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Observations on Wind and Water Power become more meaningful against some background knowledge of the physical features and the history of the locality. In the Island of Crete, history and geography combine on a heroic scale.

On the West-East axis are four principal mountain masses, Lefka Ori (2,451 m.), Ida (2,456 m.), Dikti (2,148 m.) and Afendis (1,476 m.). The higher peaks retain snow cover well into the summer. Much of the rock is porous and cavernous limestone, and the upper slopes have long been denuded of timber. These conditions do not lend themselves to continuous streams and few such exist. Within the mountains are the characteristic plateaux of Crete. These are hollows filled with deep and fertile silt from denudation of the hills above. Characteristically they have no valley outlet but drain through a sink hole (called a Katavothron) into the limestone rock below. The Dikti group encloses the largest of these, the mountain plateau of Lasithi and to the north and east of this group lies the relatively arid peninsula of Mirabello.

Villages are often built around springs which burst out of the mountain sides where the limestone overlies impervious strata. These are often within the 300 m. to 600 m. range of altitude. Some of these springs are strong enough to drive mills before they are diverted to irrigation on the lower slopes. Unfortunately, a lot of fresh water which disappears into the rock reappears as powerful springs under the sea[1] or near to the sea and polluted with salt. These are the Almyroi of Crete. At one of these, the Almyros of Malevisi, there is a surviving water mill, which is unusual, and possibly unique, in Crete in using an undershot water wheel on a horizontal axis.

On Crete arose the gentle and peacable Minoan civilisation which endured for 1,500 years and was dominant in the Aegean. Through Greece its influence is with us today. This civilisation came to a discontinuous end 3,400 years ago.[2] The Island's strategic position between the contending powers of Europe, Africa and Asia is such that it has hardly known peace (except of the Roman kind) since then. Centuries of cruel repression and desperate insurrection do not generate a climate suitable for technical innovation.

The industrial revolution passed the island by. Battye[1] suggested that steam power was still unknown in 1913 and that modern road building had hardly begun. Matters are very different now, main roads of motorway standard exist and electric power is almost universally available. Products of the grape and the olive are dealt with on an industrial scale and the growing of fruit and vegetables for export has tended to replace grain for subsistence.

An initial effect of these changes, which probably gathered momentum in the nineteen twenties, was the construction of thousands of irrigation wind pumps and the corresponding decline in both wind and water corn mills[3]. Even so, during 1972, the author located several wind-driven corn mills in working order, and during 1973 water mills were found, not only in order, but in daily use.

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[1] A. T. Battye, "Camping in Crete," (London, 1913).
[2] J. D. S. Pendlebury, "The Archaeology of Crete" (London, 1939).
[3] N. G. Calvert, "Windpower in Eastern Crete," *Transactions of Newcomen Society*, XLIV, 137-144.

The author travelled mainly in Lasithi and in Mirabello in his initial search for windmills, and in the uplands between Ida and Dikti when the search was extended to include water mills as well. Almost every journey has revealed relevant material.

With one exception, (the mill of the Almyros), all the water mills located are of the vertical axis type, rather loosely referred to as Greek or Norse. Their characteristic is that all moving parts are mounted on a single vertical shaft. There are no gears, the water wheel driving directly on to the millstone shaft. This feature, and the basic mechanical layout, they have in common with the Shetland mill described by Dickinson and Straker.[1] Hydraulically they are superior.

The basic hydraulic elements of the Cretan water mill are shown diagramatically in Fig. 1, and typical mill exteriors are shown in Plate XXXIV (*a*) and (*b*).

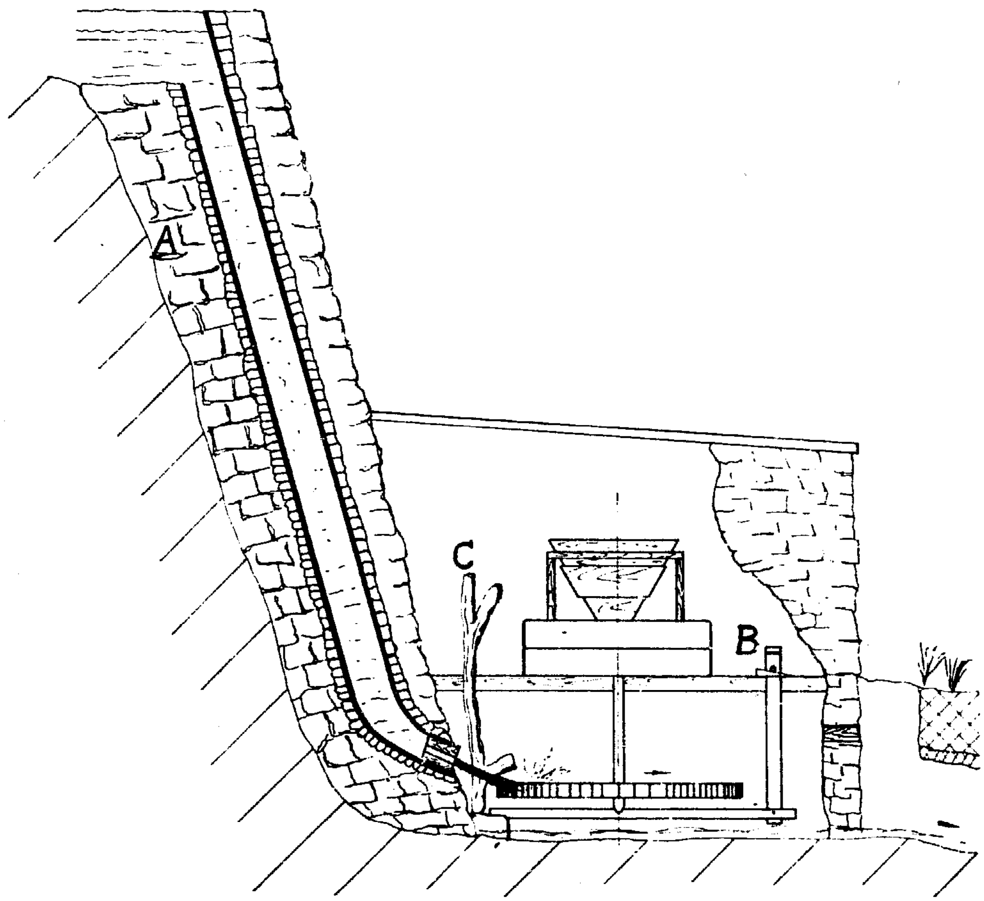


Fig. 1. Cretan water-mill.

Water from a hillside spring or contour leat, is led into a horizontal aqueduct and then to the top of what the author would describe as a water tower. Battye[1] not unreasonably, likened it to a chimney (Fig. 1, A). From the base of this tower, a nozzle forms a jet which impinges on what can only be described as a turbine wheel (Plate XXXIV (*c*)–(*d*)) in such a way that it has both axial and tangential components of velocity. The arrangement is very similar to that of a De Laval Steam turbine.

[1] S. G. Spanakis, *Crete* (Heraklion, 1964). H. W. Dickinson & E. Straker "The Shetland Watermill", *Trans. NS* XIII, 88-94.

A refinement which astonished the author was control by jet deflector. This is a method commonly associated with high head hydroelectric power stations of the present day which use Pelton-wheel turbines. A curved blade can be swung into the jet, thus diverting some of the water from the wheel (Fig. 1, C and Plate XXXIV (*d*)). This gives a rapid and sensitive control irrespective of the inertia of the column of water in the tower, and without in any way interrupting the supply to the next mill when several are used in series. (This happens in some of the mountain villages.)

The constructional materials are of the simplest and most local description. With one important exception stones are small and unworked, timber is of small scantling (often in the round), clay is used and a very little iron. An effective and sweetly running machine is built from what is literally little more than a supply of sticks and stones. It is exceptional for screw threads to be used, fastenings and adjustments being based entirely on the wedge.

Externally the dominant feature of the Cretan water mill is the tower. This is an impressive and durable structure commonly between seven and fifteen metres in height. The author has not yet found one sufficiently ruined to reveal its internal construction, nor yet the form of the passage from the base of the tower to the nozzle of the turbine. Externally the stones may be pointed with a lime and cement mortar, and internally, so far as could be seen from the top, some form of cement plastering had been applied to what (not quite correctly) may be described as the bore. The bore is generally nearly vertical and of about 0·5 m. diameter. Exceptionally, depending on the immediate topography, the whole tower structure may be built inclined so as to appear to lean back on the hillside.

From examination of indigenous related structures, the author considers it probable that inner and outer walls of the tower were built separately, and that the annular space between was packed with puddled clay and rubble stone. The tower derives its stability from the batter of its sides. Whatever the internal construction may be, they are certainly watertight, even under considerable hydrostatic pressure. Their durability is such that they remain standing when the associated works have fallen in ruin. It is interesting to speculate why the batter, so conducive to strength and stability, has not been applied to the local windmills. They almost invariably appear to have had vertical walls and it is rare to find an intact example.

The aqueduct leading to the top of the tower generally runs along the top of a stout wall built up from the ground (A in Fig. 1) or from a form of plinth of rubble masonry. Two cases have been located where the aqueduct was carried on an arch; one of these was so dilapidated that the stone facing had broken away to reveal a clay and rubble type of core. In a dry climate, clay attains some strength (as is shown by sun-dried brick), but even so this type of construction remains weak in tension. The Minoans gave tensile strength to their higher buildings by timber-reinforcement. The towers of the water mills avoid tensile stresses by their proportions.

One example of a mill aqueduct which had been built up from the ground, and subsequently cut away in the course of road construction, clearly revealed a double wall and clay-rubble core.

It should be noted that the flow of water can only be turned on or off from the top, generally by a stop board or paddle which fits in slots in the stones of the aqueduct; thus the tower structure will automatically drain out when the supply in interrupted. This is probably a factor in halting deterioration.

The nozzle has only been observed from the wheel pit. In every case it has been based on a hole of about 0·1 m. diameter bored through a large piece of stone; a hollow wooden bush fits into this hole and it is secured by a ring of wedges. In turn, a sheet metal plate is nailed onto the wood; there is a hole in the metal plate rather smaller than the hole in the wood, thus a sharp edged orifice is formed of about 0·05 m. diameter.

The turbine wheels observed have been based on a wooden disc 0·5 m. diameter into which 30 wooden blades are morticed and additionally secured by interblade wedges. A rim of sheet iron surrounds the whole wheel. The blades have a double curvature and are evidently formed with an adze. The outer diameter is about 1·25 m. and the axial length 0·08 m.

Timber and iron shafts have been observed in approximately equal numbers. Timber shafts may be of about 0·12 m. square at the base, tapering upward, and they have iron inserts at either end. Iron shafts are parallel of about 0·04 m. square section, but rounded for the bearings. In either case the wheel is secured to the shaft by wooden wedges.

The lower end of the shaft (or its metal insert) is rounded and rests in a hollow in a beam of wood, this forming the lower bearing. One end of the beam can be lifted while the other acts as the fulcrum of a second order lever; it is this which gives control to the clearance between the millstones. The upper bearing is a wooden bush located in the lower stone by a ring of wedges.

The lower bearing works under water (which is an excellent wood-metal lubricant), but the author saw no evidence of provision for the lubrication of the upper bearing within the millstone.

The mill building itself is normally built in front of the water tower and is necessarily over the wheel pit. It has split level so that meal can flow by gravity from the stones to a hopper or sack. Two control rods come up through the floor adjacent to the millstones; one is for adjusting the running clearance of the stones (B in Fig. 1) and the other is for the shaft which works the jet deflector (C in Fig. 1). This may well be a piece of round wood with a convenient branch to serve as a handle. In addition, there is a hole of about 0·1 m. diameter. This serves for observation and for a rod to give a small rotation to the wheel when an upper millstone is being re-installed.

The discharge channel from the wheel pit may be either in the open or in tunnel. In the latter case there is always an access hole very near to the mill building.

The roof of the mill building may well be of many parallel bamboo rods plastered over on the outside.

The milk-white appearance of the streams after rain shows that they carry a heavy load of silt. Consequently when a mill falls in ruin, and when roof, floor and stones subside into the wheel pit, the lower levels become silted and overgrown. The turbine wheel, the object of the greatest interest and commonly of wood, is the part of the structure most likely to decay and to be most deeply obscured. Attempts to penetrate the wheel pits of derelict mills did however yield some information. In one case a wooden hub remained when the blades had gone; this showed that circular mortice holes had been used. Another example showed corroded iron suggesting a sheet metal wheel.

Some mills had been rebuilt sufficiently recently to have a flat concrete roof and a concrete floor to the mill room. (Portland cement may have been introduced into Crete by Evans for his work at Knossos.) In one such mill an intact sheet metal wheel was found. From the method of construction (gas welding), the author considers that it could have dated from the war era. This wheel was 1·5 m. diameter and had 40 curved metal blades 0·2 m. long. It had, however, been secured to the wooden shaft by wedges in the traditional way.

The mills located by the author fell mainly into two categories. These are either valley mills which may be fed by a contour leat from a considerable distance upstream, or spring mills, situated in mountain villages near to the source of the water. The valley mills normally had a head pond with a control to allow the water to flow into the mill aqueduct. The control, which was a simple board which could be fitted in slots in the stone, could obstruct the flow. The head pond would thus allow intermittent working when the stream flow was low. All the valley mills located on the northern watershed were out of use, some evidently long derelict. One valley mill apparently intact, was found near Panagia. Spring mills (which were said to be in use throughout the year) without any pond for storage were found in use at Ano Viano, Gerigeri and Zaros. In at least two of these places there were also derelict remains of other mills. An intermediate classification was a mill in a mountain gorge at Dorakion, still in use. Another close by was derelict; this mill was said to work for seven months of the year. Two examples of a "Siamese Twin" type of mill, a tower containing two bores, feeding the mills from a common source were observed—both were derelict.

## An Engineering Assessment

The energy, or capacity for doing work possessed by a stream of water, can have three manifestations. These are its elevation, its pressure and its velocity. Energy loss, that is dissipation into the unavailable form of heat, is associated with high velocities. The Cretan water mill shows an appreciation of these factors.

Flow along the aqueduct is at a low velocity and constant high elevation. Flow down the tower is also at a low velocity. Loss of elevation in this process is compensated by an increase in pressure and there is little dissipation of energy. At the nozzle there is a transition from high pressure to high velocity manifested by the formation of the jet. The jet impinges on the wheel producing forces which cause its rotation. In the absence of test facilities it is interesting to attempt to make an estimate of the hydraulic performance of a Cretan water mill. This can be done if the combination of water tower and orifice is treated as a flow meter. Assumptions are needed, for the jets observed were less perfect than those one would find in a laboratory. Far from showing a vena-contracta there was a tendency for the jet to diverge and to lose solidity. Under such conditions hydraulic coefficients must be assumed and can only be based on the observer's engineering experience. The figures which follow are consistent with velocity and discharge coefficients of 0·91 and 0·87 respectively and with a wheel efficiency of 0·43.

Since the author was on a journey of reconnaissance and not resident near to a working mill, he was not able to get a full set of corresponding dimensions and velocities on any single mill. If the mill was running, it was not practical to enter the pit to measure the orifice and the wheel. Alternatively, if the mill was at rest, the pit could be entered, but the speed would not be known. Nevertheless, since little variation in speed was observed in the mills found to be in motion and only minor differences of wheel and orifice were measured in mills at rest, the author believes that the following figures give a reasonably representative statement of performance.

| | |
|---|---|
| Wheel diameter | 1·25 m. |
| Orifice diameter | 0·044 m. |
| Head of water | 12 m. |
| Jet velocity | 14 m./sec |
| Millstone speed | 2 revs./sec. |
| Quantity flow | 0·02 m.³/sec. |
| Power of water jet | 2·34 kw. |
| Power to millstone shaft | 1·0 kw. |
| Jet speed : rim speed | 1 : 0·56 |

From an engineering point of view, the author would say that

(*a*) Modern concepts in Engineering Science could not suggest any improvement in the basic layout of the plant.

(*b*) That no method of construction limited to local materials could use them more effectively.

(*c*) That given modern technology in the formation of the nozzle and the curvature of the blades on the wheel, the power output of the machine could be increased by about 20 per cent.

## The Mill of the Almyros

This mill is more notable for its unusual water supply than for the intrinsic interest of its structure (Plate XXXV (*a*)).

The Almyros of Malvesi (one of three Almyroi on the north coast of Crete) is a salt river which rises 1·0 km. from the sea 7 km. west of Iraklion. The source is a circular lake 100 m. in diameter and (according to its owner) 120 m. deep. The flow is quoted in local guide books as being 2·5 m.³/sec.

A dam and weir are built across its outlet which gives an immediate head of about 1·0 metre. From thence there is a rapid flow to the sea.

The "Lake" of Agios Nicholaos, which has now been levelled through to the sea by a short canal is probably a similar formation which has lost its flow through subterranean changes.

As a power site the Almyros was developed as a state enterprise in 1415 (Spanakis). Battye reported considerable milling activity in 1911. At present one mill is complete and in order but in February 1973 it was not at work. Two adjacent mills had been destroyed in the German air attack.

The surviving mill has an undershot water wheel (Plate XXXV (*b*)) 3·2 m. diameter and 0·73 m. wide. This has twelve blades of 0·5 m. radial length. The wheel is based on wooden spokes bolted to cast iron flanges. The wheel shaft is of iron 0·075 m. diameter and it is carried on wooden bearings. A cast iron gear wheel 1·6 m. diameter drives a horizontal counter shaft through a gear ratio of approximately 1:6·5 (the exact ratio was not determined by the author). The levels are such that the lower part of the main gear wheel dips into the tail water. The right angle drive to the millstones utilises a cast-iron wheel with inserted wooden teeth and a cast-iron pinion, the ratio is 1 : 3. All the present machinery is below the millroom floor, the stones are 1·3 m. diameter and the capacity is quoted as 338 kg. in four hours. There is a screw adjustment to the millstone clearance and a screw operated crane for lifting the stones (Plate XXXV (*c*)).

At the adjacent mill house a shallow well with a donkey driven chain pump (now superseded by an I.C. engine) yields fresh water despite the enormous flow of salt water only a few metres away (Plate XXXV (*d*)).

Seventy km. to the east is the Almyros of Agios Nicholaos. Spratt[1] records the ruins of a mill dam here, but the author found that there had been substantial changes due to road construction, also heavy growth obscured much of the site. In a brief visit no identifiable remains were located.

The author wishes gratefully to acknowledge help received from Dr. H. W. Catling of the British School at Athens and to thank Mr. Birchall and Miss V. Heaney for the preparation of the diagram.

## Postscript

In March 1974 it was observed that the Almyros of Agios Nicholaos had been considerably opened up by building development. Unlike the dramatic pool of Malvesi this Alymros consists of an extensive swampy area in which numerous crystal clear springs arise. These unite to form an appreciable river as they break through the sand bar into the sea. The ruins of the mill dam reported by Spratt are clearly identifiable.

Visits to further mills suggest that it is normal to use a cup-shaped metal bearing to support the lower-end of the shaft. This always works under water.

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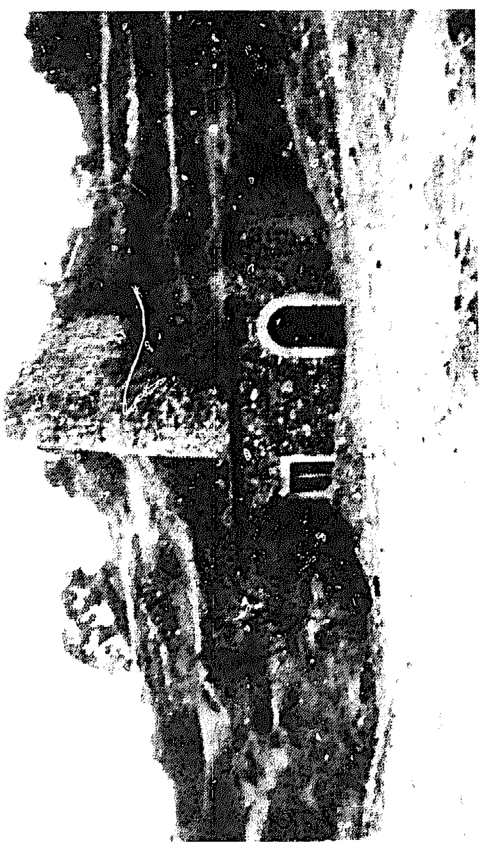
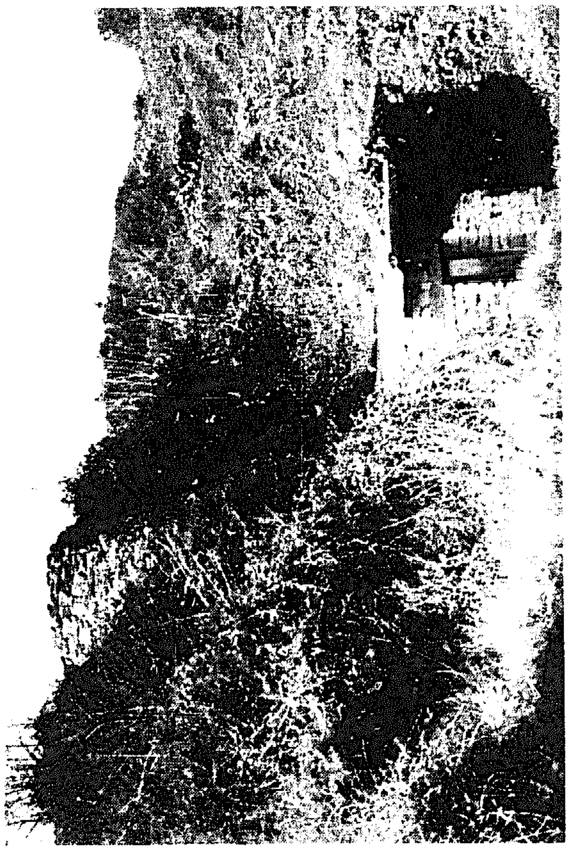
[1] T. A. B. Spratt, *Travels and Researches in Crete* (London, 1865).



(a) Mill at Gonies



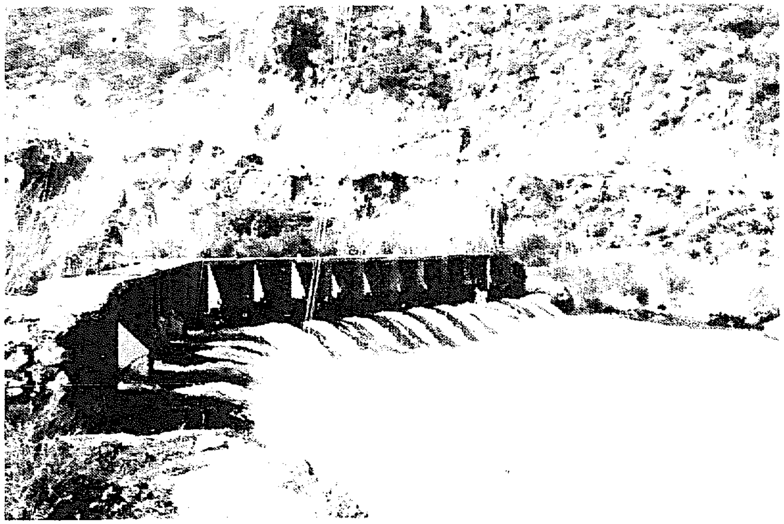
(b) Mill at Avli

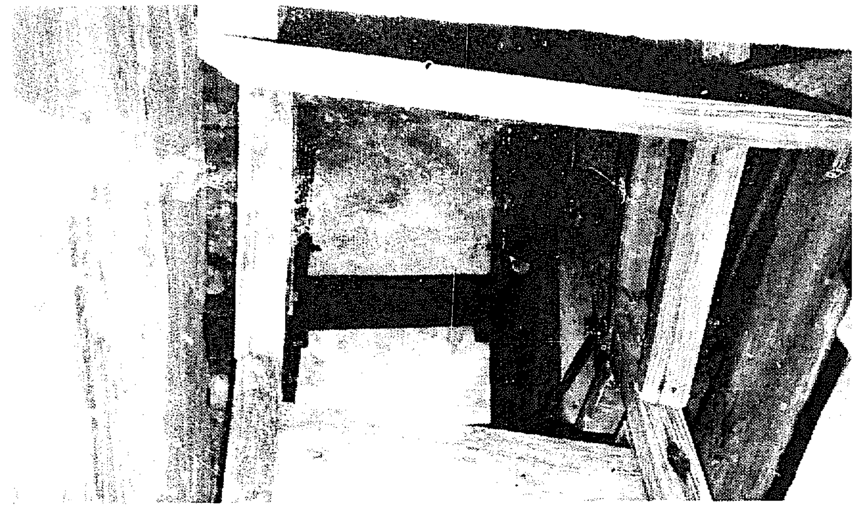
(c) Mill wheel at Zaros

(d) Nozzle and jet deflector at Zaros

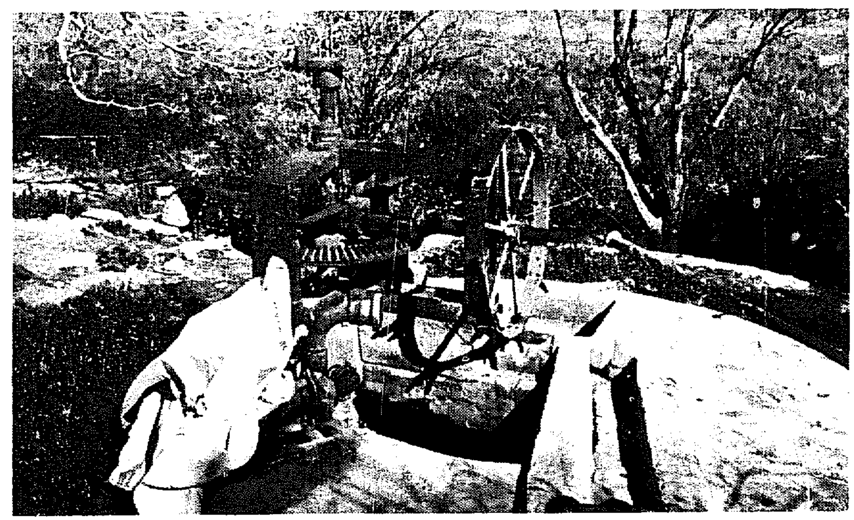
CRETAN WATERMILLS

PLATE XXXV


(a) The Weir


(b) The Wheel


(c) The Crane


(d) The Well

THE MILL ON THE ALMYROS