion of shrouds is dubious.

6. Arthur W.Parsons, 'A Roman Water-Mill in the Athenian Agora', Hesperia, Vol.5, 1936, pp.70-90.

7. R.J.Spain, 'The Roman Watermill in the Athenian Agora : A New View of the Evidence', Hesperia, 56, vol.4, pp.335-353, (Oct-Dec. 1987).

However, southward of this point, upstream, the floor tiles of the race were found preserved which allowed Parsons to suggest that originally it delivered water at a height of circa 1.4m above the top of the wheel. According to the published section and plan of the headrace the bed actually rose by 6.6cm. in 14.3m before it took a straight line towards the wheel, where it then inclined downwards at a gradient of 0.009. We have no way of telling how this profile related to the gradients that existed during the mill's life. If the gradient of 0.009 continued to the wheel-pit, then the head of water was nearer 1.3m rather than 1.4m stated by Parsons[8].

Parsons has assumed that the headrace was brought to the edge of the wheel-pit, its south face, and then accelerated down onto the overshot wheel by an inclined wooden chute. There is no archaeological evidence to tell us where the acceleration began, and it might have occurred earlier than Parsons has shown and been carried by a less steep trough. However, as already stated above, the velocity of application is insensitive to the inclination of the trough within broad limits, for it is the vertical drop which has greater relevance. The assumption that the high end of the trough was positioned above the south face of the wheel-pit is entirely reasonable being the logical position for a change of material in the headrace. No matter, wherever the change of gradient occurred, there is no doubt that a 'fast' overshot wheel existed as confirmed by the shape of the lime deposits on the sides of the wheel-pit.

A hydraulic analysis of this arrangement shows that the velocity of application was approximately 19.2ft/second when the headrace was from 50-90% full.[9] The analysis shows that if the wheel had buckets the useful effect would diminish rapidly as the speed of the wheel increased. It would probably have reached a maximum theoretical generated power of over 6.5hp. at a wheel speed of approximately 20rpm.[10] and thereafter, as the speed increased, the adverse effect

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8. See Parsons Fig. 1.

9. Spain, as note 7, pp.335-353. See p.71 above.

of centrifugal forces would rapidly reduce the power of the wheel. Coincident with centrifugal losses are the losses due to splashing as the buckets pass through the stream of water entering the wheel.

With radial floats the wheel would behave rather differently. At lower speeds it would have been unable to generate the power of a bucket arrangement, but at say 25rpm, an improved performance is theoretically evident. Above this speed the impulse effect is very great whilst the power derived from weight is negligible.

The balance of power calculations, even allowing for a top millstone three times as thick as those found, confirm that the mill was very over-powered, and this fact, combined with the high velocity of application, supports the conclusion that the Agora water-wheel had radial floats within a shrouded rim and not buckets.

The power analysis for the radial float wheel shows that it would have settled at a speed of between 28-32 rpm when the water in the headrace was between 9-15 inches deep. The following table provides a summary for the Agora mill.

RADIAL FLOAT WHEEL	MR	Speeds rpm		
		Headrace 12-15in.deep		
		Power HP	Stone	wheel
Six inches thick stones	5	2.8-3.2	120-145	24-29
	4	2.1-2.6	104-124	26-31
	3	1.75	81-96	27-32
	2	1.2	56-64	28-32
Two inches thick stones	5	less than one	165 to	33 to
	4			
	3			
	2		58	29

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10. This is with a full headrace relating to a high, rather unrealistic, average velocity within the headrace. The impulse effect is very difficult to establish. The power generated figure is gross and there is no allowance for friction.

Interpretation of the above table suggests that the choice of MR was probably influenced more than any other factor by the volume of water flowing, particularly the variation that may have occurred between the seasons. If a constant flow of, say 9inches depth existed, then the driven gear, especially when driving top stones at least 6inches thick, would have had more cogs than the Zugmantel specimen.

C. Baths of Caracalla.

Within the subterranean chambers of the Baths of Caracalla, Rome, the remains of at least three watermills have been identified[11], and a fourth conjectured.[12] Analysis has shown that an original low-head overshot wheel, possibly one of a pair, was supplemented some 40-88 years after its building, by two identical, but independent, accelerated head-race overshot wheels.

These two faster wheels were built in one half of the chamber, beside one of the original mills, which probably remained operational whilst the new mills were being built. The builders apparently used the same size waterwheels as already existed, but cleverly adopted a lapped wheel arrangement which gave them a high utilisation of space. The pits for the new wheels were made deeper to provide a greater head of water onto the wheels, with new headraces coming from the old water inlet and channelled independently into each wheel. The water head above the wheels was 1.1m (43ins.) and application must have been facilitated by an inclined wooden chute which constrained and directed the water onto each wheel. Although the inclination of the headrace is unknown, its effect on the velocity of application can be assumed as relatively insensitive, within broad limits, for it is the head which is the prime determinant of velocity.

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11. T.Schiøler, Ö.Wikander, 'A Roman Water-Mill in the Baths of Caracalla', Opuscula Romana, XIV:4, pp.47-64. An excellent reconstruction of the two most complete watermills but no attempt was made to analyse the earlier mill standing in the middle of the room.

12. R.J.Spain, 'The Watermills under the Baths of Caracalla, Rome', forthcoming publication.

The velocity of application was in the order of 4.95m/sec (16.24 ft/sec) and we can safely assume that these wheels had floats rather than buckets which would have been rendered rather ineffective because of the centrifugal force.
A hydro-mechanical analysis suggests that these wheels would have settled at a speed close to 50rpm and the power generated was easily capable of driving a pair of 29 inches diameter lava millstones.[13]

D. Lösnich

At Lösnich, during 1978, archaeologists found evidence of two water-power sites close to a Roman settlement[14]. They lie 85m apart on the same small steeply graded stream below a villa-farm settlement which is spread over the north face of the valley. Neyses has identified at the lower site a probable water-wheel position where the water was brought and applied to the wheel with a headrace whose gradient immediately approaching the wheel followed a concavo-convex path. At the upper site Neyses proposes that two wheels existed in series, the water being applied first to a larger diameter wheel, then to a smaller undershot wheel working in the tailrace of the first[15].
Both of the watermill sites have been related to the nearby Roman buildings by inference; no clear dating evidence was found although a meticulous archaeological search of both sites might prove rewarding. Unfortunately, the Roman horizons, if they existed, may have been eroded away in this steep-sided, ravine-like valley.

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13. The remains of a millstone 29ins. diameter remain embedded in one of the mill walls. If we adopt the modern limit of 1500ft/min for rim velocity, a topstone six inches thick would need 2.0 HP. As Dr.M.Lewis suggests, this millstone was most likely from the earlier mill.

14. A.Neyses, 'Die Getreidemühlen beim römischen Land-und Weingut von Lösnich (Kreis Bernkastel-Wittlich)', Trierer Zeitschrift, vol.46, 1983, pp.209-221.

15. Neyses also identified another possible area of Roman activity higher up the valley immediately below the villa.

At the higher site[16] part of a sandstone bedstone 1m diameter was found. Both the diameter and use of a local stone are typical of the Roman period as is the apparent narrow width of the waterwheels used on these sites. This evidence, such as it is, reflects Roman influence, but is not sufficiently convincing for us to ascribe a firm Roman date to it.

The two waterpower sites have strong similarities, both being cut into solid rock with the headrace accelerated by inclination. This suggests that they were built in the same period but whether operating simultaneously or sequentially we cannot tell. Neyses believes that these watermills relate to the nearby Roman villa-farmstead which has been dated from late first century to early fifth century. A plan of the area shows the Roman buildings and features lying higher up the north flank of the valley overlooking the mill sites. The villa, which is the focus of the settlement, is the nearest building to the mills, being 160m from the upstream site, and standing 30m higher. The cemetery of the settlement is further along the valley only 100m from the mill below. The two sites are therefore not remote from the cluster of Roman buildings spread over the flanks of the hillside above the Kluckertbach stream[17].

At the lower mill site[18] there is no evidence to indicate the diameter of the wheel such as bearing or gear emplacements in the rock face. However, Neyses demonstrates convincingly that it was served by an accelerated headrace, even to the extent of identifying where the wooden water-chute had been cut into the rock face. The outstanding feature and primary proof of an accelerated headrace is

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16. Neyses, site index XIII.

17. The writer rejected the Nettleton evidence from the corpus because of its remoteness from the nearest Roman settlement, absence of dating material, and adjacent site evidence which was puzzling and irreconcilable with the waterpower evidence. At Lösnich the Roman context is much stronger, for the type of wheels that existed and millstone that was found can be fitted into Roman typology.

18. Untere Muhlen XV.

the concavo-convex (vertical section) 5.84m high rock face which supported it. The concave section is clearly where the wheel stood, whereas the convex section is where the rock face had been deliberately cut and smoothed to provide least resistance and accelerated flow towards the wheel.

At the upper site, only the concave waterwheel emplacement, some 3m deep exists and all traces of the upper rock profile has disappeared. The rock face had been cut to form a wheel-pit, of trapezoidal section, 0.6m wide at the bottom and 1.18m wide at the top. In one face of this pit, opposite the end of the wheel-shaft, an emplacement has been cut to receive the outer bearing. The rock face has also been cut to allow the driver gear to be installed. Although Neyses concludes early in his analysis that it was a middle-shot (breast) he subsequently debates the merits of undershot and overshot at this site[19]. His assumptions that it was known by the builders that undershot gave greater torque with little water and, later[20], that high torque was certainly one of the reasons for installing a large wheel, brings fault to his analysis. The historian of technology cannot credit Roman engineers with such understanding, especially in the field of water-power where our knowledge is in any case so limited.
Neyses furthermore reduces our confidence by illustrating this wheel as an overshot [*obere Muhlen*] with inclined buckets and a high-level headrace trough. There is a single but telling reason why this must be an undershot arrangement because, why else would the builders have cut from solid rock, a wheel pit having a trapezoidal radial section?[21]
But what is very clear to us today, in spite of the works of man and nature, is that the gradient of this valley, 45m drop in 125m distance in the region of these mill sites, lends itself very well to an

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19. Neyses, as note 14, p.215.

20. Neyses, as note 14, p.216.

21. Neyses recognised this but was apparently unconvinced.

overshot arrangement. With such a very steep gradient, the implication in delivering water to an overshot are minimised where the length of headrace is indirectly proportional to the inclination of the slope (all other things being equal including the wheel diameter). In these physical circumstances, the installation of an overshot would have been much easier than an undershot.

It is possible that the type of wheel could have been changed to overshot after the wheel-pit was cut, but it is very difficult to justify such a change in view of the trouble taken to create the site. However, there are two other observations which lend weight to the undershot suggestion, and they both spring from adjacent archaeological evidence. The first relates to the adjacent undershot wheel which Neyses has identified immediately downstream of the 6m diameter wheel we are considering. That an undershot wheel operated here seems very likely for the driver gear cavity and the purposeful narrowing of the headrace cut into the rock offer strong evidence. Incidently, both the gradient and the narrowing of this water course approaching the second wheel confirm an accelerated headrace arrangement. It also signifies coeval operation.

But the significant feature of the conjunction of these two wheels is that the second downstream one could not have operated successfully if its neighbour was overshot. The water falling from an overshot would have dropped much too close to the next wheel creating such turbulence that the velocity into the second would have been negligible.[22] With an undershot application on the upstream wheel the efficiency of application of the downstream wheel improves greatly.

Either one of these millsites generated sufficient power to serve the corn-grinding needs of the villa-farmstead nearby, so that the mills may have worked consecutively rather than simultaneously. But against this is the fact that the watercourses and wheel pits are carved from

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22. Neyses provides no evidence as to why the second downstream wheel at both sites is so small in diameter.

solid rock so that the effect of erosion as a cause for moving site can be ignored, for it is difficult to imagine how such a site could physically degrade.

Neyses records the modern flow rate of the millstream as a maximum of 10 l/s after prolonged rain[23]. Although we do not know what effect, if any, man's farming activities within the watershed may have had on the flow rate, it seems unlikely that this steeply graded stream could have changed much over the centuries. Neyses believes that these mills were served by dammed ponds in the Roman period, and suggested that rock workings that he found on each side of the stream above the millsites may mark the position of such storage ponds.[24] If this conclusion is correct, this is the only Roman vertical waterwheel presently known to us which was served by a stored water system[25].

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23. The potential power from such a flow with a 5m. head provided at Lösnich would be 39HP.

24. What significance should we give to the apparent absence of a 'bypass', a means to divert water from the waterwheels, especially at the upper site with its conjunction of wheels? A storage system with its interruptable delivery could have facilitated the control normally provided by a diverting bypass.

25. The writer does not consider that a weir, for example which may have existed at Haltwhistle Burn, provides a water store. Although weirs and dams can both be used for diversion and increasing water height, weirs can be used for different purposes including navigation, fishing, flood control, etc., and may not necessarily be water-tight as a mill dam must be.
Reference to mill dams occur in several legal regulations of the period from c450 AD. See Ö.Wikander, 'Mill-Channels, Weirs and Ponds : The Environment of Ancient Water-Mills', Opuscula Romana, XV:13, 1985, pp.149-154. The Barbegal reservior, mentioned by Wikander, is not accepted by the writer as a millpond, see Chapter 6.

E. Venafro

Jacono's report[26] of the Venafro wheel deserves greater attention than historians have given it. The original facts provided by Jacono in 1938 have somehow become distorted by a series of historians so that all published versions in English are now misleading if not wholly wrong. The distortions, which appear to have been caused by inaccurate interpretation or translation of Jacono's words, relate to two matters, the position of the site and the date of the artefacts, and then in addition other errors have crept in.

But let us first examine the evidence for the dating of the Venafro artefacts. The only reference made to the date of the site relates to limestone deposits in which the two millstones and waterwheel impressions were found. A literal translation of the relevant words is, '*they called in Professor Bassani and found out that 2000 years which had passed were sufficient to make up the limestone stratum..*'[27] No corroborating dating evidence is given in the report, which, we should remember, was published thirty years after the finds were discovered.

Approximately two years before the Venafro finds were published, Parsons had corresponded during the preparation of his Agora article with Jacono and had apparently accepted them as Roman.[28] The only other evidence that has been published came from Inspector Cimorelli who visited the site[29] but this does not add anything significant to that evidence provided by Jacono.[30] We are therefore dealing with a single opinion, given in 1908, of unattested repute, whether in ar-

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26. Luigi Jacono, 'La Ruota idraulica de Venafro', L'ingegnere, N.12, 15th.December 1938, XVII, pp.850-853.

27. Jacono, as note 26, p.850.

28. Parsons, see note 6, 1936, p.70, footnote 2.

29. G.Cimorelli, Nel territorio di Venafro - Una importante scoperta archeologica, Venafro, 1914.

chaeology, geology or petrology, which had apparently claimed that a particular limestone deposit had been made during the last 2000 years. The quality of this dating evidence is, as Moritz has said, 'that it is not at all accurate'.[31] However Forbes has accepted it without question,[32] as did many other historians including Reynolds. At present the only other clues on dating come from the millstones and the dimensions of the wheel itself.

The diameter of the millstones, their material, and as Wikander suggests, their slightly conical shape, suggests an early Imperial date.[33] In the original publication of the Venafro finds by Jacono there is no mention of corroborating evidence for dating the artefacts. Apparently no coins or pottery were found to support the early date claimed for the site. But what significance should we place on Jacono's view that the measurements of the wheel *'in every single part correspond to the Roman foot'*? The greater proportion of the dimensions given for elements of the wheel are in increments of the digit, 1.85cms., a sixteenth of a Roman foot. More interesting is the fact that the wheel was 100 digits in diameter and its width and depth of shroud was one Roman foot. Is this a coincidence or does it represent some standardisation in design? What of other Roman waterwheels? Those whose dimensions we know fairly accurately are as follows;-

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30. Jacono, who was probably spurred into publication by the Agora finds and Parsons' enquiries into the Venafro evidence, would have been aware of the deficiencies in Cimorelli's publication of 1914. This is probably why Parsons makes no mention of it.

31. L.A.Moritz, Grain Mills and Flour in Classical Antiquity, Oxford, 1958, pp.137-8.

32. R.J.Forbes, Studies in Ancient Technology, Vol.II, p.90.

33. Ö.Wikander, 'Archaeological Evidence for Early Water-Mills - An Interim Report', History of Technology, vol.10, 1985, pp.151-179.

Mill Site	Dia.x Width(m)	Dia.x Width(Roman feet)[34]
Haltwhistle	3.66 x 0.36	12.4 x 1.2
Agora	3.24 x 0.54	10.9 x 1.8
Barbegal	2.1 x 0.74	7.1 x 2.5
Nettleton	2.6 x 0.35	8.8 x 1.2
Ickham Early	2.0 x 0.565	6.8 x 1.9
Caracalla	2.18 x 0.53	7.4 x 1.8
Venafro	1.85 x 0.3	6.3 x 1.0
Lösnich Upper	6.0 x 0.5	20.3 x 1.7

It is interesting that some of the wheels have very similar diameters and have nearly identical widths. Although we have a paucity of evidence, the size of the Venafro wheel fits in well with the current corpus. This, together with the millstone evidence and the fact that its major dimensions relate directly to Roman scales, supports the notion that these artefacts very likely relate to the Roman period.

The other mistake about Venafro which is commonly found in the literature relates to the position of the site. Both this and the dating problem appear to be related to the same source of error, namely the nature of the deposits under which the artefacts were found.

Jacono states that the millstones and the impression of the waterwheel were found in *limestone* deposits and later in calcium carbonate[35] which was also reported by Parsons[36] but Forbes has it as tufa[37] and Reynolds as lava[38]. The clue to Reynolds misunderstanding

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34. No attempt is made to relate these dimensions to the Roman digit, which in the early period was one sixteenth of the Roman foot and later one twelfth. The accuracy of the dimensions makes the exercise suspect.

35. Jacono, as note 26, pp.850, 852.

36. Parsons, as note 6, p.76.

37. R.J.Forbes, 'Power', in Charles Singer et. al., eds., History of Technology, vol. 2, p.597. Tufa, a stony coating left by hard water when it evaporates, known as travertine or calcereous

occurs in his statement that the Venafro wheel had been found near Pompeii, covered by the eruption of Vesuvius late in the first century AD.[39] It would seem that he derived the date from the false assumption that the wheel was covered in lava, but he may not have been the first historian to do so. In fact Venafro is 80km. north of Vesuvius so why have Reynolds and others gone wrong? There appear to be two possibilities. The obvious answer may be that because the model of this Venafro waterwheel is in the Museum at Naples, it is mistakenly related to the Roman archaeology identified with and dominated by Vesuvius. Parsons may have further misled people by calling it the Naples wheel.
The second and more likely reason is that Jacono's Italian text has been misinterpreted because both lava and Pompeii are mentioned, in context with the millstones.

How was the water applied to this wheel and what was the head?
Jacono states that the millstones were discovered 3m from the surface of a bank made up of limestone deposits. Then the wheel impression was found '..*a short distance from these millstones and on the same bank of the river further down in the limestone bed..*' He goes on to describe '..*the remains of the walls of a Roman canal which could be seen just below the surface..*' which we can take as being the headrace. Jacono's single reference to the head of water says '..*The*

(limy) tufa. Limestone consists of calcite (calcium carbonate) discoloured by impurities, which can vary greatly in colour and hardness.

38. Reynolds, Terry. S, Stronger Than a Hundred Men : A History of the Vertical Water Wheel, Baltimore, 1983, p.36. Reynolds may have been misled or confused by tuff, a rock formed from volcanic ashes, [French, tuffe=Tufa], The Oxford Illustrated Dictionary, 2nd. Edition, 1975, p.915.

39. Reynolds, as note 38, pp.18, 30, 36.

extent to which the water ran down H, we can work out approximately bearing in mind the date of the excavation, as being approximately 4m..' This rather abstruse statement suggests that Jacono did have the benefit of measured site levels.

From this evidence, such as it is, it is not possible to speculate with much advantage. It is quite possible that the millstones and the wheel were found in the position that they had worked in, with the wheel 'a short distance away and at a greater depth'. This could have been confirmed if the stones were on the line of the wheel shaft and within say, 2m of the wheel. If they were positioned like this, then the centre of the wheel would have been 2-3ft below the millstones. With the bed of the headrace at say, one foot below surface, the head of water was close to 2.4 to 2.7m above the wheel, on the basis that the millstones were found under 3m of deposits. If we assume that the wheel was undershot and the water was applied at a height, say of one quarter of the wheel diameter above the bottom of the wheel, the head would have been approximately 3.75-4.1m which agrees with Jacono's figure. If overshot, and applied say a quarter from the top then the head was 2.4-2.7m.

Whatever we make of the figures, the head of water is unusually high as must have been the velocity of application. Table One provides the velocity due to free fall which we can assume to be close to the velocity of application allowing that the resistance to flow within the delivery chute balances the specific energy at the top of the chute.

Position of application	Head (m)	(ft)	Velocity per sec. (m)	(ft)
quarter down	2.5	8.2	7	23
shaft level	3.25	10.7	8	26.2
quarter up	4.0	13.1	8.9	29.1

There is no indication from the report as to how the position of the watercourse relates to the waterwheel which might have helped us to decide how the water was taken and applied to the wheel. The few

words that Jacono devotes to this are not very helpful. '*..Bearing in mind that there is no sort of internal seal between the inside ends of the fins*[40]*, it seems to me that this must have been a side wheel on which the water pushed the bottom section..*' What is clear from this is that Jacono's ideas on how the water was applied stem from the design of the wheel and not site evidence of water flow. Although this suggests a lack of evidence, it does give us a clear field for speculation.

Both Reynolds and Forbes declare the wheel as undershot, presumably influenced by Jacono's words, but a re-examination of this unusual wheel is worthwhile.

In the Venafro wheel we do not know the direction or point of application of the headrace to the wheel; neither do we know if its direction could be varied by a pivoted trough, conduit or nozzle. Jacono does not appear to state directly whether the wheel was undershot although it is implicit in his suggestion that the wheel was pushed from the bottom section. However, the point is we do not know for sure the arrangement that existed.[41]

The Venafro wheel shows distinct features of an unusual design which are;-

(a) There are only three different elements used in its construction, radial floats which are morticed in a solid shaped hub and side shrouds - a very simple but strong design.

(b) The solid hub and radial floats are relieved on the sides which gives a 'dished' appearance to the wheel. This must have been to allow some or all of the water to pass through between the floats and out of the sides of the wheel.

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40. He alludes to a sole plate.

41. If any of the excavator's site notes exist thay might shed light on this point and other critical features.

(c) The unusually high head combined with a small diameter wheel (absolute not relative) shows that the wheel was capable of running at a high speed. If the velocity of application was, say 25ft/sec., and if we assume that the centre of the floats moved at 50% of the water velocity, then the wheel would have been running at 46rpm.
(d) There were no sole plates on the floats between the innermost edges of the two parallel shrouds.

All of these features can be identified with an impulse wheel or turbine where the speed was largely dependent upon the velocity of the water.

Although a sole plate is absent we can recognise the shrouds as having provided greater effect by partial confinement. What is the significance of the dished wheel and the curved section hub? Why did the builders not use a clasp-armed construction?
An interesting feature of the design of this wheel is that when a straight jet of water is brought to bear on the wheel on an axis tangential to a circle inside the rim, virtually all of the water strikes the radial floats at an angle, which causes a deflection towards the centre of the wheel. The angle of deflection becomes particularly noticeable when the stream is directed towards the middle of the floats. In this position, as the floats intercept the stream the deflection is approximately 120 degrees.
If sole boards were present, this deflection would cause violent turbulence and, significantly, a reversal of flow back onto the incoming stream of water and the laminar flow of the approaching water would be destroyed. This phenomenon would occur at whatever position around the wheel the approach was made, because the velocity of application is so great.[42] Now we can begin to see an advantage in not having sole boards. Furthermore, the dished effect, produced by the curved edges of the tapered floats morticed into the elliptical sectioned solid hub, would have provided a natural relief for the water flowing

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42. How interesting it would be to test a model of this wheel in a hydraulic laboratory to explore its operating characteristics.

into the wheel. As the water coursed through each of the float chambers and passed by the shrouds, it was bifurcated by the curved rim of the hub and discharged through the two open ports, one in each flank of the wheel. The shrouds would have provided strength and stability to the wheel which would have been receiving considerable shocks and stress from the high velocity water. They also helped to constrain and guide the water inwards towards the shaft. This is a form of inward-flowing vertical impulse turbine, which, if Roman, was not met again, according to our present knowledge, until the nineteenth century.

The only historian who appears to have studied this wheel, Reynolds, does not recognise these unusual design features as being progressive or advanced. Indeed he condemns the design saying that the hub was very large and heavy[43] and may have impaired the wheel's effective operation. He saw the shrouds as impeding the exit of water after impact. The elliptical section of the hub is surely a balance of strength in its juncture with the shaft combined with the hydrodynamic shape necessary to encourage the bifurcation and exit of the water; why otherwise have curved surfaces over the whole of the hub? He summarises his opinion of the Venafro wheel as indicating that Roman technological knowledge in the area of hydropower may have been seriously incomplete.

Reynolds' criticism of the hub as being heavy was probably made without giving due thought to the alternative solutions. There are two other types of construction which the builders could have adopted, clasp-armed or radial-armed. Let us briefly examine them, clasp-armed first.

Because the wheel is small in diameter the sections used for the arms need not have been great. Each pair of arms would have been of single piece, possibly half morticed at the cross over, and most certainly tapered towards the rim. Both pairs of arms would not have clasped the small wheel-shaft for this would have put them too close together and created a less stable shroud support. To be spaced off this shaft they would need solid annular cores or flanges, the alternative being

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43. Reynolds, as note 38, p.43.

either a larger diameter shaft or a shaft which was bellied or made from a single bole with flange type protuberances. With clasp-arms the shrouds would not have been as well supported as in the actual wheel, where the radial floats acted as arms themselves. The shrouds, made in sections like the felloes of a wheel, would have needed to have been either half-lapped, and therefore slightly thicker than the Venafro shrouds, or, cross-jointed together with additional external segments of wood.

In a radial-armed arrangement the shrouds could have been identical in size and construction to the Venafro wheel. The wheel could have been supported from, say, at least eight pairs of radial tapered arms. It would not have been possible to mortice these arms into the small diameter wheel shaft and so, as with the clasp-armed arrangement, additional material has to be introduced at the centre of the wheel. A likely arrangement is that which is adopted in Roman drainage wheels which generally were much larger in diameter with many more arms. Support is achieved by having a pair of disc flanges or flaunches into which the arms are morticed.

Whichever of these arrangements, clasp-armed of radial armed, is chosen, the additional amount of material necessary to match the strength and stability of the Venafro wheel would have produced a similar weight wheel. They would also have involved a greater number of different components. Finally, and perhaps significantly, neither would have provided such free egress for the high velocity water, because the additional structural elements at the junction of arms and shaft would have generated violent dispersion and agitation of the water.

Let us now consider at what position the water was applied to the Venafro wheel.

First let us avoid the complexities of geometric variation of stream and float inclination and simplify our view; the lower on the wheel the water is applied, the greater the head and the higher the velocity and torque generated. If the alternatives are represented by parallel streams, then the points of application are diametrically opposed to each other and the difference in head is Sine45 degrees x

2R. On the Venafro wheel this is equivalent to 1.5m, which in terms of power, means that the lower position is 25% more powerful than the higher position.

When the Romans created accelerated headraces they must have been aware of some basic hydraulic behaviour, certainly of how velocity increased with the height of fall. Whether or not they understood why this occurred or the natural laws that related to this phenomenon, matters not. We might also credit them with recognising that with increased velocity came greater pressure or force, and that the same effect could be produced by increasing the weight or volume of water flowing. They may not have had any understanding of the relationships between velocity, mass and the energy they can produce, nor words in their language to express them, but this does not mean that they were not conscious of such forces.[44] Faced with the Venafro evidence we cannot avoid concluding that they purposely sought to create a high velocity stream and waterwheel. Therefore it seems very likely that the wheel received its water low down rather than near the crown. To have done otherwise would have wasted some of the head that they had created. This produces a head of close to 4m which agrees with Jacono's figure.

Jacono appears to be the first historian of technology to attempt a hydro-mechanical analysis of a watermill. He says that the power stored up in the millstones of the size found is 3.0 HP. but does not state the speed that this relates to.[45] Later in his text he clearly mentions the millstones as having a speed of 46 rpm, which he had earlier given as the wheel speed. Unfortunately in his final paragraph he brings confusion to the subject when he expresses the opinion that the millstones would have been geared down because the wheel revolved so fast.

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44. Their everyday use of such things as piledrivers, battering rams, javelins and even sledgehammers would have provided them with an understanding of the effects and relationships between velocity and mass. All this was well within the daily experience of artificers.

45. To absorb this power the stones would be revolving at 91.5 rpm.

If we accept Jacono's flow rate of 0.093 cubic metres/second and assume the width of the water stream being applied as having the same width as the wheel[46], then its thickness, after a vertical fall of 4m would be 1.35 inches. The total kinetic energy in the water would be 4.89 HP which presumably is to be compared with Jacono's *nominal power given by the speed of the water* which he gives as 5 HP. With this flow being applied the maximum power generated by the wheel, when its rim velocity is 50% of the water velocity[47], is close to 2 HP allowing for friction.
With this flow of water, driving the millstones that were found, a balance of power would occur when both wheel and stone were revolving close to 55 rpm[48]. The maximum stone speed that the wheel could maintain would be approximately 60 rpm when the MR would be 1 : 1.3 [wheel/stone]. To maintain any faster stone speed would require either a lighter top stone or more water, obviously with a higher MR.

F. Crocodilian River dam site.

The recent analysis of one of the mill sites adjacent to the dam across the Crocodilion river, near Caesarea, which is claimed as a Roman watermill, does not reach the threshold of acceptance[49]

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46. This flow rate could be provided by a headrace 1ft x 1ft in section and a velocity of 1m/sec.

47. At a wheel speed of 46 rpm.

48. MR 1:1, at 1.8HP.

49. J.P.Oleson, 'A Roman Water Mill on the Crocodilion River near Caesarea', Zeitschrift des Deutschen Palästina-Vereins, vol.100, pp.137-152. From Oleson's examination of this site, we can be reasonably certain of only one thing, that water power was generated here; all other conclusions suggested by Oleson, including the Roman origin claimed by his title, fail to reach the threshold of acceptance. The dating is inconclusive, relying solely on circumstantial evidence from the environs, and Oleson fails to demonstrate convincingly how the water power was generated and to what use it was put, which is hardly surprising in view of its most puzzling and unorthodox layout. Most disappointing is that Oleson has attempted analysis and reconstruction

G. Conclusions.

With the possible exception of Haltwhistle, it has not been necessary to use hydraulic analysis to demonstrate the existence of accelerated headraces. The four continental sites, which include surely the best known and most complete specimens of Roman water-power, after Barbegal, had such obviously high heads of water as to suggest that this arrangement was common-place. Their effect on the Continental corpus is great, for only Barbegal and Martres de Veyre, the Gallo-Roman specimens, are the exceptions. We can therefore confidently assume that the accelerated headrace was a tried and tested method of creating a high speed machine and this confirms moreover that it was normal practice to have fast wheels.

Analysis shows that these mills must have varied in speed throughout the life of the mill as the millstones wore away to become thinner, lighter and faster. If during stone life the gears remained unaltered, then the mills would have steadily increased in speed according to the balance of the generated and absorbed power curves. Such operating conditions existed in all water powered corn mills, although in multi-stoned mills (absent in the Roman period) this phenomenon is less obvious. We may never know if it was common practice to alter the gearing during the life of a top millstone. It seems unlikely that they would have gone to this trouble for whilst the gradual increase in speed would have virtually gone un-noticed, the production rate would have remained more or less constant[50]. Only

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with incomplete excavation; what else will we learn when the half-full chambers are cleared of debris? His speculative paper has probably come too soon, and unfortunately its confident title will undoubtedly mislead future historians.

50. On the basis that production is proportional to the product of speed and weight (ie. power), where the increase in speed is directly related to, and caused by, the decrease in weight.

if the builder had inadvertently selected a gear ratio which gave extremes of performance, too slow or fast, would they have changed the ratio. But once done, there would be no need to make further change unless there was a radical alteration in the size of the millstone, wheel or water flow. And so it is suggested that gear changes probably would have occurred of necessity early in the life of a mill, and thereafter would have remained constant, matching the weight range of the top millstone.

The adoption of accelerated headraces, with their higher velocities of application and greater potential power, provided opportunities for either;-

(a) the wheels being made smaller than hitherto but still producing, more or less, the same power and therefore output, or,

(b) the wheels could generally remain the same size as hitherto but be rather more powerful and possibly faster[51].

In other words the changes brought about by accelerated headraces produced a combination of greater output and faster machines. These presented the parameters of development that could and may have occurred, but what were the criteria that influenced development?
We have seen that by increasing the forces of reaction, thereby lessening the effect of weight, the design of wheels was affected. In a new build situation there was no problem because radial floats could have been incorporated in the design. But if the head of an existing wheel was improved by acceleration, and that wheel had buckets, then alterations would have to be made to convert it to a radial float wheel. We have also identified that the design would become more simple with the adoption of impulse type wheels. Additional ad-

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51. All other factors, including water flow rate, constant.

vantages would also occur with smaller faster wheels, both in terms of material and labour. Higher wheel speeds meant that the gear ratio would decrease producing a further saving of materials.

What does the evidence say? Did millstones increase in weight and wheels in size reflecting the advantages of accelerated headraces?
If wheels were held in size when accelerated headraces were adopted, then the increase in power should manifest in larger waterpowered millstones. If this is right, then at those sites where the increase in power did not show in faster operation, we could expect the stones to be larger and reflect the availability of greater power.

But there are factors which make an assessment of the evidence difficult. The first is that it seems likely that many mills may simply have continued to use more or less the same size stones but took the extra power in additional speed. This had the advantage, providing they did not approach excessive rim velocities and produce burnt meal, that they could also continue to use the MR that they had hitherto used.
Secondly, weightier stones need not necessarily be larger in diameter; they may have been thicker. The chances of finding evidence of such stones is remote, simply because all millstones found, with few exceptions, were discarded well used.
Thirdly, it is almost impossible to accurately date a millstone within the lifetime of a mill, because it could have been discarded at any time. Thus nearly all millstones have a date as short or long as the mill itself.
Finally the variation in the power of different mills was likely to have affected the sizes of the stones employed i.e., a more powerful mill would tend to use larger stones. So variations in stone size could be caused by variations in the power of coeval mills rather than the adoption of accelerated headraces. In other words, the results are inseparable. In conclusion, no meaningful development concerning the size of millstones has yet been identified throughout this period due, no doubt, to the above difficulties.

The evidence of how the adoption of accelerated headraces may have effected wheel sizes is limited. First and most valuable is the Caracalla evidence which shows that when two new mills with accelerated headraces were built beside an existing one between AD 275-300, the same size wheels were adopted. This involved excavating new deeper wheel pits and presumably laying in a lower drainage system.
When Barbegal was built in c250-4th Century AD, accelerated headraces were not used and normal size wheels were adopted. The Agora mill, built during AD 457-474 as an accelerated headrace arrangement had a slightly larger wheel, whereas Venafro, which was probably a late Empire construction had the fastest and smallest wheel known. What does this tell us? It suggests that in the initial stages of adopting accelerated headraces no change in wheel size occurred, but later, variations in size did take place. But the truth is we do not have sufficient evidence to support the suggestion that wheel sizes were influenced by this development.

One is tempted to suggest that both the wheels and millstones remained more or less unchanged as the use of accelerated headraces spread. There must have been an entrenchment in long standing and well proven methods which the builders and artificers of mills would have adopted by custom and practice.

We have identified the advantages that the use of accelerated headraces could bring; what of the disadvantages?
Aside from design, the changes in operational and maintenance methods which this development brought may be related to faster machinery and greater throughput. We could expect that bearing material and lubrication was prominent in these developments, although what changes this brought, as yet we have no evidence. Whatever changes occurred in the skills and expertise of the miller were surely assimilated relatively quickly. Perhaps the major disadvantage of an accelerated headrace need not be its effect on the life of the mill, but rather its building.

How the water was brought to the site was largely dictated by the choice of position and the environs, and to create an elevated accelerated headrace would more likely require an artificial watercourse than a natural one. If the terrain, whether urban or rural, dictated that the water had to be carried by aqueduct towards the wheel, then this required more work by the builder. In such circumstances, it is likely that a high head needed a longer artificial headrace and more groundworks for its creation. But faced with such works, it gave the builder greater freedom in positioning the mill.
The variations in applying the water to the wheels must have been well known (undershot, traditional overshot and then the accelerated headrace); so too was the basic knowledge of relating a size of wheel, allowing for these variations, to a typical (standard) pair of millstones. But it is still possible that there existed great variation from one province to another and, differences within one province.

The five examples of accelerated headraces have little in common when comparing how their heads of water were achieved. At Caracalla the entire arrangement is artificial and displays great ingenuity, not only for the way it was integrated in this great aqua-leisure centre but also the manner in which it was subsequently modified. We must not lose sight of the fact that these mills were in the nexus of the empire, and although in the subterranean chambers of this vast establishment, must have been well known to many of the visitors and clientele. In such circumstances we should view the Caracalla specimens as exemplars.
The builders of the Agora mill brought the headrace in an aqueduct 50m from the next mill upstream. To get the head they wanted above the wheel the tailrace was cut into solid bedrock so that the wheel could be kept low.
Little is known about the environs of the Venafro mill including the direction of flow of the head and tail races in relation to each other and the mill. Apparently the headrace was carried in an aqueduct but the archaeological record fails to show its size, construction and how it was supported.

Lösnich relates to a rural establishment as surely does Venafro, whereas Haltwhistle was a military creation on the remote fringes of the Empire. At Lösnich the mills were founded on an insignificant but steeply graded stream, whereas, by contrast, the Haltwhistle mill was served by a cut from a fast flowing river.

When necessary the builders did not hesitate to cut deep into bedrock to make their watercourses [Haltwhistle, Lösnich, headraces; Agora, tailrace;] wheel emplacements [Lösnich and Haltwhistle] and gear pits [Lösnich]. The prime reason for this, of creating a satisfactory head, also brought the advantage of very stable foundations for the machinery and building.

Chapter Eight

THE EVOLUTION OF POWER CORN MILLING

Charles Parsons, the eminent engineer, once said '..it may be remarked that in the history of engineering progress, the laws of natural selection generally operate in favour of those methods which are characterised by the greater simplicity and greater efficiency, whether those advantages be great or small.'[1]

Parsons unmistakable use of the Darwinistic term 'laws of natural selection' is not the first reference to the concept. Not long after the appearance of the Darwinian theory of evolution several writers began to interpret the evolution of technological development through organic analogy. Samuel Butler debated the application of Darwin's theory to machines, suggesting that they developed in the same way as living beings and could be arranged into the Linaean ordering of genera, species and varieties[2]. Pitt-Rivers applied this concept to the anthropological world illustrating his collection of primitive weapons and tools in sequence of closely related form.

But Parsons focus on simplicity and efficiency is worthy of more attention; his remarks, made in 1899, related in part to the recent advances in marine engineering with the use of turbine engines so that Parsons use of the word 'efficiency' therefore meant performance in terms of mechanical and heat energy. In ancient history, efficiency, or more appropriately, economy, was related to the factors of production, expressed in terms of the primary resources of labour, materials and time.

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1. Scientific Papers and Addresses of the Hon. Sir Charles A Parsons. edit. by G.L.Parsons, 1934, p.25. An extract from a presidential address given to the Institution of Junior Engineers, November 3rd, 1899.

2. The Works of Samuel Butler : Canterbury settlement, New York, 1968, inc., 'Darwin among the machines', 1863.

We shall see that this study, which proposes an evolutionary model for the vertical waterwheel, supports the notion that technological progress in ancient history was greatly influenced by a progression towards simplicity and the economy of resources.

Although biological evolution theory is still being discussed and developed great advances have been made in establishing various concepts of evolutionary mechanisms and models. It is suggested that in this analysis of technological evolution, consideration be given both to the theory and language used in the biological parallel[3]. The strength of this approach is that this mode of treatment appears to be fruitful and has relevance to the technological world. However, caution is needed because of its novelty.

Evolution has endowed the animal species with means to influence or control their environment. The relation between organisms and their environment [bionomics] and other species is determined largely by their inherited and intuitive faculties, and aside from reproductive success, survival is the primary criteria for the selection of all species, including man.

The adaptive nature of all animals, including humans, occurs genetically and environmentally. Therefore all creative work, including the tools and methods by which it is executed, should be seen as an extension of the animal. Evolutionary studies should embrace the animal, its methods of work, creations, tools etc., because this is all part of the evolutionary process. The evolution of man cannot be considered without his technology, nor could the spider without his web, or birds and termites without nests.

The balance between the species and their environments is constantly changing. Aided by technology, man has entered environments where hitherto other species held sway. It has brought him fast locomotion on land, taken him into the air and under the sea. The technological evolution of man is the fastest changing evolution within the living

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3. Following the lead of Samuel Butler, one of the first historians to relate the biological parallel was M.C.Duffy with his 'technomorphology' [morphology = branch of biology concerned with the form and structure of organisms.] See below for further discussion.

world. Man is barely able to control its growth; its scale and multitudinous forms is such as to affect, to some degree, all other living species and, more ominously, the very environment which he seeks to control.

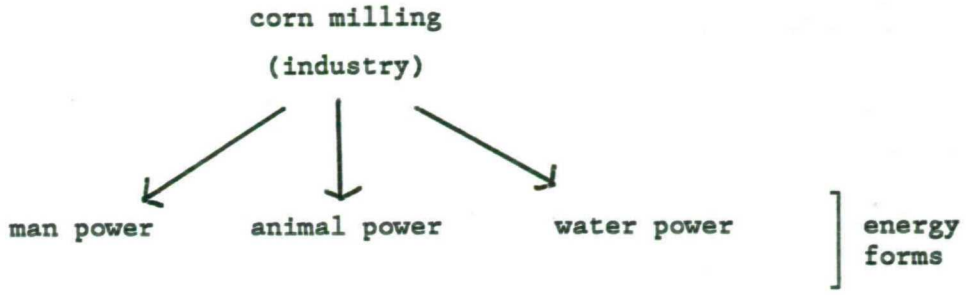
A. Technological Evolution : Definition and Terms.

It is important to recognise the difference between evolution and diffusion. They can be related to time and space; evolution occurs through time and not space whereas diffusion is the reverse.
The evolution of a species of artefact is its development from earlier forms, its metamorphosis through time and the establishment of a developmental sequence. The distribution of the artefacts and their movement during the evolutionary period are not relevant. Distance, space and geography have no relevance in the concept.
Diffusion of a single type of artefact (or a technological process) concerns movement and spread as expressed in terms of distance, area or geography. It can occur by movement of artefacts or their creation in areas where they did not previously exist. The evolution of the artefact is not relevant to diffusion and neither is the density of its occurrence.

In biological evolution the subjects of study are classified according to Linaean ordering[4] but a comprehensive scheme for ranking to facilitate technological classification has not yet been agreed. In this technological study it is suggested that the collective term comprising several sub-ordinate classifications is the <u>industry</u> corn milling and we shall make the subject of the primary evolutionary analysis the energy forms of <u>animal</u>, <u>water</u>, <u>man</u>, etc. In terms of evolution we are concerned with their lineal descent.

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4. Principal rank names in hierarchical order include Phylon, Class, Order, Family, Genus, and Species.



Speciation[5] in biological evolution is the creation of a new species, whereas in technological evolution speciation would be the appearance of say a new energy form, e.g., wind power, or a new process, an improved mechanism or a better structural form. Intermediate forms showing the transition from one energy form to another probably do not exist, although hybrids using two energy forms can exist, e.g., steam working with water power. The evolution of an artefact or process will tend to progress towards perfection - to the point where no further changes are possible to improve or make more efficient its functions. It will have reached stasis.[6] The concept of stasis should not be confused with the term design impasse as used by Duffy. Although related to modern technology, his description is applied, 'when a design evolves to a stage from which further development to a more advanced state would meet with increasing difficulty, generating more problems than have been solved. Coming at the end of a series of pseudo-innovations, it signals obsolescence..'[7] Although

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5. In biological evolution speciation is the formation of two or more reproductive communities from a single ancestor.

6. Stasis, inactivity; stagnation; a state of motionless or unchanging equilibrium. A Supplement to the Oxford English Dictionary, Vol.iv, 1986, p.488. Stasis in Greek means standing. See N.Eldredge, 'Progress in Evolution', New Scientist, 5th June 1986, pp.54-57.

7. M.C.Duffy, 'Technomorphology and the Stephenson Traction System', Transactions of the Newcomen Society, Vol.54, 1982-83, pp.55-78.

recognising a limit to the development of an artefact's design, Duffy identifies this with obsolescence and adds, '..no component or system should ever be developed to the ultimate which is technically possible. Entering the design impasse is a most grave error.' Duffy's basic concept of technological evolution, technomorphology as he calls it, together with his definitions of his basic terms used in his related analyses[8] give no indication of being limited to any specific period of history. This concept is patently not applicable to a great many artefacts in ancient history, such as the sickle, the vertical wheeled watermill, the wood plane etc., where the principle of operation and form of the artefact remained unchanged for more than a millennium. Such artefacts had reached impasse early in their existence and their continued use cannot be related to their obsolescence.

Examples of ancient artefacts considered to have reached stasis are, the sakiyeh[9] threshing board, winnowing shovel,[10] the noria,[11] and the Pompeian mill.

In the biological world the criterion for survival is recognised as the ability to adapt to the physical and biological environments whilst maintaining reproducibility. This criterion is embodied in the concept of 'survival of the fittest' which has a parallel in the technological world, where the criteria are economy of resources (both in making and maintenance) and functional success.

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8. Duffy, as note 7, See also, M.C.Duffy, 'Evolution of Engineering Design Technique', 6 parts, Engineering Designer, 1979, Jan/Feb. pp.19-22; Mar/April. pp.19-22; May/June, pp.21-26; July/Aug. pp.31-35; Sept/Oct. pp.19-23; Nov/Dec. pp.21-26.

9. As suggested by K.D.White, Greek and Roman Technology, London, 1984, p.53.

10. White, as note 9, p.62

11. N.A.F.Smith, 'The Origins of Water Power : A Problem of Evidence and Expectation' in Transactions of the Newcomen Society, vol.55, 1983-84, pp.67-84.

The extinction of a technological species occurs when it ceases to be used. The most likely causes of this are (a) function being replaced by other technological species, e.g., flint tools displaced by bronze swords and knives, (b) changes in the technological environment, or (c) when some limit to the technology has been reached. Both (a) and (b) may be brought about by natural or man-made cataclysmic changes e.g. war, famine, displacement of a civilisation geographically, widespread disease, climatic or landscape changes etc. Generally extinction coincides with a disruption of the technological environment, particularly when one culture or tradition replaces another.

B. The Dynamics of Technological Evolution.

Reynolds considers that power technology is important to the evolution of culture and that it is 'embedded in complex and interdependent social and technological matrices'.[12] There is a unique relationship between any culture and its technology. At any point in time the degree of control and exploitation of man's environment is determined almost wholly by his knowledge of technology and one of the most powerful determinants of this advancement is his knowledge of power technology. Smith has warned us that technology's role and man's expectation of it have not been the same in different periods.[13] The intellectual climate can have great effect[14] and a society may well have the technical ability to tap a new source of energy but refrain for a variety of socio-economic, geographic or religious and philosophical reasons.[15] Such factors or influences as

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12. Terry S.Reynolds, Stronger than a Hundred Men, A History of the Vertical Water Wheel, Baltimore, 1983, pp.2,3.

13. N.A.F.Smith, 'Attitudes to Roman Engineering and the Question of the Inverted Siphon', History of Technology, 1976, vol.1, pp.45-71, p.47.

14. See Lynn White Jnr., 'Cultural Climates and Technological Advance in the Middle Ages', Viator, 2, 1971, pp.175-6. A good example is the comparison between the Islamic and Christian cultures and their exploitation of windmills.

these and others can be inhibitors or stimulants to the development of technology. They may therefore be identified as comprising the technological evolutionary environment.

Theory would suggest that if two separate technological environments are identical, evolution will tend to follow the same paths and have a similar time scale. In reality differences in the environments can have a disproportionate effect on development, and innovations or inventions which are critical to technological achievement do not occur e.g., the wheel in Aztec and Mayan cultures.

The concept that evolution is essentially linear has as its basis that each improvement, however slight, is used as further progress for the future. This is cumulative variation as distinct from single step random variation, where each new try is fresh.[16] As in biological evolution, cumulative variation or selection is much more effective for technological evolution.

If technological evolution is linear and non-random, what of its direction? A feature of modern technological development is that it can be arranged in a hierarchy of 'ascent' from the simple to the complex. Technical development facilitates an increasing sophistication of function as materials, methods and miniaturisation increase. But ancient technology does not often display this 'ascent of complexity', and the refinement and simplification of the complex is just as likely to occur.[17]

Two views support this. The first is that when a function is to be performed the most simple way of effecting it will be naturally sought. A second view is that when stasis is approached, ie., perfec-

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15. Reynolds, as note 12, p.3.

16. R.Dawkins, 'Creation and Natural Selection', New Scientist, 25th September, 1986, pp.34-38.

17. N.A.F.Smith, as note 11.

tion of function, it tends by its very nature, to search for the most economic combination of resources (materials, labour, neuro-muscular ergonomics etc.).

Evolution can suffer reversion. In some environmental circumstances man may revert to an earlier form of species or even (but rarely) go back within the same species to an earlier development in the evolutionary sequence. If an evolutionary development occurred more that once in the history of a culture a reversion must have occurred. One culture may miss out a species which another may have used to reach the same point on the evolutionary scale. It is the technological environment which determines this. Technological evolution being a derivative of environment, does not proceed at a constant speed.

In the evolution of an artefact we are concerned with change, its appearance, innovation, development and disappearance. What factors influence change in an artefact?

Probably the primary influence on the rate or advance of evolution (accepting that there is a demand or need to change) is its life cycle and frequency of function. An artefact which has relatively short life will present more opportunities for change and innovation than one having a longer life. This opportunity of change or pulse for say, a dip light or candle is measured in days; for a bronze or iron sickle, in seasons; and in roads, dams, aqueducts in generations. Scale and complexity of an artefact can and probably will affect the pulse rate. A simplified view of this pulse expressed by the interrelation of time with technological scale and complexity is given in Fig.33.

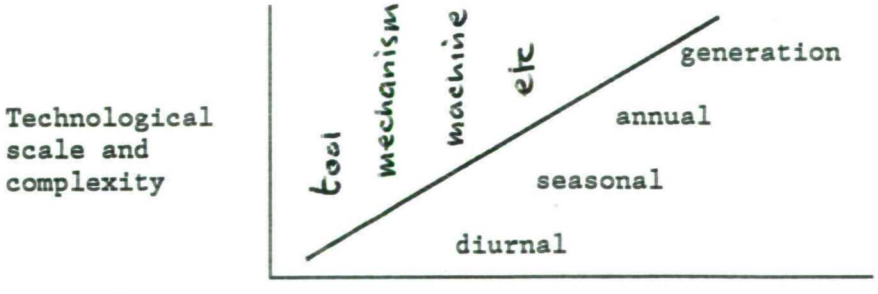


Fig.33 The Pulse of Change.

The pulse of change is different for each species of artefact. Major changes invariably occur at every life cycle upon the renewal or creation of a replacement or additional one, and secondary changes, during operation and maintenance. A simple example is provided by a sickle. When a new one is made the opportunity is provided for changing the shape, size and material of the handle and the blade etc. During its operating life only the replacement of the handle, the sharpening and serration of the blade provide the opportunity for change of design. Any change to design which becomes a permanent feature in the artefacts subsequently made can be identified as evolutionary.

There is one other major factor affecting the pulse of change which we need to consider. This is the intensity of the distribution of the artefact. Let us suppose there are two communities, A and B, having the same population, some distance apart and not in contact with each other. Both communities are using the same type of artefact but community A has twice as many as B. The opportunity for changes to the design of the artefacts would be twice as great in community A compared with B and therefore, disregarding all other factors, evolution would tend to proceed faster in community A, until stasis was reached.

This theoretical mechanism may now be summarised as,-

Evolutionary Rate α Opportunity x Intensity
(Pulse of Change)

Where opportunity is the summation of opportunities occurring in operations and maintenance (functioning of the artefact), life cycle (renewal) and new creations and intensity, the intensity of man's experience of the artefact.

The opportunity for change which occurs in a watermill is complicated by the different elements of which it is comprised. Each different element or component is an artefact having its own evolutionary development and life cycle. If we examine a 'vertical' watermill and limit our examination to the machinery - all moving parts - the opportunity for change can be summarised as follows.

C. The Opportunity for Change : Watermill Machinery.

Element (artefact)	Opportunity	Features liable to change	Approx. life (years)
Millstones	During life	Dress; inclination.	
	At renewal	Material; size; weight.	2-10
Gears	During life	Material and shape of cogs.	
	At renewal	Diameter; pitch circle; size	5-15
Waterwheel	During life	Additional strengthening; sealing; application of water (volume and direction)	
	At renewal	Construction; shape; dimensions float/bucket design etc.	20-50
Bearings (journal or footstep)	During life	None significant	
	At renewal	Material; size.	1-5

It should be noted that all of the features that can be changed during the operational life can also be changed when the artefact is renewed. The working life of each of these machinery elements is debatable and subject to many indeterminable influences. However, an attempt has been made to give figures, which although influenced by modern experience, are considered to be realistic when related to a Roman environment. Greater relevance can be given to the comparison between the life cycles of the elements than to the life span for any one.

We must also consider the life cycles of the various types of building fabric which occur in ancient watermills. There are basically three different types,

(a) those whose foundation and walls are made of brick or stone (Agora, Barbegal, Baths of Caracalla etc.)

(b) those which are wholly timber framed and either earth-fast or timber soled (Ickham Late, Ickham Early etc.)

(c) those which are part timber and part brick or masonry (Haltwhistle Burn Head etc.)

The opportunity to change the building structure once built was very limited. Masonry or brick foundations, pits and waterways suffer little from decay or wear, especially in warmer climes, and their strength and massiveness rendered change unlikely. Additions and extensions and modifications to the rooms no doubt occurred but the fabric adjacent to the machinery and waterways, invariably below ground and forming part of the foundations, was rarely altered.
Wooden framed watermills suffered much more from natural decay and operational wear and the nature of the fabric was such that changes to the machinery arrangements were much easier to effect.[18]
Building fabric generally had a longer life than machinery elements; and in many cases its permanence and inflexibility limited the opportunity to make radical changes to the design of the machinery. This meant that the type of waterwheel (undershot, overshot etc.) and its size tended to remain unchanged throughout the life of the mill. Unfortunately only a few of the known Roman watermills yield evidence of their duration of life. These are,

Watermill	Approximate operating life (years)	Notes
Haltwhistle Burn Head	45	stone walls (plus timber?)
Ickham Early	130	timber - abandoned
Ickham Late	c50	timber
Barbegal	150	stone
Fullerton	100?	timber
Athenian Agora	90-120	stone - destroyed
Baths of Caracalla (Early)	40-88	concrete and brick destroyed by fire
Baths of Caracalla (Late)	200-262	concrete and brick

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18. The remains of the wooden-framed earth-fast Early Ickham Mill showed distinct signs of modification to arrest settlement and decay and extension to the building.

One of the above sites was abandoned, one ended in a conflagration and another was destroyed by man; What happened to the others is unknown.
The value of these figures is that they suggest that an ancient watermill's life was measured in generations, anything between two and ten.

We have identified the incidence of opportunity for change that occurs for the major machinery elements comprising a watermill. Although the figures are open for debate, especially in view of the numerous and wide-ranging environmental and operational factors which can be applied, it would appear that during the life of a typical watermill the opportunity for change can be summarised as follows, in order of greatest first,

Element	Opportunity for change
Bearings	Numerous
Millstones	Many
Gears	Several
Waterwheel	At least two

We should remember that the remains of any watermill are relevant only to that moment when it ceased to work, after which no further changes were made. Any developments which might be taking place within a mill cease when it is abandoned by man, although innovations can be continued in other mills. Its design when it was first built and operated may have been substantially different to what it was at the end. Much of its machinery may have been changed and improvements made during the life of the mill.
In view of the above analysis the historian of technology should consider the general arrangement of a watermill (overshot, undershot etc.) as being related to the date of the building, whereas the machinery and other fitting are related to the date of abandonment. Any evolutionary analysis should be viewed in the light of these considerations. Such developments as can be identified within an in-

dividual mill should not be considered as evolutionary unless they can be related to other mill sites in support of the establishment of a developmental sequence.

D. Technological Evolution Model.

Having discussed the theoretical aspects of technological evolution we may now propose a model.

The model assumes that evolution is driven solely by environmental factors;[19] that technological evolution will cease in the absence of changes in the environment.[20]

If the technological environment is in equilibrium, a steady state where all inhibitors or stimulants (demands, influences etc.,) are satisfied or non-existent, technological evolution will not progress; no further changes to the artefact will occur. Further demands for the function, whatever it may be, are met by building more of them.

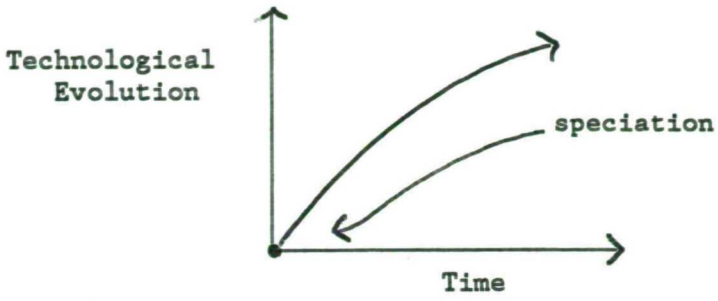
The essential feature of the model is that change is concentrated into bursts during branching speciation and thereafter the rate of evolutionary change is not gradual but episodic. Each new major development causes an acceleration of evolution followed by periods of relative static.[21]

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19. A Palaeontologist's view is that evolution responds to the physical environment whereas an ecologist's view would be that evolution responds to the competition between organisms.

20. There is a parallel within the biological world, which is called the stationary model, which assumes that evolution is driven mainly by abiotic (physical) factors and that it will cease in the absence of changes in the physical environment. This model was formalised by Nils Stenseth and John Maynard Smith in 1984. See M.Benton, 'At the Court of the Red Queen' in New Scientist, 28th November 1985, pp.52-54.

21. In biological evolution this concept of having long periods of stability punctuated by relatively brief changes, called the punctuated equilibrium theory is attributed to Stephen Gould and Niles Eldredge; see J.Cherfar, 'The Difficulties of Darwinism' in New Scientist, 17th May 1987, pp.25-30. See also George Basalla, The Evolution of Technology, 1988. Basalla explores the contribution to technological evolution made by diversity, necessity and selection.



It is suggested that from this environment-based evolutionary model two corollaries can be derived.

Corollary One

If different environments exist at the same time in different places, evolution will have different stages of development at the same time. One area can be more advanced than another.

Corollary Two

An environment which supports an advanced level of technology can simultaneously support lower levels of the same technological lineage.[22] Different levels of technology can co-exist at the same time in the same area.

E. Evolution Model of the Pompeian Mill.

This model is concerned with the evolution of the Pompeian type mill and seeks to identify how it may have evolved from disc-type millstones.[23] It is based on a dynamic analysis of both types and includes a brief examination of their maintenance and operation.

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22. For example querns can exist beside millstones.

23. With both types of mill we are concerned with animal and man-power. In the man-powered category we are concerned with man's power from walking and not hand-power, which with disc stones is the difference between querns and millstones proper.

The origin of the Pompeian hour-glass shaped mill is unclear, although we can be certain that it was earlier than Moritz' suggested date of introduction in the second century BC[24]. Moritz was aware of the smaller Pompeian-type mill that was used for grinding mineral ore in the silver mines in the Attic peninsula[25], but thought it unlikely to have been in use when these mines were most intensively exploited in the fifth and early fourth centuries BC[26]. However additional evidence has appeared of Pompeian mills in Sicily of third and possibly fourth century date from Morgantina[27] and Punic Motya destroyed in 397 BC[28]. Recently a Balearic shipwreck was found with Pompeian millstones from Pantellaria dated 375-350 BC[29].

The assumption that Pompeian mills evolved from rotary disc mills is contrary to Curwen's hypothesis[30] which proposes that the rotary principle was first applied to donkey mills (=Pompeian?) then to rotary hand mills. Moritz draws to our attention that the slope of

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24. L.A.Moritz, Grain-Mills and Flour in Classical Antiquity, Oxford, 1958, pp.58-9.

25. J.E.Jones, 'Ancient Athenian Silver Mines, Dressing Floors and Smelting Sites', Journal of the Historical Metallurgy Society, vol.18, no.2, 1984, pp.61-81. See pp.68, 69, figs. 7 and 8.

26. Moritz, as note 24, p.59. As Dr.M.Lewis suggests in correspondence with the writer, Moritz' date of early second century BC for the introduction of the Pompeian mill may still hold good for the then Roman world; it might have been imported to Italy from Sicily after the capture of Syracuse in 211 BC.

27. D.White, American Journal of Archaeology, vol.67, 1963, p.205.

28. White, as note 27, p.206.

29. Archaeometry, vol.32, pp.115-137.

30. E.Cecil Curwen, Antiquity, vol.xi, 1937, p.141.

grinding surfaces does little to support Curwen's view because some of the earliest querns from Britain and Spain are comparatively flat[31]. However, aside from the inconclusive comparisons of their form and features, there is currently no archaeological evidence of disc mills existing before these early fourth century BC Pompeian specimens. Yet we cannot place confidence in this, for only thirty years ago, when Moritz considered the question, the archaeological evidence apparently suggested the reverse. Then, as now the question of origins is imponderable, however this dynamic analysis hopefully brings a different view to the problem.

Roman archaeology has shown that the Pompeian mill was used in corn-milling and was predominantly animal-powered although smaller man-powered examples have been found.[32] It would appear therefore that this type of mill occurs within the animal-powered lineage of corn-milling and possibly the man-powered lineage as well.

Let us first make a comparison between a typical pair of Roman style disc millstones with a typical Pompeian mill of the same diameter by analysing their power requirements. For convenience we can adopt the Pompeian mill design illustrated by Moritz[33] and reproduced by K.D.White in his *Greek and Roman Technology*.[34] The size indicates that this was a donkey-driven mill as distinct from the larger type driven by horses or mules. The maximum effective diameter[35] of the

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31. Moritz, as note 24, p.111.

32. White, as note 9, p.65. Specimens were found at Morgantina, Sicily.

33. Moritz, as note 24, pp.75-6, Fig.8.

34. White, as note 9. The drawing appears on the dust jacket and inside the book. See p.65 fig.54. A comparison between the dimension shown and the drawing indicates that the scale is not constant. Wherever possible dimensions have been taken in preference to the scaling from the drawing. The inaccuracies are considered as unimportant for the purposes of this comparison. See Appendix A. Measurements taken from a mill in the Casa di Sallustio, Pompeii.

35. The greatest diameter where the grinding surfaces of the meta and catillus are in contact.

meta (lower stone) and *catillus* (hollow hour-glass shaped upper stone) on this specimen is 22inches (See Appendix A for the detailed drawings and calculations that follow) so that this would be the diameter of comparable disc-type millstones. Basic properties of these two different mills is given in the following table.

Properties	Pompeian *catillus*	Disc-type upper millstone
Weight[36]	372.5 lbs.	118.3 lbs.[37]
Area of grinding face.[38]	5.63 sq.ft.	2.4 sq.ft.
Power needed to rotate at 6rpm.[39]	0.178 HP.	0.0514 HP.
Pressure[40]	123.3 lbs/sq.ft.	91.1 lbs/sq.ft.[41]

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36. Density taken at 132lbs/cu.ft. based on the Westree lava stone specimen from Mayen. This compares favourably with the densities of two Roman lava millstones in the Museum of London which have been calculated at 127lbs/cu.ft. and 139lbs/cu.ft. (respectively a complete topstone 80cm. diameter, 77.3kg and a complete bottom stone 65cm diameter, 45.5kg.)

37. (a) Using the same rim and eye diameter, and a grinding face slope of 8.5 degrees. (b) In this comparison the thickness that is adopted for the upper disc millstone is important. A rim thickness of five inches and an eye thickness of just less than four inches has been used. This is probably representative of a Roman millstone which is approaching mid-life, i.e., nearer new than old. The age of the catillus as a proportion of its life is not known and could only be ascertained if we knew the wall thickness and sizes of most Pompeian-type specimens.

38. It is assumed that for the catillus the grinding process begins the moment the grain enters between the stones and continues more or less to the maximum radius of the inside face of the lower skirt of the catillus.

39. (a) Using a coefficient of friction coming from the Westree Rig experiments of 0.356 (b) Calculating the torque according to the simplified formula shown on p.51 above. The apparent poor fit between the meta and catillus as depicted by the drawing is ignored. In practice it is thought that they would wear in and thereafter maintain complete contact.

40. Allowing that a driving beam of say 100lbs. weight in each mill is carried by the top stone. It should be noted, however, that in the case of an overdriven disc mill the weight of the beam or frame is not necessarily carried by the stone - it depends on the support arrangement. The

The theoretical power required for this Pompeian mill compares favourably with Jasny's estimate of 1.25 HP hr./day for a donkey mill of this type.[42] If we assume for this exercise that power is proportional to throughput[43] then the Pompeian mill can produce 3.5 times as much as the disc type of the same diameter. The main reason for this is the great increase in the grinding area which the Pompeian mill provides in the form of a steep grinding profile.

If a thinner top disc millstone is used in this comparison the difference between the power and the output for the two mills becomes even greater.

A brief comment is necessary concerning dressing. The open porosity and hardness of lava stone makes it an ideal stone for grain milling, which retains its rough surface even after wear. There is substantial evidence that without furrows lava millstones could produce an acceptable product by Roman standards, and in support of this we should note that very few Pompeian-type mills have been found with furrows[44] which is perhaps not surprising because it would be impossible to put

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pressure is based on a projected area of 2.37 square feet in each case.

41. If the beam weight was not carried by the upper stone the pressure would be 49.4lbs/sq.ft.

42. This would equate to 7.0 hours of continuous work. See N.Jasny, Wheat Prices and Milling Costs in Classical Rome, Wheat Studies of the Food Research Institute, vol.xx, part 4, March 1944, pp.135-170. See p.159.

43. Reasonable within fairly wide pressure limits.

44. The writer is indebted to Dr.M.Lewis for bringing to his notice that White has identified a grooved meta from Morgantina [See White as note 9, p.203.] and Moritz points out that the Chiaramonti and Zethus reliefs apparently show furrows on the meta [See Moritz, as note 24, p.79, p.64.]. These are the only examples known among the numerous extant specimens.

them on the inside surface of the *catillus*. Moreover their maintenance would necessitate the burden of lifting-off the top stone to allow dressing.

On the other hand Roman disc type millstones are found often dressed with furrows. The effect of having furrows is to improve the efficiency of the process, primarily by cracking and reducing the grain although the limit of reduction is determined by the stone material as we have concluded above[45].

In the comparison between the types of mill, dressing with furrows has been ignored. If allowed within the disc stones it would probably increase slightly their throughput, but there would be a corresponding increase in the power necessary to drive them.

The theoretical pressure within the Pompeian mill is noticeably higher than in the disc mill and it would be comparatively even greater if (a) the weight of the driving beam was excluded from the grinding pressure and (b) if the thickness of the top disc stone is reduced below 5inches at the rim.

This dynamic analysis must include a consideration of operation and maintenance and to facilitate this we should first examine the driving arrangements. For simplicity it is suggested we examine animal-powered mills only.

Contemporary illustrations of the Pompeian type animal mill do not show a top bearing above the mill attached to the building fabric, which confirms that they were inherently stable during use. The motive force was applied to a wooden frame which embraced the *catillus*, involving vertical curved braces bolted or locked to projecting lugs in the waist of the stone. These lugs were part of the *catillus* which was a monolith. Across the top of the *catillus* was a horizontal beam which was bolted or spiked to the tops of the curved side braces and which also held a vertical spindle or shaft supported by the *meta*. In

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45. Furrows, when dressed correctly on both upper and lower stones, could assist the radial transportation of the grain and meal. Declination of the grinding surface from eye to rim was not necessary to assist radial movement though the Romans may have thought this; centrifugal force did this quite naturally.

the larger type of Pompeian mill the *catillus* was apparently supported by a circular iron plate resting on an iron pivot recessed into the top of the meta.[46] This circular iron plate was pierced with holes to allow the grain to feed through at a controlled rate which confirms that the *catillus* also acted as a hopper. It seems likely that this device acted as a pivot, stabilising the rotating *catillus*, and a feeding device rather than a tentering device.[47] The smaller type of animal-powered *catillus* apparently had no pivot or support arrangement at the top of the meta according to White's illustration but other depictions show a vertical spindle.[48] Disc mills would also require a wooden top frame to enable the animal/man to drive the runner stone. Because disc millstones have only a slight inclination of the grinding surfaces they are relatively unstable when being pushed around. It was therefore necessary to provide either (a) a pivot bearing within the bedstone or (b) arrange for the stone to rotate about a vertical spindle or beam, whose lower end passes through the runner and is carried by a footstep bearing resting in the bedstone or the floor beneath, and whose upper end is held by an overhead bearing fixed to the building fabric above.

If only a pivot bearing was used, we should expect to find some upper millstones with lugs or cavities where the driving frame was attached; none have been found, which suggests that the vertical shaft

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46. A.Neuburger, The Technical Arts and Sciences of the Ancients, trans. H.L.Brose, London, 1930, pp.93-94, 99, Figs.153-6, 165.

47. Neuburger, as note 46, proposes that this device was for tentering, pp.93-4, but the author is not convinced of this. If the catillus was suspended near its centre there was a danger that any downward pressure on one side, which was almost impossible to avoid with a single animal drive, would cause the inside face adjacent to the animal to wear away producing an elliptical shaped horizontal section inside the catillus. It would also tend to lift the skirt on the other side creating a greater gap allowing coarser meal and unground grain to fall through.
See also Moritz' discussion on this [Moritz, as note 24, pp.84-88.]

48. Neuburger, as note 46, p.54, Fig.155. Jasny, as note 42, p.152, Figs.5,6.

and overhead bearing was the arrangement used. The method of how the overdriven stone was engaged is not strictly relevant to this analysis.[49]

Disc millstones required a hopper mounted above the stones and attached to the frame. The Pompeian type, as far as can be ascertained, and as suggested by Moritz, were reversible[50] which gave the catillus a much longer life.

Moritz has suggested that the bell-shaped Pompeian *meta* was poor fitting but functional, and was probably dressed in this manner to achieve a scissor action with only a small part of its surface coming into contact with the *catillus*[51]. His drawing of the 'normal' Pompeian mill shows a *meta* with a concave flank touching the *catillus* in only two places. The writer does not agree with this theory for two reasons.

The first is that there are in existence Roman rotary millstones that show that the grinding surface profile can vary from flat, to conical, concavo-convex, sinusoidal and irregular. All of these stones

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49. This is rather an obscure subject. No remains of Roman disc runners have been found with evidence of an engagement/driving method other than a bar or winged rynd. Disc millstones have been found with a double winged rynd cavity right through the stone which may have been overdriven, and were certainly not tentered. If these were overdriven, (in milling terms overdrift), the weight of the vertical beam and top frame did not add weight to the top millstone. At least one example has been found of a runner millstone with a rynd cavity on top, strongly suggesting an overdriven arrangement, where again tentering was most unlikely. The shaft and top frame may have added weight to the runner; in either event it would have required a footstep bearing.

50. See Moritz, as note 24, p.77. All pictures suggest perfect symmetry above and below the middle and the few dimensioned drawings that exist confirm this. After all, there is no need to have a stone hopper! Is it coincidence that the sides are just steeper than the repose angle of grain?

51. Moritz, as note 24, p.87.

show distinct evidence of being a continuous grinding surface confirming that their partner stone possessed a corresponding mirror-image grinding profile[52]. In other words they mated perfectly together. Whatever shape and dress is given by man to rotary millstones, whether disc or Pompeian, as they are used and wear away the whole surface area of both grinding faces, from eye to rim, come together, separated only by the grain and meal. The natural laws of mechanics prevail, the 'high spots', initially areas of high pressure, will wear down, until the whole area bears the weight of the topstone. Modern engineering experience, including that of millstone dressers, bears this out. Irregular profiles can no doubt occur if the stones are not homogeneous, when a local hardness in one will cause differential wear, but even then the surfaces will still meet.
The second reason for disagreement with Moritz is that his photographs of extant *metae* shows that all six specimens where the profile can be seen, do not have the concavity that he shows in his drawing at mid-height on the *meta*[53]. Furthermore, in support of the theory of natural wear over the whole surface of the *meta*, extant specimens show entire surfaces (which were covered by the topstone) as perfectly smooth and clearly generated by rotational friction.

It is quite likely that the *meta* and *catillus* had different life cycles, especially in a group of them, so that mixing may have occurred. Moreover, if dressing of the grinding faces took place, for whatever reason, it is quite likely that at any one time some millstones fitted rather poorly prior to bedding-in.
The writer believes that if the skirt of the *catillus* does not overhang the *meta*, that a concave profile will naturally appear at the edge of the *meta*. If the top of the *meta* is made slightly convex to

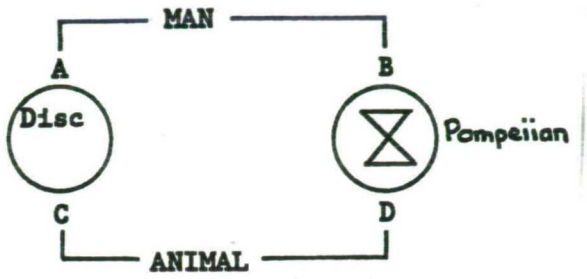
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52. The writer has seen the remains of a Roman millstone having a deep wave-like profile, whose smooth grinding surface showed that the meal, in its migration towards the rim, moved uphill! Such a profile must surely have evolved largely unaided by man.

53. Moritz, as note 24, plates 6, a, and 10, a and b.

create a 'throat' to admit the grain, then a bell-shaped *meta* will naturally appear. Thus, normal development will create a radial section comprising two curves joined by a straight surface.

In this comparison between the two types of mills we have limited our examination to the animal-powered arrangements, i.e, between C and D and we are not concerned with a comparison of A with C or B with D. However, we must realise that the Pompeian type mill with its greater throughput and power requirement would have tended to encourage the use of animal power.[54] Strictly speaking therefore, this advantage, which is related to change of power source, cannot be used to support the notion of evolution from disc to hour-glass type.



We may now summarise our comparison of the disc and Pompeian type mills. The advantages that each type has over the other are as follows;-

DISC MILLSTONES	POMPEIAN MILL
1.Easier to make	A.Does not need an overhead bearing - more stable.
2.Requires less stone at the quarry.	B.Self contained hopper.
3.Easier to transport.	C.Reversible.
4.Easier to dismount	D.The driving beam adds useful weight to the grinding.
5.Easier to maintain the grinding faces.[55]	E.3.5 times greater throughput for same diameter (less floor space).

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54. The power required by the 22inch. diameter disc stones was well within the capabilities of one man whereas the same diameter of the Pompeian type would have required two men. See Jasny, as note 42, pp.158-9. This is related to a figure of 0.75 H.P.hrs/day for a man and 1.25 H.P.hrs/day for a donkey.

55. Like for like. No furrows in either type of mill.

If we limit ourselves to lava stone we should note that items 1,2 and 3 will affect the purchase price of the mill and therefore become geographic factors.[56] However, operations and maintenance are considered to have a far greater influence on the development and adoption of a mill type.

The labour involved in maintaining the grinding face of a Pompeian mill was probably insignificant providing the animal was harnessed correctly, therefore item 5 is of no consequence. The advantages in not having an overhead bearing was significant,[57] but it is far more difficult to put a value on reversibility.

By far the outstanding advantage of the Pompeian mill was its greater power and output when related to floor space. All grain processing, by its very nature was an indoor function, and the economy of space offered by the use of the Pompeian mill, made it an ideal development from the disc mill.

This high utilisation of floor space is most obvious in the remains of some of the milling establishments in Pompeii, where the plinths of the mills are set so close together that they immediately thrust upon the observer the question of how they were driven[58]. In these situations, the need for maximum output from minimum floor area was the *raison d'etre* for the Pompeian mill; indeed we must also consider this to have been an influence upon its origin.

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56. Evidence of only three Roman Pompeian style mills have been found in Britannia. This was caused by geographic factors which are related to diffusion and not evolution.

57. Flexibility of position within a building.

58. Neuburger, as note 46, illustrates two Pompeian bakers' premises which provide excellent examples of congested milling. In one of them four large-type mills, six and a half feet high, stand in line surprisingly close to each other, (p.94, Fig. 156.). In another bakery at the Casa di Sallustio, three somewhat smaller Pompeian mills appear to be so close to each other and to the wall of the workroom as to preclude the use of animals, (p.99. Fig. 165.). See also Moritz, as note 24, p.82.

It is therefore suggested, that this evolutionary model should be related to a change of scale in the corn-milling industry and as such, a technological development related to, and the product of, the urban environment.

F. Evolution Model of the Vertical Waterwheel.

Finley says that it is inherent in model construction that there is a one-sided concentration on certain factors, to the neglect of others, relative or total.[59] They can provide a simplified structuring of reality which presents supposedly significant relationships in a generalised form.[60] Being selective they are valuable in obscuring incidental detail but it can mean that the model has limited probability and range of conditions over which it can apply.
This model has as its subject the evolution of the vertical-wheeled watermill. It is essentially a non-mathematical model but has been developed using hydro-mechanical analysis. As we have found with the disc/pompeian mill evolutionary model, dynamic analysis provides a better understanding of operational behaviour which is a major influence of evolutionary development

We can begin the development of this model by examining the undershot mode of applying water to vertical wheels.
In an undershot waterwheel the power developed is a function of the speed of the wheel and the torque generated by the force or pressure of the water acting at a radius from the axis of rotation. For a given size and design of wheel (diameter, width, number and arrangements of floats etc.) and assuming a constant rate of water flow in the headrace approaching the wheel, the power developed is proportional to the velocity of the water striking the floats.[61] In simple

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59. M.I.Finley, Ancient History : Evidence and Models, 1985, pp.84-5, see also p.60.

60. R.J.Chorley, P.Haggett, editors, Socio-Economic Models in Geography, London, 1968, p.22.

61. The force is theoretically at a maximum when the float velocity is 50% of the water velocity.

terms the faster the water the greater the power developed.



Point of application to wheel.

Greater headrace inclination increases available (latent) energy at x.

Total energy = velocity head + pressure head

By inclining the headrace, increasing its bed gradient, the water is accelerated and more of its energy is taken by the wheel. The best example of this arrangement of an accelerated undershot is the Romano-British watermill at Haltwhistle Burn Head.[62] This was no accident of siting, for the lower reaches, near the mill, were cut out of bedrock. A considerable advantage was gained by doing this for the velocity was probably three times greater than it would otherwise have been with a nominal gradient. And so this particular watermill was made three times as powerful by accelerating the water into the wheel.

Keeping for the moment to the undershot mode, how does the power vary if the size of the wheel is changed?

Let us assume that the volume and velocity of the water entering the wheel is constant, and therefore the potential force is constant. We must also assume the float area and velocity of the float to be constant, in which case-

Power generated α wheel speed (rpm) x torque

= 60/3.142D/rim velocity x (force x radius)

where rim velocity and force are constant.

Therefore Power α radius/diameter = constant

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62. Over a distance of 57.5ft the gradient of the headrace increased as it approached the wheel so that its theoretical velocity was some 14.8ft/sec. entering the waterwheel.

In other words, theoretically, the power developed by different sized wheels served by the same absolute head of water is constant. Of course there are limits to this. The wheel could become so large as to become disproportionate for the volume of water flowing; nearly all of the power generated would be absorbed by the bearings.

As the wheel is made smaller the geometry of the floats and the water striking against them would alter and the application would become inefficient. Again this is a function of water flow and wheel size.

The essential point of this analysis, is that the theoretical power generated by an 8foot diameter undershot waterwheel is the same as for a 16foot diameter undershot having the same flow rates and velocities (wheel and water).

In these circumstances the choice of a smaller wheel has the following advantages-

(1) The construction involves less time and less material and its design can be more simple than a larger wheel.

(2) Being a faster wheel the gear ratio can be less to achieve the same millstone speed. If the driven gear is small and constant in size[63] then the change in driver gear diameter is proportional to the wheel diameter; i.e., if the wheel is halved in size then the driver gear is halved. Thus the driver gear construction involves less time and material.

(3) The loads upon the wheel-shaft and bearings would be less.[64]

(4) The design of the mill building, in particular the wheel and gear pits, and the foundations of the machinery could be smaller.

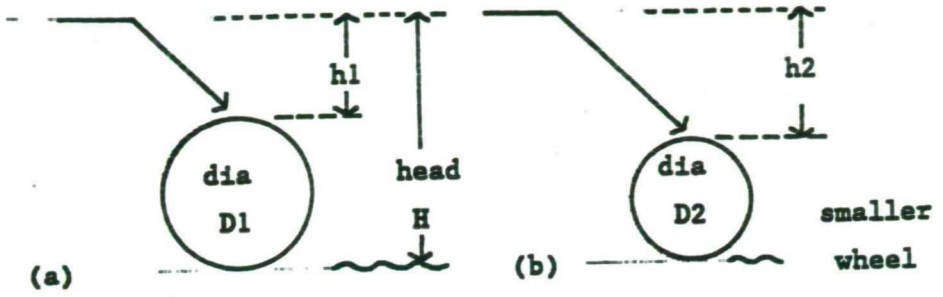
(5) The maintenance and operation of the smaller 'machine' would be considerably easier in terms of cost, labour and materials.

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63. It is not unreasonable to adopt the Zugmantel specimen as typical. This had six iron staves which almost certainly engaged wooden cogs in the driven gear.

64. Though not the torque in the shafts and gears in this analysis.

The second hydro-mechanical arrangement which deserves our attention is the overshot wheel. How do the dynamic properties of an overshot change as the wheel is made smaller beneath a fixed head of water? Thus-



Again, let us assume that the volume (cfm) of water flowing into the wheels is constant and we can also assume that the tailrace clearance is constant. As the head of water (h) onto the wheel increases in a direct relationship, thus (D1 + h1) = (D2 + h2). The increase in (h) accelerates the water onto the wheel; the rate of flow stays the same but its velocity increases.

Simultaneously, another phenomenon will occur involving the wheel. The smaller in diameter the wheel becomes, the faster it tends to revolve regardless of the volume of water flowing - providing there is enough to cause continuous motion. This phenomenon, of water acting solely by weight being applied to an unloaded free running wheel with only its bearings taking power, has never been well defined in the corpus of water power and hydraulic studies. Variation in wheel design can tend to cloud the issue but for this exercise it is best to consider a wheel having a constant design, simply being scaled down. Accepting that the buckets are reasonably effective in holding, for as long as possible, a sufficient quantity of water and then freely releasing it, the speed of the wheel is a function of wheel diameter and gravity acting on the water.

In addition to the phenomenon of a smaller wheel naturally revolving faster, the water being applied is accelerated by virtue of the increased head (h2). As (h) increases and the velocity of the application increases, the water causes more agitation entering the buckets until the disturbance reaches the point where the weight effect becomes less efficient and the impulse effect more significant. When

this occurs it affects the design of the wheel. Moving from a weight to an impulse mode means that the buckets should change to become more efficient at harnessing the force and kinetic energy of the incoming water. Essentially this means that radial vanes or floats would be required.

We might at this juncture benefit by examining the Athenian Agora wheel which fits into this category rather well.

At the Agora mill the archaeological evidence provided us with the size of the overshot wheel but not its structure or bucket or float design. The 10.62ft. diameter wheel was fed by a stone-lined headrace which brought the water to a level 4.59ft. above the crown of the wheel. Inclination of the wooden trough brought the water to a velocity of 19.2ft/sec. as it struck the wheel. This was a fast overshot wheel probably running at between 28-32rpm. Analysis shows that if the wheel used buckets the useful effect of the water carried diminishes rapidly as the speed of the wheel increases. At a speed above approximately 18rpm the adverse effect of centrifugal forces rapidly reduces the volume of water held by the wheel and further losses occur due to the buckets which scatter the water as they pass through the stream entering the wheel. With buckets the power of the wheel falls away at higher speeds.

With radial floats the wheel would behave rather differently; at lower speeds it was unable to generate the power of a bucket arrangement but at say, 20rpm an improved performance is theoretically evident. Above this speed the impulse effect is very great whilst the power derived from the weight of water is negligible.

It seems likely therefore that the wheel had radial floats or vanes rather than buckets.

The Agora wheel could be viewed as a hybrid; a fast overshot whose design was verging on the radial vane (with or without sole boards) rather than the bucket type. Its large head of water gave the wheel a considerable increase in speed - undoubtedly an intentional design on the part of the builders.

The advantages in having a smaller and faster overshot arrangement are exactly the same as those enumerated above for the accelerated undershot wheel. Additionally, the design and construction of radial floats or vanes is much easier than buckets and the need for sealing (watertight buckets) disappears.

Now let us examine the third and final element providing the theoretical basis of this evolutionary model. We must now turn our attention to the impulse wheel; a vertical waterwheel where the head of water is such that all of the power generated comes from impulse and none from weight.[65] At the time of writing evidence of only one vertical waterwheel has been found of this type, believed to be Roman. This is the Venafro wheel.
This unique wheel was 6.13ft. in diameter and we are told that it operated under a head of 13.12ft.(4m) of water. There appears to be no archaeological record to confirm whether or not this was an over or undershot arrangement. As an undershot it could take advantage of a curved wheel pit breast, whereas the overshot would be more efficient at releasing water through the side vents of the wheel.
Using Jacono's suggested flow rate of 3.28 cubic feet per second[66] and a wooden trough inclined at 45 degrees, of the same width as the shrouds of the wheel, the water would have entered the wheel at 25.6 ft/sec.[67] If the trough was made steeper to say 67.5 degrees from the

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65. Unless the water flow is vertically downwards and passes straight through the wheel on one side without being constrained within the wheel, the mode of application can be classified as other vertical waterwheels are, as either 'undershot' or 'overshot'. Where the water is constrained, say by a curved breast under the wheel, the weight of the water is having some effect, however slight. in such cases, where the weight effect is slight, the wheel can still be classified as impulse especially where radial floats or vanes exist.

66. Luigi Jacono, 'La ruota idraulica di Venafro', L'ingegnere, vol.12, 1938, pp.850-853.

67. This is very similar to the entry velocity at the Agora watermill but there the volume of water flowing was probably three times the Venafro flow rate.

horizontal the velocity increased to 28.3 ft/sec and the wheel would have rotated faster. The following table summarises the theoretical conditions of these two different trough arrangements.

Trough inclination (degees)	Velocity of application (ft/sec)	HP generated	Waterwheel speed (rpm)
45	25.6	1.86	48.9
67.5	28.3	2.3	54.0

Finally, if the water is applied to the wheel in a vertical drop, there is a further, though negligible, increase in the velocity of the water.

From this analysis it can be seen that for any situation where a head of water exists, the steeper the trough delivering the water, the faster the wheel will tend to rotate and therefore the power developed by the wheel will be greater.

It should be noted that as the trough becomes more inclined and approaches the vertical, the stream of water, hitherto exhibiting laminar flow, will tend to become more agitated and entrain air as it moves to a vertical free-fall situation. To avoid splashing and delamination of the stream the trough needs to be boxed-in when its angle is very steep. When it is in the vertical position control of the water is greatly improved if it is constrained by a four-sided chute. This ensures that losses are kept to a minimum and that the water is applied exactly where it is wanted. Such an arrangement is very necessary when the volume of water flowing is small.

One final development can be identified in this progression of accelerating the flow by inclination of the headrace. As the water moves down the inclination its velocity increases, and with a constant width trough, the depth of water gets less, a phenomenon that would have been obvious and well known to the miller. This lends itself to a tapering of the trough especially where the width of headrace is greater than the wheel.[68] Tapering would also assist in

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68. Tapering troughs are commonly found with horizontal wheels where the water needs to be con-

creating a smooth flow and a depth of water probably better suited to laying on the wheel.

We have identified the advantages, indeed the necessity, of covering the trough to make an enclosed chute when the direction of flow is vertical or nearly so. Thus we can anticipate the development of a vertical four-sided tapered chute for the impulse application.

With this arrangement it was only a matter of time before the miller found that when the flow rate in the headrace increased and exceeded the amount that the lower narrow chute could deliver, that the wheel chute would become flooded. At this point the hydraulic conditions completely change. The velocity of flow is no longer determined by the inclination and resistance of the trough; instead pressure caused by the head of water above the outlet is the determinant. The shape of the vertical chute does not matter, for it has no effect on the water issuing from the bottom providing its section does not restrict the flow rate.

We have arrived at the Arubah[69]; a column and reservoir of water kept flooded by the headrace above, feeding the outlet at the bottom of the column solely by pressure head. The arubah of Middle-East tradition has apparently always been vertical, contained in brick, stone or concrete and serving a horizontal water-wheel. At present there is no evidence that they existed within Roman-held provinces.

We have no evidence that a vertical chute or arubah was used in conjunction with a vertical waterwheel of the Roman period, but this is not to say that it could not have occurred. Such an arrangement may

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centrated onto the wheel.

69. A spring or stream-fed reservoir whose main feature is a vertical circular or square-sectioned tower which is kept flooded, forcing water out through an aperture in its base onto a horizontal waterwheel. The tower is usually large enough to admit a man or boy for maintenance purposes and presumably to facilitate changing of the removable, circular section clay nozzle near the bottom of the shaft, which applied the water to the wheel.

have existed at Venafro. Inclined wooden box-type chutes are certainly much in evidence in later periods for both horizontal wheels and high speed vertical impulse wheels.[70]

Critical to the acceptance of this 'learning path' is the assumption that ancient man would progress from one development to another; that the threshold of awareness of improvement was so low, that discovery was inevitable. When artefacts are being used comparative performance is usually taking place to a greater or lesser extent, especially when duplication is observed or experienced first hand. This learning process has always existed in ancient or modern man because all makers and users of artefacts have a level of awareness and motivation that generates progress.

Summary. The three analyses can now be brought together.

In both the undershot and overshot modes, acceleration of the headrace into the wheel facilitates higher wheel speeds and greater power. Coincidentally, further advantages can be gained by using a smaller diameter wheel. A smaller diameter prime mover which is easier to build and maintain, means lighter loads which reflect in a smaller wheelshaft and support bearings. With the same head of water a smaller wheel rotates faster so that the driver gear (which is usually the largest in the mill) can be smaller.

The power provided by these prime-movers was always related to a single pair of millstones, and the matching of the generating potential of a mill site to a set of stones presented no difficulties. The tolerance on millstone operating speeds was so great, as was the power capacity of most waterwheels, that the millwrights could explore and develop the advantages of moving from large-scale slow-moving machines to smaller scale faster machines.

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70. Weisbach,J, A Manual of the Mechanics of Engineering and of the Construction of Machines, vol.2, edit. A.J.Du Bois, 1877, pp.336-7. Small wheels of 2.5-3m in diameter and less served by falls up to 6 and 7m found in the Pyrenees and the Alps. J.F.d'Aubuisson de Voisins, A Treatise on Hydraulics for the use of Engineers, trans. Joseph Bennett, 1852, p.400. Vertical box-type chutes serving vertical waterwheels, invariably hammer mills, could also be found in such places as Westphalia and Sweden.

This model suggests that the evolution of the Roman vertical waterwheel can be related to the development of accelerated flow, in both undershot and overshot modes, from effect by weight through to pure impulse motivation. Integral to this development was the change towards smaller and faster waterwheels with lower gear ratios.
It is important to note that this evolutionary model does not incorporate the development of more powerful or efficient machines. Such improvements no doubt occurred, whether by chance or planning, and were probably repeated. But these are considered as not being primary factors of evolution during the Roman period and are excluded in preference to the influences associated with the provision of resources for making, operating and maintaining the machinery.

G. The Horizontal Waterwheel.

The developmental sequence of the vertical waterwheel has been related to the extant archaeological evidence for the whole of the Roman Empire. The degree of compatibility between the field evidence and the theoretical model is in many ways a reflection of the strength of that evidence. As the corpus of knowledge of vertical watermills has grown during the last decade or so the number of sites and variations of design has steadily increased, giving opportunity and greater strength to these considerations of technological evolution.

Our knowledge of horizontal wheels for the same period is much less, both in terms of the number of sites and archaeological quality. At present, there is not a single undisputed example of a Roman horizontal wheel, although numerous examples have been discovered within or close to provinces of the Eastern frontier. As with vertical mills, the number of known sites is growing as more discoveries occur, but this corpus suffers from two distinct disadvantages. First the quality of archaeological work is poor, especially in technological detail and dating.[71] Secondly, there is an apparent dearth of

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71. Much of the evidence recently found forms part of surveys embracing a full range of cultural and demographic enquiry. Technology plays a very small part of such work.

evidence of machinery (millstones, shafts, waterwheels) at these sites.

A high proportion of the horizontal mills so far discovered are *arubah* type, mainly from the Middle East in frontier areas and related to non-Roman traditions. The enigmatic Chemtou specimens in Tunisia provide us with an unusual variant and, at the end of the Roman period we have numerous Irish specimens. The almost total absence of millstone and horizontal wheel evidence makes a dynamic analysis in the form of hydro-mechanical theory nearly valueless. In some cases details of the *arubahs* will allow a very basic calculation to be made of hydraulic pressure, but this cannot be related to potential power without details of the nozzles.[72]

Notwithstanding this absence of evidence, the developmental sequence proposed for the application of water to the vertical wheel is considered to have relevance to horizontal wheels. However it is not possible to offer any evolution theory concerning the wheels themselves, simply because of lack of evidence.

Taking a broad view of the evidence we can identify four distinct styles or methods of applying water to horizontal wheels. These are-

(H1) Inclined open trough

(H2) Inclined troughs either closed over or partly closed at the lower end with or without a nozzle or aperture. Included within this category are inclined pipes.

(H3) *Arubah* type.

(H4) Where the wheel is contained in a circular chamber through which the water passes (Chemtou type).

In classifications H1 and H2 the trough would probably be tapered, at least at its lower end. The above categorisation (H1-H3) forms the basis of the proposed developmental sequence for the application of

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72. In some more recent arubahs different nozzles were used. This gave the miller the opportunity to vary flow rate, power and thus the speed of the mill. It also helped to conserve water.

water to the horizontal waterwheel. Essentially it involves a change from a low-velocity weight induced flow to high velocity concentrated gravity induced flow, through to a head-induced pressure flow.

The Chemtou specimens are difficult to place within this evolutionary sequence. Archaeological evidence shows that the headrace approaching the mill was tapered to create greater velocity as it entered the top of the wheel chamber. Furthermore, on plan, the head race entered each chamber off centre tangentially, presumably to encourage the water to impinge on the curved wall of the chamber to induce a spiral course down through the wheel.

These features, combined with the basic arrangement of the wheel operating within a vertical chamber, suggest an advanced design. Clearly it does not lie within the developmental sequence of H1 to H3 which are all associated with free standing wheels. In terms of water application it has little relationship with the *arubah* type but H2 does. A simplified view of the Chemtou design is that it is arrangement H2 within a chamber, with the flow accelerated by tapering the headrace and then dropping onto the wheel. But we should take note that these structures are well made being within a masonry dam-like structure with the wheel chambers and head races stone-lined.

The final developmental phase of the vertical wheel has great similarity to the third phase of the horizontal wheel. In terms of water application the way in which the velocity and direction are created, they are identical, with the only difference being the wheel type which can be viewed as a shift of axis.

We do not yet have enough evidence to suggest that speciation may have occurred between the two type of mills, nor do we have a clear view of which traditions can be related to each type.

H. Evolution of Corn Milling - The Model.

All three of the proposed developmental sequences can now be brought together and schematically related. See Figure 34.

In the schematic illustration time advances generally from the top to the bottom, following the large arrows. There is no fixed scale for time and it is possible that the delay between successive developments could be as short as a few years or longer than a century. The

relative positions and sizes of the primary lineages (water, man, animal) are arbitrary and only relate to each other where speciation occurs.

The absence of undisputed examples of horizontal wheels within the Roman Empire[73] invites further speculation on the validity of the proposed speciation of the horizontal wheel from the vertical.

In Figure 34 it is suggested that speciation occurred following the development of the accelerated headrace and although the diagram shows vertical wheel type V3 as the progenitor, it is entirely possible that it originated later in the vertical lineage.

Nomatter; recognizing that different technological environments could have existed at the same time but in different places e.g., either side of the Roman frontier, it follows that the horizontal lineage may have developed first outside of the Empire. Furthermore, we must remember that speciation may have occurred at any time and any place after the progenitor appeared.

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73. The evidence from Bolle, Denmark, and that from Caesarea, claimed as dating from the Roman period, is not convincing and therefore not included. The Chemtou mills have been dated only by circumstantial evidence relating to the Roman environs (marble quarries, workshops and labour camps). See F.Rakob, G.Röder, 'Die Mühle am Medjerda-FluB : High Tech vor 1700 Jahren', ['The Mill on the Medjerda River : High Tech 1700 years ago'], Bild Der Wissenschaft, 1989, 26, Jahrg., Heft., 12(Dec.), pp.95-100.

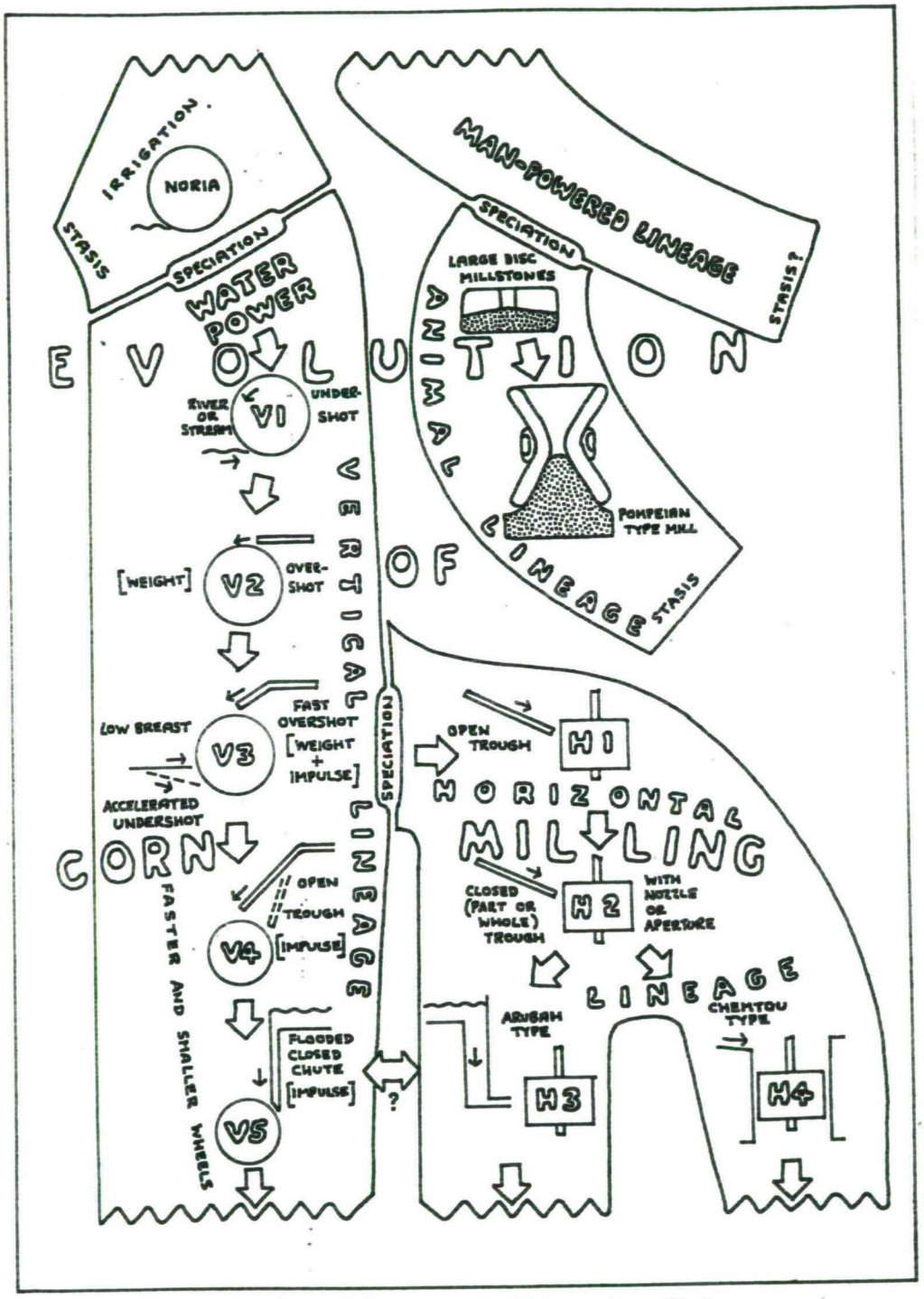


Fig. 34. Evolution of Corn Milling.

I. Testing the Model - the Evidence.

We are currently restricted to the following evidence of Roman water-mills having vertical wheels. In each case we need only to consider the date of their erection on the assumption that the arrangement and type at each site did not alter thereafter. The following table provides a summary of all these sites.

ARCHAEOLOGICAL EVIDENCE OF VERTICAL WATERWHEELS

Site	Type and Classification	Date of Construction
Ickham (early)	u/shot	V1 c150 AD
Ickham (late)	u/shot	V1 c330 AD
Martres-de-Veyre	u/shot accelerated	V3 c100 AD
Fullerton	u/shot	V1 250 AD (Wikander)
Chollerford (Chesters)	u/shot	V1 Early 3rd C?
Willowford	u/shot	V1 Mid 3rd C? (Shaw)
Barbegal	o/shot gravity	V2 250AD to 4thC
Venafro	small fast impulse	V4 unknown
Athenian Agora	o/shot accelerated	V3 457-474AD(Parsons)
Baths of Caracalla (early)	"	V2 c212 AD
Baths of Caracalla (late)	" "	V3 c275-300 AD
Haltwhistle Burn Head	u/shot accelerated	V3 c225-240
Lösnich	u/shot accelerated	V4 c100? (Neyses)

This evidence is best seen on a time matrix. See Figure 35.

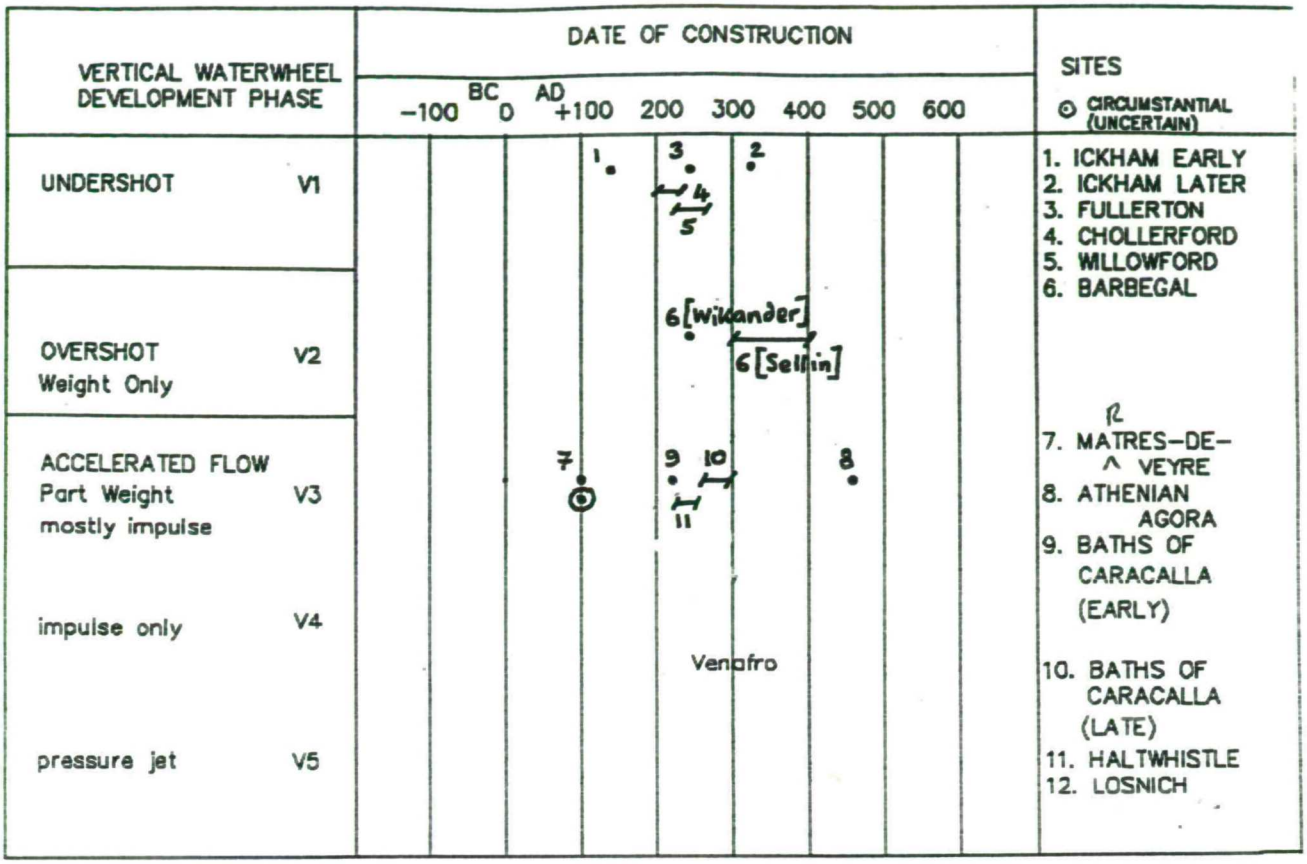


Fig.35. Vertical waterwheel evolution.

There are far too few dated sites to create an evolution 'profile'. As more sites are discovered and dated the earliest example of each phase will be shifted towards the left on the matrix.

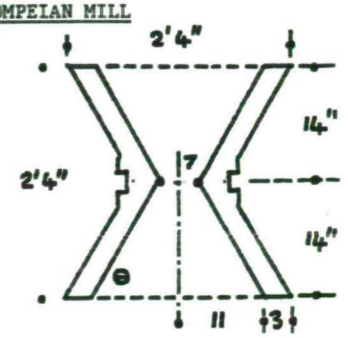
On this time matrix the profile created by the first and earliest example of each of the phases V1 onwards, must slope. Moving from V1 to V5 the profile will move towards the right. It is inconceivable that all of the developments, or indeed most of them, would have been discovered simultaneously - i.e., a vertical profile. The gradient, when established, will probably vary between each phase depending upon the time delay between each. Until many more new sites are found and dated the profile may not become clear.

In theory, as each new development occurs, the profile moves downwards, thus evolution proceeds by leaps and bounds. If no further development occurs stasis is approached and the line becomes horizontal. If a reversion occurs, the profile drops back to an earlier phase until re-discovery takes place.

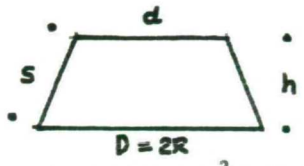
Notice also from the matrix that an environment which supports an advanced technological phase can simultaneously support lower phases or levels of the same technological lineage. This is the second corollary of the evolution model.

Appendix A

POMPEIAN MILL



Frustrum of a cone:-



Where volume $V = 0.2618\ h\ (D^2 + Dd + d^2)$

and area $A = 1.5708\ s\ (D + d)$

$\text{Tan}\ \theta = \frac{14}{11} = 1.2727 = 51.8$ degrees.

Using $V = 0.2618 \times 14(22^2 + 154 + 49) = 2518$ ins.^{3} (inner)

$V_o = 0.2618 \times 14(28^2 + 364 + 169) = 4827$ ins.^{3} (outer)

Therefore difference = 2309 x 2 = 4618 ins.^{3}

plus for sockets and lugs say 282

4900 ins.^{3}

Volume of catillus = $\frac{4900}{1728}$ = 2.83 ft.^{3} at 131.6 lbs/ft^3 = 372.5 lbs.

$$\text{Torque} = \frac{5\mu W R_1}{8} \cdot \frac{1}{\text{Sin}(90-\theta)}$$

where W = 372.5 + 100 for beam.

$$= \frac{5 \times 0.356 \times 472.5 \times 0.917 \times 1.617}{8}$$

= 155.89 ft. lbs.

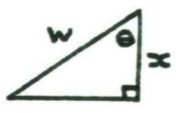
$$\text{HP} = \frac{2\pi N T}{33000} = \frac{2.\pi \times 6 \times 155.89}{33000} = 0.178\ \text{HP.}$$

Area of grinding face

$$= \frac{1.5708 \times 17.8 \times (22+7)}{144}$$

= 5.63 ft.^{3}

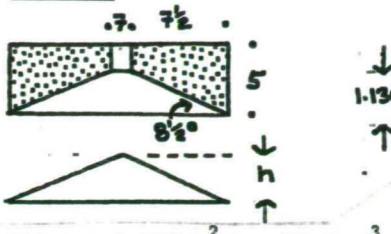
Pressure

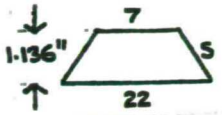


W = 472.5 lbs. x = 472.5 Cos.51.8° = 292.2 lbs.

Therefore pressure $= \frac{292.2}{\text{area}} = 123.3$ lbs/ft^2

DISC MILL





Area of face.

$s = \sqrt{56.25} + 1.29$
$= 7.59$

Area = 1.5708 s (D+d)
= 345.7 ins.^{2} (2.4 ft.^{2})

Volume = $1.0472\ r^2\ h$ = 211 ins.^{3}
where h = 1.666

Total volume of solid = $\pi \times 11_2 \times 5$ = 1901 ins.^{3}

eye volume = $\pi\ 3.5^2\ 3.3$ = 127 ins.^{3}

Final volume = 1901 - 211 - 127 = 1563 ins.^{3} less say 10 ins.^{3} for the rynd

$$= 1553 \times \frac{131.6}{1728} = 118.3 \text{ lbs.}$$

$$\text{Torque, } T = \frac{5}{8}\ \mu\ W\ R_1 \ \frac{1}{\text{Sin}\ (90 - \theta)}$$

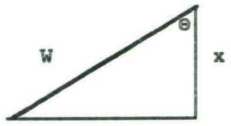
where $\theta = 8.5°$
W = 118.3 + 100lbs.

$$= \frac{5}{8} \times 0.356 \times 218.3 \times 0.917 \times 1.011$$

= 45.0 ft.lbs.

$$\text{HP} = \frac{2\ \pi\ N\ T}{33000} = \frac{2\ \pi\ 6\ 45.0}{33000} = 0.0514 \text{ HP}$$

Pressure



Where W = 118.3 lbs. (without beam)
or W = 218.3 lbs (with beam)

x = 118.3 Cos 8.5° = 117.0 lbs.
or x = 218.3 Cos 8.5° = 215.9 lbs.

$$\text{Pressure} = \frac{x}{\text{area}} = \frac{117.0}{2.37} = 49.36 \text{ lbs/ft.}^2 \text{ (without beam)}$$

Where projected vertical area is 2.37 ft.^{2}

$$\text{or } \frac{215.9}{2.37} = 91.1 \text{ lbs/ft.}^2 \text{ (with beam)}$$

Chapter Nine

CONCLUSION

The objective of this work was to take a fresh look at 'old problems' and re-examine the evolution of the Roman watermill. This new examination of the archaeological evidence was facilitated by theoretical hydro-mechanical analysis which was found to lend itself very well to watermills. It has provided us with a retrospective insight into their design, behaviour and performance, which is particularly welcome in an area of technical history for which the archaeological evidence is relatively sparse.

The bulk of the power absorbed by the millstones is for grinding, which has been determined by a full-scale laboratory rig using Roman-style lava stones. This unique experiment provided brief operational grinding experience, and also raised questions about the use of replicas. The rig also provided a useful guide to the meal output/power ratio for the operation of lava stones dressed in Roman style, which has been usefully applied in the Barbegal analysis.

A hydro-mechanical analysis was only possible at a few of the more complete sites, (Barbegal, Haltwhistle, Agora and Caracalla), where the archaeological evidence provides the critical facts necessary to support a full study. At each of these sites the hydraulic conditions have been analysed and compared with the power absorbed by the millstones, with the balance of power expressed in terms of different gear ratios[1]. The result, which comes from an integration of assumptions and variables, was an appraisal of each machine's performance by an order of magnitude combined with an improved understanding of how speed, power, water flow and output relate to each other.

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1. These lengthy calculation sequences would lend themselves very well to resolution by computer programmes, in which the interaction of the numerous variables could be more fully explored to determine their sensitivity to the end result.

Our familiarity with the British corpus, with its distinctive archaeological emphasis, has prompted an unusual separate analysis of the military and civilian areas. Although there is a paucity of evidence of the watermill machinery, a study of the building technology reveals a very broad adaptation of water-power to the different faces of the English landscape.

Hydro-mechanical analysis, supported by site surveys and observation, has both illuminated and expanded the Barbegal enigma. Substantial improvements in our knowledge of the remains of both the mill building and the adjacent aqueducts has enabled us to speculate further on its building sequence and development. At the same time a reappraisal of its performance has brought into focus the question of its builders and their purpose, but all these advances are counterbalanced by yet more imponderable questions, including the difficulties of relating Barbegal's throughput with the agricultural, transportation and demographic infrastructure.

The unexpected preponderance of undershot mills in Britannia is in contrast to the outstanding examples of accelerated headraces on the Continent, where full hydro-mechanical analyses of the Caracalla, Agora and Barbegal evidence are supplemented by studies of the unusual and unique accelerated headraces of Lösnich and Venafro. These examples help to confirm the conclusion that the accelerated headrace operating in conjunction with a relatively small fast waterwheel was a well known arrangement in the late Roman period.

Theoretical aspects of technological evolution have been discussed and an environment-based model has been proposed from which two corollaries are derived. Dynamic analysis has supported the evolutionary model of how the Pompeian mill may have evolved from disc millstones.

Central to the whole thesis and the relationship of the chapters is the evolutionary model for the vertical waterwheel. This model relates to the advantages of accelerating the headrace and proposes a development from open to closed headrace channels, and finally to ap-

plications generated by fully-flooded pressure heads. A succession of development phases are identified; first, slow moving vertical wheels where the power is generated wholly or mostly by weight of water, through further development to smaller, faster vertical wheels driven mainly by impulse, and finally to a wholly impulse-driven arrangement which can apply to either horizontal or vertical wheels. The model suggests that speciation of the horizontal wheel did not occur until the vertical wheel had been evolved and the accelerated headrace was in use. Headrace development from closed chute to a fully flooded mode with the creation of pressure head facilitated the development of the *arubah*.

Within this evolutionary model the Agora specimen can be seen as an advanced machine which appears late in the development sequence. So too is the Venafro specimen, which has been re-appraised as the vertical water-wheel in its most advanced form. Analysis confirms that the Venafro wheel was an impulse wheel having the design features of a turbine which, in the proposed evolution trail, was a likely progenitor of the horizontal wheel. Although we are unable to date the Venafro evidence, its position within the developmental sequence is entirely logical, and provides a link between the vertical and horizontal types.

This evolutionary hypothesis was tested by categorising all water-mills into their development phases and then placing them onto a chronological matrix. At present there are far too few examples to make a fair test of the theory, but as more specimens come to light, an evolutionary 'profile' should be generated for the sequence on the matrix which should confirm the progressive appearance of the phases of development.

In the history of ancient technology evidence of invention, whether artefact or process, cannot be provided by archaeology. Only the written word or oral tradition can reveal a new or novel creation whereas archaeology can bear witness where and when diffusion took place. In one sense therefore archaeology will provide a focus and background for the development of a hypothesis, but in the case of

the proposed evolutionary model, the theoretical concept is bound to precede archaeological confirmation. So we have an evolutionary model which cannot be fully tested, at least not for a very long time.

An evolution of the vertical and horizontal waterwheels has been proposed by most historians of technology. A simplified view is either that one type of wheel was the progenitor of the other, or, that they both came from unrelated origins[2]. Reynolds provides a good summary of the current views on this question[3]. All of these views appear to be supposition based on subjective examination; theories which hang loosely on the logic of comparative form and function. None of the historians of technology who have written on the origins of the waterwheel, have demonstrated or supported their theories with any form of functional analysis; instead they have relied on imaginative resolution and conjecture. The evolutionary model which this thesis proposes is therefore quite different from all others, because its foundation and critical path result from dynamic analysis and are demonstrable using hydraulic laws.

Essential to this thesis is the notion that technological evolution was greatly influenced by a progression towards simplicity as well as the economy of resources. The proposed development of the vertical water-wheel lineage is put forward as an example of this; moreover, speciation of the horizontal water-wheel should also be seen as a technological simplification, where water-powered corn milling was made possible without gearing.

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2. Only Moritz has suggested that the horizontal developed from the vertical wheel, whilst the majority of those that suggest they were directly related, believing the horizontal to be a more primitive machine, propose that it was the progenitor of the vertical wheel.

3. T.S.Reynolds, Stronger Than a Hundred Men : A History of the Vertical Water Wheel, Baltimore, 1983. See pp.14-30 for a discussion of all early literature references relating to origins.

The sparseness and ambiguity of Roman literary references to watermills has done little to advance our knowledge of their design and development and it is archaeological evidence which feeds and enlarges the corpus. In spite of the incidence and the recent growth in archaeological evidence of Roman watermills and the application of new methodology of analysis, our knowledge and understanding of this technology is clearly in the formative stages. Nevertheless few areas of Roman history, even in technology, have advanced at such a rate as the study of waterpower has in the last one or two decades. Symptomatic of this growth and the nature of the evidence are the problems and questions which it poses for the historian of technology.

As time passes and the archaeology of early history provides more examples of sites and artefacts, our knowledge of when innovation and development occurred increases. Theories of origins, evolution and diffusion are liable to change; they may appear reasonable today, but tomorrow they could have shifted or been abandoned. As more specimens of any particular artefact are un-earthed, and its distribution and diffusion are progressively revealed, the contribution made by subsequent discoveries diminish. Their marginal effect on our knowledge reduces as the number of extant hidden specimens are exhausted. In the early stages of such a process, which is where the archaeology of Roman waterpower stands, the first few specimens found have a disproportionate effect on the corpus, inviting speculation and theory on what remains to be found and its meaning. Statistically they cannot fail to distort our view as we attempt synthesis of origins, developments and diffusion.

There are other influences which can distort or harm the historical interpretation of archaeological evidence, which in the study of ancient molinology can be broadly classified into two groups, those which are historical and inherent in the evidence itself, and those which come from historians.

The different forms which the evidence takes can itself cause distortion of view. Wikander found this when he integrated all types of evidence to shed new light on diffusion and the incidence of water mills[4]. He found that some forms of literary evidence taken by themselves, e.g, charters of the Merovingian epoch (VI and VII centuries), are quite misleading, whereas taken with other evidence they become complementary and constructive. The archaeological evidence itself, on which we have to rely almost wholly for technical knowledge, can cause distortion by being simply fractioned into types, say by design or building, or into rural, urban and military elements. These sub-divisions immediately reduce the numbers being considered making the sample groups smaller and the historian's tasks more difficult. But the most damaging influence on this interpretation is surely the attitudes and prejudices of historians.

Smith has stated that twentieth century experience and expectations can cause problems[5], so too can his archaeological interests and skills. This is perhaps most marked between nations although considerable differences in skills and competence can occur within particular countries and archaeological institutions. The great interest that archaeologists and historians have in classical cultures has already been mentioned, but what of publication and dissemination? The speed at which modern knowledge is broadcast and the quality of the interpretation can have great affect on advancement[6].

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4. Ö.J.Wikander, 'Exploitation of Water-Power or Technological Stagnation? A Reappraisal of the Productive Forces in the Roman Empire', Scripta Minora, 1983-4, No.3, Lund, Royal Society of Letters, 1984.

5. N.A.F.Smith, 'The Origins of Water Power : A Problem of Evidence and Expectations', Transactions of The Newcomen Society, vol.55, 1983-4, pp.67-84.

6. With regard to speed of dissemination what better examples than the Haltwhistle and Chemtou evidence?

One of the worst forms of distortion, and one which we have some experience of and yet apparently fail to come to terms with, is that caused by the absence of evidence. When there is a void in the evidence, or for that matter in our understanding, historians tend to apply theories to the few facts that exist, producing weak and widely varying hypotheses[7]. We might now in hindsight agree that this happened, to a degree, with the subject of Roman technological stagnation. The historian of technology's view has shifted towards enlightenment as fresh evidence and interpretation is synthesised.
How ironic, that as our understanding of the Roman period grows and the Middle Ages by contrast becomes 'darker', we already have reputable historians wishing to fill the 'void' with theories based on the premise that no evidence equals inactivity and stagnation. Take for example Holt's view:
'On the contrary, medieval man did not just inherit the design of the mill: he inherited a world in which mills were a commonplace. And furthermore he contributed nothing of his own to the device, so that the watermill he beqeathed to subsequent generations was no different from the machine handed down to him'[8].

We have heard before claims of technological stagnation. How can it be said with such conviction when we are still struggling to determine medieval man's legacy from the Romans? Moreover, archaeology has so far failed in the provision of medieval evidence; we know far too little about medieval water power machinery and the various forms that it took. Holt points out that archaeological evidence shows that horizontal mills existed in the Dark Ages on the English landscape, and that post-Conquest documentary sources confirm their

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7. Bennet and Elton's supposition that Vitruvius' failure to mention the horizontal mill indicated its widespread use, is another example of advantage being taken of a historical void. This is an earlier form of response whereupon the void, being identified, is simply filled.

8. R.Holt, 'The Medieval Mill - A Productivity Breakthrough?', History Today, July 1989, pp. 26-31. See also R.Holt, The Mills of Medieval England, Basil Blackwell, 1988.

disappearance, admitting that why this change occurred is uncertain. He gives no consideration to the hydro-mechanical design of the Anglo-Saxon horizontal mill[9], yet concludes that they represented neither technological advance nor regression[10]. How can we measure advancement, stagnation or regression through a period of time without a meaningful picture of what existed at the beginning, during and at the end? And even with such pictures, a hypothesis would need to address the period's technological environment in all its forms to be of any value. In direct contrast to Holt, Lynn White would have us believe that the use of water power in the medieval period reached a 'high', which suggests that there is an inclination for historians to find what they are looking for. And what influences have we yet to discover? Why haven't we found any Domesday mills?

So much for the problems relating to the nature of the evidence and the questions we ask of it. What position have we now reached?

The evidence appears to have reached the point where we may confidently suggest that;-

(a) the Roman water-power tradition comprised of the vertical wheel in many cases working with an accelerated headrace,

(b) the Romans pobably did not know the horizontal machine[11], unless it made an appearance at a late date in the south-eastern provinces of the Empire,

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9. How could he with so little evidence?

10. R.Holt, 'Milling Technology in the Middle Ages : The Direction of Recent Research', Industrial Archaeology Review, vol.XIII, no.1, Autumn 1990, pp.50-58; see p.53. In spite of the title, Holt offers no evidence of qualitative changes in watermill technology even though he mentions recent research on excavated structures; his discussion on the Anglo-Saxon period relates solely to quantitative considerations.

11. A view proposed by Smith. See footnote 5.

(c) during the same period, water-power was apparently unknown in Europe outside of the Empire.

The evidence which might be offered to counter these suggestions, does not reach the threshold of acceptance. Neither Bolle, Caesarea nor Chemtou have been securely dated and gained general acceptance by historians of technology. The passage of time may change this, but it does presently appear that the Romans generated water-power using only the vertical waterwheel. We can truly call this a Roman machine, the very one described by Vitruvius[12].

In recognising these limits to Roman water-power technology, clearly only a part of the proposed evolutionary model relates to the Empire before, say, AD 500. This is essentially the lineage of the vertical water-power wheel up to and including smaller and faster impulse wheels. When speciation from vertical to horizontal lineage occurred is in doubt, for whilst the logic of hydro-mechanical development may suggest that the opportunity followed from the appearance of the accelerated headrace, current archaeological evidence suggests that it occurred later. We should notice too that at present there is no evidence of horizontal wheels existing prior to the appearance of accelerated headrace vertical wheels.

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12. Vitruvius chose to precede this entry in his book de Architectura with a passage on the noria. Is it a coincidence that in his chapter devoted to water-power, he first described the noria and then the watermill, skilfully using their common features to lead from one to the other? At the very least his presentation follows a developmental path which Reynolds recognised as well. Are there any other parts of his treatise, whether architecture or technology, in which order of presentation might relate to evolution?

We have seen above the limitations of the Roman evidence when it comes to substantiating the proposed evolution model whose credibility is dependent entirely upon future archaeological discovery. Can an examination of post-Roman developments in water-power shed any light on the proposals?

To be credible an evolution model must be proved by evidence of continuity, the existence of a developmental sequence, but what is continuity of an artefact whose existence in the ancient world is only testified by archaeology?
If technological evolution proceeds from a common time origin in, say, two geographically separate diffusions, each having a different time scale[13], then the archaeology of those two traditions could confuse the overall picture of continuity. This is especially likely to happen when the archaeological evidence is scant and only recently discovered. A further complication occurs if we accept that an advanced level of technology can co-exist with lower levels of the same technological lineage[14]. And what time or geographic limits do we put on evidence to demonstrate continuity? No; the problem of attempting to demonstrate continuity of Roman water-power technology from archaeological evidence is at present difficult.

It has been suggested that if Roman water-power traditions were adopted by the inheritors of the Empire, whether Islamic, Christian or Pagan, we should expect to have found evidence of continuity. This presupposes, given that the archaeological evidence exists, that archaeological work has been of sufficient intensity, quality and geographically appropriate to have found it. For whole areas of Europe, whether within or outside the Empire, either devoid of or

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13. Technological evolution, being a derivative of environment, does not necessarily proceed at a constant speed. Corollary One of the environment-based evolutionary model expresses this. See p.257 above.

14. Corollary Two of the model. See p.257 above.

with limited evidence of water-power, post-Roman archaeology cannot be used to support the notion of a dis-continuity in the waterwheels development.

Neither can we turn to diffusion of water-power technology for enlightenment of its possible evolution[15]. The European evidence is insufficient to sustain even the most superficial ideas concerning diffusion or continuity, and it is not surprising that different views are currently held by historians. It is far too early to suggest that because we are unable to detect continuity of the Roman tradition we should look for other explanations for the appearance of horizontal wheels. We must wait for archaeology to advance and expand the corpus to a threshold which will enable historians of technology to analyse and synthesise with confidence.

The traditional view of the Roman period, that of being one of technical stagnation and retrogression, has been questioned as increasing evidence has weakened earlier hypotheses. Kiechle[16] questioned the orthodox view and more recently Wikander[17] has provided a cautious but strong case for its re-appraisal. If the accelerated headrace evolutionary hypothesis is accepted then we need also to assimilate additional fresh views of the development of Roman water-mills and these include: the fact that the Romans had exploited the forces of impulsion to develop undershot and overshot wheels towards a precursor of the vertical turbine; that they may have provided a legacy to medieval man of the accelerated headrace, faster machinery and higher gear ratios (greater torque) and impulse wheels; that such technology was exploited by the military, state, commercial, and private sectors of Roman society.

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15. See Chapter 8, p.246 above.

16. F.Kiechle, Sklavenarbeit und technischer Fortschritt im römischen Reich, Weisbaden, 1969.

17. Wikander, as footnote 4.

As we reconsider our views of Roman technology we might benefit by reflecting on the attitudes and expectations of historians of technology themselves.

There appears to be a naivety among historians when dealing with technology, a propensity to ignore or failure to recognise the part that technical analysis plays in the assessment of problems. This may partly be due to the failure to reconcile old views with changing evidence, and partly that such evidence requires a different interpretation. After all, the study of machines is a different discipline, and herein lies the nub of the problem. Technical design, behaviour and performance are the technologist's domain by definition but it is incumbent on him to recognise the fact and make his contribution accordingly.

But the fact is, that the disciplines must move together. Unless there is an awareness, understanding and an acceptance of the contribution and part which each discipline plays in relation to the others, their synthesis will be much less than perfect. For the historians of technology, both the direction of their energies and the efficacy of their resources must improve. They should continually search for new methodology to facilitate analysis and understanding, whether scientific or philosophical. They should also seek to recognise the limits of their contribution, of the evidence and its interpretation, and temper speculation and hypothesis with a maturity of vision and purpose.

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