FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES FOR ASIA AND THE NEAR EAST

REVISED AGENDA

Meeting Room: UNICEF BUILDING, 5TH FLOOR, PHRA ATIT ROAD

Date	Hour	ACTIVITY
Monday, 3 December		Arrival of participants in Bangkok
Tuesday, 4 December	✓09.30	Registration
	✓10.30	Opening of Workshop
	✓12.00	Lunchbreak
	✓14.00	Item 1: Water lifting devices for irrigation: history and general background. Discussion. Prof. Schiøler
Wednesday, 5 December		Public holiday/Review of papers & preparation of Country Statements
Thursday, 6 December	✓08.00	Item 1: discussion continued
	✓08.30	Ms. Chilcott Item 2: Wind powered water lifting for small scale irrigation. Discussion.
	✓10.00	Ms J. Collett Item 3: Hydro-powered water lifting devices for irrigation
	✓10.45	Coffee break
	✓11.00	Item 4: Solar-powered water lifting devices for irrigation. Discussion of Items 3 and 4. Mr. B. McNellis (presented by J.C.)
	✓12.30	Lunchbreak
	✓13.30 -14.15	Item 5: Manual pumping of water for community water supply and small scale irrigation. Ms E.H.A. Hofkes
	✓15.00 -16.15	Discussion
	✓16.30	Item 7: Water lifting devices and water management. Discussion. Prof. Sivanappan

REVISED AGENDA (cont'd)

Date	Hour	ACTIVITY Dr. Abichart
Friday, 7 December	08.00	Item ~~8~~ 7: Water lifting devices and water management. Discussion.
	09.30	Item 6: Development of private tubewells in Pakistan, using locally manufactured equipment. Discussion. Prof. Awan
	10.30	Coffee break
	10.45	Item 11: Socio-economic aspects - general discussion. Mr. Krantz
	12.00	Lunchbreak
	13.00	Slide show of water lifting devices.
	13.45 - 16.00	Country Statements. Prof. Schidler
Saturday, 8 December to Monday, 9 December		3-day study tour to northern Thailand
Tuesday, 11 December ①	09.00	Review of study tour
	10.00	Country Statements and discussion.
	12.00	Lunchbreak
	13.00	Country Statements and discussion.
Wednesday, 12 December ②	08.00	Country Statements continued
	12.00	Lunchbreak
	13.00 - 16.00	General discussion - technical, social and economic aspects.
Thursday, 13 December (2½)	08.00	General discussion continued
	12.30	Lunchbreak
	13.30	Secretariat: Draft summary report. Participants: Study tour (details to be announced later)
Friday, 14 December	09.00	Discussion and approval of draft summary and recommendations
	12.30	Lunchbreak
	13.30	Continuation of morning session if needed and closing of Workshop.
Saturday, 15 December		Departure from Bangkok.

CONSULTANTS/LECTURERS

Item 1:	Professor Thorkild Schioler, Technical College of Copenhagen, Denmark
Item 2:	Mr. R.E. Chilcott, Senior Lecturer, New Zealand/ UK
Item 3:	Mr. J. Collett, Intermediate Technology Development Group Ltd., UK.
Item 4:	Mr. B. McNellis, Intermediate Technology Development Group Ltd., UK (presented by Mr. Collett).
Item 5:	Mr. E.H.A. Hofkes, WHO International Reference Centre for Community Water Supply, The Hague, The Netherlands.
Item 6:	Professor N.M. Awan, University of Engineering and Technology, Lahore, Pakistan.
Item 7:	Dr. Apichart Anukularmphai, Asian Institute of Technology, Bangkok.
Item 8:	Professor R.K. Sivanappan, Tamil Nadu Agricultural University, Coimbatore, India
Item 9:	All participants.
Item 11:	Mr. D.B. Kraatz, FAO.

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES FOR ASIA AND THE NEAR EAST

List of Participants as at 08.00 hrs 6.12.1979

Country	Name	Official Designation	Viengtai Hot. Room No.
Afghanistan	Mr. Abdul Ahad	Engineer, Hadrulik Dam Designation	620
Bangladesh	Mr. M.R. Chowdhury	Chief Engineer, EADC, Dacca	219
	Prof. Hamidur R. Khan	Prof. Head, Dept. of Water Resources Eng. Bangladesh Univ. of Eng. & Tech., Dacca	
Burma	Mr. U. Khin Hla	Executive Engineer (Mechanical) Irrigation Dept., Rangoon	415
	Mr. U. Kyee Nyunt	Director, Agric. Mech. Dept.	415
China, Peoples Republic of	Mr. Zhu Zhongde	Engineer, Ministry of Water Conservancy, Beijing	421
	Mr. Gao Rushan	Engineer, Ministry of Water Conservancy, Beijing	421
Egypt	Mr. Talaat Younan	Engineer, Mech. & Elec. Res. Institute, Cairo	318
Indonesia	Mr. Soedigdo Wiryowidagdo	Chief of Development, Sub-Directorate of Groundwater Dev.	218
	Mr. Sukismo Wiryosuparno	Agric. Service, Yogyakarta Provinces	218
Lao	Mr. Sitaheng Rasphone	Sous-Directeur de la Societe d'Etat de la Construction Hydraulique	
	Mr. Vanthong Phommaconga	Directeur de la Societe d'Etat de la Construction Hydraulique	
	Mr. Thongvanh Phanrajsavong	Directeur du Service National de l'hydraulique	
Sri Lanka	Dr. Leslie Herath	Chairman, Water Resources Board	528
Syria	Mr. Nizar Elmir	Director, Ministry of Public Works and Water	320
Viet Nam	Mr. Nguyen Trong Lac	Hydraulic Engineer, Viet Nam Agric. & Hydraul. Dept.	317
	Mr. Thai Van Le	Dep. Dir. of Irrig. & Drainage Management Dept.	317

Country	Name	Official Designation	Viengtai Room No.
Thailand	Mr. Krod Karakovida	Chief, Mechanical Engineering Division, Royal Irrigation Department	
	Mr. Samroeng Srichanngam	Chief Mechanical Engineer, Royal Irrigation Department	

CONSULTANTS

Thailand	Dr. Apichart Anukulamphai	Assist. Prof., Asian Institute of Technology, Bangkok	
Netherlands	Mr. E.H.A. Hofkes	Programme Officer, WHO International Reference Centre for Community Water Supply, The Hague	215
New Zealand	Mr. R.E. Chilcott	Senior Lecturer Consultant (Wind Power), Dept. of Agric. Engineering, Lincoln College Canterbury	
U.K.	Mr. J. Collett	Water Project Officer, Intermediate Technology Group, London	
India	Prof. R.K. Sivanappan	Dean, College of Agricultural Eng., Tamil Nadu Agric. University, Coimbatore	
Denmark	Prof. Th. Schioler	Professor, Technical College, Copenhagen	

INTERNATIONAL ORGANIZATIONS

ESCAP/Bangkok	Mr. Chung-Daw Wang	Senior Economic Affairs Officer
ESCAP/ "	Mr. M. Kanai	Agricultural Economist
ESCAP "	Mr. Robert A.R. Oliver	Information Systems Expert
ICID "	Mr. Nipond Saihom	Representative
WHO "	Dr. Boleslaw Jan Kukielka	Team Leader

FAO SECRETARIAT

Mr. H. Tsutsui (Co-Director of Workshop)
Mr. D.B. Kraatz (Secretary)
Mr. A. Arar (Regional Office for the Near East)
Mr. K.S. Park (Regional Office for the Far East)

OBSERVERS

Mr. George Klassen, Agricultural Engineer, Mennonite Central Committee, Bangladesh
Mr. Dan Spare, Agricultural Engineer, Mennonite Central Committee, Bangladesh

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FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Agenda Item 1

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

BACKGROUND PAPER

by

Professor Th. Schioler

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FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

BACKGROUND PAPER

by

Th. Schioler

PREFACE

Twenty years ago an FAO publication entitled 'Water Lifting Devices for Irrigation' was prepared by Aldert Molenaar and it soon became so popular that a few years later it was out of stock.

At that time the numbers of man- and animal-powered devices were believed to decline, but today the numbers are greater than ever before. It is estimated that the area for small-scale irrigation in the next decade will be increased by one million hectares. This again will require about two million water lifting devices. Therefore the time has come to reassess the subject in all its various aspects.

1. INTRODUCTION

Simple water lifting devices are used far more than is commonly believed. A rough calculation has shown that there must be about 10 million devices worked by both man and Animal beast. One would expect, therefore, a vast amount of literature to be available on the subject, but apart from the FAO Agricultural Development Publication No. 60 very little has been written.

The purpose of this paper is to familiarize participants with the vast subject of water lifting devices. It deals with devices powered by man, animal and wind; little is said about motor pumps as these are covered in other workshop contributions. The present paper will deal only with devices which have proved to be successful over more than 10 years. Here, success means any contribution to improved crop production and the lot of the small farmer. Cost calculation is a far more complicated matter than one would believe as it is intermixed with social aspects, availability of foreign currency, reliability of the devices, etc. Economic calculations should be based on rather pessimistic figures such as breakdown of a motor, lack of spare parts, dried-up wells and the fact that the crop could not survive more than five days without water.

Successful
> 10 yrs

2. ASPECTS OF A GENERAL NATURE

Some aspects and problems are common to approximately one hundred different devices found throughout the world. Such aspects will be treated one by one as we start with a simple question and end up with a more complex one.

2.1 Local Material

Most of the devices mentioned in this paper are made of local materials, such as wood, mud bricks, stone, rope, basketwork, hide and leather, and sometimes steel wire. Today other material has been added, such as planks and boards, bamboo, cement, plastic tubes, plastic boxes, petrol cans, nylon lines, automobile tyre tubes used as a hose. Scraps from cars may be useful but are subject to price inflation as the demand rises.

2.2 Craftsmanship

There are many questions to be raised on the subject of craftsmanship. The range from handicrafts of a high standard to those of poor quality is enormous. Unfortunately, water lifting devices often range at the lower end of the scale.

2.3 Device Ownership

Small scale irrigation: when a man has his own device he is independent of external purchase of equipment, delivery delays and bureaucracy. In fact, there are few examples of three or four men sharing one motor pump.

2.4 Transportation

If a lifting device is stationary long ditches may be required to distribute water to the land. Fifty percent of the water may disappear on the journey. If the device is movable much water and hence work may be saved. But as the paths to and from the fields are unsuitable for vehicles, transportation must be done on foot or horseback. If is therefore important that the devices can be easily dismantled and separated so that each member of the family can carry a section. A farm of no more than one ha could have three or four wells but only one device which could be shifted from one well to another. The best way to protect the device from thieves is to bring it home under lock.

2.5 Definition of Water Power

Those engaged in the field of water lifting devices should have an understanding of the meaning of power, which in turn needs a definition of force. In practice, the definition of a force is drawn from the second law of Newton and is called a newton:

$$\overset{N}{F} = \overset{kg}{m}\ \overset{m/s^2}{g}$$

N = kracht om 1 kg een versnelling van 1 m/sec² te geven.

Here F = force in newton (N)
m = mass in kilogramme (kg)
g = acceleration of gravity (m/s^2)

In practice 1 newton is equal to the force generated by the gravity acting on the mass of 0.1 kg. In short it is called N. So ~~the force on 1 kg~~ 1 kgf is 10 newton.

$1\ kgf \simeq 10\ N$

Power is given in watt. One watt is equal to one newton lifted one metre ~~within~~ in one second; or, which is the same, one watt is equal to one newton every second lifted through one metre. The output power from a water lifting device is very easy to find. It is the flow (where the flow should be given in newton per second) multiplied by the waterhead. (Flow = capacity of discharge)

1 Newtonmeter/sec = watt

Example:

A Persian wheel lifts the water 5 metres and 60 litres of water leave the device each minute. The ~~flow~~ discharge is then 1 litre/second. A litre is one kg, and the force on one kg is 10 newton so 1 litre/second is 10 newton/second.

$$P = \overset{1l/s \times 5m}{Q_n \cdot h} = 10 \cdot 5 = \underline{50} \text{ watts}$$

As the output from a water lifting device is always water we will call the 50 watts "50 water watts".

In an economic calculation the efficiency of a water lifting device should be given in water watt per US dollar.

N.B. The old term "horsepower" (HP) should be avoided.

hm. P

2.6 Law of Nature

The law of nature for all water lifting devices is that the water must be lifted higher than the theoretically determined waterhead. If the vertical height is 20 m and the water is lifted 21 m the excessive lift is 1 m or only 5 percent. On the other hand, if the head is 2 m and the water is to be lifted 3 m, then 50 percent of the power is wasted.

2.7 Power Requirements

The smallest power in use for irrigation is the output from a boy and that is only 2 water watts. At the other end of the scale there is no limit, but for small-scale irrigation it is in the order of 8 000 water watts (see Figure 1).

A rather natural way to classify the range between 2 and 8 000 is to use a doubling scale, viz. 2 - 4 - 8 - 16 - 32 - 64 - 125 - 250 - 500 - 1 000 - 2 000 - 4 000 - 8 000 water watts. In Figure 1 we see that a camel has an output of about 250 watts, but if we prefer to use manpower instead we need 30 men. Further up the scale one diesel pump may replace 10 camels, and may still lie idle for most of the time. Therefore, in small-scale irrigation investment in motor pumps is often yielding poor return. The same method of a doubling scale should be used in showing the distribution of depth of wells. Field work has shown that the mean depth of wells powered by animals is around 5 m. This means that 50 percent of all powered devices (probably 5 million) are to be found within the limits 32-250 water watts. Obviously, when we consider well irrigation the seminar should concentrate on these devices.

2.8 Power Adjustment

The devices should be selected according to the power source available. For example, a strong man should not work a device intended for a child. A camel-powered Persian wheel should not be drawn by a donkey. A girl should not carry 25 kg (see Figure 2).

2.9 Reliability

Reliability is a new term used very much today in modern technology. Reliability is expressed in terms of probability, e.g. out of 100 devices the occurrence of a given event is for instance 80 out of 100.

We will now talk for a moment about the lifetime of machines and devices. Field studies on the lifetime of machines have shown that the probability of survival is following a model called the negative exponential function $p(t) = e^{-\frac{1}{MTBF} t}$. However, the term lifetime is not adequate as the machine or device can be repaired and so be born again. The correct term is "time between failure" and an important parameter is Mean Time Between Failure = MTBF. The probability that a device will be older than MTBF is: $p(MTBF) = e^{-1} = 0.37$. This means that 37 out of 100 will be working more than the mean time between two failures.

Just as the lifetime of man depends very much on where he lives so does the MTBF of an electric motor depend very much on how it is protected against rain, frost, wind-blown sands, overloading, voltage drops, voltage peaks, blackouts by lightning, etc. If there are no risks of these kinds the MTBF is 8 000 hours for an electric motor. So out of 100 electric motors 37 will work more than 8 000 hours (about 100 days irrigation, 8 hours per day, 10 years is 8 000 hours). But if the motor is not protected with protecting devices, the MTBF may be only 80 hours (daily voltage drops are particularly serious). So the probability that 10 000 motors in a region will survive 10 times the MTBF is $e^{-10} = 0.000045$ which means that half a motor will survive. But if there is a possibility for repair things will change.

If a big town has 100 000 automobiles there should be about 300 workshops for repair. Let us assume that in a region with 10 000 elctromotors for irrigation 30 repair shops will suffice. The distribution of time for repair is also negative exponential. The Mean Time for Repair = MTFR is 20 hours.

Mathematically, it can be shown that the probability of the electromotor to be in a "failing condition" at time t is

$$F(t) = \frac{\frac{1}{MTBF}}{\frac{1}{MTBF} + \frac{1}{MTFR}} \left[1 - e^{-\left(\frac{1}{MTFR} + \frac{1}{MTBF}\right)t} \right]$$

Taking 5 days as the tolerance limit for interruption of irrigation flow due to motor failure, the probability for crop losses is the probability for a non-working condition multiplied by the probability that the repair time will exceed 5 days. This is:

$$F(t) \cdot e^{-\frac{5}{MTFR}}$$

3. MAN-POWERED DEVICES

3.1 Water Bowl

If the irrigated field is less than 200 m^2 the water could be lifted and spread over the paddy by means of a metal bowl. Aluminium bowls are preferred because of their lightness. A child or an old man can lift 3 to 4 m^3/h of water from a pond to the field at its side at a level difference of 0.15 m with an output of 1 or 2 water watts (Figures 3 and 4).

Another method of irrigation of paddy fields is by taking water from a lake (Figure 5a) in a 20 litre jar and spreading it over the paddy, placing the palm of one's hand over the opening to control the flow of water coming out (see Figure 5b). Walking on the paddy would damage it; therefore, in order to reach the whole of the paddy the water is transferred from the jar to a basin and thrown over the field (see Figure 5c). It is wise to have two different-sized basins, one big and one small. The latter is for the long throw. A strong man should do the work as walking with a 20 litre earthenware jar is strenuous. Yet the output power of the paddy watering man is only 5 water watts. In this example the investment of 10 cents on the jar and 0.5 dollars on the bowl is the only reason for doing this work and using this time-consuming device.

3.2 Water Scoop

Using a shovel or scoop, as shown in Figure 6, is a good method for lifting water. It is a substitute for the bowl in Figure 4 and has more of a "raindrop" effect when throwing water. For many crops this is far better than being submerged as it saves water. The shovel should be light and formed in such a way as to give optimum efficiency and performance with regard to the sprinkling effect. Further research into this and the most suitable material to be used seems to be highly warranted.

3.3 Suspended Shovel

If the shovel is suspended from a tripod it can take much more water but is less mobile. This method, which is used in the Far East (see Figure 7) is ideal for lifting water up to 0.5 m head. Instead of using the word lifting it is more descriptive to say pushing. The handle of the shovel is pushed and guided in such a way that a layer of water is washed up the blade and goes down again when the blade is in its upper position (see Figure 8). The waterhead can be about 0.5 m but a lift of 0.7 m is required. The blade of the shovel pushes about 5 litres at every swing and is worked at a high speed. The frequency is 30 swings per minute. The mean power requirement is about 15 water watts. There is a suction zone behind the blade of the shovel which draws with it a great amount of water. Unfortunately this water never reaches the paddy fields as it is dropped on the way. About one third of the lifted water is wasted in this fashion.

The tripod construction should be rigid and fixed to the ground by means of pegs and cords. The shape of the bladescoop is either triangular or trough-like.

The suspension is not only simple but ingenious. It is a double pendulum, and therefore the edge of the blade can be guided in such a way that it has a shaving effect on the water surface. Two of the suspension ropes are fastened to the blade and one is tied to the handle by means of a loop so as to permit adjustment of the position of the blade. The perpendicular rope is fastened to the bamboo beam with a loop and can be adjusted. Before the man starts his job he puts the broomstick in a vertical position to see whether the edge of the blade has touched the surface. If not he makes the necessary adjustment at the two loops. With this apparatus something between 10 and 15 m^3/h can be lifted 0.5 m. This device is particularly suitable for paddy fields of less than 1 ha and up to 0.5 m head. It is worked by one man and the total investment is in the order of a few dollars. It is easy to take down and could be carried to the next field by the man himself.

0,5 m head
10-15 m^3/h

e

A curious way of working this apparatus is seen in Figure 9. Some research should be made on this construction to see whether it is or can be optimized.

3.4 Swing Basket

The swing basket (Figure 10) is still very much used and is not as primitive as one would first believe. Its great advantage is that it is cheap, small, mobile and can be made of local materials (Figure 11). The basket may also be made of iron plate (see Figure 12). Three sizes are commonly used, the smallest for a lift of over one metre, the middle-size for around half a metre, and the biggest for a lift of 0.2 metres. The medium size has a capacity of about 8 litres but holds only 4 litres during the work. We may say that the volumetric efficiency is just 50 percent.

The bucket or basket has attached to its rim four ropes with handles. The basket is hewn into the water and then lifted by the pull of the man leaning backwards (see Figure 13). The motion is easily learned and can be continued for hours, with short rest periods. To the young boys in Bangladesh it is a sport to make 2 000 swings before a rest. In one installation in the same country four of these swing baskets powered by eight men are used to lift water 5.5 metres. The first lift is 1.2 metres, the next 1.3 and then 2 m. The last has a waterhead of 1.7 m. This makes a total of 6.2 m. The extra head 6.2 - 5.5 = 0.7 m is due to the head needed to have the water run from one device to the next. The effective mean power delivered by two men appears to be only between 8 and 15 water watts as the suction zone behind the basket lifts a great amount of water, which is returned to the supply.

effective
power
8–15 watts

3.5 Canoe-type

The one-sided supported canoe is very much used (see Figure 14a). Probably around one million are in use along the Ganges and the Bramaputhra. The canoe can be made from a tree trunk or planks (see Figure 14b). If the canoe is straight it can only lift the water about half a metre.

As can be seen from the illustration (see Figure 14c), the man first pulls down the upper beam connected to the canoe and stands with one foot on the canoe. He then lowers half of the canoe beneath the water before transferring himself to the lower rod on which he stands. He then lifts the canoe until the counterweight can take over; just before the canoe is completely emptied, he stops the movement by restraining the beam (Figure 14d). On the way down he pulls with a force of about 10 kg or 100 newtons. The moment the canoe hits the surface a greater force must be used because of the upthrust. A cycle takes about 6 to 9 seconds but many pauses are needed. The mean power is a little above 10 water watts. At a head of 0.5 m the flow will be 7 m^3/h.

10 watts
7 m^3/h
head: 0,5 m

The moment the canoe comes to the surface a big volume of water rushes back to the water source. About half of the lifted water never reaches the rice field.

As the farmer's land is normally scattered (in as much as 9 parcels) it is important that he himself can haul the canoe from one field to the next.

3.6 Counterpoise Lift

The counterpoise lift is a well-known, easy-to-build and easily worked device. The best construction is found in Egypt (see Figure 15). The horizontal arm consists of a beam which has a weight at one end made up of a network of branches filled-in with mud and at the other end a perpendicular rod holding a bowl or metal-type dipper. The beam is supported by two upright posts which are made of a sheaf of sugarcane filled-in with mud.

The work is done by drawing down the dipper under which the counterpoise is lifted. Partly filled with water the dipper goes up. The whole system forms a double pendulum. This has a dynamic equation which could be solved by means of a special FORTRAN programme. The computation shows that if the dipper should be raised at a reasonable speed the dipper must only be filled with 70 percent of the total holding.

The mean power should be about 20 water watts.

In India the counterpoise is replaced by a to-and-fro walking man (see Figures 16 and 17).

3.7 Paddle Wheel

The paddle wheel splashes the water up into the field. The illustration in Figure 18 shows an improved paddle wheel.

3.8 Water Ladder

A very much used device is the water ladder (see Figure 19). It is used in China and some other parts of the Far East. It is made entirely of wood, is turned with one's feet and is perhaps the best man-powered device for small lifts. This is because it is turned by the feet. The human body has more power in its legs than in its arms. On the upper shaft there could be pedals attached so that it may be worked by up to 8 men. This is the only case where we have the possibility of a regulation of the input power. Much power is lost in friction and by return water. Probably no more than 10 percent is effectively used. The water ladder can be worked by animals and wind (see Figures 20, 21 and 22). It is not in use in India and Egypt.

efficiency! < 10%

3.9 The Archimedean Screw

This device belongs to Egypt where it was invented two thousand years ago. It is turned by one or two men (see Figure 23). If one man turns it the output is about 20 to 30 watts. This is a rather high output.

There are many advantages to this device compared with others. The power application is based on a rotation rather than on a to and fro or up and down motion.

As the screw is nailed to the drum, water is not leaking between these two parts. But some return water exists. If the intake is submerged 100 percent it takes in more water than can be guided up the snail. This is a sort of super charge. A great amount of surplus water will return to the water source. For more than 2 000 years the drum has been a straight cylindrical but this may not be the ideal form. A slightly conical form will probably raise more water and save some of the return water. At the same time the iron hoops round the drum could be adjusted by the farmer himself (compare with the shape of a vat or barrel). The water has to be lifted about 5 centimetres more than the water head, which is about 0.4 metres. This is a small waste of power. Laboratory tests have shown that no more than 50 percent of the available power is used; however, most other devices have an efficiency far below this figure.

eff. 75%

The Archimedean screw can be made entirely of local materials except for the iron rod which follows the centre line. The mantle is often made of iron plate, but planks can also be used. A number of hoops are fastened round the drum, but as it is not barrel-shaped the hoops are stretched - in a rather poor way - by means of wedges. The screw is made of about 80 propellers (Figure 24) which are put together over an iron rod whose upper end is shaped to a crank-handle. A post is placed in the water and serves as support for the lower end. Its upper end is supported by a beam. Much can be done to improve this excellent construction and steps are being taken in this direction. In Egypt manpower has been replaced by the donkey, which turns the screw by means of a rear axle gear obtained from used cars. Now the manpowered device is changed to an animal powered machine, but at the same time the device is now stationary and not easily moved from one place to another (Figure 25).

X

As engineering computations are rarely made in this field, here is an opportunity to do so.

The Archimedean screw is constructed in relation to the power of a man. The gear ratio is constructed in relation to a car. A pleasant speed for the donkey walking in a circular track is the same as the normal speed of a walking man (Figure 26). At this speed the donkey can supply a device with a power of 100 watts, but as the screw is constructed for a man 20 water watts would be sufficient. It would therefore be necessary to adapt the screw to the output of a donkey, for example, by enlarging the diameter of the screw.

The screw is a 20 watt device at 30 rpm. A pleasant speed in the circular track is equal to 3 rpm. The gear should then be of a ratio of 1 : 10 but it is 1 : 5 which makes the screw turn 15 rpm only equal to just 10 watts. As the flow is proportional to the diameter of the screw in square, and the water watts are proportional to the flow, the diameter should be multiplied with a square root of 10. This is about 3.15; the diameter should be enlarged from 0.4 to 1.25 m.

The Archimedean screw is the only water lifting device which has been studied scientifically, and this more than 50 years ago; the Institute of Civil Engineers, Selected Engineering Papers, No. 75. Experiments on an Archimedean Screw by Herbert Addison, London 1929.

Research has been done ✓

3.10 Manpowered Devices for Well Watering

There are more than 10 million irrigation wells in the world. Among the various power sources employed for lifting water from wells, man is still the main power source.

3.10.1 High lift counterpoise

The high lift counterpoise (see Figure 27) is capable of lifting water 7 metres and is worked by three men. Two of the workers act as counterweights by walking to and fro on the beam, while the third man controls the output of the water. Most of these devices are to be found in India.

If the beam is too slender to form a gangway for the workers, they have to stand on the field and pull the device down by means of ropes (see Figure 28). Two hardworking men have a maximum output of about 80 water watts.

In Bangladesh an elegant bamboo type is built. It can lift the water 6 to 8 metres. The bamboo mast is so slender that it sways because of the weight. It is usually operated by a boy and can irrigate a garden of up to 400 m^2. The well is slender, one metre in diameter only. The cyclus is about 13 seconds and it lifts 7 litres every time. An hour's work will give 5 mm water on a 400 m^2 garden. Vegetables are grown. (See Figure 29.)

All these devices are made by the farmer himself and have many weak points in the construction. The MTBF is probably in the order of 100 hours [1] but what is important is that MTFR is only 0.5 hours because the farmer himself can repair it immediately on the spot. The probability that the counterpoise is in working condition at time t is 1 - 0.005 = 0.995 or 99.5 percent, which is extremely high.

reliability ✓

3.10.2 Hand and foot-powered potgarland wheel

Man uses his arms and legs to turn the wheels of some devices. If this is a potgarland wheel (see Figure 30) the water flow is continuous. The wheel must be fitted with a pawl mechanism to prevent it from reversing should the man lose his grip on the handle. This device is working in India on the west coast but we should like to receive further information concerning its output, etc.

X

3.10.3 Farmyard pump

More attention should be given to the farmyard pump or the hand pump which has proved to be extremely successful as an irrigation device in Bangladesh. Out of 400 000 new hand pumps intended for

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[1] 100 hours or 4 days = 20 working hours. Buses in Toronto have a MTBF of 100 working hours or 10 days.

domestic use, about 120 000 have been used as irrigation pumps. As it is a sensitive device and for the farmer a rather complicated machine, the number of failures is most important. MTBF is governed by the number of strokes per day v.i.; MTFR is governed by the availability of spare parts.

Historically the hand pump started as a family farmyard pump. In Sweden in the 19th century it was made of wood. Later on it was made of cast iron. It was in fact used very little. We may assume that during 100 days only 8 000 strokes were made (i.e. a high MTBF). Today, as an irrigation pump, it is worked by two strong men for 10 hours per day in 100 days. This makes 1 200 000 strokes during the same period (i.e. a low MTBF). The irrigation handpump should by no means be compared with the farmyard pump, but more with the village handpump.

20 × 60 = 1200 strokes per hour

100 days irrigation ✓

During the last ten years the World Health Organization (WHO) has given considerable professional attention to the handpump for domestic use. It has published a book entitled "Hand Pumps for Use in Drinking Water Supplies in Developing Countries", Technical Paper No. 10, International Reference Center for Community Water Supply, Woorburg (The Hague), Netherlands, 1977, which could be used as a standard work for its way of treatment.

The output for a hand pump should be around 20 to 30 water watts. The flow is about 40 litres per minute but field research has shown that 60 percent of a big number of hand pumps in Thailand was out of order. This figure concerns MTFR which is perhaps several months. Intensive maintenance is necessary for the effective use of handpumps in irrigation areas due to the heavy use and poor quality of the pump. Special emphasis should be placed on the quality of the cylinder casting. The grade of phosphorous used in the cast iron should not contain more than 0.15 and 0.20 percent.

If the cylinder and the plunger (piston) together with the pin and fulcrum construction were of the same high quality as the internal combustion engine in an automobile, the hand pump used as an irrigation pump would last for more than 300 years. X

Man can do more work with his feet than with his hands; therefore some sort of pedal should replace the handle. If the pedal is connected to a flywheel which could store some energy for a moment and return it in the next moment the pedal work would be more convenient (Figure 31). The moment of inertia depends on the degree of irregularity of the crankshaft. To avoid big forces on the piston one should try to put in a spring between the crank and the piston rod.

The hand pump has proved successful as an irrigstion pump in Bangladesh where more than 120 000 are in operation. As the repair time = MTFR is very long every pump used for irrigation should have a standby in order to prevent disastrous interruptions in irrigation water supply.

Used as irrigation pump MOST!

4. ANIMAL-POWERED DEVICES

The traction animal, such as the donkey, ox, mule, horse and camel, has three to thirty times the power of man but roughly one tenth of the motor pump.

In most cases the peasant must have an animal for riding, ploughing, harrowing, transporting and threshing as well as for irrigating.

The harnessing of the animal is still a big problem. The wrong pull and strings cut into the hide which cause wounds filled with flies is the rule rather than the exception. Not only man should be protected against sun and rain but also animals and equipment. An ill and underfed beast has less power than a man. In some cases the animal walking in a Persian wheel has a boy to look after whether it is working or not.

Those animals which do not need a boy are normally walking at a moderate speed. They are well harnessed and well-fed and perhaps covered by a net to protect them against flies. They may stop for a moment but then start work again on their own.

4.1 Sack and Pulley Device

This device consists of a sack provided with a big opening at the top where the water gushes in, when the sack is dipped into the well water. In the top opening there is a main rope at which the animal pulls. On its way up through the well the sack's bottom opening is held at the same level as the top opening. At the rim of the well the second rope pulls the bottom in a horizontal direction whereas the main rope is still in a vertical position. The water escapes from the sack in a big flow. (See Figure 32.)

The sack and pulley is a very much used device (some millions) and is far better than it appears at first sight. Local material is normally used but Figure 33 shows an example where the sack is made of a manufactured metal drum. The hose is made of a tyre tube from a car. The pulley belongs to the bricklayer's tools. The rope was a blue nylon rope found on the beach. The pillow which is placed between the shoulders of the mule and the two sticks which serve as harnesses is made from a pair of trousers filled in with straw. This device was seen in Tunis where scraps have little value but in other countries a rope of nylon could mean a fortune. The path of the animal is sloping away from the water well so as to facilitate the animal's pulling operation.

A peasant may have only one sack-pulley device for three to four wells, moving the device from one well to another as required. ! Wells from 6 to 60 m depth are worked in this way. Deep wells should be powered by a camel.

The force in the heavy rope on the first metre is rather small because the sack is submerged. It rises gradually as does the force.

Sack & Pulley Device

At the very moment when the sack is getting clear of the water surface, it becomes very heavy and the man has to assist the animal. For a few seconds the man, beast and the slope yield a power of about 500 water watts. When the water runs out of the sack the force decreases and the beast can take a rest. When the man lifts the two side straps, the animal is able to turn round and then walks up the slope. At the top of the slope it turns again and has a little rest before its next effort. The water empties into a basin from where it is discharged in a steady stream without eroding the ditch.

This device is commonly used in India (see Figure 34) where the water table is usually less than 6 metres below the rim. In winter it is often 2 to 3 m only. Where the rope is pulled only 3 metres the bullocks do not turn round as it takes too much time, but are forced to walk backwards by means of a rein which goes through their noses. The sack can be made of leather but is often replaced by a big metal bowl which resembles a wash boiler with a hole for the hose to which end the second rope is fastened. Such a container holds about 100 litres, but as the container itself is heavy the total weight is about 120 kg. For such a big force two bullocks are needed (Figure 35). During their way down the slope they generate a power of about 800 watts. When irrigation has been completed at one well all the objects as pulley, container and two rollers are loaded on the animal or the members of the family and moved to the next well (Figure 36).

It is obvious that a great amount of power, or more correct, work is wasted in this device but the degree of reliability is very high. To the farmer this is most important. The container made by the local blacksmith may hold for years, cost about 10 dollars and can be brought under lock. The hose made of leather is more sensitive but is rather cheap and can be made in a day.

4.2 The Persian Wheel

Several kinds of Persian wheel designs, ranging from gigantic wood constructions to small factory-made gear machines, are found from Morocco to China (Figure 37).

Persian wheel

For the gear we have a potgarland wheel on which the potgarland is hung. The potgarland may be of earthenware pots lashed to two endless ropes or may consist of ironmade containers or buckets each of which is fastened to two iron rods. Pair by pair the iron rods are connected to form an endless chain.

In some respects the pot and rope construction surpasses the iron bucket chain. It is very easy to change the distance from one pot to the next. This is nearly the only way of changing the flow from the device. The flow is equal to the numbers of pots passing the top of the potgarland wheel per minute. This again has to do with the depth of the well. If the depth is about 20 metres, the distance between the two consecutive pots should be about 2 metres but for a 4 metre well the distance should be 0.4 metres only. This is obvious as the required power is the product of flow and head. If the head is divided by five the flow should be multiplied by five. This is by no means obvious to the farmer. If the water head is doubled during the dry season, the number of pots should be halved. If it is a bucket chain this is impossible. In such a case the ox or oxen would have to adjust of its own accord by means of reducing the speed. It can change the speed but not the traction force so the force tension on its neck will be doubled.

Normally the diameter of the well should be more than 2 metres according to the diameter of the potgarland wheel. It must be a big wheel if the jet from the pouring pot is inside, and it must be inside the wheel because of the trough. A 2 metre diameter well costs four times that of a one metre well. A Persian wheel type with a one metre wheel does exist. Here the trough is not placed inside the wheel but under it. The trough is about 2 x 2 metres and has two holes, one for the upgoing potgarland part and the other for the downgoing part. Each hole is equipped with a rim.

The gear is the weak spot in the Persian wheel construction. Failures occur if craftsmanship is poor, and if newly felled wood is used instead of seasoned wood stored for about 3 years. Due to alternate moisture-drought exposure the serviceable life of the gearwheels is usually short. The best wheels are found in Afghanistan and Pakistan. Made of hard wood and kept together with wooden pegs the laminated rims can last for a long time. (Figure 38)

Small factories exist which make cog wheels in iron. Using a hammer, chisel, taper pin and forge with a bellow, both wheels and bucket chains are manufactured to a price just a little over material cost price. (See Figure 39.)

The Persian wheel construction is reliable and is working with a high degree of efficiency. As all parts are visible the farmer can detect any weakness in time. He can call for the carpenter long before the part in question breaks down.

4.2.1 Examples of outputs from different Persian wheels

Power output from a Persian wheel (Noria de sangre) in Spain drawn by an exhausted donkey but without anyone to keep watch. Measured in 1955.	44 water watts
Power output from a Persian wheel drawn by a healthy bullock; none to keep watch. Measured in 1979.	90 water watts
Power output from Persian wheel in Pakistan drawn by two exhausted oxen. Looked after by the farmer.	170 water watts
The same Persian wheel but after the farmer has whipped the oxen. The output was then for a very short time.	500 water watts
Power output from a Persian wheel in India near Agra worked by two Zebu oxen.	180 water watts

Power output from Persian wheel near Agra worked by a camel which had rested.	240 water watts
Power output from Persian wheel in India, well greased, drawn by an ox which was held at top speed by an old woman with a whip. Measured in 1979.	120 water watts

5. WIND-POWERED DEVICES

Worldwide interest in wind power has increased considerably during the time since 1973. A good deal of literature is available; even bibliographies have appeared. A great many projects have been launched in Africa and Asia but not all have been successful. Here we should deal with small-scale windmills only.

And we shall only deal with those constructions which have proved successful.

A steady wind is needed for reliable irrigation; in practice, this means that during the irrigation season it should be windy every day with few exceptions. However, wind as a power source is far better for irrigation than for electric light because water can be easily stored from day to day.

Along the border of the Mediterranean Sea - forty years ago - there were more than 50 000 windmills in operation for irrigation. During the last 25 years the farmers along the same border have increased their income many times because of the tourist industry. They have therefore invested in motor pumps. This is also true for the coastline of Crete but up in the hills 100 kilometres from the hotels about half of the 6 000 windmills in the Lattashi plateau are still working 100 days a year.

5.1 Windmills on Crete

A great many facts about windmills can be learned from the 6 000 windmills on the Lattashi plateau on Crete. Here again the reliability is most important. We will look at two different types.

i. A 20 m high steel tower windmill of modern design with a gear box which has an oilpump for lubrication - this can work for five years without problems. Although wind is a power source free of charge, the price of mills is so high that very few farmers can pay the investment. For the same money a farmer may buy a little motorpump including gasoline for five years.

ii. The poor farmer has to look for a cheap and perhaps less reliable windmill, but it can be made by local craftsmen and he can repair it himself.

The rotor should be of the Cretian type (see Figure 40a) which turns even for low wind velocity and has a big momentum. The area of the sails can be made very small when the wind speed increases. In cases of storm and when not used the wind blown area is set to zero. Otherwise with the rosette rotor some wind blown area is always present and with high speed winds, e.g. 100 km/h, makes a force on the rosette of about 2 000 kg (20 000 N). This force would overturn the mill. In Tunisia thousands of such wrecks can be seen.

The rotor with its sails has to face the wind. This is achieved by the tail. At low wind the force on the tail is too weak to overcome the friction of the turntable. The turntable is rather sensitive and is often one of the weak points of the construction. It should be greased nearly every day and so should the bearings. The steel tower, which on Crete is just 6 m high, is made of section iron and all the joints are bolted. Welding is not practised.

The shaft for the rotor is supported in two bearings (Figure 40b). The front bearing takes over the vertical and horizontal force whereas the tailbearing just supports the vertical force. The bearing pans are of hard wood. The crank is between the two bearings and gives a stroke for the plunger of 180 mm. Between the plunger and the crank there is a long piston rod. On its way up a big force is needed to lift the water. Whereas on its way down no work should be done. Therefore a stone (some kilogrammes) is fastened to the end of one of the sticks which holds the sail. When the crank is going up the stone is going down and dynamic balance is achieved.

The weak point in this mill construction is the pump. But all the problems are of the same kind as for the hand pump. The cylinder (D=180 mm) should be of brass or other very smooth material. Cast iron bored on a lathe is like a file for the plunger cup seal. The piston rod is rocking a little to and fro because of the crank motion which will also spoil the cup seal.

When the mill stops there is plenty of water over the seal cup but if this water evaporates then the seal cup is not lubricated, and together with the wind blown dust - which works as polishing powder - the necessary tightness between the cup seal and the cylinder is spoiled. The foot valve is of a rather poor construction; it is made of leather and serves at the same time as packing. It has a rather short life but is easy to replace as it is very cheap or could be made by the farmer himself. The plunger valve is in most cases of bronze and this and the plunger construction is factory made. As can be understood from the above, the pump is the weak part of the device, not the wind rotor.

The following is a comparison between windmill no. 1 and no. 2 using the theory about reliability as discussed in Section 2.9.

The MTBF of the windmill of high standard (no. 1) is 1 year and the home-made mill on Crete (no. 2) is about one month (1/12 year).

To have a high standard mill (no. 1) repaired is most difficult and MTFR is about 3 months (1/4 year). Mill no. 2 can be repaired by the farmer himself so the MTFR is just 7 days (1/50 year).

First we have to compute the probability that the mill is in the failing state at t = 2 months (1/6 year) after installation (t is chosen arbitrarily). For the home-made mill (no. 2) it is:

$$F_{home}(1/6) = \frac{12}{12+50}\left(1 - e^{-(50+12)1/6}\right)$$
$$= 0.193\ (1-0.00003) = \underline{0.19}$$

For the high-standard mill (no. 1) it is:

$$F_{high}(1/6) = \frac{1}{1+4}\left(1 - e^{-(1+4)1/6}\right)$$
$$= 0.2\ (1 - e^{-5/6}) = \underline{0.113}$$

The calculation shows that the probability that the home-made mill is in the failing state is two times the same probability for the high standard mill.

The next step is to find the probability that the repair time surpasses 5 days:

$$F_{home} = e^{-\frac{5}{7}} = \underline{0.49}\ ; \qquad F_{high} = e^{\frac{5}{-90}} = \underline{0.94}$$

These probabilities should be multiplied by the probabilities derived above, hence:

$$F_{home} = 0.19 \times 0.49 \simeq 0.1 \qquad F_{high} = 0.11 \times 0.94 \simeq 0.1$$

The result is that the two mills are working with the same degree of probability of failing to provide water after 5 days stop. In absolute terms the probability of failure, however, is low. What should be learned from this is that a relatively unreliable home-made device is made reliable thanks to favourable conditions (Figure 40c).

6. WATER-POWERED DEVICES

This subject will only briefly be touched as it is covered by other contributions to the Workshop. The most important of the traditional water powered devices is the water wheel. Some wheels - called hydraulic norias - have diameters up to 30 m (see the Hama wheels on the front page). The wheel is equipped with blades and between these are fastened earthen pots or vessels of any kind. Bamboo tubes are excellent as vessels because of the slender form. The vessels lift water to the top of the wheel. A low, fat bucket will waste most of its content long before passing the top of its circular path. If the water is to be lifted over a high bank or there is need for a high water head to transport the water by an aqueduct far from the river, then the water wheel noria is excellent. The wheel is easy to build and powerful. Those in Hama (Syria) must have an output of several kilowatts. There are two problems which should be considered: 1) when there is most need for irrigation water there is probably no water in the river; 2) the wheel should be in some way secured against floods as the wheels can be washed away. However, there seems to be no such arrangement and therefore the noria-wheels are shortlived if not repaired. Their long history and distribution in the world can be learned from; Julio Caro Baraja, Norias, Azudas, Aceñas to be found in Revista de Dialectología y Tradiciones Populares, Vol. 10 (Madrid, 1954) p. 29-160.

7. MOTOR-POWERED PUMP

7.1 Internal Combustion Engines

The step from an animal-powered device - around 200 water watts - to an average oil engine pump - around 1 700 water watts - is too big if it is to be used for the same purpose. Not only the step in water watts is big but the technology is much more advanced. The farmer must understand flow, water head and power if he is going to buy the correct motor and connect it to the right pump. He should understand the value of lubrication and cooling of the cylinder wall etc.

A bigger pump working from the same well results in a bigger flow. Therefore the farmer tends to over-irrigate his fields. He then tries to reduce the revolutions per minute and after that he lets the pump work just a few hours per day although it should work 10 hours at least from an economic point of view.

In a big country like India there are 300 to 400 different brands of fuel engines and these are combined with at least as many pumps. To select the right pair needs knowledge in prices, irrigated area, the degree of reliability for the motor and even the flow resistance of the submerged foot valve is most important. Field tests have shown that 60 percent of all sets were under- or overloaded. This confirms that farmers are insufficiently familiar with equipment selection and that little guidance from manufacturers and dealers is obtained. The term deep tube wells is rather misleading as the majority of the wells are not deep. A field test in Pakistan has shown that the depth of the water table is distributed after a logarithmic Gauss distribution law. This means that more than 50 percent of all wells fall into the depth range from 1.25 to 10 metres. The distribution of flows is of another kind as it follows the normal Gauss distribution. A little more than 50 percent of the flows lie between 20 and 150 m^3/h. Field tests showed that the power had logarithmic Gauss distribution, and a little more than 50 percent of the output power lies between 2 000 and 7 000 water watts. As the overall efficiency is very low, about 30 percent, the input power lies between 7 000 and 24 000 wW (10-33 hp input).

As light diesel oil is cheaper than gasoline the farmers prefer - without any calculation - to import fast-running diesel engines. These are usually more sensitive and last only 10 to 15 years. On the other hand, some British-made (Pakistan and India) slow-running oil engines can work for several decades without any trouble.

Excellent field work on motor pumps has been carried out in the last few years in Pakistan (1 874 private pump sets tested), and in India (1 724 private pump sets). The results of this field work are yet to be published.

7.2 Electric-powered Pumps

~~Electronic~~ Electric motors are undoubtedly the best power source for irrigation but most peasants in the world are without electricity. If an electric distribution network is established, a great many problems occur, such as overloading of the network in the irrigation season, with many and long interruptions. As a consumer the farmer has to pay for periods where he is not using any power. An electromotor without a protective device has a short life because of daily voltage drops or voltage peaks. Many motors are installed in the well and sometimes submerged.

The most reliable electric irrigation plants are found around the big towns. The interaction between town and land makes electricity economical.

8. CONCLUSION AND RECOMMENDATION

The purpose of this background paper serves to present some of the essential problems involved around water lifting devices.

Some of the devices are very old and of a really simple construction. They are to be found in millions. Others are more elaborate but still the maintenance can be mastered by the local craftsmen.

A further step in technology needs some skilled workers with special tools using ironplate and section iron as materials.

The next step takes us to the 20th century technology. For many communities this is a ~~vast~~ big step because the smooth change from handicraft to industry has been left out. Hitherto the centrifugal pump has been the only one which has been treated as an object of engineering science. If some of the simpler devices were treated in the same manner they could perhaps be optimized and then be offered as possible solutions to many small-scale irrigation farmers.

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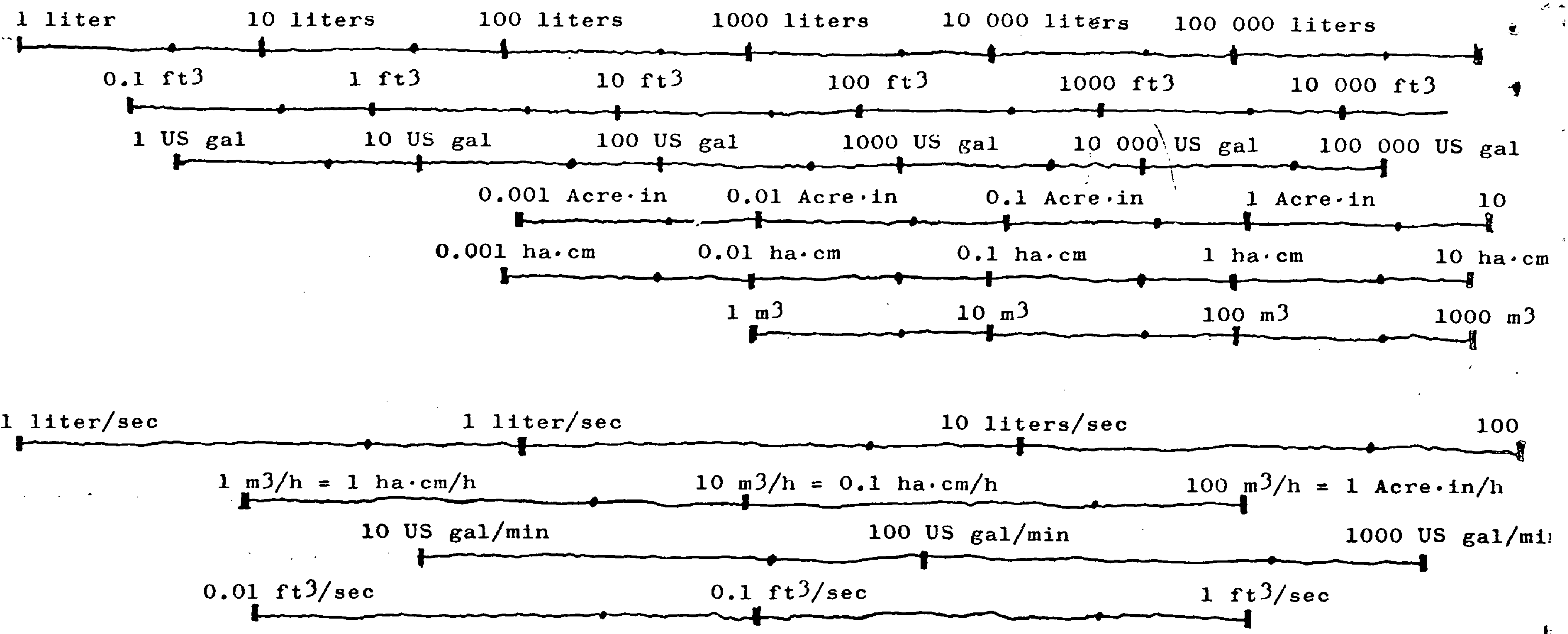
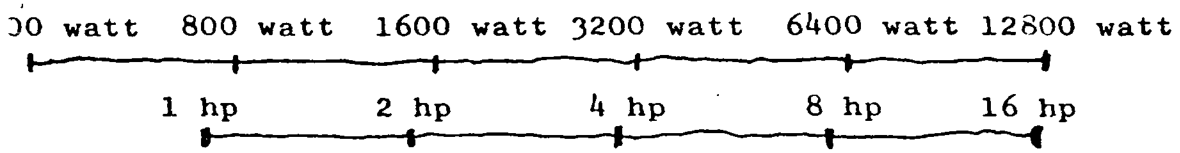
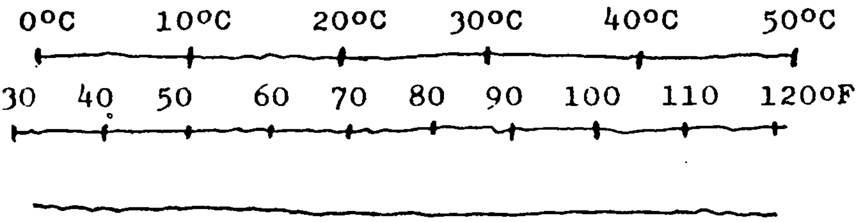
APPENDIX: CONVERSION OF MEASURES







1 lakh = 10^5

1 crore= 10^7

US gal pr min x feet $\frac{746}{3960}$-- = wW

ft^3/sec x feet -$\frac{746}{8.8}$ = water Watt

1 acre = 0.405 ha = 4050 m^2

1 ha = 2.47 acres

1 ft^3 H_2O = 62.4 lbs

g m/sec^2 = 10 m/sec2 = 32.8 ft/sec2

4/12

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Agenda Item 2

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

WIND-POWERED WATER LIFTING FOR SMALL-SCALE IRRIGATION

by

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1. Introduction

In many parts of the world irrigation development is limited by the cost of conventional sources of energy for water lifting. Often the pumping power requirement can be met by the use of a prime mover such as a small diesel engine. However, the diesel pump-set has certain disadvantages in areas where the recurrent costs of maintenance, spares, diesel fuel and lubricants are high and where there is generally a lack of sufficient qualified technicians.

In view of the likely future cost and reduced availability of diesel fuel the question arises: Can wind-powered water-lifting devices compete with conventional pumping equipment? Although wind is freely available, the low density of air relative to water (1.23 kg/m^3: 1000 kg/m^3) implies that windmills tend to be rather large and therefore expensive. Furthermore wind power is unsuited to the supply of firm power unless the system has inherent energy storage capacity or arrangements are made for energy storage. In general windpump size requirements and the need for water storage compound to make wind-powered irrigation capital intensive.

The scale of wind-powered water lifting devices used at present ranges from about 2 m diameter for windpumps (Hayes, Southern Cross) used for watering livestock and vegetable patches or used for trickle irrigation, up to about 10 m diameter for relatively high-speed wind turbines coupled to centrifugal pumps (Vadot, Chilcott) used for sprinkler irrigation. For Small-scale irrigation ~~at the~~ (1 ha) ~~scale~~ the type of wind-powered water lifting device needed is likely to have a diameter within the range 2 to 10 m. Windpumps in this size range are commercially available or can be made locally to a variety of designs suitable for local production conditions (Fraenkel).

In order to provide an insight into the energy-conversion performance of low-speed wind powered water lifting devices a non-dimensional performance prediction method has been developed. This takes account of positive displacement pump characteristics, windmill rotor characteristics and wind characteristics. The approach leads to the conclusion that, where conditions permit, the type of system best suited to small-scale irrigation comprises a piston pump coupled to a multi-bladed or sail-type windmill rotor, together with a galvanized steel or reinforced concrete water storage tank. This is in accord with current practice in some special areas, Fig. 1.

2. Wind-energy availability

2.1. Wind-speed frequency.

The fundamental problem with wind energy is to determine: How much is available, how frequently and with what reliability? The problem is solved by using probability distributions to characterise the variability of wind. For example annual-mean wind speed is likely to vary from year to year about the long-term mean wind speed. To determine reliability it can be assumed that the variation is normal with typical coefficients of variation in the range $C_V = 0.10$ to 0.15.

Variation of 10 minute or hourly-mean wind speed during a season or year can be characterised by the Weibull probability distribution:

$$p(x) = r\,k\,x^{k-1}\,\exp(-r\,x^{k}), \quad r = \Gamma^{k}\left(1 + \frac{1}{k}\right),$$

where the shape parameter k is usually in the range 1 to 2. Unfortunately in most practical applications only a rough estimate of long-term average wind speed is available to classify the local wind regime, Table 1. Under these conditions it is convenient to use a linearised wind-speed frequency distribution for design and performance estimates. A suitable linear distribution is the probability density function $p(x) = \frac{2}{3}\left(1 - \frac{x}{3}\right) \quad , \quad 0 \leqslant x \leqslant 3.$

For this distribution, the per unit time the wind speed is above a given value is given by

$$P(x) = 1 - \int_0^{x} p(x)\,dx = 1 - \frac{2}{3}x + \frac{1}{9}x^{2} .$$

These relationships are illustrated in Fig. 7, which shows that the wind-speed frequency distribution is skewed to the left and characterised by frequent low wind speeds and relatively infrequent high wind speeds. The wind speed is above the mean wind speed only about 44 per cent of the time.

2.2. Wind-energy frequency

The wind-energy frequency distribution for the linear wind-speed frequency distribution is given by

$$f_v(x) = \frac{x^3}{M_3}\, p(x) \quad = \frac{20}{81}\, x^3 \left(1 - \frac{x}{3}\right),$$

where $M_3 = \int_0^3 x^3 p(x)\, dx = 2.7.$

The per unit wind energy available above a given value of wind speed is

$$F(x) = 1 - \int_0^x x^3 p(x)\, dx = 1 - \frac{20}{81}\, x^4 \left(\frac{1}{4} - \frac{x}{15}\right).$$

These relationships are illustrated in Fig. 7, which shows that the wind-energy frequency distribution is skewed to the right and that the most energetic wind speed is 2.25 times the mean wind speed. Comparing wind-speed frequency and wind-energy frequency, it can be seen that wind speeds greater than 1.5 times the mean wind speed occur only 25 per cent of the time but contribute over 80 per cent of the wind energy available. Typical values of $P(x)$ and $F(x)$ for a mean wind speed $\bar{V} = 4$ m/s are shown in Table 2.

2.3. Wind-energy flux.

The energy in the wind flowing normal to the cross-sectional area swept by a windmill rotor is

$$E_{WIND} = T \int_0^\infty \tfrac{1}{2} \rho V^3 \pi R^2 \quad p(V)\, dV, \quad J.$$

The wind energy flux is therefore approximately

$$F_{WIND} = \frac{E_{WIND}}{\pi R^2 T} = \tfrac{1}{2} \rho \bar{V}^3 \int_0^\infty x^3 p(x) dx = \tfrac{1}{2} \rho \bar{V}^3 M_3, \quad W/m^2.$$

For a mean wind speed of $\bar{V} = 4$m/s at standard 15°C sea-level atmospheric density, $\rho = 1.23$ kg/m^3, the wind energy flux would be

$F\ WIND = \tfrac{1}{2} \times 1.23 \times 4^3 \times 2.7 = \underline{106\ W/m^2}$.

In tropical areas the atmospheric density will be reduced; for example at 30°C the density relative to 15°C is given by:

$$\sigma = \frac{273 + 15}{273 + 30} = \frac{288}{303} = 0.95$$

Allowing a reduction of 5 per cent for temperature and 1 per cent for altitude gives a typical design and performance estimate of wind-energy flux for irrigation where $\overline{V} = 4$ m/s as $\underline{F\ WIND = 100\ W/m^2}$.

3. Wind-energy conversion.

3.1. Windpump power-output: wind-speed characteristics.

The variation of windpump power output with wind speed depends on the windmill rotor aerodynamic-torque coefficient : tip-speed ratio characteristic and the pump torque-speed characteristic, together with the choice of either starting or matching wind speed. These factors will be considered separately using a non-dimensiaonal approach.

3.1.1. Low-speed windmill rotor torque-speed characteristics.

Shefter states that 'It is not difficult to be convinced that, due to their large value of starting torque, it is advantageous to use slow-running windmills'. These have been made in a wide range of diameters, from 1.5 to 15m, and can be recommended for use under non-gusty conditions in the present small-scale irrigation application.

A linearised non-dimensional aerodynamic torque-coefficient: tip-speed ratio characteristic for a low-speed windmill is shown in Fig. 8. The 'nominal' torque coefficient and speed-ratio are those for maximum power conversion efficiency. This linear model is applicable to nominal tip-speed ratios in the range 1 to 2; rotors in this range have the advantage of starting torques about 1.5 times the nominal torque, Fig. 9. Runaway or synchronous tip-speed ratio is assumed to be about 2.0 times nominal tip-speed ratio and the torque-speed characteristic is assumed to be linear between about 0.5 and 2.0 times the nominal tip-speed ratio. The model closely resembles those of Betz (1), Vadot (20), and Shefter (15) and UNESCAP (19).

For operation on the falling characteristic to the right of the stall point

$$\frac{C_T}{C_{TN}} = 2 - \frac{X}{X_N} \quad .$$

3.1.2. Constant-torque operation above a matching wind speed

In general the windmill rotor aerodynamic torque is given by

$$T = \tfrac{1}{2}\rho V^2 \pi R^3 C_T ,$$

so that for the linear model

$$T = \tfrac{1}{2}\rho V^2 \pi R^3 C_{TN}\left(2 - \frac{X}{X_N}\right) , \quad \frac{X}{X_N} \geqslant 0.5.$$

When the rotor is matched to a constant torque load T_M at a matching wind speed V_M and allowed to operate at wind speeds V above V_M

$$T_M = \tfrac{1}{2}\rho V_M^2 \pi R^3 C_{TN}\left(2 - \frac{X_M}{X_N}\right) = \tfrac{1}{2}\rho V^2 \pi R^3 C_{TN}\left(2 - \frac{X}{X_N}\right),$$

or $$V_M^2\left(2 - \frac{X_M}{X_N}\right) = V^2\left(2 - \frac{X}{X_N}\right).$$

To obtain a relationship between wind-speed ratio $\frac{V}{V_M}$ and windmill shaft-speed ratio $\frac{\Omega}{\Omega_N}$, or power ratio $\frac{W}{W_M}$ at constant torque, substitute

$$\frac{X}{X_N} = \frac{X}{X_M}\frac{X_M}{X_N} = \frac{\Omega}{\Omega_M}\frac{V_M}{V}\frac{X_M}{X_N} = \frac{W}{W_M}\frac{V_M}{V}\frac{X_M}{X_N} .$$

Then $$\frac{\Omega}{\Omega_M} = \frac{W}{W_M} = \frac{1}{\frac{X_M}{X_N}}\left[2\frac{V}{V_M} - \left(2 - \frac{X_M}{X_N}\right)\frac{1}{\frac{V}{V_M}}\right].$$

For windpump systems the starting wind speed is used as the matching wind speed, in which case

$$\frac{\Omega}{\Omega_o} = \frac{W}{W_o} = \frac{1}{\frac{X_M}{X_N}}\left[2\frac{V}{V_o} - \left(2 - \frac{X_M}{X_N}\right)\frac{1}{\frac{V}{V_o}}\right] .$$

The expected power output variation above the starting wind speed is shown for a range of values of $\frac{X_M}{X_N}$ in Fig. 10. The curves are assymptotic to straight lines through the origin and similar to those given by Vadot (20) for discharge of various piston pumps against a constant head.

In order to limit shaft speed and power, and pump discharge, the windmill rotor is governed above the rated wind speed given by V_R = (2 to 2.5) V_o. This is achieved by arranging for the rotor to be progressively turned out of wind, under the action of aerodynamic and spring (or gravity) forces and moments on the rotor and tail, above the rated wind speed Figs. 2 and 6. With this method of orientation and governing the gyroscopic forces and moments due to slewing rates of up to 1 rad/s need to be taken into account when designing the rotor and its supporting structure. To avoid escessive gust overloads, which may be up to 5 times rated values, the rotor is 'furled' completely out of wind at wind speeds above about $V_2 = 5V_o$.

3.1.3. Positive-displacement pump starting-torque requirements

When running at a steady state at any wind speed it is assumed that the mean pump torque and windmill rotor aerodynamic torque are related approximately by

$$\bar{Q} = \frac{1}{2\pi}\int_0^{2\pi} Q(\omega t)\, d\omega t = G\,T_M .$$

At the starting wind speed it is assumed that the windmill rotor aerodynamic torque just overcomes the maximum pump torque and allows the pump to accelerate to the matching point, so that for starting

$$Q_o \leqslant G\,T_o .$$

The windmill rotor matching-to-starting torque ratio is therefore

$$\frac{T_M}{T_o} = \frac{\bar{Q}}{Q_o} .$$

Idealised pump turning-moment diagrams are shown in Fig. 11. Several cases are considered:

1. Smooth-torque pump (ST) $\quad \frac{\bar{Q}}{Q_{o\,ST}} = 1 .$

2. Double-acting pump (DA)

$$\frac{\bar{Q}}{Q_{o\,DA}} = \frac{1}{2\pi}\int_0^{\pi} 2\sin\omega t\, d\omega t = \frac{2}{\pi} .$$

3. Single-acting pump (SA)

$$\frac{\bar{Q}}{Q_{0\,SA}} = \frac{1}{2\pi}\int_0^{\pi} \sin\omega t \, d\omega t = \frac{1}{\pi} \quad .$$

4. Single-acting pump with spring compensation (SC): Spring compensation can be used to halve the starting torque Vadot (20), Fig. 2 .

Allowing for the pump starting torque gives the starting wind speed matching-point coordinates, Table 3.

$$\frac{T_M}{T_N} = \frac{T_0}{T_N}\,\frac{T_M}{T_0} = 1{\cdot}5\,\frac{\bar{Q}}{Q_0} \quad ,$$

$$\frac{X_M}{X_N} = 2 - \frac{T_M}{T_N} = 2 - 1{\cdot}5\,\frac{\bar{Q}}{Q_0} \quad .$$

It can be seen that the pump type and its starting characteristics determine the matching point coordinates: the smoother the pump torque the lower will be the value of $\frac{X_M}{X_N}$. The double-acting pump has a matching point close to the nominal point and is likely to be somewhat more effective than a single-acting pump. Comparing piston pumps with smooth-torque perforated-belt pumps, Shefter concludes that in zones with seasonal average wind speeds in the range 3 to 4m/s piston pumps are preferable on the grounds of efficiency. Where water conditions permit, the use of piston pumps with low-speed windmills is therefore recommended.

For the present low-lift type of application with suction heads of up to 7m the use of surface mounted double-acting piston pumps is recommended. Table 4 gives technical details of a 3m diameter windpump designed for water lifting with piston pumps from pit and pipe wells of depths to 30m in regions where average wind speeds are in the range 3 to 5 m/s. Such machines use step-down gearing to allow the pump to operate below 1Hz, typically pump frequency is in the range 0.25 to 0.75Hz.

3.2. Energy-conversion efficiency

The overall wind-to-water energy conversion efficiency is the ratio of the useful energy output to the wind energy available. It is a function of the starting-to- mean wind-speed ratio and the matching-point tip-speed ratio, or type of pump used. To obtain the energy-conversion efficiency the wind-speed frequency distribution is recast into a form involving the starting-to-mean wind speed ratio as a parameter. The transformed linear-parametric wind-speed frequency model becomes

$$p\left[\left(\frac{V}{V_0}\right)\left(\frac{V_0}{\bar{V}}\right)\right] = \frac{2}{3}\left[\left(\frac{V_0}{\bar{V}}\right) - \frac{1}{3}\left(\frac{V_0}{\bar{V}}\right)^2\left(\frac{V}{V_0}\right)\right] ,$$

where $\frac{V_0}{\bar{V}}$ is treated as a parameter,

$$\text{for} \quad p\left[\left(\frac{V}{V_0}\right)\left(\frac{V_0}{\bar{V}}\right)\right] = 0 , \quad \left(\frac{V}{V_0}\right) = 3\left(\frac{\bar{V}}{V_0}\right) ,$$

$$\text{and} \quad \int_0^{3\frac{\bar{V}}{V_0}} p\left[\left(\frac{V}{V_0}\right)\left(\frac{V_0}{\bar{V}}\right)\right] d\left(\frac{V}{V_0}\right) = 1 .$$

The windmill rotor power at the starting wind speed is given by

$$W_0 = \frac{1}{2} \rho V_0^3 \pi R^2 C_{PM} .$$

But

$$C_{PM} = \left(\frac{C_{PM}}{C_{PN}}\right) C_{PN} = \left(\frac{X_M}{X_N}\right)\left(\frac{C_{TM}}{C_{TN}}\right) C_{PN} = \frac{X_M}{X_N}\left(2 - \frac{X_M}{X_N}\right) C_{PN} .$$

Therefore

$$W_0 = \frac{1}{2} \rho V_0^3 \pi R^2 \frac{X_M}{X_N}\left(2 - \frac{X_M}{X_N}\right) C_{PN} .$$

The useful energy output above the starting windspeed is

$$E_{WATER} = \eta_P T \int_{V_0}^{3\bar{V}} W \, p(V) \, dV , \quad J .$$

The useful energy output flux is therefore

$$F_{WATER} = \frac{\eta_P W_o}{\pi R^2} \int_1^{3\left(\frac{\bar{V}}{V_o}\right)} \left(\frac{W}{W_o}\right) p\left[\left(\frac{V}{V_o}\right)\left(\frac{V_o}{\bar{V}}\right)\right] d\left(\frac{V}{V_o}\right), \quad W/m^2 .$$

The energy-conversion efficiency is given by

$$C_E = \frac{F\ WATER}{F\ WIND} = \frac{\eta_P W_o I}{\frac{1}{2}\rho \bar{V}^3 M_3 \pi R^2} = \frac{\eta_P \frac{1}{2}\rho V_o^3 \pi R^2 \frac{X_M}{X_N}\left(2-\frac{X_M}{X_N}\right) I}{\frac{1}{2}\rho \bar{V}^3 M_3 \pi R^2}$$

$$= \frac{C_P \eta_P}{M_3}\left(\frac{V_o}{\bar{V}}\right)^3 \frac{X_M}{X_N}\left(2-\frac{X_M}{X_N}\right) I .$$

The matching efficiency is therefore

$$\eta_M = \frac{C_E}{C_P \eta_P} = \frac{1}{M_3}\left(\frac{V_o}{\bar{V}}\right)^3 \frac{X_M}{X_N}\left(2-\frac{X_M}{X_N}\right) I\left(\frac{X_M}{X_N}, \frac{V_o}{\bar{V}}\right),$$

$$= \frac{20}{81}\left(2-\frac{X_M}{X_N}\right)\left\{3\left(\frac{V_o}{\bar{V}}\right)^2 + \left[\left(2-\frac{X_M}{X_N}\right)\log_e\left(\frac{1}{3}\frac{V_o}{\bar{V}}\right) + \left(1-\frac{X_M}{X_N}\right)\right]\left(\frac{V_o}{\bar{V}}\right)^4 - \frac{1}{3}\left(\frac{4}{3}-\frac{X_M}{X_N}\right)\left(\frac{V_o}{\bar{V}}\right)^5\right\} .$$

The above analysis neglects the loss in energy due to governing above the rated wind speed and the gain in energy below the starting wind speed Dixon (4,5). Assuming that these effects balance one another it can be seen that the energy-conversion efficiency is sensitive to the choice of starting wind speed and pump type. Typical matching efficiences are shown in Fig. 12 , which emphasizes the trade-off between energy-conversion efficiency and time of operation.

In order to achive sufficient running time a starting wind speed below the mean wind speed is usually selected. In the present case matching for operation 50 per cent of the time, P $(V_o) = 0.5$, gives $V_o = 0.88\bar{V}$. Table 5 shows, that under the assumed conditions, the energy conversion efficiency for a double-acting pump system is only about 5 per cent. This gives a windmill rotor useful power loading of $5W/m^2$. Table 6 shows the variation of relative output above and below the assumed 4m/s mean wind speed for a constant starting wind speed of 3.5m/s. The relative output is $0.4\bar{V} - 0.6$ and it is concluded that a starting wind speed of 3.5 m/s can be recommended for the type of application under consideration.

4. Small-scale irrigation case study.

To get a feel for possible implications of using wind-powered water lifting for small-scale irrigation Hilton (12) has made a comparative study of windmill and diesel powered systems at the 1ha scale. Several equipment options were considered and the cost estimates given in 1977 Kenyan shillings. For the present purpose the estimates have been converted to 'notional' dollars by dividing by 10.

4.1. Irrigation water requirements

It is assumed that annual rainfall is less than 400mm, evapotranspiration is 8mm/day and that without irrigation growing cash crops is not possible.

Size of irrigated plot		1ha
Evapotranspiration		8mm/day
Furrow-irrigation application efficiency		0.55
Water application rate required	$\frac{8}{0.55}$ =	15mm/day
Daily rate requirement	$\frac{15}{1000}$ x 10000 =	150 kl m^3
Annual water requirement	365 x 0.15 =	54.75Ml

$\frac{150}{24} = 6{,}25\ m^3/hr$

$\frac{150}{8} \sim 20\ m^3/hr$

4.2 Windpump and storage-tank requirements

4.2.1. Windmill rotor diameter

Assumed mean wind speed		4m/s
Wind energy flux, assuming linear wind-speed frequency and tropical conditions		100 W/m^2
Wind-to-water energy conversion efficiency for a windpump with double-acting piston operating in the assumed wind regime		0.05
Useful water-energy flux	100 x 0.05 =	5W/m^2
Assumed total effective head for windpump and storage tank system		8m
Daily water energy requirement	8 x 150 x 1000 x 9.81 =	1.77MJ
Continuous water power requirement	$\frac{1.77 \times 10^6}{24 \times 3600}$ =	136W
Windmill rotor swept area required	$\frac{136}{5}$ =	27.2m^2
Windmill rotor diameter required	$\left(\frac{4 \times 27.2}{\pi}\right)^{\frac{1}{2}}$ =	5.88m
Typical locally-made rotor diameter, Cp = 0.30		6m
Typical imported rotor diameter, Cp = 0.33		5m

4.2.2. Storage tank volume

Daily water requirement		150kl
Assumed design period of calms		3.5days
Assumed loss due to evaporation		4 to 5 per cent
Storage tank efficiency	(1-0.045) =	0.955
Tank volume required	$\frac{150 \times 3.5}{0.955}$ =	550kl

4.3. Diesel pump-set requirements

4.3.1 Engine operating power and time

Assumed total effective head on centrifugal pump		6 m
Assumed pump discharge		20.8 l/s
Hourly volume flow	$\frac{20.8 \times 3600}{1000} =$	75 kl
Assumed pump and transmission efficiency		0.6
Engine power required	$\frac{6 \times 75 \times 1000 \times 9.81}{3600 \times 0.6 \times 1000} =$	2kW
Daily operating time for 150kl (1ha)		2 hours
Maximum daily operating time for 1.5Ml (10ha)		20 hours

4.3.2 Engine fuel consumption at 2kW

Assumed fuel consumption	0.4 l/kWh
Fuel consumed at 2kW	0.8 l/h
Fuel consumed during 2h operation per day (1ha)	1.6 Litres
Fuel consumed during 20h operation per day (10ha)	16 Litres

4.4 Pumping costs

4.4.1. Capital costs

Estimates of capital equipment costs for various options are shown in Table 6. Comparing the two wind pumps, the locally-made windpump has a relatively low capital cost. The windpump storage tank represents a significant cost penalty. The diesel pump-set has the lowest total installed capital cost.

4.4.2. Annual costs

Equivalent annual costs are shown in Table 7.

1. Annual fuel costs

Assumed fuel cost	20 cents/litre

Fuel cost at 2 hours operation per day I.6 x 365 x 0.2 = $117

Fuel cost at 20 hours operation per day 16 x 365 x 0.2 = $1168

(Lubricating oil cost has not been included).

2. Annual maintenance costs

Windpump

Maintenance estimate for locally-made windpump	$60
Maintenance estimate for imported windpump	$40

Diesel pump-set

Maintenance cost is based on $20 for decoking every 1500 hours and spares at $5 every 1000 hours:

Maintenance cost for 2 hours operation per day (1ha)	$30
Maintenance cost for 20 hours operation per day (10ha)	$134

3. Annual labour costs

Labour cost for 2 hours operation per day (1ha): $15 per month $180

Labour cost for 20 hours operation per day (10ha):

Day shift $20 per month	$240	
Night shift $25 per month	$300	
		$540

4. **Total operating cost**

Operating cost of the diesel pump-set is significantly higher than that of the windpumps. Comparing the diesel pump-set options: for the 1ha optional labour cost is relatively high and fuel cost is relatively low.

5. Depreciation.

Depreciation is based on a straight-line method with expected lifetimes as shown in Table 8 .

6. Opportunity cost

This is charged on the basis of the average interest which could be earned at 10 per cent on a sum equivalent to half the initial value of the equipment.

7. Equivalent annual cost

Comparing the options for 1ha, equivalent annual cost is lowest for the locally-made windpump. The imported windpump and diesel pump-set have similar equivalent annual costs.

8. Annual volume pumped

Annual volumes are proportional to area: 20 hours per day diesel operation gives 10 times the volume of the other options.

9. Equivalent annual water cost

Water cost is lowest for the 10ha diesel pump-set option. Comparing the 1ha options indicates that water cost is lowest for the locally-made windpump; water costs for the imported windpump and diesel pump-set are similar.

10. Effect of doubling fuel cost

Comparing the 1ha and 10ha diesel pump-set options indicates that (assuming fuel is available) the 1ha options is less sensetive to fuel-cost increase. The 10ha diesel pump-set option has a water cost slightly higher than the 1ha locally-made windpump option.

4.5. Irrigated-plot viability.

An example of typical farm income from a 0.75 irrigated plot growing high-value crops under arid conditions in NE Kenya is given by Hilton (12) and reproduced in Tables 9 and 10. The agronomic model allows for crop rotation and some flexibility should there be a seasonal lack of wind for one or two months of the year.

4.5.1. Windpump water-supply reliability

The use of 0.75 ha, rather than lha, takes some account of the likely variation of annual mean wind speed from year to year and raises the water-supply reliability, above 50 per cent. To quantify the reliability, assume that the long-term mean wind speed is 4m/s and that other things are equal. The relative output or relative area irrigated is $0.4\bar{V}_{0.75} - 0.6 = 0.75$.

This implies that the 0.75 ha plot water-supply requirement can be met at a mean annual wind speed $\bar{V}_{0.75} = 3.375$ m/s.

Assuming a coefficient of variation for annual mean wind speeds of $C_V = 1.25$ gives the standard normal variable (or number of standard deviations) as

$$x_R = \left[\left(\frac{\bar{V}}{\bar{\bar{V}}}\right) - 1\right]\frac{1}{C_V} = -1.25.$$

Assuming a normal distribution of annual mean wind speeds gives a reliability

$$R = 0.5 + 0.3944 \simeq 0.89 .$$

The water supply reliability therefore approaches 90 per cent and the plot water supply requirement can be met 'nine years out of ten'.

Irrigation reliability is also improved for the 0.75ha plot as the storage tank capacity is now capable of meeting a 'calm' period of about 5 days, (during which the wind speed is less than the starting wind speed $V_o = 3.5$m/s).

4.5.2. Income in relation to pumping costs

The yields shown in Table 9 are for good, but not maximum, yields. Allowance has been made in Table 10 for 70 per cent yield. No charge is made for contract labour since manual work is done by the family. The farmer's pay is relatively low but gives an above average standard of living. It can be assumed from Table 10 that about $500 is available annually to pay for irrigation; anything above this ceiling would be set aside as a reserve against crop failure, or investment in more land and equipment.

X Considering the equivalent annual costs of the various 1ha options, Table 7 indicates that the imported windpump and the diesel pump-set options are barely viable. On the other hand, under the assumed conditions, the locally-made windpump represents a good economic propostion.

5. Conclusion

The performance-prediction method presented shows that, in a region with a medium annual-mean wind speed of 4m/s the wind-energy flux is about 100W/m^2 and that the overall wind-to-water energy-conversion efficiency is likely to be about 5 per cent for systems suitable for small-scale irrigation. The type of system recommended, on the grounds of low starting wind speed (3.5 m/s) and high efficiency, is the well-established multi-bladed low-speed windmill rotor coupled to a surface-mounted double-acting piston pump. Systems with a sail-type rotor coupled to a piston pump are also well proven and highly recommended. The water storage tank needed for windpump systems represents a significant cost penalty and optimisation studies are needed to quantify the precise water-storage requirements for wind-powered irrigation.

The small-scale irrigation case study shows that, provided windpump system costs are held down for example by local manufacture, wind-powered irrigation at the 1ha scale can represent a viable economic proposition. Several basic windpump designs are available and can be recommended for local production. Where necessary they can be adapted to suit local conditions or modified to incorporate key imported items. It is concluded that in many areas special local conditions can often combine to make small-scale wind-powered irrigation technically feasible and economically attractive.

6. Notation

C_E = $\frac{F\ WATER}{F\ WIND}$, overall wind-to-water energy conversion efficiency

C_P = $\frac{W}{\frac{1}{2}\rho V^3 \pi R^2} = X\, C_T$, windmill rotor power coefficient

C_T = $\frac{T}{\frac{1}{2}\rho V^2 \pi R^3}$, windmill rotor torque coefficient

C_V = coefficient of variation of seasonal or annual mean wind speed

D = windmill rotor diameter, m

E = energy, J

F = per unit wind energy available above a given value of wind speed

F WATER = water-energy flux, referred to windmill rotor swept area, W/m^2.

F WIND = wind-energy flux, referred to windmill rotor swept area, W/m^2

f = wind energy probability density function with respect to wind speed; pump frequency, Hz

G = $\frac{\Omega}{\omega}$, gear ratio, greater than unity

g = gravitational acceleration, 9.81 m/s^2

k = Weibull exponent

M_3 = wind energy pattern factor

P = per unit time wind speed is above a given value of wind speed

p = wind speed probability density function

Q = $Q(\omega t)$, pump torque, Nm

$\bar{Q}$ = mean pump torque, Nm

R = re liability; windmill rotor radius, m

T = time period, sec; windmill rotor torque, (turning moment assumed uniform) Nm

T_M = windmill rotor matching torque, (driven-machine load-torque referred to rotor), Nm

U = windmill rotor tip speed, m/s

V = 10-minute or hourly-mean wind speed, m/s

$\bar{V}$ = seasonal or annual mean wind speed, m/s

$\bar{\bar{V}}$ = long-term mean wind speed, m/s

V_o = starting wind speed, m/s

W = windmill rotor power, W

$\frac{U}{V} = \frac{R\Omega}{V}$,

X = χ windmill rotor tip-speed ratio

x_R = standard normal variable, number of standard deviations

x = $\frac{V}{V}$, wind speed to mean wind speed ratio

γ = relative output

η_M = $\frac{C_E}{C_P \eta_P}$, matching efficiency

η_P = overall pump hydraulic and windmill rotor-to-pump power-transmission efficiency, assumed constant

ρ = $\sigma \rho_0$, atmospheric density, kg/m^3

ρ_0 = standard atmospheric density, 1.23 kg/m^3

ω = $2\pi f$, pump angular frequency, rad/s.

Ω = windmill rotor shaft speed, rad/s

Subscripts

M	matching point, referring to conditions at which windmill-rotor torque is arranged to match mean driven-machine torque
N	nominal, referring to maximum power coefficient
V	ratio at a particular wind speed
0	starting
1	rated
2	furling
3	stopping

Volume

1 litre = 0.001 m^3

1kL = 1m^3

1ML = 1000m^3

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Table 1 Seasonal or annual mean wind-speed classification.

Mean wind speed $\bar{V}$ m/s	Classification
3	Low
4	Medium
5	High

Table 2 Wind-speed and wind-energy probability for $\bar{V} = 4$ m/s.

V m/s	$\left(\frac{V}{\bar{V}}\right)$	$P\left(\frac{V}{\bar{V}}\right)$	$F\left(\frac{V}{\bar{V}}\right)$
3.5	0.875	0.502	0.972
4	1.0	0.444	0.955
6	1.5	0.250	0.813
8	2.0	0.111	0.539
10	2.5	0.028	0.196
12	3.0	0	0

Table 3 Positive-displacement pump starting-torque and matching-point characteristics for $T_o = 1.5T_N$.

Code	Pump type	Starting-torque requirement		Matching-point coordinate	
		$\frac{T_o}{T_M}$	$\frac{T_M}{T_o}$	$\frac{X_M}{X_N}$	$\frac{T_M}{T_N}$
ST	Smooth torque	1.0	1.0	0.5	1.5
DA	Double-acting piston	$\frac{2}{\pi}$	0.637	1.045	0.955
SA	Single-acting piston	$\frac{1}{\pi}$	0.318	1.523	0.477

Table 4 Technical details of windpump TVM-3 "Chayka".

Rotor diameter	3m
Number of blades	12
Nominal windmill rotational speed	61 rev/min
Nominal power, at ρ = 1.25 kg/m^3, V_N = 8m/s	0.75 kW
Range of working wind speeds	3.5 to 17 m/s
Maximum survival wind speed	30 m/s
Transmission and pump efficiency	0.6
Rotor centreline height	5.1m
Weight of assembled machine	490kg

Note: Designed for use with piston pumps in regions with average wind speeds in the range 3 to 5 m/s.

Table 5 Wind-to-water energy conversion efficiency for a double-acting piston starting at $V_o = 0.88\bar{V}$

Symbol	Efficiency component	Maximum value	Factor for normal operating conditions	Typical normal operating value
C_p	Power coefficient	0.33	0.9	0.30
η_P	Power transmission and pump hydraulic efficiency	0.60	0.8	0.48
M	Matching efficiency, $P(V_c) = 0{\cdot}5$			0.35
C_E	Overall wind-to-water energy conversion efficiency			0.05

Table 6 Variation of relative output with mean wind speed for constant starting wind speed.

Mean wind speed $\bar{V}$ m/s	$\frac{V_o}{\bar{V}}$	η_M (approx)	C_E	F_{WIND} W/m^2	F_{WATER} W/m^2	Relative output γ	P(Vo)
3	1.17	0.50	0.072	42	3.0	0.6	0.37
4	0.88	0.35	0.050	100	5.0	1.0	0.50
5	0.70	0.25	0.036	195	7.0	1.4	0.59

Note 1. $V_o = 3.5$ m/s ,

2. $C_E = 0.30 \times 0.48 \times \eta_M = 0.144\,\eta_M$,

3. Relative output $\gamma = 0.4\bar{V} - 0.6$.

Table 6 Capital equipment cost estimates, notional dollars.

Equipment option Item description	1 Locally-made windpump 6m dia.	2 Imported windpump 5m dia.	3 and 4 Imported diesel pump-set, run at 2kW
Windpump	1200	4312	
Diesel-pump set			
Engine			425
Pump			275
Base pulleys belts			350
Pumphouse			100
Concrete foundation	30	30	20
Pipes and fittings	70	70	70
550kl concrete storage tank, materials and labour	1100	1100	
Transport and installation	200	200	200
Totals	$2600	$5712	$1440

Table 7 Equivalent annual cost estimates, notional dollars.

Ref.	System option	1	2	3	4
	Description and operating conditions	Locally-made windpump. 6m dia Mean wind speed 4m/s	Imported windpump. 5m dia. Mean wind speed 4m/s.	Imported diesel pump-set. Run at 2kW 2hours/day.	Imported diesel pump-set. Run at 2kW 20hours/day.
	Irrigated area	1ha	1ha	1ha	10ha
1	Fuel at 20 cents/litre			117	1168
2	Maintenance	60	40	30	134
3	Labour			180	540
4	Total operating cost	60	40	327	1842
5	Depreciation	136	229	104	416
6	Opportunity cost	130	286	72	72
7	Equivalent annual cost	326	555	503	2330
8	Annual volume pumped	54.75Ml	54.75Ml	54.75Ml	547.5Ml
9	Equivalent annual water cost $/Ml	5.95 (6)	10.14 (10)	9.19 (9)	4.26 (4)
10	Effect of doubling cost of fuel to 40 cents/litre:				
	Equivalent annual cost			620	3498
	Equivalent annual water cost $/Ml			11.32 (11)	6.39 (6)

Table 8 Expected lifetime of equipment.

Option	Item	Expected lifetime
1	Locally-made windpump.	15 years
2	Imported windpump.	25 years
3	Diesel engine, run below rated power. Utilization lower than 4 hours per day: lesser of 10000 hours or 15 years. Note 2 hours per day is equivalent to 13.7 years.	10000 hours
4	Diesel engine, run below rated power Maximum practical utilization of 20 hours per day, to allow for daily and weekly maintenance.	20000 hours
3,4	Centrifugal pump and V-belts. Lesser of 20,000 hours or 15 years.	
3,4	Baseplate, pulleys and capital installations.	25 years.

Table 9 Typical annual yields and cash values of crops.

Area ha	Crop type	Yield per crop kg	Number of crops	Annual yield kg	Cash value, notional dollars.
0.25	Melons	1250	3	3750	938
0.25	Tomatoes	750	3	2250	675
0.20	Onions/Chillies	1000/250	1	1000/250	300/125
0.05	Subsistence				
0.75 ha	: Total annual crop cash value				$2038

Table 10 Annual contributions to farm income, notional dollars.

Crop type	Cash values Good yield	Cash values 70 per cent yield	Cost of inputs: fertilizer, seeds pesticides and fungicides etc.	Contribution from crops Good yield	Contribution from crops 70 per cent yield
Melons	938	656	250	688	406
Tomatoes	675	473	238	437	235
Onions	300	210	80	220	130
Chillies	125	88	45	80	43
Total gross contribution				1425	814
Cash taken out by farmer, (statutory minimum wage).				288	288
Net annual contribution, (available for water supply and rent).				1137	526 ($500)

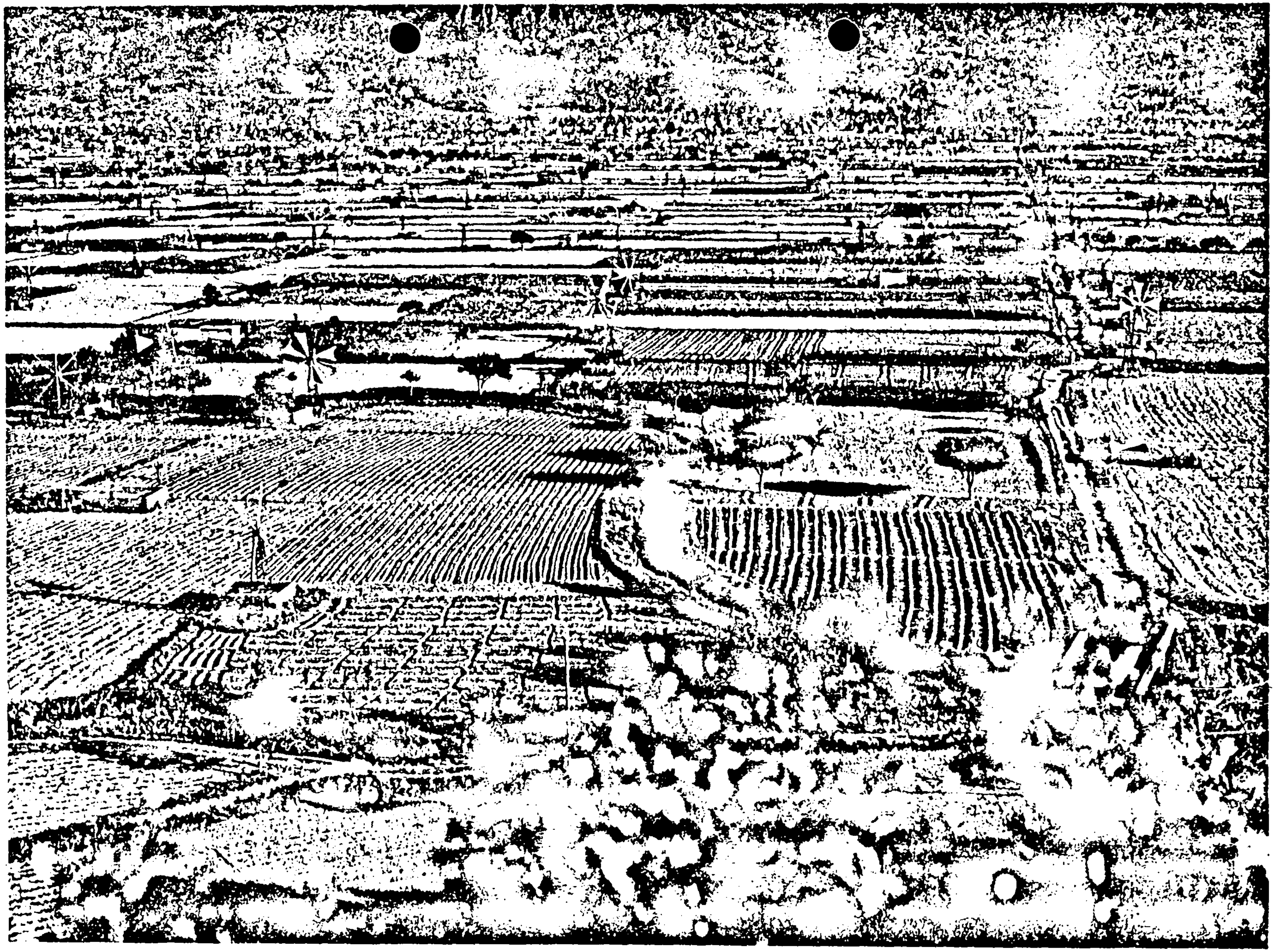


Figure 1. Wind-powered irrigation using sail-type rotors, typical diameter 5.4m directly coupled to piston pumps, Plain of Lassiti, Crete. Courtesy National Tourist Organisation of Greece.

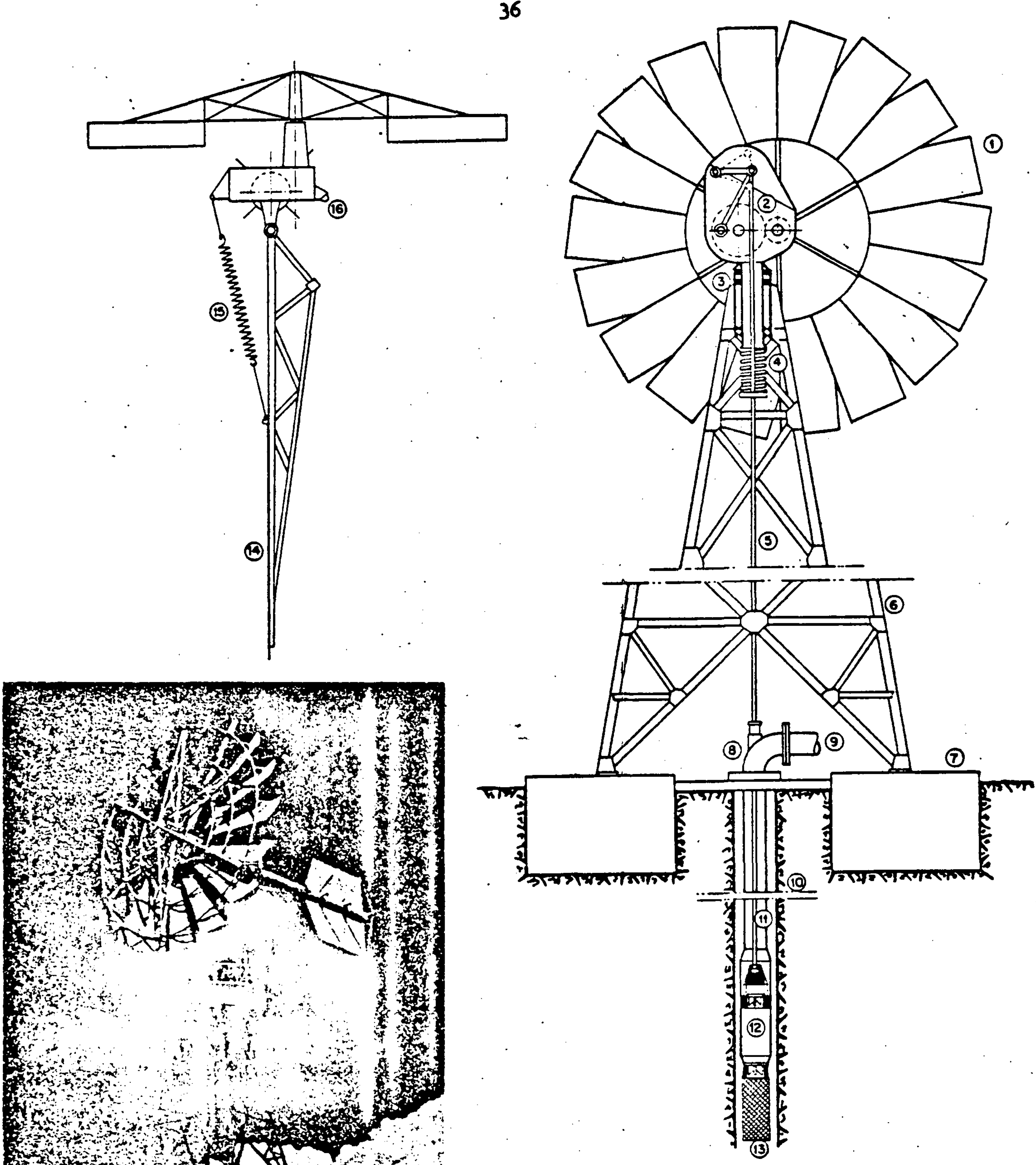
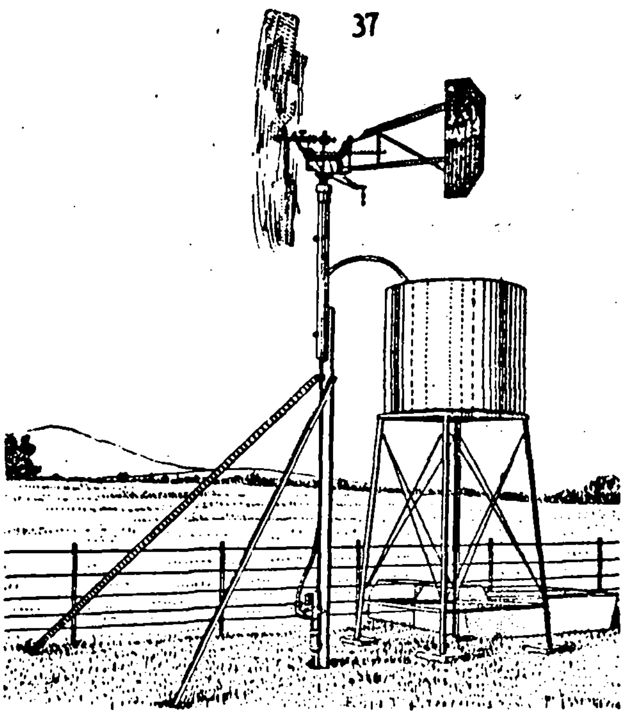


Figure 2. Low-speed multi-bladed windmill, rotor diameter 6.1m, coupled to a single acting piston pump through step-down gearing, (Vadot-Neyrpic, 1957).



HAYES WONDER WINDMILLS — INFORMATION CHART

Indicate which of the illustrations is nearest to your particular set-up. 'A' 'B' 'C' ....

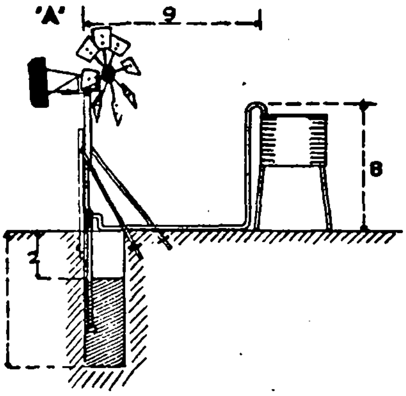
1. Depth of Bore or Well? - - ....
2. Distance from Ground Level to Normal Water Level? - - - ....
3. Diameter of Bore or Well? - - ....
4. What will the water be used for? - - - Domestic / Stock / Irrigation
5. Approximate quantity of water required daily? - - - - - ....
6. The Maximum hourly supply available for pumping? - - ....
7. If the water is pumped at maximum rate of supply, what will the water level drop to in the Bore or Well? - - - - ....
8. Vertical Height to top of Reservoir or Tank above ground level at pumping site? - - - - ....
9. Distance to Reservoir or Tank from pumping site? - - - ....
1[illegible]apacity and type of Storage Tank? - - - - - - - ....
11. Can the prevailing winds easily reach the site? - - - - - ....
12. Are the average wind conditions light, medium or heavy? - - ....
13. Are there any obstructions in the way of trees, buildings etc., within 150m of the mill site? If so, give distance and heights - - - - - - ....
14. If there is a pipeline already installed, state size and age? ....

If pumping from other than a Bore or Well, please state the following:

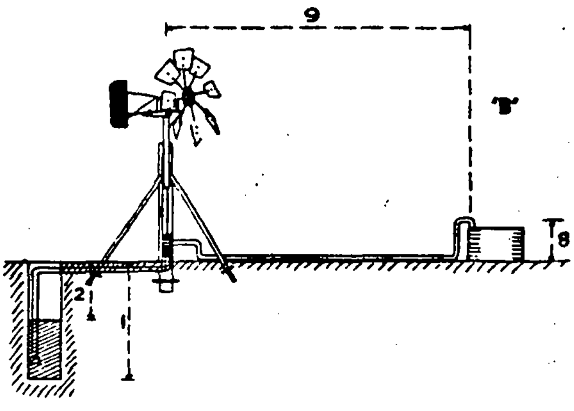
15. Source of supply - - - - ....
16. Also state length of suction pipe from foot valve to pump - - ....
17. Vertical height from normal water level to pump? - - - ....
18. Vertical height from lowest water level to pump? - - - ....

Since we began making Windmills in 1912, we have gained a considerable amount of experience in this field. We are sure that we have a Windmill that will handle the particular pumping job you wish to undertake. To enable us to advise you on the most suitable size of Windmill, would you kindly supply details as requested at left. We have illustrated three different layouts. However if your own set-up will be considerably different from any of these, use the back page for a rough drawing. Upon receipt of these particulars we will be pleased to quote you for one of our plants. **Filling in this Form does not place you under any obligation. To qualify for any Guarantee it is essential that full details are supplied.**

'A'



'B'



'C'

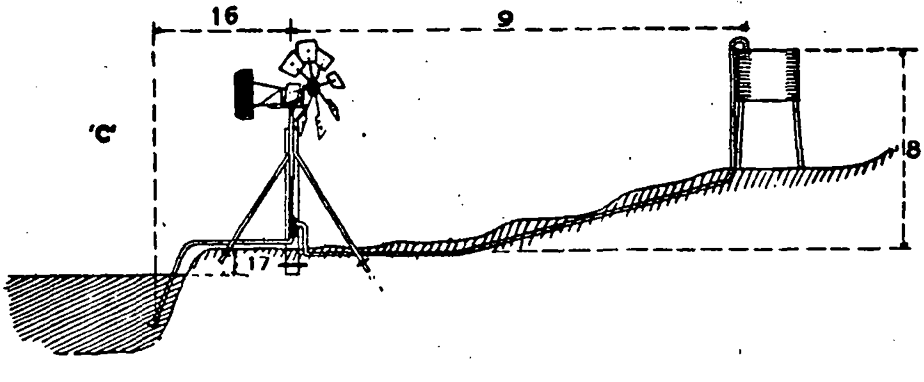
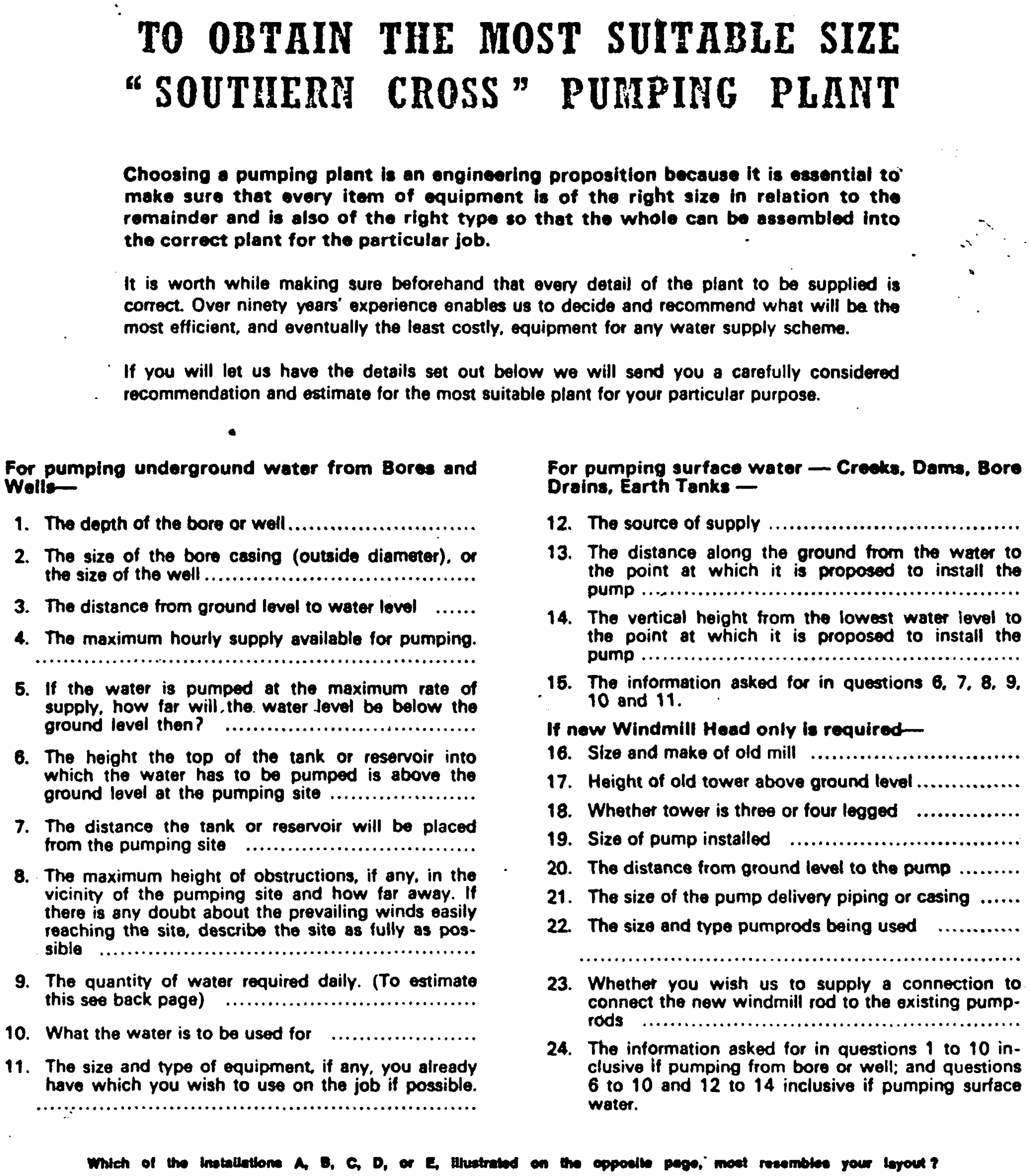


Figure 3. Hayes windpump information chart. Rotor diameters 1.8, 2.5 and 2.6m, directly coupled to piston pumps.



TO OBTAIN THE MOST SUITABLE SIZE "SOUTHERN CROSS" PUMPING PLANT

Choosing a pumping plant is an engineering proposition because it is essential to make sure that every item of equipment is of the right size in relation to the remainder and is also of the right type so that the whole can be assembled into the correct plant for the particular job.

It is worth while making sure beforehand that every detail of the plant to be supplied is correct. Over ninety years' experience enables us to decide and recommend what will be the most efficient, and eventually the least costly, equipment for any water supply scheme.

If you will let us have the details set out below we will send you a carefully considered recommendation and estimate for the most suitable plant for your particular purpose.

For pumping underground water from Bores and Wells—

1. The depth of the bore or well ....
2. The size of the bore casing (outside diameter), or the size of the well ....
3. The distance from ground level to water level ......
4. The maximum hourly supply available for pumping. ....
5. If the water is pumped at the maximum rate of supply, how far will the water level be below the ground level then? ....
6. The height the top of the tank or reservoir into which the water has to be pumped is above the ground level at the pumping site ....
7. The distance the tank or reservoir will be placed from the pumping site ....
8. The maximum height of obstructions, if any, in the vicinity of the pumping site and how far away. If there is any doubt about the prevailing winds easily reaching the site, describe the site as fully as possible ....
9. The quantity of water required daily. (To estimate this see back page) ....
10. What the water is to be used for ....
11. The size and type of equipment, if any, you already have which you wish to use on the job if possible. ....

For pumping surface water — Creeks, Dams, Bore Drains, Earth Tanks —

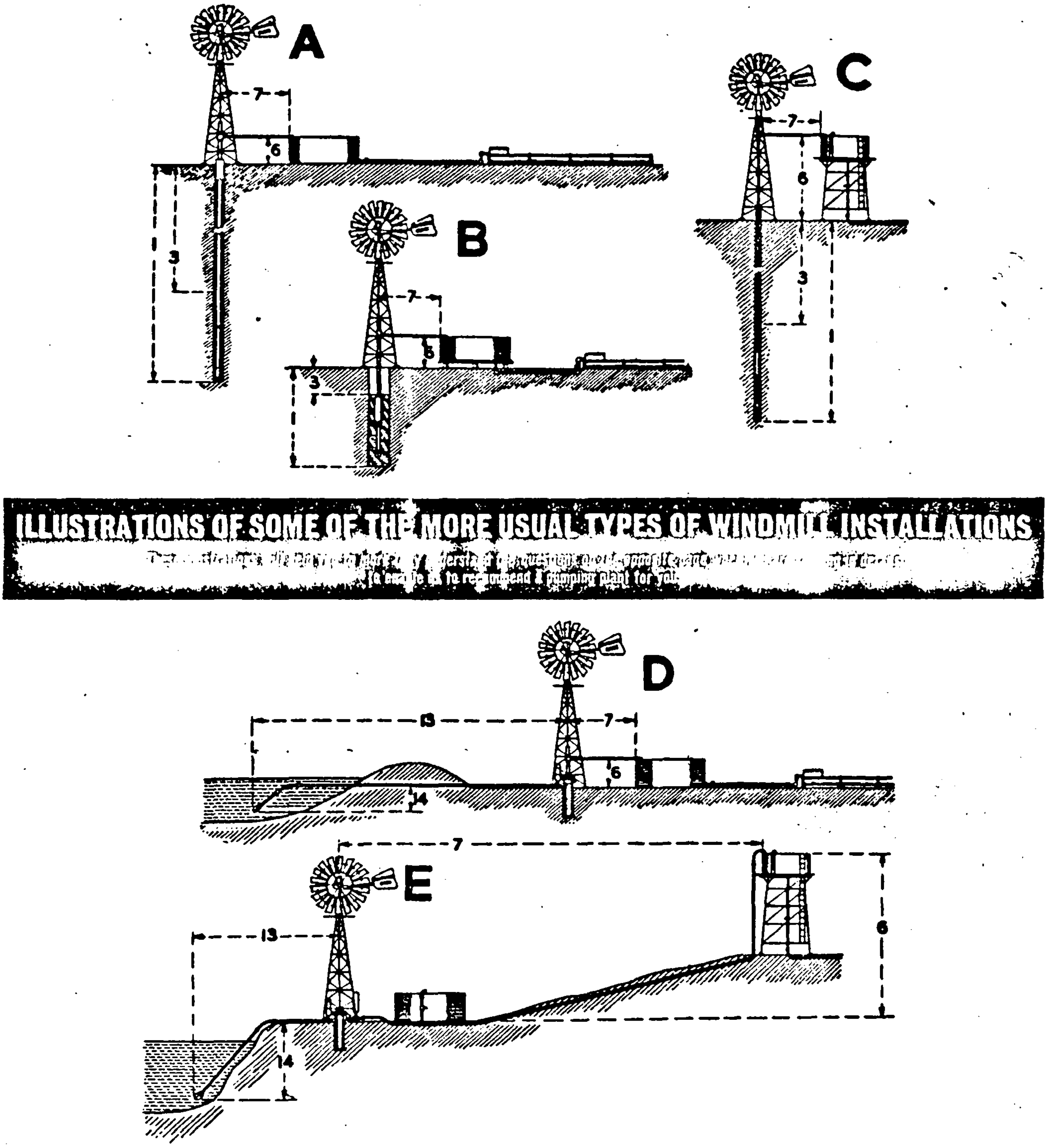
12. The source of supply ....
13. The distance along the ground from the water to the point at which it is proposed to install the pump ....
14. The vertical height from the lowest water level to the point at which it is proposed to install the pump ....
15. The information asked for in questions 6, 7, 8, 9, 10 and 11.

If new Windmill Head only is required—

16. Size and make of old mill ....
17. Height of old tower above ground level ....
18. Whether tower is three or four legged ....
19. Size of pump installed ....
20. The distance from ground level to the pump ....
21. The size of the pump delivery piping or casing ......
22. The size and type pumprods being used ....
23. Whether you wish us to supply a connection to connect the new windmill rod to the existing pumprods ....
24. The information asked for in questions 1 to 10 inclusive if pumping from bore or well; and questions 6 to 10 and 12 to 14 inclusive if pumping surface water.

Which of the installations A, B, C, D, or E, illustrated on the opposite page, most resembles your layout?

Figure 4. Southern Cross windpump data sheet, 1/2.

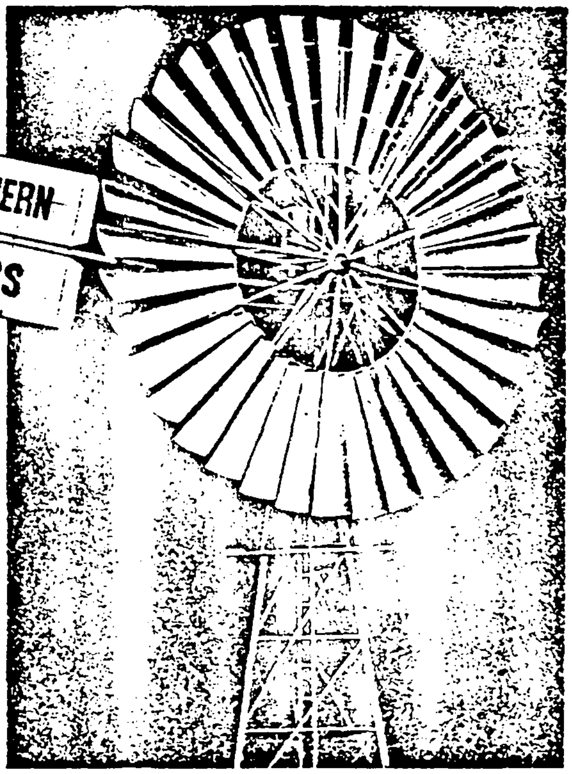


ILLUSTRATIONS OF SOME OF THE MORE USUAL TYPES OF WINDMILL INSTALLATIONS

[illegible]
[illegible] to enable us to recommend a pumping plant for you.

Figure 5. Southern Cross windpump data sheet, 2 /2.

These superbly engineered windmills have proven "Stock Route" Dependability



Where men and animals must stake their successful movement on a Windmill's reliability at watering stops — it is a SOUTHERN CROSS Mill that is chosen for the task. In the remote areas of the Northern Territory, the Kimberleys and the Great Australian Desert, these free pivoting, easy starting, direct acting Windmills maintain vital water supplies. The efficiency of the "Seneschal" year in and year out on these lonely outposts has amply proven the higher engineering standards of their manufacture and, at the same time, explains why thousands of similar Mills are installed on stations and farms throughout Australia and overseas.

The SOUTHERN CROSS "Seneschal" windwheel, starts very easily, for the scientifically shaped, curved and spaced sails take advantage of even the lightest breeze to transmit power to the job of pumping.

Self-sufficient, requires little attention — automatic governing — positive automatic oiling guards all working parts against wear and COMPLETE GALVANISING OF ALL EXPOSED STEEL PARTS effectively protects the Mill from the corrosive action of wind and weather.

From the top of the topmost sail to the lowest foundation bolt, every section of a SOUTHERN CROSS Mill and Tower has been tested and improved continuously over years of manufacture to give you today, not just a windmill, but a precision machine of highly developed efficiency — a reliable power plant in which you can have complete and lasting confidence.

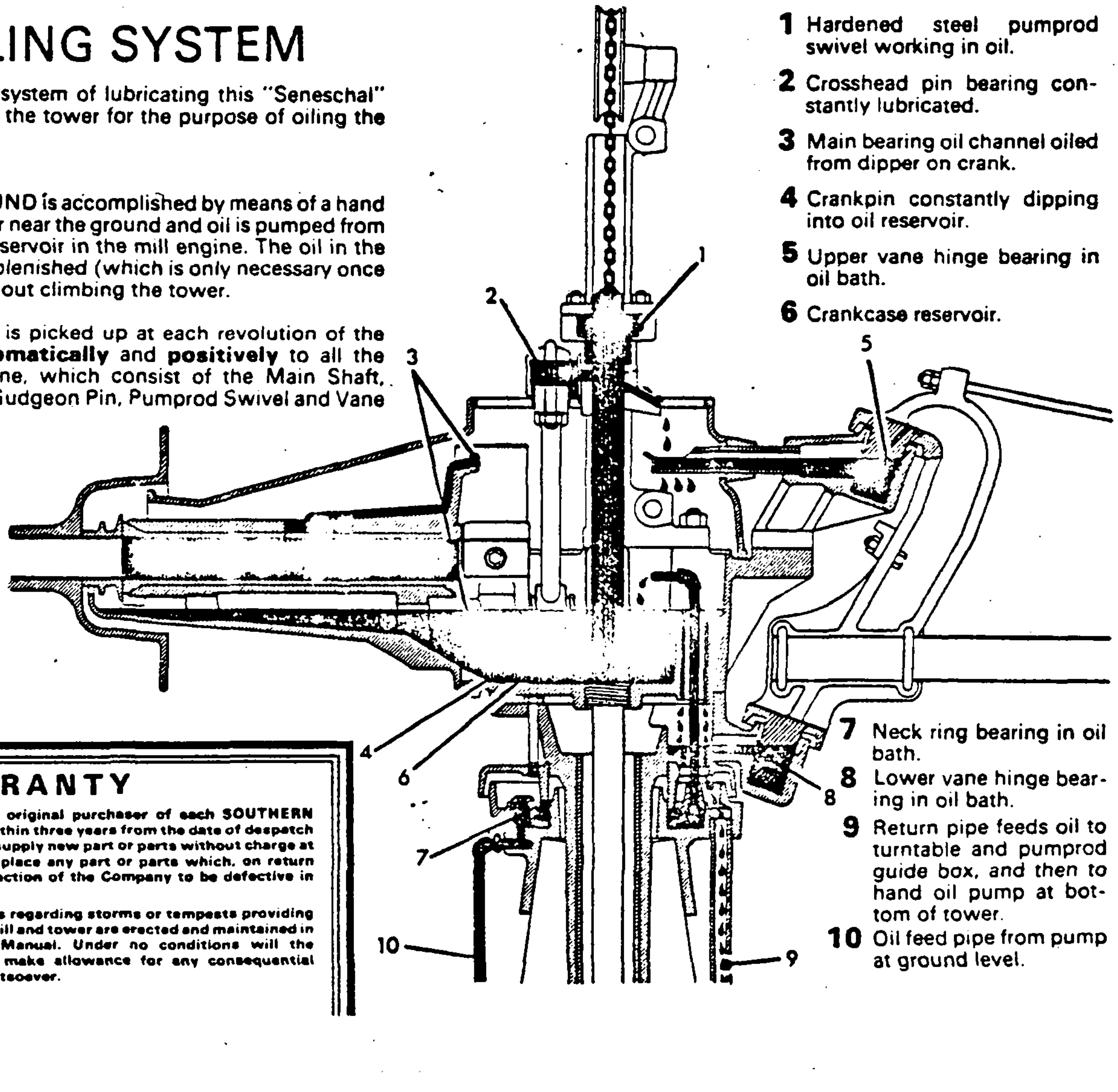
THE OILING SYSTEM

The SOUTHERN CROSS system of lubricating this "Seneschal" Windmill renders climbing the tower for the purpose of oiling the windmill unnecessary.

OILING FROM THE GROUND is accomplished by means of a hand pump attached to the tower near the ground and oil is pumped from there into the crankcase reservoir in the mill engine. The oil in the reservoir can thereby be replenished (which is only necessary once every twelve months) without climbing the tower.

From this reservoir the oil is picked up at each revolution of the crank and is carried **automatically** and **positively** to all the moving parts of the engine, which consist of the Main Shaft, Crankpin, Crosshead and Gudgeon Pin, Pumprod Swivel and Vane Hinge.

The Neck Bearing at the top of the tower and the Turntable and Pumprod Guide at the bottom of the Mast Pipe are also arranged so as to be continuously running in an oil bath as they, too, are in the automatic oiling circuit.



1 Hardened steel pumprod swivel working in oil.

2 Crosshead pin bearing constantly lubricated.

3 Main bearing oil channel oiled from dipper on crank.

4 Crankpin constantly dipping into oil reservoir.

5 Upper vane hinge bearing in oil bath.

6 Crankcase reservoir.

7 Neck ring bearing in oil bath.

8 Lower vane hinge bearing in oil bath.

9 Return pipe feeds oil to turntable and pumprod guide box, and then to hand oil pump at bottom of tower.

10 Oil feed pipe from pump at ground level.

WARRANTY

THE COMPANY AGREES with the original purchaser of each SOUTHERN CROSS Windmill that, at any time within three years from the date of despatch of such windmill, the Company will supply new part or parts without charge at the original point of despatch to replace any part or parts which, on return freight prepaid, prove to the satisfaction of the Company to be defective in material or workmanship.

The Company makes no reservations regarding storms or tempests providing the tower anchorages hold and the mill and tower are erected and maintained in accordance with the Instruction Manual. Under no conditions will the Company accept responsibility or make allowance for any consequential damages or any other expenses whatsoever.

Figure 6. Southern Cross 'Seneschal' windpump. Rotor diameters 5.2, 6.4 and 7.6m, directly coupled to piston pumps.

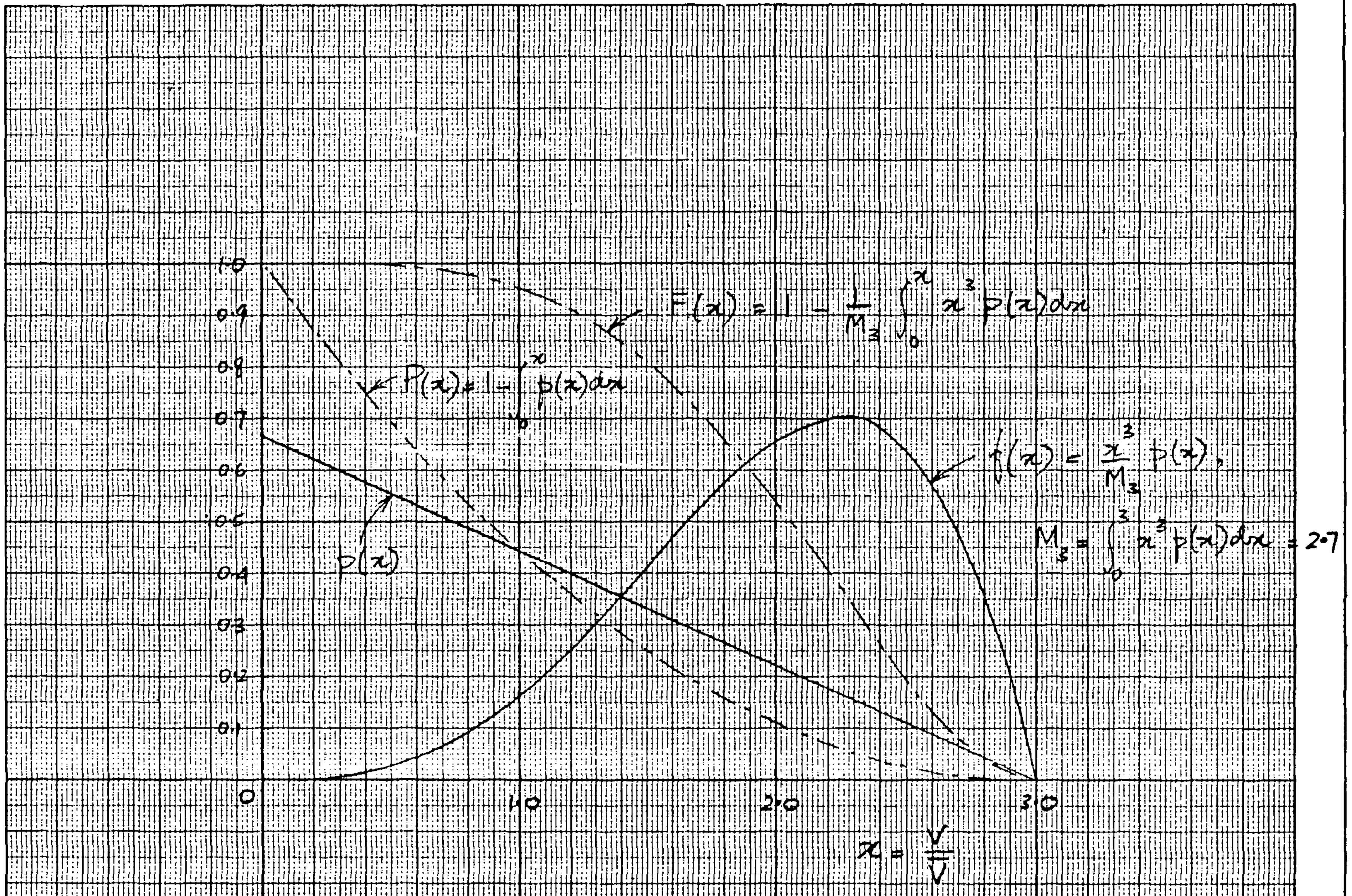


Figure 7. Linear wind-speed frequency distribution and wind-energy frequency distribution, $M_3 = 2.7$.

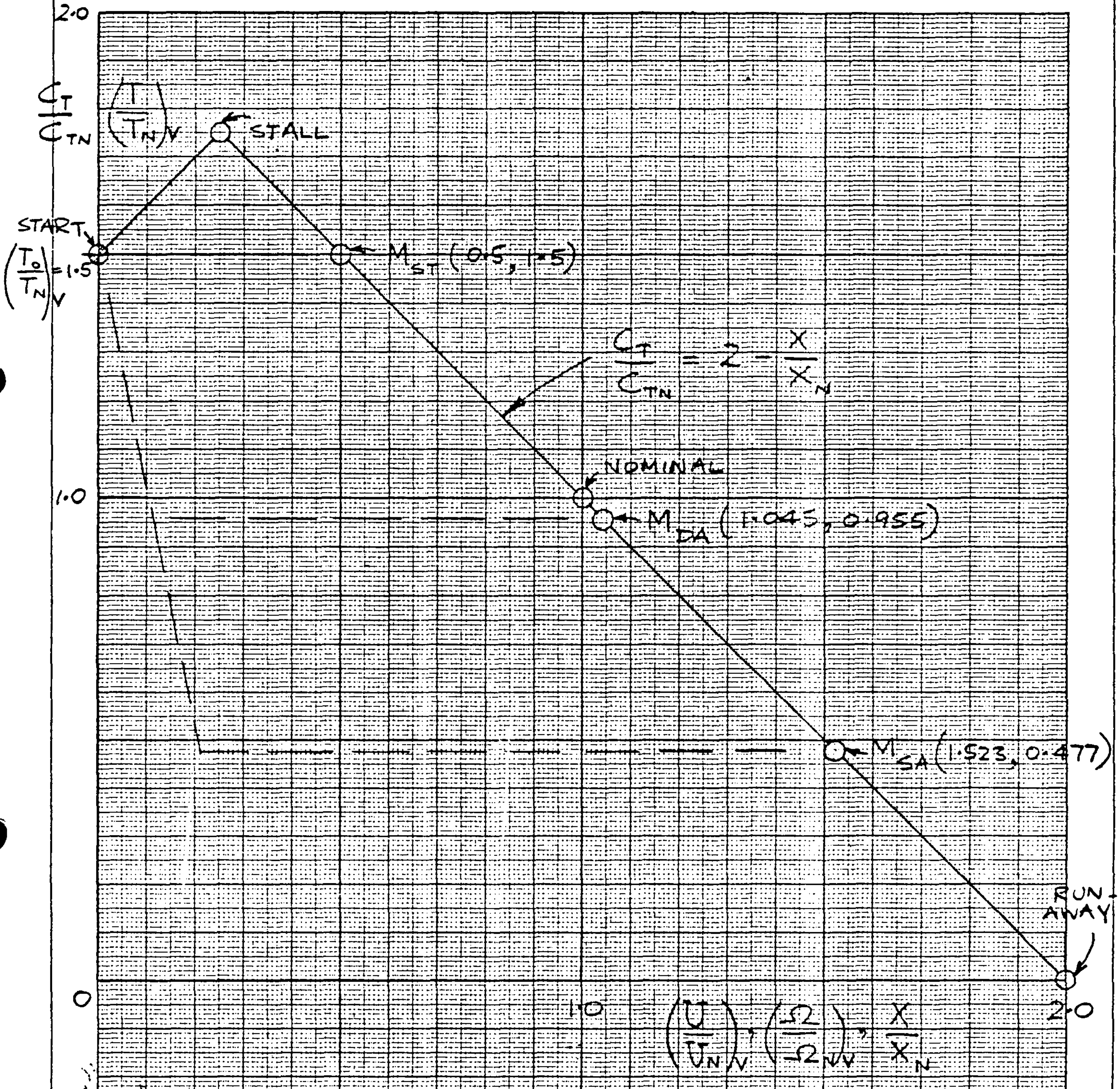


Figure 8. Low-speed windmill rotor torque coefficient: tip-speed ratio characteristic.

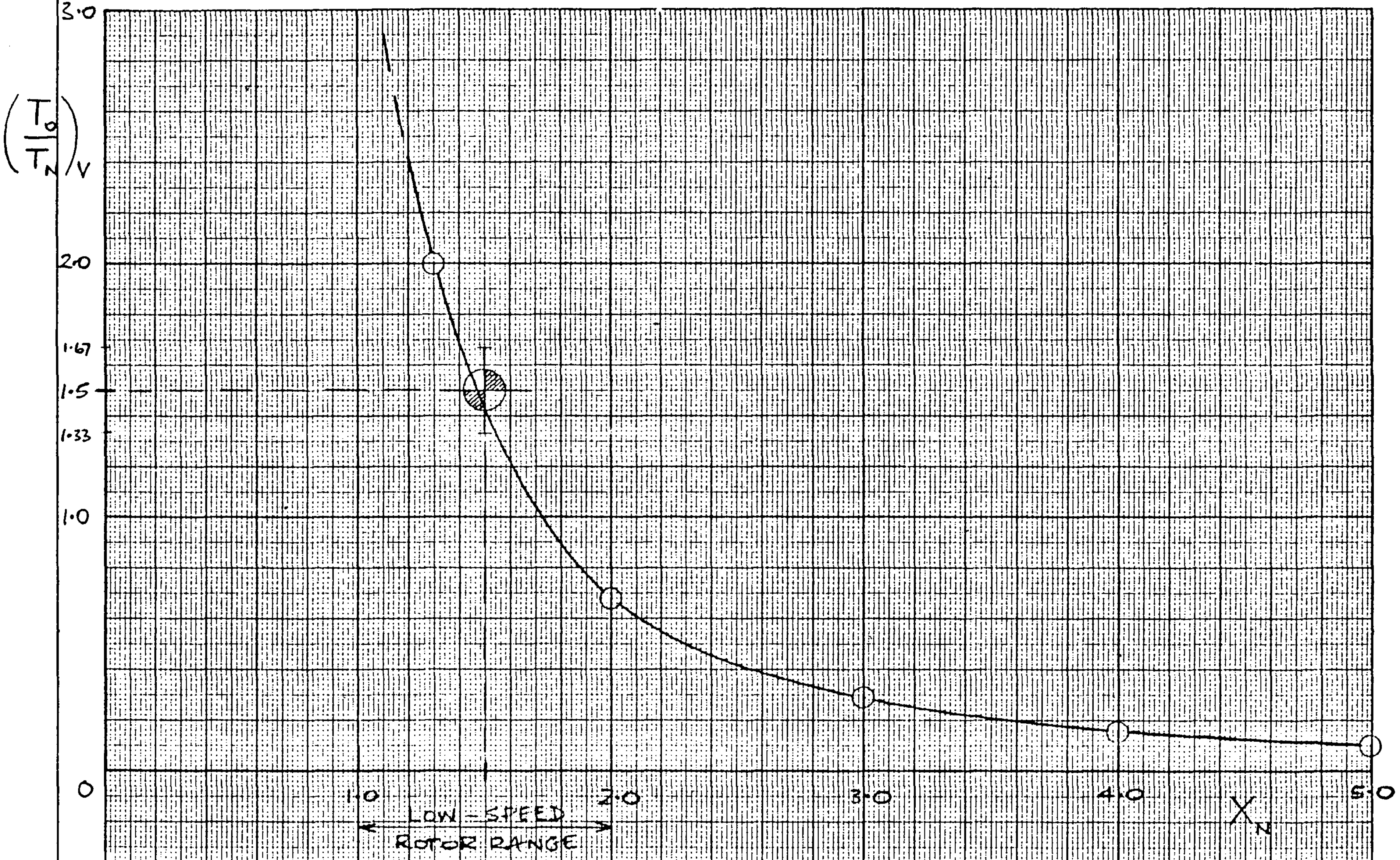


Figure 9. Variation of windmill rotor starting torque with nominal tip-speed ratio.

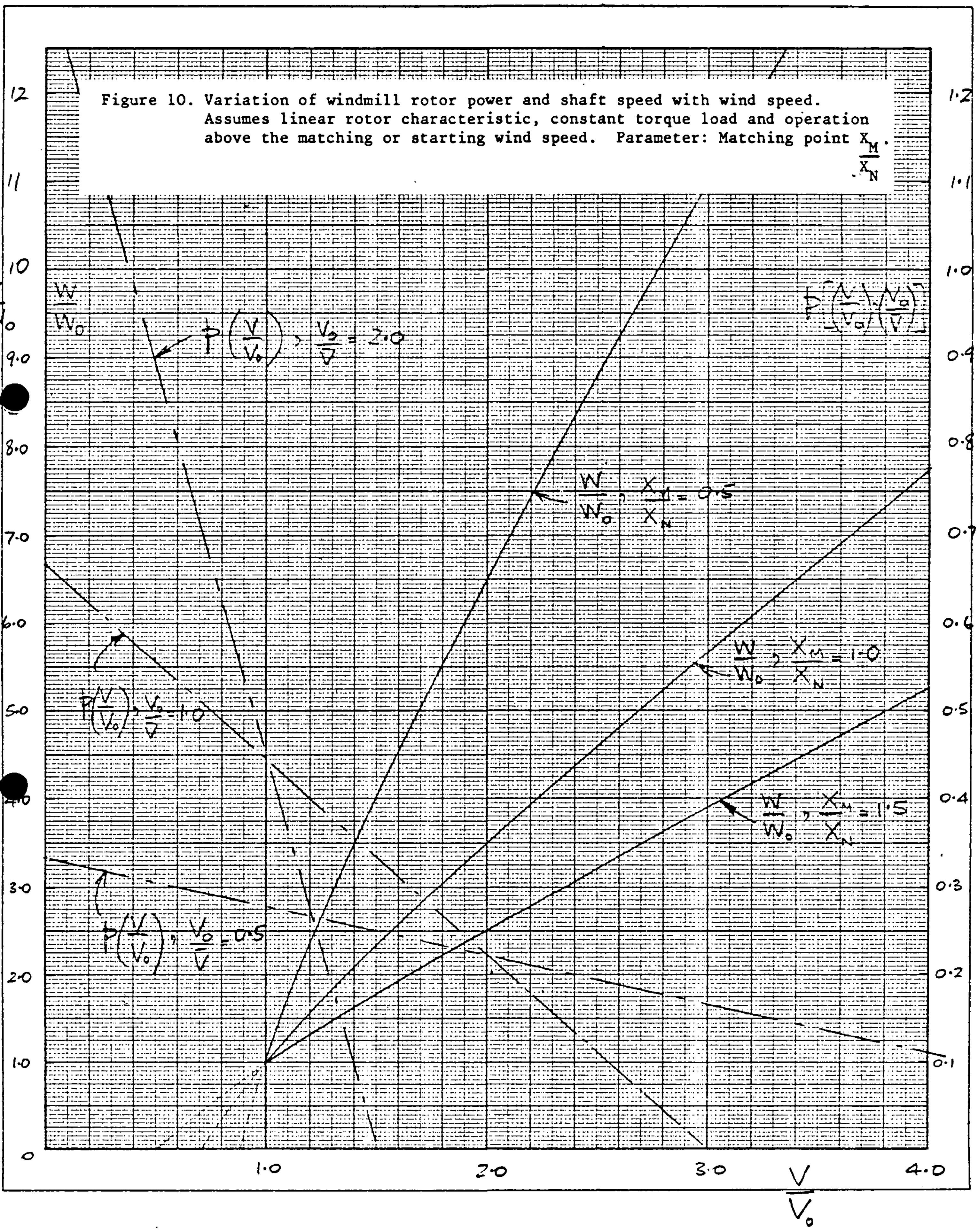


Figure 10. Variation of windmill rotor power and shaft speed with wind speed. Assumes linear rotor characteristic, constant torque load and operation above the matching or starting wind speed. Parameter: Matching point $\frac{X_M}{X_N}$.

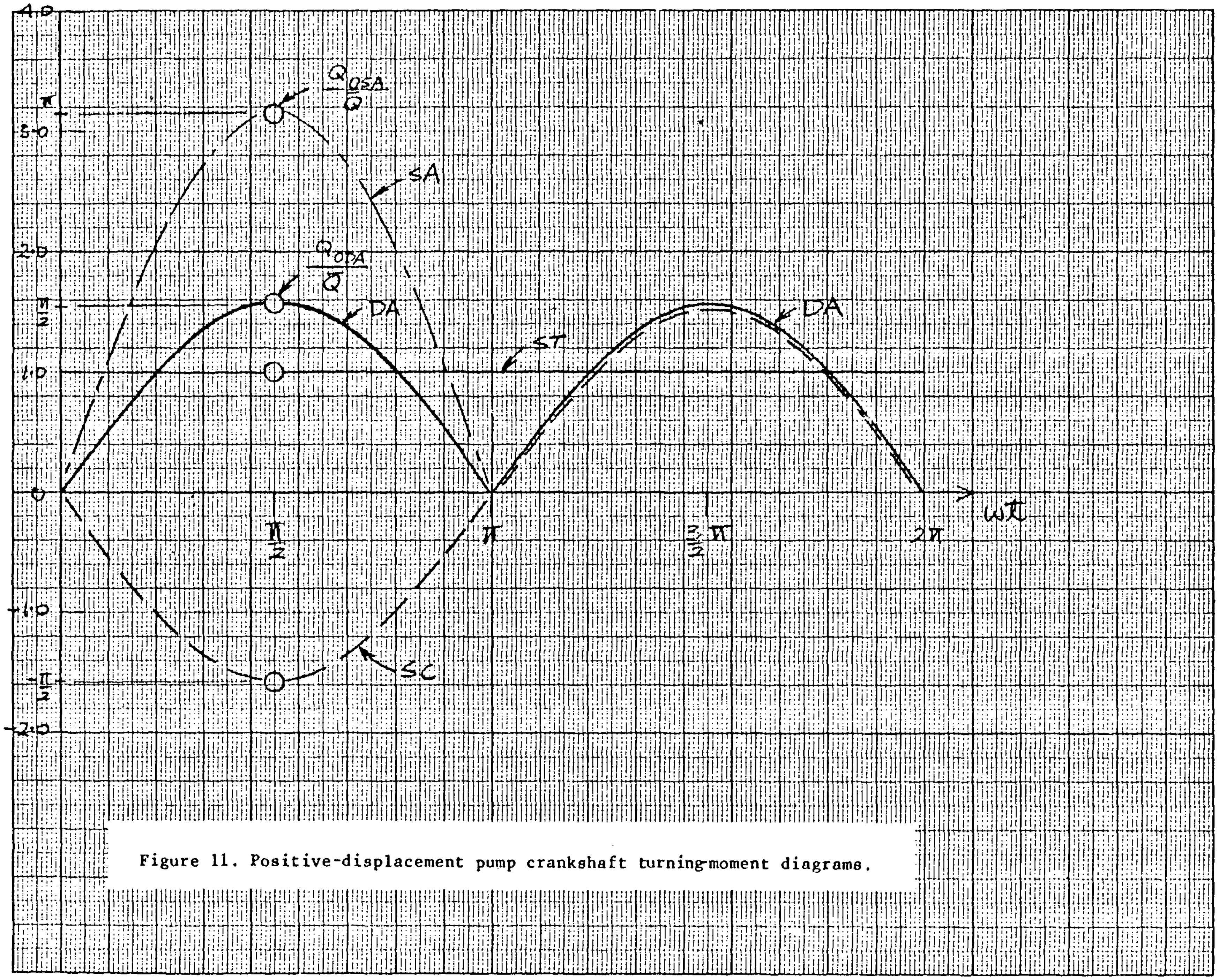
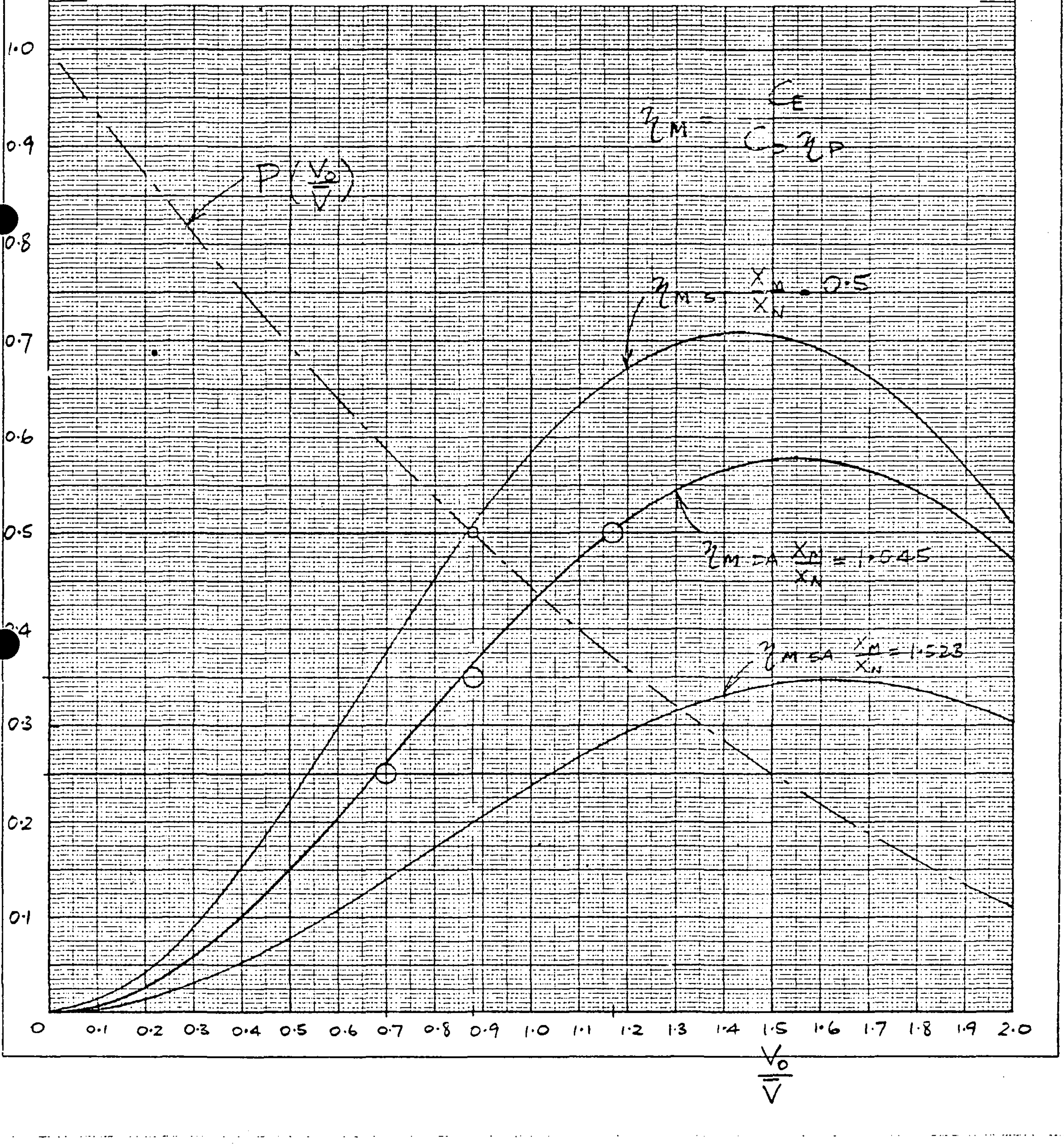


Figure 11. Positive-displacement pump crankshaft turning-moment diagrams.

Figure 12. Variation of matching efficiency with starting-to-mean wind speed ratio. Assumes positive-displacement pumps coupled to low-speed windmill rotors operating in linear wind-speed frequency distributions. Parameter: Matching point $\frac{X_M}{X_N}$.



4/11

Item 4

INTERMEDIATE TECHNOLOGY DEVELOPMENT GROUP

SOLAR POWERED WATER LIFTING DEVICES FOR IRRIGATION

Prepared for

FAO/DANIDA

WORKSHOP ON WATER LIFTING

IN ASIA AND NEAR EAST

4-14 December 1979

Bangkok

By

Bernard McNelis

ITDG Ltd.,
9 King Street,
London,
WC2E 8HN

October, 1979

CONTENTS

1. INTRODUCTION

In many regions of the developing world agriculture is dependent on irrigation and there are large areas of land which are at present barren but would support crops if sufficient water could be provided. Farmers are concerned to find the most appropriate and economic method of lifting water from boreholes, wells, rivers or canals onto their land. Traditionally human labour and draught animals have been the power source for water pumping. Today, if a grid supply of electricity is available then electrically driven pumps are used, while in unelectrified areas internal combustion engines using petroleum fuel find application. Both these approaches require only a small capital investment by the farmer.

Because large areas do not have grid electricity and as engine systems require regular maintainance, have a relatively short life and consume expensive, usually imported, fuel, there is widespread interest in the development of reliable systems based on renewable energy sources such as solar, wind and water power. Solar energy is the only source which is almost universally available both where and when it is needed, it is also ubiquitous and everlasting. The use of solar energy in developing countries is presently seen as a serious and worthwhile endeavour (1,2). For many years it has been said that an inexpensive solar pump will revolutionise third world agriculture (3). However the cheap solar pump does not yet exist although current research and development activity and the application of low cost manufacture methods may achieve the necessary breakthrough.

The principles of solar water pumping have been described elswhere (4) and existing and historic installations have been surveyed (5,6). Most solar water pumps have been employed to supply water for human and animal consumption from deep boreholes where the water must be lifted through a head of 25m or more. It is clear that for economic irrigation a low head is essential, because the power requirements and hence the cost per unit of water delivered is directly proportional to head, while the value of the crops is independent of head.

It must also be stated that today's solar water pumps cannot be considered as applying "appropriate" technology as they are technically sophisticated and could not be manufactured easily in developing countries. Indeed there has been recent critism that solar energy systems which could be of major benefit to developing countries are the subject of increased interest by manufacturing companies in industrialised countries which view the Third World simply as a new market area(7).

Solar pumps employ a similar level of technology to fossil fueled systems and should have a similar social impact on village communities. The principal differences are that solar pumps require larger land areas but do not require fuel. They have a considerably higher capital cost than fossil fueled equivalent sized units but near zero running costs. Photovoltaic pumps also scale down to fractional horsepower sizes more readily than do fossil fueled engines.

X

2. THE AVAILABILITY OF SOLAR ENERGY

The amount of energy received from the sun is immense; the present rate of world energy consumption is less than the rate at which solar energy is intercepted by a region 100km square in a favourable location.

Outside the Earth's atmosphere the solar energy flux is almost constant at about 1.35 kW/m^2, but absorption and scattering processes in the atmosphere

700 – 2300 kWh/m²

reduces this flux to a maximum of about 1.0kW/m ^{2} at sea level. The total solar energy available in a year at a given location depends on a latitude and local climatic conditions. Solar intensity is diminished at high latitudes because of the longer path through the atmosphere and hence absorption and scattering, and at higher latitudes there is a pronounced variation between summer and winter energy availability.

The solar energy input (horizontal surface) to the inhabited part of the Earth varies from about 700 kWh/m^2/year in temperate climates such as Northern Europe to typically about 2300 kWh/m^2/year in desert regions. Figure 1 illustrates the annual insolation cycle for Bangkok, Colombo and Tokyo (based on average monthly values(8). It can be seen that there is a more pronounced seasonal variation for Tokyo (1.9 to 3.9 kWh/m^2/day with an annual average of 3.0 kWh/m^2/day) while Bangkok and Colombo have less marked variation and achieve annual averages of 5.0 and 5.8 kWh/m^2/day respectively. There can also be considerable day to day variation at most locations. On a "good" day the total insolation can be considered as about 6.5 kWh/m^2.

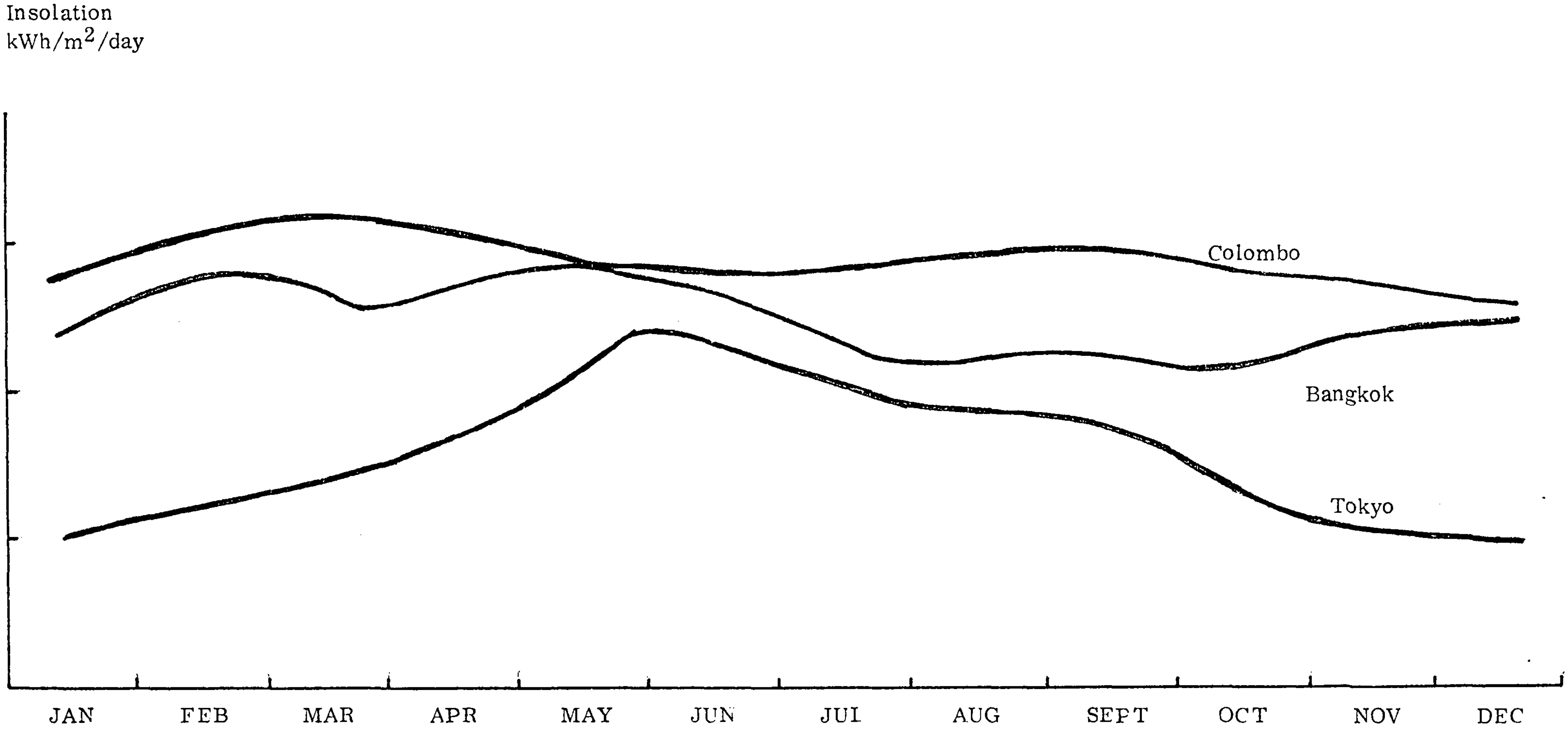
1 l/sec } 10W
1 m

1 kW/m²

10 l/sec } 1kW
10 m

1m²

Clearly when considering the power required for lifting water, which is approximately 10W to lift water at a rate of 1 litre/sec. through 1 m, solar energy received is considerable. Thus a 1m^2 solar collector, if coupled to a perfectly efficient converter and pump, could lift water at a peak rate of 10 1/s through 10m or provide 234m^3/day. Obviously perfect efficiency is impossible and it is the cost of the pumping system which is important. Because the cost of any device is to a great extent proportional to its size a major aim in the development of solar pumps is to achieve high efficiency and hence small size.



ANNUAL INSOLATION PATTERN FOR THREE LOCATIONS
FIG 1.

Overall Conversion 1-5%

Typical conversion efficiencies for solar pumping systems are in the range 1-5%. In a favorable location receiving 6kWh/m^2/day of solar energy, the useful output power will be 60 to 300Wh/day from each m^2 of collector area. 60Wh represents, say, 4m^3/day of water delivered through a head of 5m, while 300Wh would deliver about 20m^3/day through the same head. Typical peak output near noon will be 10 to 50W for each m^2 of collector, representing a peak pumping capacity of 0.2 to 1 litre/sec through 5m head per m^2 of collector.

3 SOLAR WATER PUMPING SYSTEMS

There are two distinct approaches by which solar energy may be employed to lift water. These are thermodynamic and photovoltaic conversion. With thermodynamic conversion there are several different engines and in both cases there are many alternative combinations of motor and pump. All the systems have advantages and disadvantages and it is not possible at present to say which, if any, system has a clear advantage, although small photovoltaic pumps are commercially available and have proven successful in the field.

The following sections described the alternative approaches and commercial systems. It must be noted that most of the solar pumps developed have been for village water supply from deep boreholes.

3.1 THERMAL ENGINE BASED SOLAR PUMPING SYSTEMS

A large number of heat engines, which convert thermal into mechanical energy have been developed and are in use throughout the world. Solar radiation can be the source of heat for the engine which provides mechanical energy for water pumping. The best known heat engine is the steam engine which applies the Rankine thermodynamic cycle. Rankine engines using working fluids other than water have been developed. Freons, as used in air conditioning systems are used for low temperature units. Air or other gases can be used in an alternative heat engine known as the Stirling Engine.

Much of the pioneering research into solar energy utilisation, in the late nineteenth and early twentieth centuries, was directed towards the production of mechanical power using thermal engines. Several ingenious systems were built, a number of these being used for water pumping purposes.

There are several options for the solar collector part of the system and the types of arrangements which are employed are illustrated in fig 2.
The efficiency of conversion of solar radiation into thermal energy by a solar collector decreases with increase in operating temperature because heat losses become greater, but there is considerable variation between designs of collector as is discussed later.

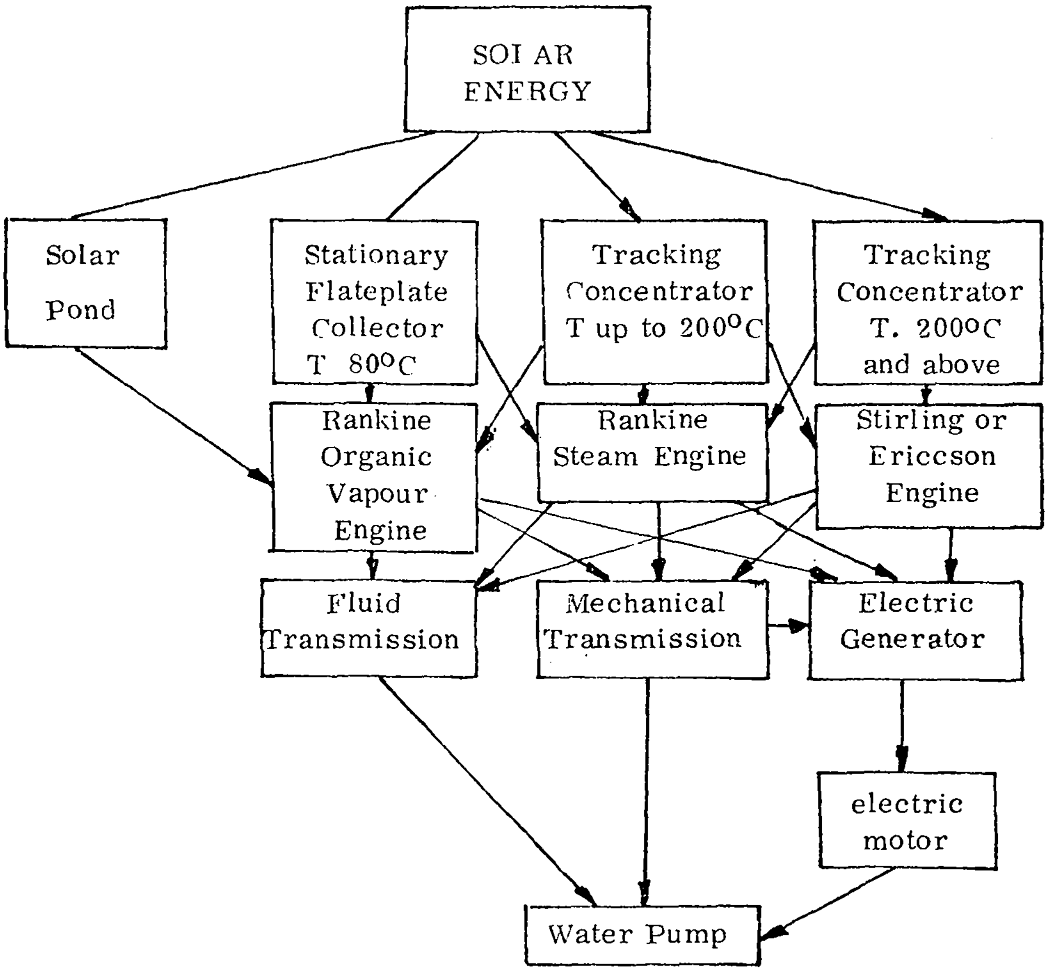
The maximum efficiency for the conversion of thermal into mechanical energy, Carnot efficiency, in a heat engine is defined as the absolute temperature difference between the heat source and heat sink, divided by the heat source temperature. The principal types of solar thermal systems of relevance for solar water pumping are:-

a) low temperature organic fluid Rankine cycle devices (input temperature (50-150°C). Carnot efficiency 10-25%, practical efficiency 2-10%

b) medium temperature water/steam Rankine cycle devices (input temperature 150-300°C). Carnot efficiency 25-45%, practical efficiency 10-20%.

c) Stirling gas cycle devices using air, hydrogen or helium as working fluid (input temperatures generally in excess of 300°C). Carnot efficiency 15-30%, practical efficiency 10-25%.

The efficiencies quoted assume a cold sink temperature of 25°C



SOME APPROACHES TO SOLAR THERMAL WATER PUMPING
FIG 2

3.1.1 Small-scale low-temperature Rankine engine pumps

The refrigerator applies the Rankine cycle in reverse (mechanical energy is used to cause a heat flow from the cold to the hot source), and this is a well developed and understood technology. As refrigerators are manufactured in large quantities and are both cheap and reliable it is reasonable to assume that engines employing similar technology could also be mass produced quite cheaply and some attempts have been made to develop such engines for use in solar systems.

The Rankine cycle operates by pumping a liquid under pressure into a boiler where heat is used to boil the liquid into a vapour; the vapour is then expanded in a piston, turbine or screw to produce mechanical energy; low pressure vapour emerges from the expander and is condensed to a liquid which is pumped back to the boiler where the cycle begins again, see Fig. 4 .

Organic fluids, such as the fluoro-carbon (freon) refrigerants, are commonly used and are suitable at temperatures of about 65° to 350°C. At the lower end of this range relatively simple flat plate solar collectors, as described later, can be employed.

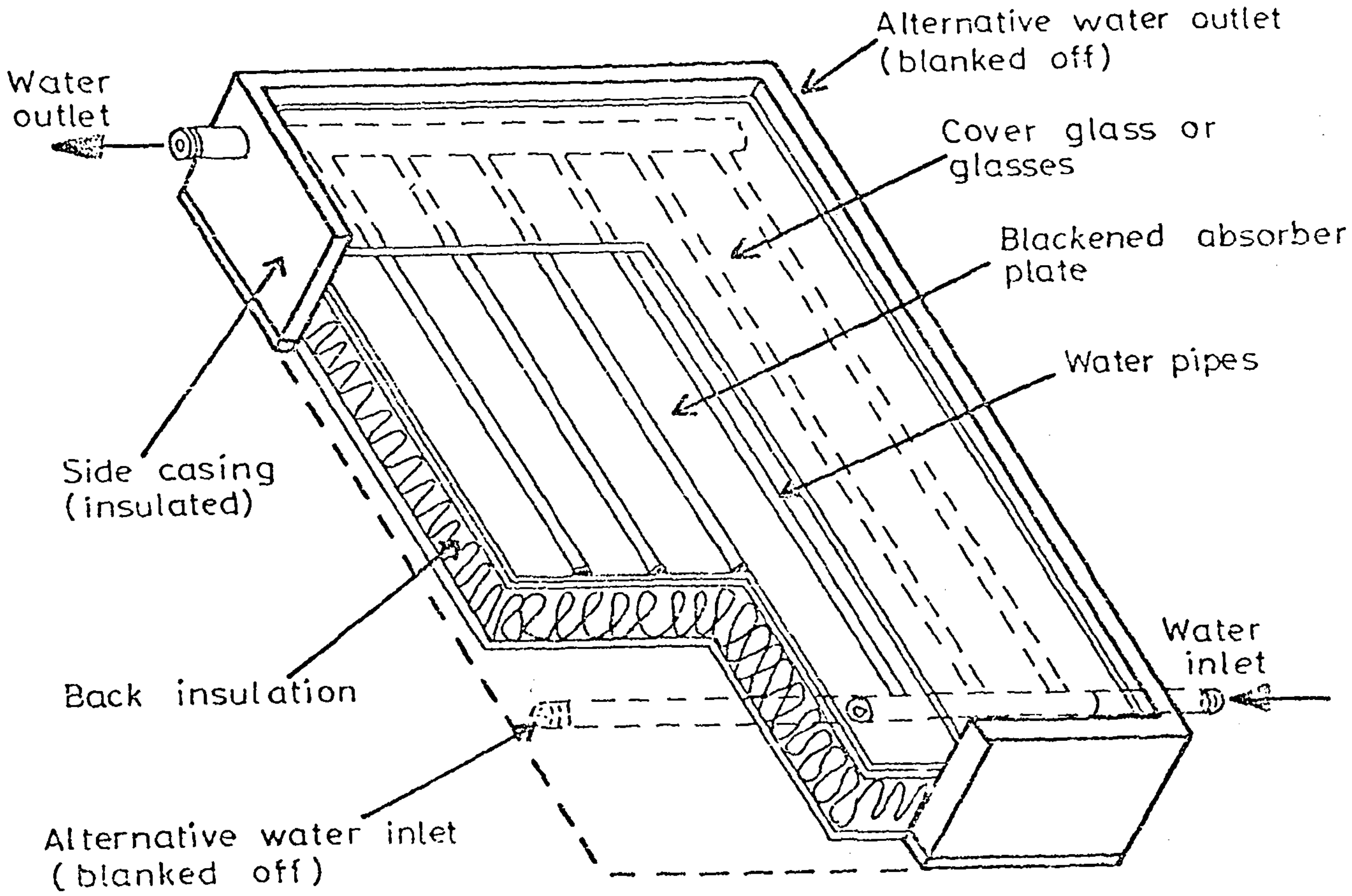
Expander efficiency is limited by the size of the machine in addition to the operating temperature. With current designs small systems are not very efficient. This is mainly due to the fact that there must be a clearance between the pistons or turbine blades and the containment cylinder, and the fluid which passes through the clearance space does not perform work. In a small system this area is a larger fraction of the total working area than in a large system.

Flat plate collector

When radiant energy strikes the surface of an object a proportion, depending upon the angle of incidence and the nature of the surface, is reflected, part is absorbed and part may be transmitted through the object. With a few important exceptions (such as photovoltaic cells - see later) the energy of the absorbed radiation is degraded rapidly to heat.

The temperature attained is determined by a balance between the input of absorbed energy and the heat loss to the environment. The heat loss increases with the temperature and limits the ultimate temperature attained by a collector system. It also reduces the proportion of useful heat extractable from the system. Maximum temperatures and maximum useful power output are therefore obtained when a highly absorbing, well-insulated body is exposed to a high intensity of solar radiation. A wide range of systems, designed to meet a variety of needs and situations have been developed and many are available commercially.

The flat plate collector absorbs as much as possible of the incident solar energy that falls upon it. Since the collector is normally immobile the plate is close to perpendicular to the beam of sunlight only at limited times of day and not in all seasons. The input of direct sunlight therefore varies more strongly with time and season than does the actual intensity of the solar radiation. Due to the large area over which heat can be lost, the retention of heat, and hence the collection efficiency, falls off rapidly with increase in collection temperature. The technical complexity and the present cost of such collectors generally rises steeply if reasonable efficiences are required above about 90°C in bright sunlight. Nevertheless flat plate collectors, including some manufactured in developing countries have been sucessfully employed in water pumping systems. The construction of a typical flat plate collector is illustrated in Fig 3.



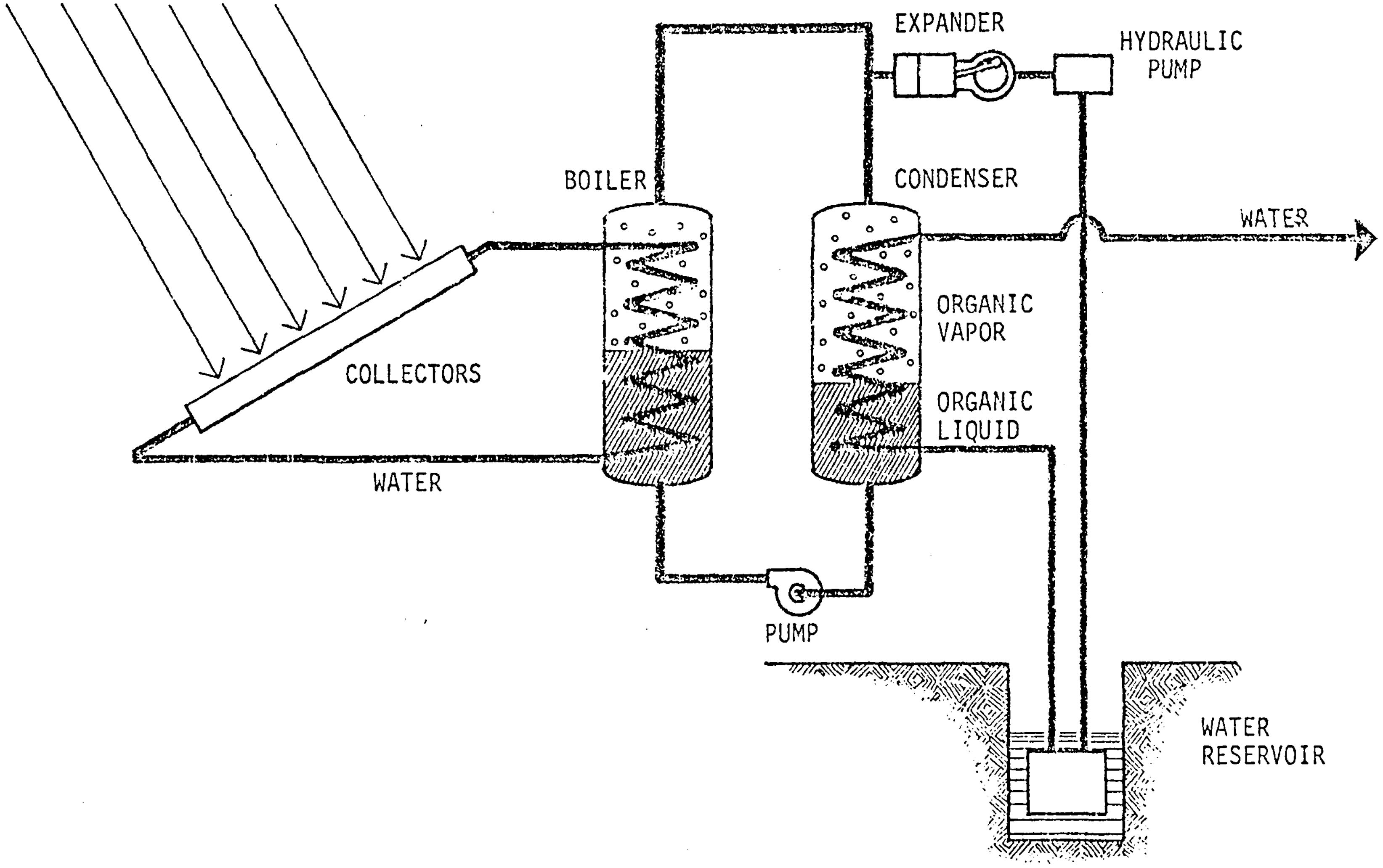
UK-ISES

FIGURE 3 CONSTRUCTION OF SIMPLE FLAT PLATE COLLECTOR

ORMAT turbine

In the early 1960's work in Israel led to the development of the ORMAT turbine.(9) This is a Rankine Cycle hermetically sealed turbogenerator with one rotating part and monochlorobenzene as the working fluid. The system uses flat plate collectors which produce low pressure steam which heats a tube and shell type heat exchanger/boiler. An irrigation plant of this type was installed in Mali in 1967 which lifted 11.3m^3/d of water through a head of 45.7m (5).

More than 2000 gas burning ORMAT engines, in the power range of several hundred watts to 15kW$_{(e)}$ have been manufactured over the last ten years, and these have been proved to be extremly reliable. Work with solar systems is continuing, including solar ponds (see below), but solar water pumps are not produced on a commercial scale, possibly because the large collector area required makes them too expensive.



Georgia Institute of Technology (reproduced from Ref. 6)

Schematic of a small SOFRETES Solar Water Pumping System
Fig 4.

SOFRETES Pump

In parallel to the work on the ORMAT system a solar water pump was developed in Senegal. The design was further refined in France by the SOFRETES company which has become the best known manufacturer of solar thermal pumps.

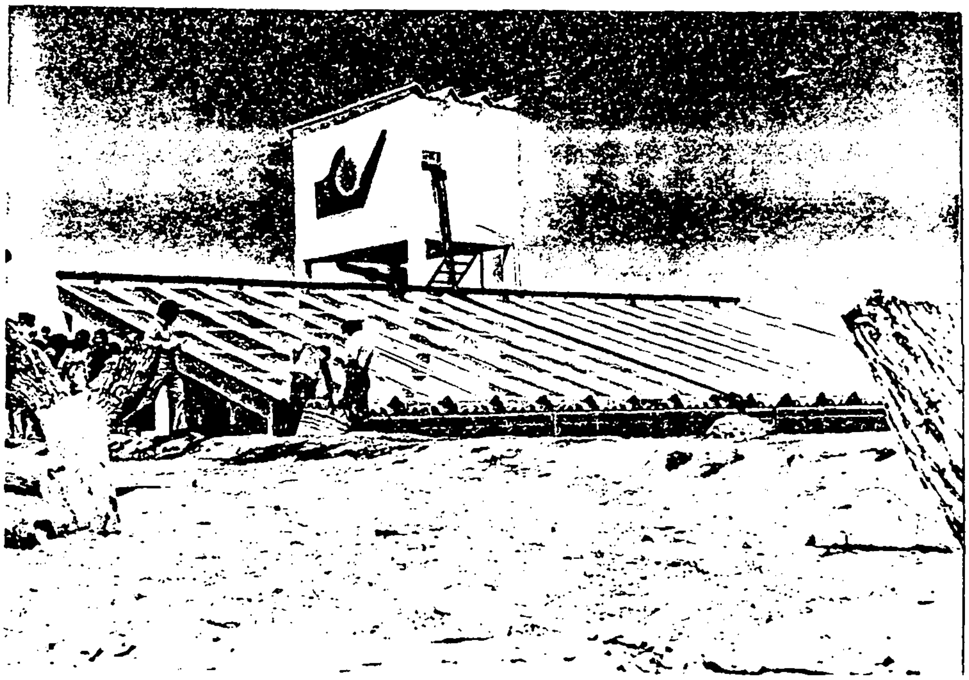
The standard SOFRETES pump uses 70 to 100 m^2 of flat plate solar collectors with water as the heat transfer fluid to evaporate butane or Freon in a heat exchanger/boiler. The vapour at about $80^{o}C$ is expanded through a reciprocating engine and is condensed in another heat exchanger which is cooled by the water being pumped. The condensed liquid is returned to the boiler by a pump driven by the engine. The engine drives a hydraulic pump which lifts the water. Overall peak efficiency is about 1%. A schematic of the system is given in fig 4 . The system is rated as about 1kW (mech).

About sixty of these have been, or are currently being, installed throughout the world. Most of these have been for pumping from deep wells. One used for irrigation in Mali pumped water at 6 to $7m^3/h$ for 5h/day through a head of 15m.

Fig 5 shows a 1kW system which was installed at a farm at Cedral, Mexico in 1975. This pumps water at $4m^3/h$ from a 20m for 5 to 6 h/day for irrigation of tomato crops.

These pumps are elaborate and appear to be well engineered although a number have failed to operate reliably in the field. A 100W system is currently being evaluated in India. (11)

Most of the 1kW installations were installed as part of bi-laterial aid programmes and cost around $50,000 each although similar pumps would now cost about $25,000 (6), but this is too high a cost to be economically attractive. The 1kW pumps are no longer manufactured by Sofretes.

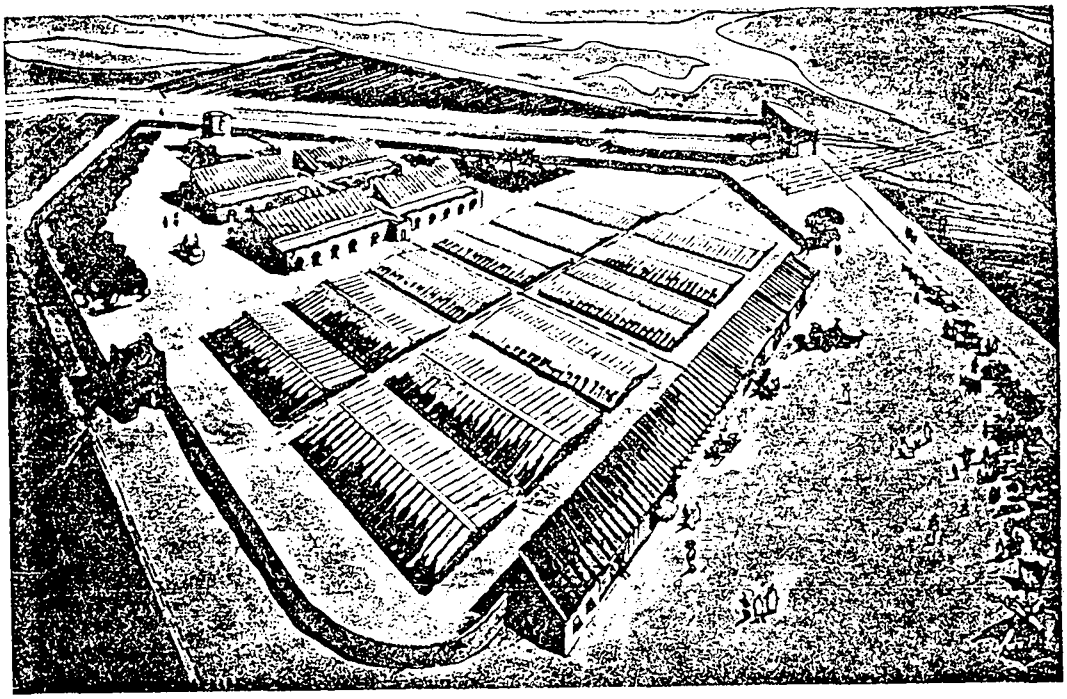


SOFRETES

1kW SOFRETES WATER PUMP AT CEDRAL, MEXICO
FIG 5.

Sofretes are currently manufacturing a system which uses a screw expander with organic fluid operating at about 90^{o}C. An advanced flat plate collector which is efficient at this temperature is currently employed, while development work is underway on higher temperature collectors. Some Sofretes irrigation projects are listed in table 1. In Niger and Senegal collectors are manufactured locally.

The system at Dire, which will be completed during 1979 is the largest of its type and as well as pumping water from the Niger river for irrigation will pump potable water for human consumption from a borehole and provide electricity for the associated farm. An artist's impression of Dire is shown in Fig 6.
The larger Sofretes systems achieve conversion efficiencies of around 2%.



SOFRETES

SOFRETES WATER PUMPING INSTALLATION AT DIRE.
FIG 6.

Location	Power kW	Collector Area m^2	Delivery Flow Rate m^3/h	Water Head m	Daily Operating Time	Area Irrigated ha	Cost $
DIRE, Mali	70	3200	1800	8	6-11	150	1.8M
TABALAK, Niger	5	400	150	6	5-6		
KARMA, Niger	10	800	300	6	5-6		
BAKEL, Senegal	32	1870	600	10	10	100	600,000

IRRIGATION PROJECTS USING SOFRETES PUMPS.

TABLE1.

The characteristics of Sofretes present product range are given in table 2. The stated output is for a water head of 10m and daily insolation of 6.5 kWh/m^2.

MODEL	APPROXIMATE SHAFT POWER kW	COLLECTOR AREA m^2	MAXIMUM DAILY OUTPUT (h=10m) m^3
NADJE	6.5	320	850
NADJE 1.PS	10	360	1300
TONATIUH 2.PS	14	540	2000
RA 3.PS	25	864	3800
PROMETHEE 4.PS	40	1280	5200

SOFRETES SOLAR WATER PUMPS
TABLE 2.

Solar Ponds

Solar ponds have been proposed as a simple, cheap method of collecting and storing solar energy, on a potentially large scale. Such a pond is a shallow body of water, typically 1 to 2m deep, with a black bottom. When incident solar radiation penetrates the pond some is absorbed by the liquid and a large proportion reaches the bottom and is absorbed by the black surface which is consequently heated. Thus water at the bottom of the pond reaches a higher temperature than that nearer the surface. Convection currents which would normally develop and equalise this temperature difference are prevented by the presence of a strong density gradient from bottom to top by the use of dissolved salts. Many natural salt water ponds are known which exhibit these properties, and successful scientific research into their use began in the 1950's in Israel. (12)

The principal aims of research into solar ponds has been concerned with methods of extracting energy from the pond. Success has been achieved by recycling the hot layers through a heat exchanger and temperatures of 90°C have been achieved. Currently a power generation system using an Ormat turbine is operating in Israel (13). In India solar pond has been used for the production of salt (14) and biogas digester heating. (15)

The solar pond could be a useful collector for solar pumping systems but must be designed for a specific location.

Other low temperature Rankine systems

Several other low temperature Rankine engine systems are under development but are not yet commercial products. Dornier in Germany have a system in which the working fluid (Freon) is evaporated directly in the flat plate solar collectors and development work is proceeding in partnership with

BHEL in India. It is hoped that this will lead to mass production of these units.

Another interesting development is being persued by Hindustan Brown Boveri who claim that because of its mechanical simplicity it should be cheaper than other systems. In this a volatile organic fluid which is immiscible with water is heated above its building point in a flate plate collector and allowed to flash into vapour in a tank. The pressure produced is employed to lift water. Again this system is still at the prototype stage.

Other very simple systems which have been proposed include the "Camel" pump being developed in Botswana and the "Minto Wheel" in the USA. However, these are based on evaporating a low boiling point fluid and then condensing the vapour in such a way that the weight of the resulting liquid condensate drives the machine. Although this is a simple process the efficiency is thought to be exremely poor and may place such devices at a disadvantage.

3.1.2 High temperature engine pumps

As explained earler it is possible to achieve much better operating efficiencies by operating at higher temperatures.

In order to achieve such higher temperatures with reasonable efficiency a focusing solar collector must be used. In this the solar energy input to an absorber is increased by concentration with suitable mirrors or lenses. Because of the apparent motion of the sun, tracking is required to follow the sun through its seasonal, and, in most systems, its daily variation in position. At the expense of increased complexity reasonable efficiencies can be achieved at temperatures of several hundred °C. Only the direct radiation can be collected, since diffuse radiation cannot be focussed. This implies that focussed collection can only be considered seriously in areas having a high proportion of uninterrupted direct sunshine. The problems of wind-loading and tracking limit the size of individual reflectors, and add to the system cost.

There are two basic families of focussing collectors. These are:

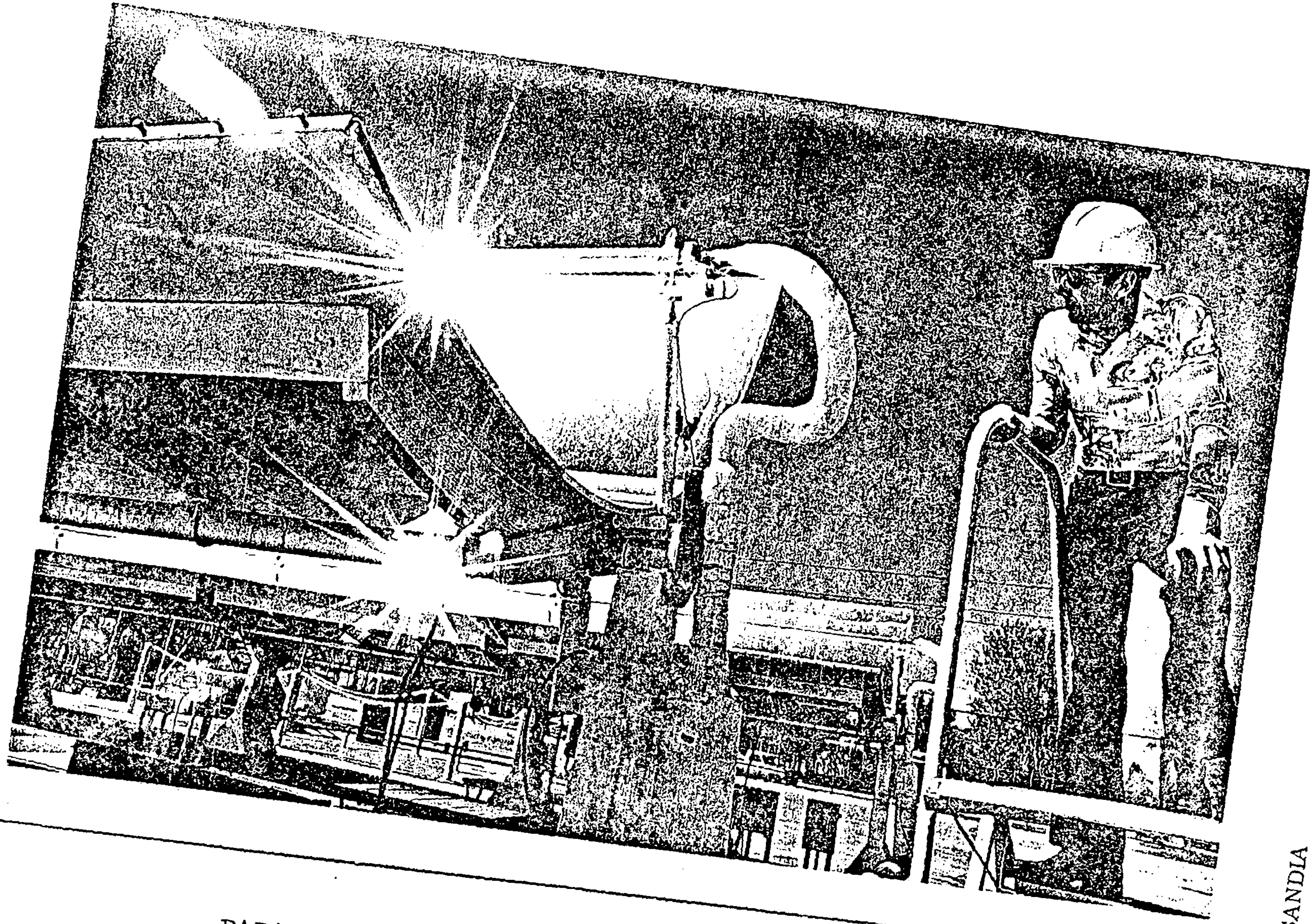
a) the central focus collector - sunlight is reflected to a point by a parabolic dish or a field or mirrors or focussed by a lens

b) the linear focus collector - sunlight is reflected to a linear absorber by a parabolic trough or a series of faceted mirror strips or focussed through a linear Fresnel lens.

The best developed is the linear focus parabolic trough collector and several models are commercially available. In the simplest of these the reflector is mounted with its long axis orientated north-south (polar axis) and this is rotated at a constant rate of 15°/hour around its axis so as to follow the sun. This can be achieved using a timing mechanism and provision must also be made to reset the collector each evening so as to be ready to start tracking again the next morning. It is also possible to mount the collector on an east-west axis but tracking is not so simple because the required speed of rotation varies from hour to hour and day to day. In order to improve on the simple clock tracking system a sun-sensor can be employed. This is generally a pair of photoelectric cells mounted on the moveable assembly and separated by a shading device. The outputs of the cells are compared by a differential amplifier which is connected to an electric drive motor, and each time a difference in output from the two cells is detected the collector is driven to follow the sun and nullify the signal. Although this approach is complex, simpler devices have been proposed to achieve sun sensing tracking though the use of small cylinders filled with Freon which are shaded when the collector is correctly orientated but which become progressively exposed to the sun when it is incorrectly orientated. Exposure to the sun pressurises the Freon which provides the driving force to move the collector. It is possible that a breakthrough in tracking technology will render tracking systems much more attractive than flat plate systems in the future. Figure 7 shows a typical collector which uses reflectors of aluminium coated teflon and a steel tube absorber enclosed in an evacuated glass cylinder achieving an operating temperature of 300°C.

Parabolic dish type solar collectors featured in much of the early solar research work, and recently the idea, as the central receiver/heliostat field (so called "power tower") principle has been receiving much attention in relation to large scale solar power generation. Focussing the sun to a central point requires that the reflector must track in two axes. It is possible to arrange the reflector on an equatorial mounting (as with astronomical telescopes) and rotate in one axis at 15°/hour with either the absorber or the reflector mounting being adjusted daily to allow for seasonal variation. In practice it is difficult to achieve a cheap and simple equatorial tracking system and the more favoured alternative is to move the reflector by rotation around a horizontal and a vertical axis. In the system rotation speed around the two axes must change continuously and so in achieving a simpler mechanical system a more complex tracking system (either sun sensing, or a microprocessor) must be used.

Linear parabolic collectors are now being used with Rankine engines for water pumping applications mainly on a large scale. The main activity has been in the United States and details of the three principal projects are presented in Table 3.



SANDIA

PARABOLIC TROUGH COLLECTOR (SANDIA LABORATORIES)

FIG. 7.

Location	Power kW	Collector + Manufacturer + Type	Collector Area m^2	Operating Temperature °C	Delivery Flow Rate m^3/h	Water Head m	Daily Operating Time h	Cost $
Willard, New Mexico	19	Acurex	624	163	202	25-31	5-7	500,000
GILABEND, Arizona	37	Battelle	554	138	2280 (peak)	3.7	5-7	240,000*
COOLIDGE Arizona	$150_{(el)}$	Acurex parabolic trough	4550	287	317	115		

* approximate cost of pump including assembly, installation and check out but excluding development costs the total project cost is $2.5M.

LARGE SCALE SOLAR IRRIGATION SYSTEMS
TABLE 3.

Stirling (or Eriksson) cycle engines use a gas such as air, hydrogen or helium as a working fluid and are generally capable of higher thermodynamic efficiency than Rankine cycle engines at a given operating temperature. Their heat exchange interfaces can also be smaller and therefore cheaper, but in practice Stirling engines require heat inputs at temperatures in excess of about 300°C, so that a solar powered Stirling engine would almost certainly require a high concentration solar collector.

In recent years considerable effort has been made to develop high technology Stirling engines capable of competing with diesel engines for automotive applications, particularly by Philips in the Netherlands.

At least two manufacturers are developing devices based on the Stirling cycle which offer promise for small-scale solar pumping applications. Sunpower, USA, are developing the Beale engine (16) and Metal Box (India) Limited are developing the Fluidyne pump originally invented by the Atomic Energy Authority at Harwell, UK.

3.2 PUMPING SYSTEMS EMPLOYING DIRECT CONVERSION OF SOLAR ENERGY

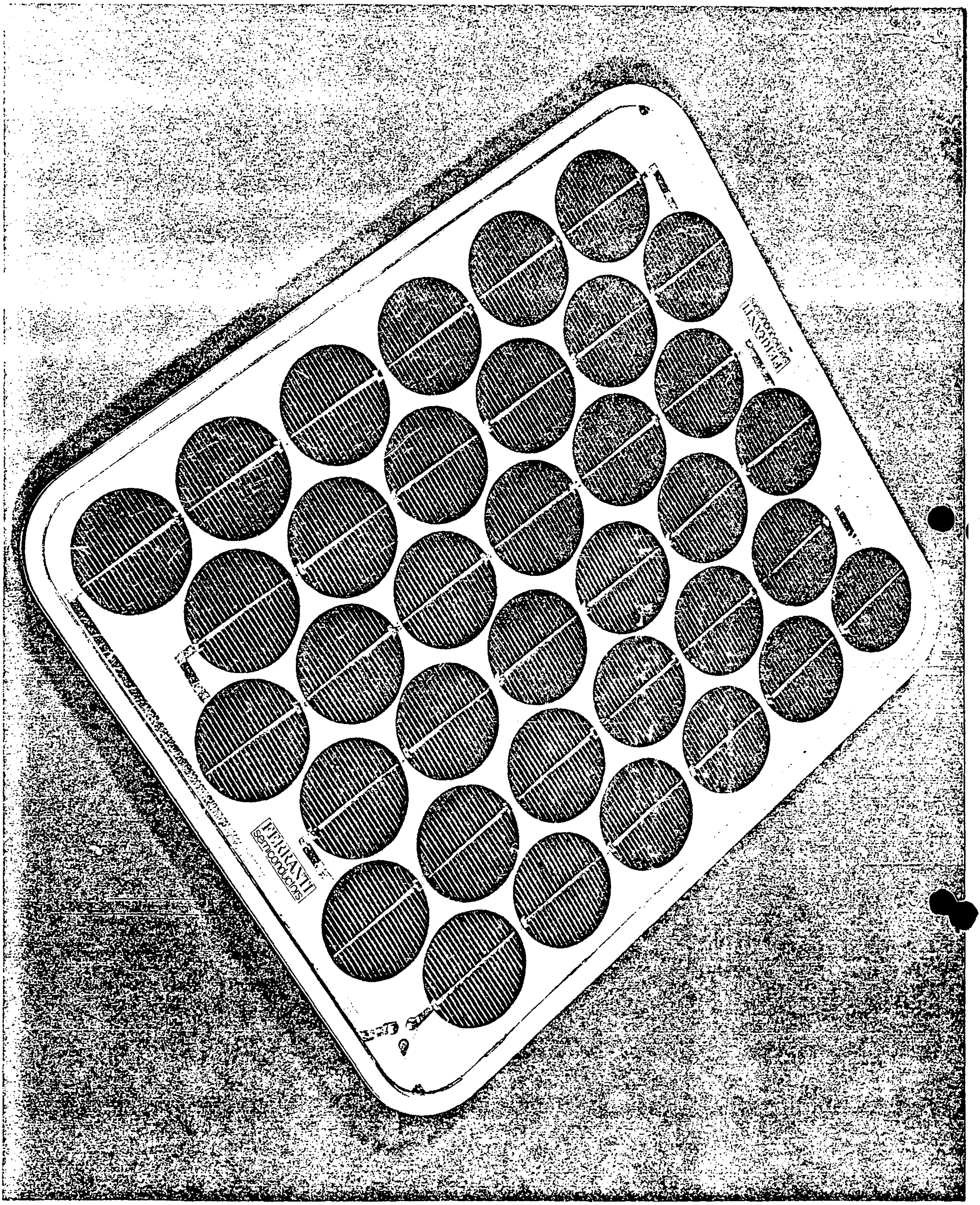
Solar radiation can be converted directly into electricity using a semiconductor device known as a photovoltaic, or solar, cell. This was developed during the 1950 and early 1960's as a power source for satellites and costs were extremely high. Recently improvements in manufacturing techniques and increased volume of production have greatly reduced costs.

Several materials exhibit photovoltaic properties but, the only type commercially available at present is the silicon cell, which has the considerable advantage of being based on well-known semiconductor technology. Its mode of operation is well understood and it has been manufactured in large quantities. The cell consists of a thin slice of specially-doped single-crystal silicon, commonly 50mm to 100mm in diameter or, more recently, square, with metal contacts on the front and back surfaces. The silicon solar cell develops a potential of about 0.5V when exposed to sunlight and can deliver a current which is proportional to the light intensity and its surface area , being about 25mA for each cm^2 of cell area with insolation of 1kW/m^2

Under peak conditions the conversion efficiency of the photovoltaic cell is around 13%, but the electrical characteristics are such that the current and voltage must be maintained within fixed limits (at the maximum power point) to maintain this efficiency of conversion and average operating efficiency is around 10%. An increase in cell temperature causes a slight rise in short-circuit current but a sharp fall in open-circuit voltage. As a result, the maximum power and efficiency fall by about 0.5% per ^{o}C rise. Becuase of the serious loss of power at high temperatures, it is important in array design and installation to ensure that the cells run as coolly as possible.

The unit building block for all photovoltaic power systems is the photovoltaic module such as that shown in Fig 8. Each module consists of a number of series and parallel connected silicon cells encapsulated in a weather-tight structure, the design of which varies with manufacturer. Typically 36 cells are series connected so that a module open circuit voltage of about 18V is obtained. In the module shown the cells are 76m in diameter and has a short circuit current capacity of 1.1A with 1kW/m^2 insolation. The peak useable power output is 15W.

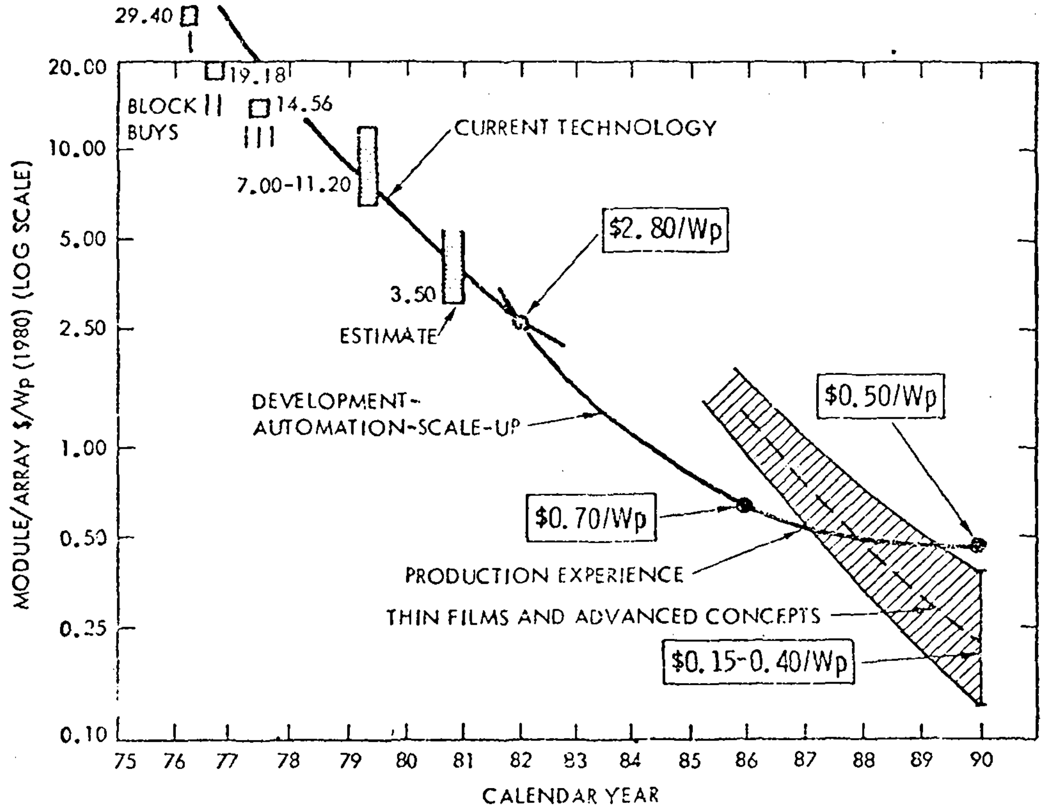
The current world price level for photovoltaic modules is $10 to $12/Wp, with $7 being quoted by one manufacturer, electricity delivered costs about $1.00 to $1.50/kWh. However, it is believed that costs can be reduced substantially. In the United States, where the bulk of development and manufacturing is underway the Department of Energy has predicted



PHOTOVOLTAIC MODULE
Fig 8

costs of less than \$1/Wp by 1984. The trend is illustrated in fig 9 and there is cautious optimism that these targets will be achieved, possibly even bettered. (17)

Unlike solar-thermal power systems, photovoltaic systems are now being quite widely installed in practical and economically viable applications even at current prices. These are in areas remote from the electric grid and where small levels of power (tens to hundreds of Watts) are required with high reliability, for example microwave repeaters.



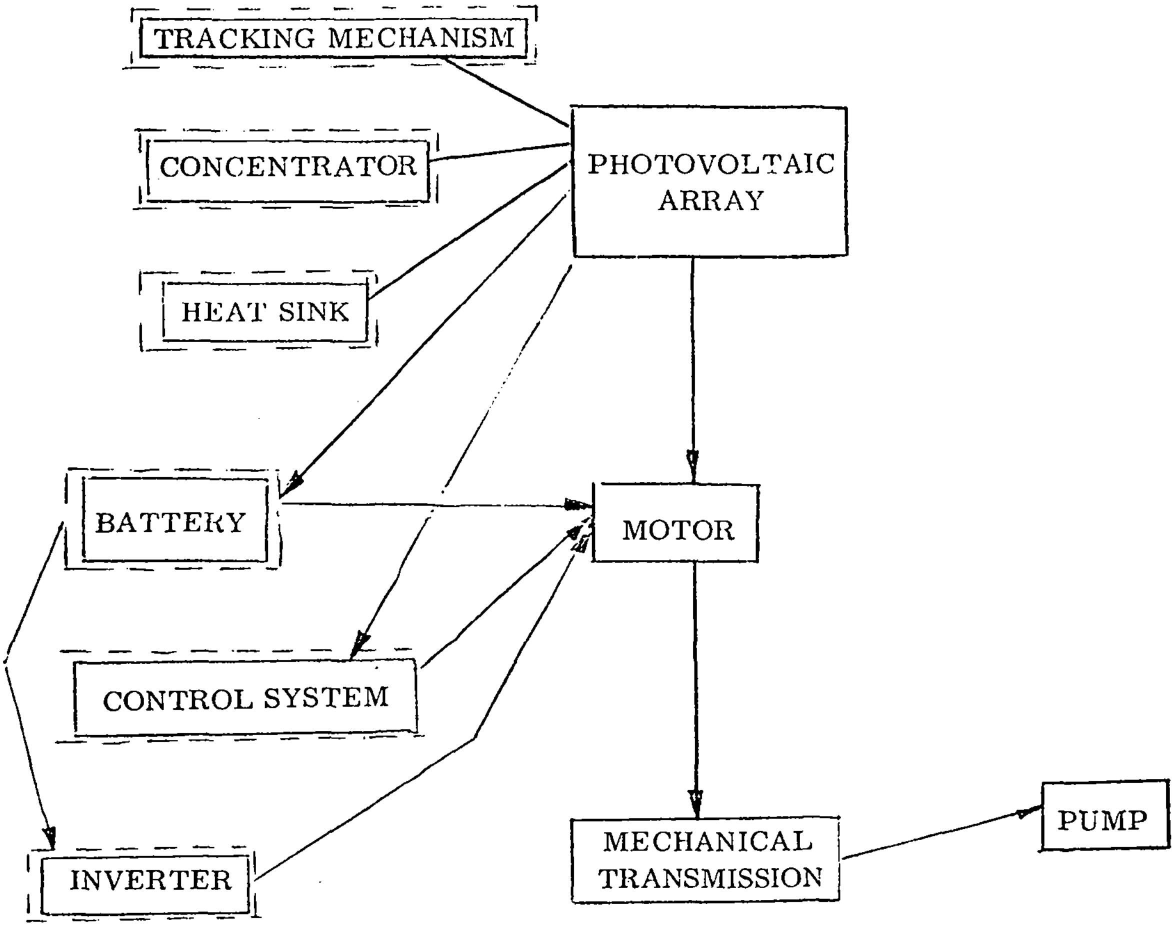
USDOE/JPL

Photovoltaic Module/Array Price
Goals and History (in 1980 \$)
(-United States Department of Energy)

Fig 9

Photovoltaic water pumps

A photovoltaic array can be used to power an electrically driven pump. In its simplest form a fixed flat plate photovoltaic array drives a direct current motor directly and this is mechanically linked to the pump. It is also possible to employ an array which has sun tracking and/or concentration, and the electric system may involve batteries and other components the options are illustrated in fig 10 and several different systems have been built.



PHOTOVOLTAIC WATER PUMPING SYSTEM CONFIGURATION OPTIONS

FIG 10

Components indicated in solid outlined boxes are essential to any photovoltaic system, whereas the components indicated within broken line boxes are options that have been offered by some but not all system suppliers.

The best developed photovoltaic water pumping system is manufactured in France by Pompes Guinard. This employs silicon photovoltaic cell modules which are coupled directly to a permanent magnet, direct current, motor which has a direct mechanical connection to a centrifugal pump. Both the motor and the pumps have been specifically designed for this application.

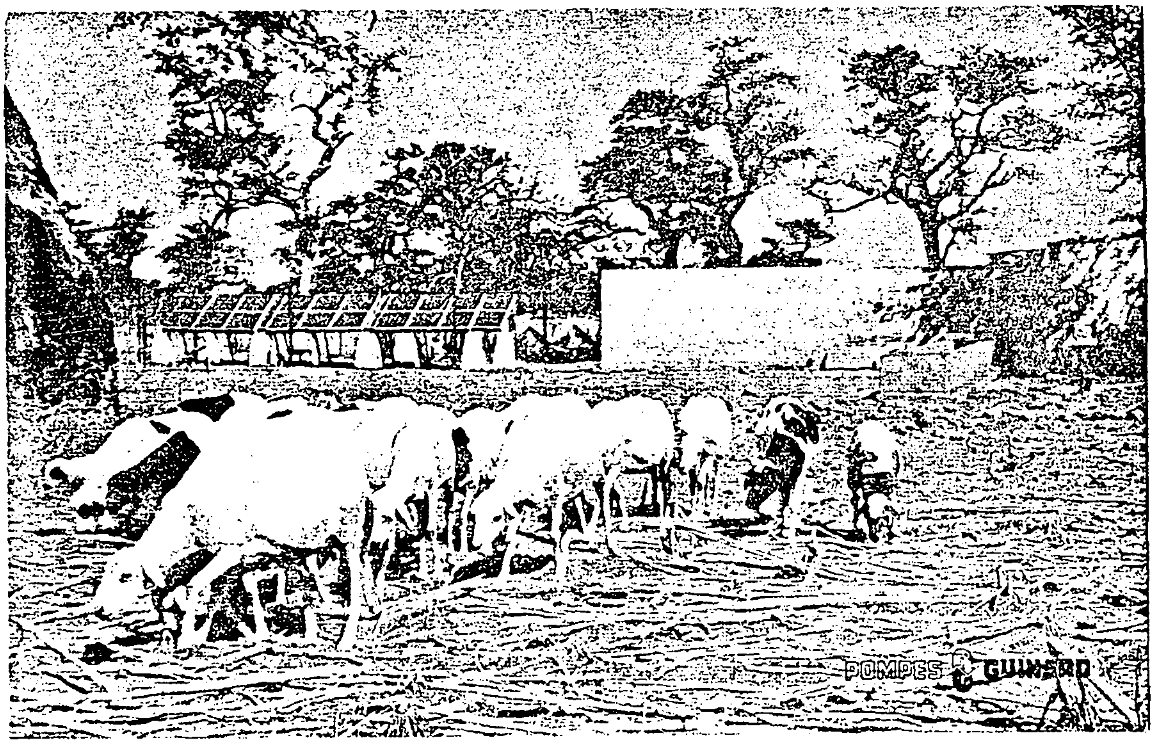
The first pump of this type was installed at a farm in Corsica in 1974. This is still in operation and pumps water at a rate of $16m^3$/day through a head of 25m. Since then a total of about fifty further pumps have been installed, the majority being in Africa and Latin America. A 900W system at Bambey, Senegal pumps water at a rate of $100m^3$/day through a 10m head for irrigation. Another 900W system at Nabasso, Mali provides $30m^3$/day from 24m to supply water for 2000 head of cattle. This installation is shown in fig 11. All of these pumps operate unattended the only regular attention which is required is washing of the photovoltaic arrays. The motor and pump require routine maintaince every five years.

Details of three of the standard Pompes Guinard systems are presented in table 4 . The purchase price of the smallest (600W) system is approximately $18,000 with the larger systems prices increasing in proportion.

With the Pompes Guinard system no regulation or energy storage (batteries) are provided. Manufacturers claim that there is good matching between the motor/pump and photovoltaic cell characteristics, i.e. reasonable performance under part load conditions. Work carried out in France supports this view. (18)

Model	Photovoltaic Power W	Collector Area m^2	Maximum Daily Output (h=10m) m^3
Alta X 600	600	10	51
Alta X 1300	1300	20	157
Alta X 6600	6600	100	836

POMPES GUINARD SOLAR WATER PUMPS
TABLE 4.



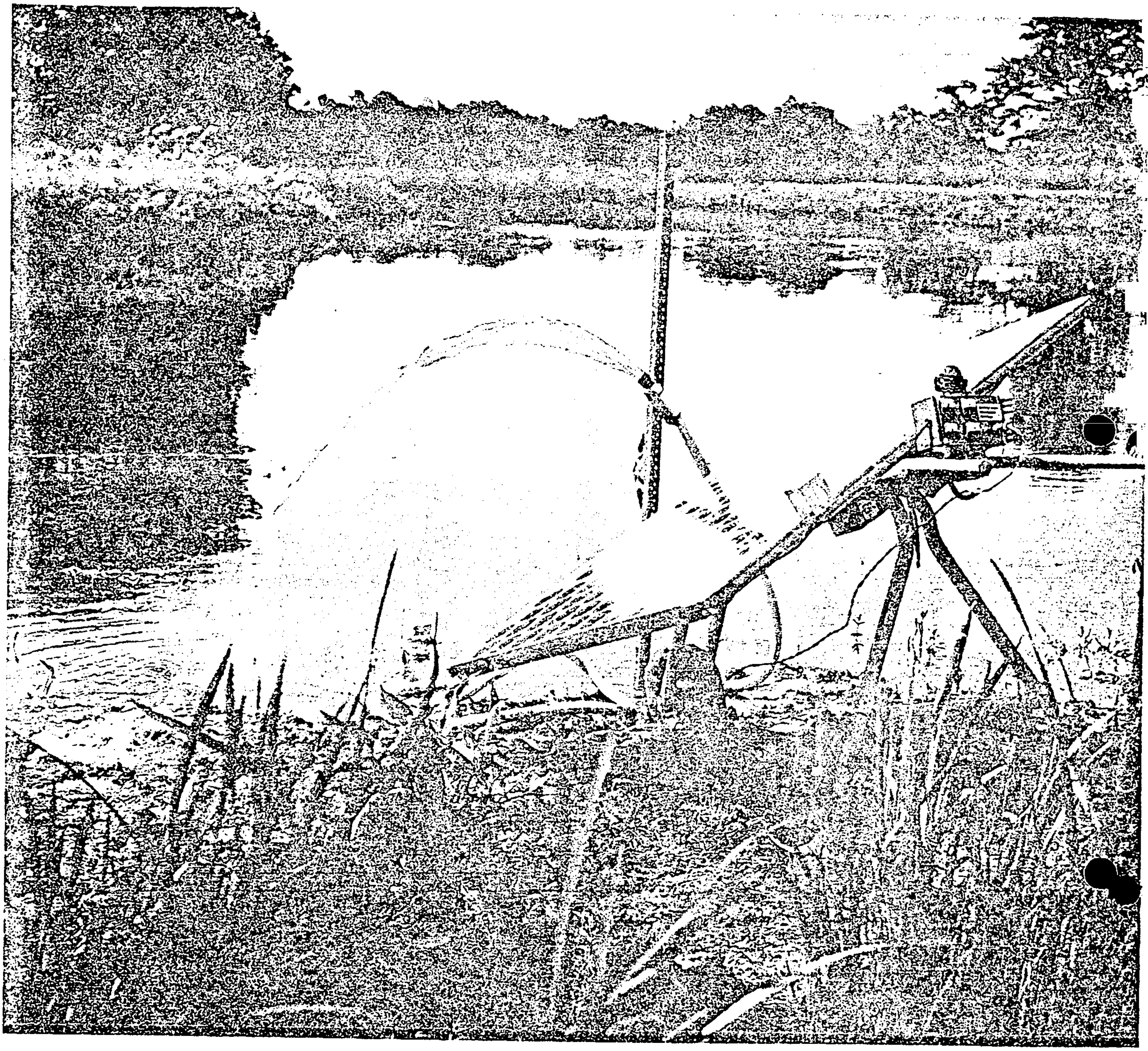
900W POMPES GUINARD INSTALLATION AT NABASSO, MALI
FIG 11

Another French manufacturer, Briau, has supplied several systems which employ electronic regulators and batteries with different types of pump depending on application. Work in Senegal with one of these systems has suggested that the use of an electronic constant current converter can double the output of the pump. (19)

A tracking flat plate photovoltaic water pump has been designed in the USA by Solar Electric International. In this the photovoltaic array is faced towards the east in the morning and manually swivelled westwards at intervals during the day. This simple feature can significantly increase the energy received in a day compared with a fixed array, but to take advantage of this the owner/operator must regularly visit the equipment and make the required adjustments. This is designed to be a mass produced unit which will lift between 50 and $100m^3$/day from a head of about 5m. This is to irrigate an area of about 1ha and is intended for small farmers. An example is shown in fig 12. This small size has been determined by the large number of farms in India, Pakistan and Bangladesh. 17 of these pumps have already been installed and 200 are being fabricated for installation during 1980. It is also believed that up to 15,000 may be installed in these three countries over the next 4 years.

This pump presently costs about $7000, with the price for 1980 projected as under $ 5000, with $1200 being achieved with the large quantities.

More recently several photovoltaic cell manufacturers such as ARCO Solar (USA) have developed their own pumps and a wide variety of experimental and prototype systems are expected to be installed in the near future. Also a number of large photovoltaic pumping systems are in operation including a 25kW installation in Nebraska, USA, (20) and Montpellier, France.



SOLAR ELECTRIC INTERNATIONAL PHOTOVOLTAIC PUMP

FIGURE 12

X

Other systems which employ concentration in addition to tracking are also under development but are not generally available. One problem with these is that cooling of the photovoltaic cells is necessary.

4. CONCLUSIONS

From the forgoing it can be seen that there is considerable activity in developing the low-cost solar water pump. At present only small photovoltaic cell based systems have been demonstrated as reliable and these are also the only ones which are commercially available. However their present cost is beyond all except governments and aid agencies. If the cost reductions predicted for photovoltaic cells are achieved then the cheap solar pump could become a reality for general use.

present cost high

Experimental prototype and solar thermal water pumps have been demonstrated but further development work is necessary to achieve reliable systems. Additionally there is potential for simple systems which could be manufactured in developing countries.

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FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Agenda Item 3

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

HYDRO POWERED WATER LIFTING DEVICES FOR IRRIGATION

by

John Collett
ITDG Ltd.
UK

CONTENTS

INTRODUCTION

Small-scale
surface water

In many parts of the developing world farmers have a long tradition of irrigation practice. Their systems are generally characterised by two important features - smallness of scale and the use of surface water as their supply. Where topography permits, the simplest and most efficient way to irrigate is to gravity feed the water directly to the land. Where this is not possible - for example when the supply is from shallow ground water - water lifting will be necessary. Traditionally human labour, draught animals, water and wind have been the power sources for this water lifting. In some areas there has been a tendency for modern pumping equipment to supplant the traditional devices, but this trend is likely to be retarded by the increasing shortage and rising cost of fossil fuels, which is also stimulating efforts to improve and develop reliable systems based on renewable energy sources.

Water power
not likely to
be present
when needed
most

Historically, water power was one of the first energy sources to be exploited by mankind. The potential energy of water at an elevation above sea level is a primary source of power and, over the centuries, man has devised a wide range of hydro-dynamic prime movers to convert this energy into useful work. The great variety of devices has developed to suit the widely differing characteristics of water power sites and user requirements. Selecting a system will depend upon the complex relationship of many considerations which include :

- the use to which the power will be put
- the form in which it will be used
- the economic and natural resources available
- the availability of suitable maintenance facilities
- whether the machinery must be portable or not.

direct
conversion of
energy for
water lifting

This paper will focus attention on hydro-mechanical devices that convert the energy of water directly to power water-lifting machines for irrigation. The devices examined include well-established machines such as water wheels, water turbines and hydraulic ram pumps; and some new innovations - the Plata pump, the Run-of-the-stream turbine and the Coil pump. A common feature of all these systems is that they can operate for twentyfour hours a day without fuel or running costs. It is not intended to give the impression that these are the most important or the only uses to which water power may be put. The generation of hydro-electricity is an immediately obvious application but this is a conventional technology, well developed on all scales, and so does not need to be described here.

In order to make full use of the potential 24hr supply available from the water lifting devices, it will usually be necessary to construct storage tanks or reservoirs, thereby adding greatly to the cost of the equipment. Also, the water wheel, turbine, ram pump and Plata pump are fixed devices which will require civil works such as dams, intakes, weirs, sluices, pipelines and penstocks. The scale of these structures will depend on the individual site, and the associated costs will be a further significant addition to the equipment costs.

Any impact assessment of the devices described, should examine social as well as physical factors. Many of the problems encountered are likely to be similar to those attendant to other pumping programmes with the exception of the 24hr pumping potential - this may necessitate a high degree of co-operation and management if the supply is to be efficiently used. The consequence of failure, excessive irrigation, the need for drainage, health hazards associated with standing water, deprivation of downstream users and the need for ancilliary services, are some of the many aspects which will deserve attention.

Finally, it should be noted that a limiting factor in the application of hydro power for irrigation water pumping is the enormous variation in flow of many water courses. When irrigation is required river levels may be so low that water power will not be attainable.

Likely that flow inadequate when
irrigation is needed <u>most</u>.

2.

THE HYDRAULIC RAM PUMP

Scope of small-scale irrigation application very limited.

Introduction

1. The automatic hydraulic ram pump was invented in 1796 by Joseph Michael Montgolfier and it has been widely used for nearly a century in rural areas of several countries of the Northern hemisphere. It is an ideal machine for water pumping if certain topographical conditions can be found for its installation. It works solely by the power from falling water carried in an inclined pipe from a spring, stream or river, without any need for an additional power source. Although described as "automatic", starting and stopping are usually performed manually. It has only two moving parts, and has an exceptional record of trouble-free operation. In the US, France, Britain and the USSR, many thousands of ram pump installations were in operation (1) until about the 1930's when expansion of rural electrification led to their replacement by power driven units and large centralised systems. Although the ram pump cannot be used everywhere, there are many parts of the world where it could find application if its existence and advantages were more widely known. The most common application for the pump is water supplies for domestic and livestock needs. Experience in the use of ram pumps for irrigation has been very limited, and until more research work is done to develop larger capacity installations, it is ~~[illegible]~~ highly Unlikely that this type of pump will make a major contribution to irrigation water pumping.

Hm!

Description and Principles of Operation (2)

2. The ram pump exploits the phenomenon of water hammer. It uses the kinetic energy of water flowing in a pipe to raise a small fraction of that water to a level that can be much higher than the source of

the flow. The pump can only be used in places where there is a steady and reliable supply of water with a sufficient fall. For example, a ram pump operating with a working head of 4 metres will deliver about 5% of the flow to an elevation of say 40 metres; if the delivery head is only 8 metres about 20% of the flowing water will be elevated. A labelled diagram of a typical working ram installation is shown in Figure 1.

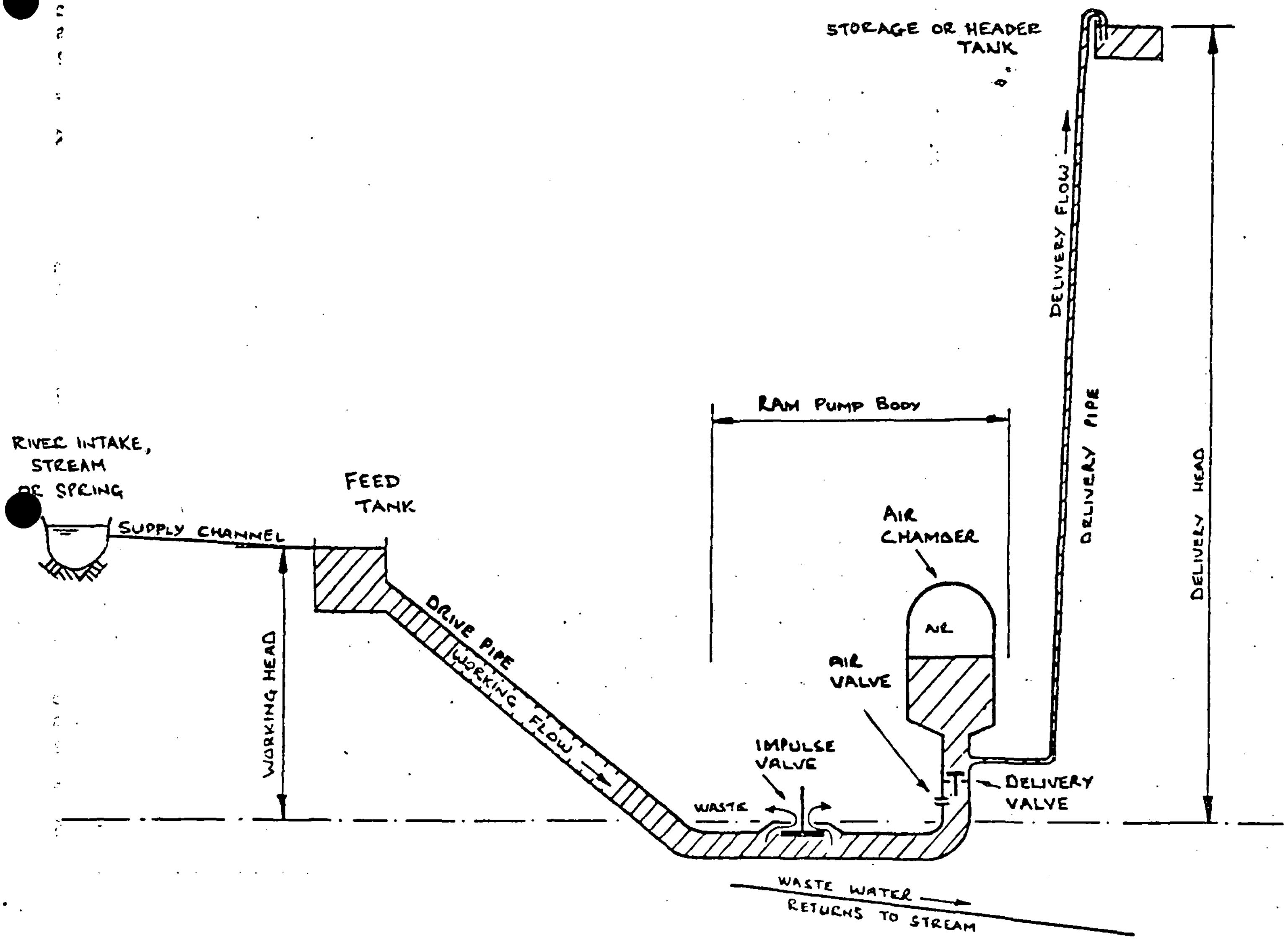

Figure 1

3. Water flows down the drive pipe from the source and escapes out through the impulse valve. When the flow of water past the impulse valve is fast enough, this flow and the upward force on the valve causes the valve to shut suddenly, halting the column of water in the drive pipe. The momentum of the stopped column of water produces a sudden pressure rise in the ram, which will, if it is large enough, overcome the pressure in the air chamber above the delivery valve, allowing water to flow into the air chamber and then up to the header tank. The pressure surge or hammer in the ram is partly reduced by the escape of water into the air chamber, and the pressure pulse "rebounds" back up the drive pipe producing a slight suction in the ram body. This causes the delivery valve to close, preventing the pumped water from flowing back into the ram. The impulse valve drops down, water begins to flow out again, and the cycle is repeated.

4. A small amount of air enters through the air valve during the suction part of the ram cycle, and passes into the air chamber with each surge of water up through the delivery valve. The air chamber is necessary to even out the drastic pressure changes in the ram, allowing a more steady flow of water to the header tank. The air in the chamber is always compressed, and needs to be constantly replaced as it becomes mixed with the water and lost to the header tank.

Performance and efficiency

5. Typical performance figures of commercially available ram pumps and some noteworthy installations are given in Table 1. Summarising this table , it can be seen that the maximum delivery volume of a

Table 1 (Metric Units)

MANUFACTURE OR DESIGN	DRIVE PIPE Internal Diameter (min)	DELIVERY PIPE (min)	DELIVERY VOLUME (litres/sec)	DELIVERY VOLUME (litres/min)	DELIVERY VOLUME (m^3/24hrs)	DELIVERY HEAD (metres)	WORKING HEAD (metres)	WORKING FLOW (litres/sec)	WORKING FLOW (litres/min
BLAKES:									
7 standard sizes	32 to 127	19 to 76	0.005 to 1.3	0.31 to 80	0.45 to 114	100 to 150	1 to 20	0.1 to 7.0	7 to 410
RIFE:									
Series B. 5 sizes	32 to 76	19 to 32				45	0.6 to 4.5		7 to 225
Standard "Everlasting" 8 sizes	32 to 203	19 to 102				75	0.9 to 7.5		14 to 1600
[illegible]vy Duty "Everlasting" 6 sizes	32 to 152	19 to 76				150	0.9 to 15.0		14 to 1800
DANKS:									
5 standard sizes	25 to 102	12 to 50	to 0.6	to 36	to 52	60	0.6 to 6.0		6 to 450
VITA ITDG SPATF	32	20	0.04	2.5	3.6	45	1 to 20		5.0
Seattle Waterworks Installation	Two 295 mm pumps				1600 to 2900	45	15		
[illegible]aval Coaling Station Rife Installation	Two 295 mm pumps		17.5	1050	1500	25	11		2550
SSR Research	500 mm to 1000 mm		15 to 20	900 to 1200	1300 to 1700				

Table 1 (Imperial Units)

MANUFACTURE OR DESIGN	DRIVE PIPE Internal Diameter (inches)	DELIVERY PIPE (inches)	DELIVERY VOLUME (gallons/sec)	(gallons/min)	(gallons/day)	DELIVERY HEAD (feet)	WORKING HEAD (feet)	WORKING FLOW (gallons/sec)	(gallons/min
BLAKES:									
7 standard sizes	1¼ to 5	¾ to 3	0.001 to 0.28	0.07 to 17	100 to 25000	350 to 500	3.5 to 100	0.025 to 1.5	1.5 to 90
RIFE:									
Series B. 5 sizes	1¼ to 3	¾ to 1¼				150	2 to 15		1.5 to 50
Standard "Everlasting" 8 sizes	1¼ to 8	¾ to 4				250	3 to 25		3 to 350
Heavy Duty "Everlasting" 6 sizes	1¼ to 6	¾ to 3				500	3 to 50		3 to 400
DANKS:									
6 standard sizes	1 to 4	½ to 2	to 0.13	to 8	to 11500	200	2 to 20		1.25 to 100
VITA ITDG SPATF	1¼	¾	0.01	0.55	790	150	3.5 to 100		1.1
Seattle Waterworks Installation	Two 12" pumps				360000 to 650000	150	50		
US Naval Coaling Station Rife Installation	Two 12" pumps		3.85	231	330000	84	37		580
USSR Research	20" to 40"		3.3 to 4.4	198 to 264	286000 to 374000				

commercial ram pump is of the order of a few litres per second. In terms of irrigation requirements this is a very small flow, limiting applications to situations where cash crops are grown intensively on small plots or where water-saving irrigation techniques can be used. However, it is available continuously, and this 24 hour supply can be utilised providing storage capacity and good management are available.

6. The greatest amount of water a ram pump can use from the source is governed by the size of the ram pump body itself, which is generally limited by the high forces set up during the operation cycle, to match drive pipe diameters of 150 mm or less. Although ram pumps can work extremely well over a wide range of working conditions - they can be adjusted to work with quantities of driving water varying from their design maximum down to less than one-half of this - they need to be "tuned" to deliver their maximum volume beyond which their output cannot be increased. This lack of flexibility to meet increased demand is an important limitation which applies to most of the devices described in this paper. If the ram pump installation is not large enough to deliver the amount of water needed and a larger model is not available, additional ram pumps may be installed alongside. Each unit needs its own drive pipe but they can be connected to a common delivery pipe, see Figure 2.

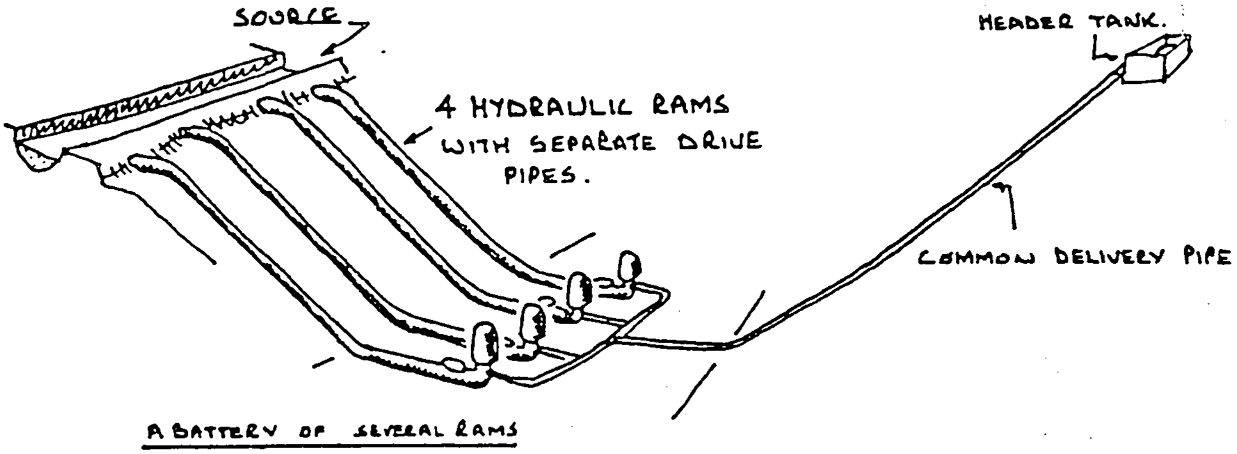

Figure 2

Such installations could take advantage of seasonal variations in flow - at times of minimum flow the reduced potential energy could be used to power one pump.

7. The efficiency of a ram pump is generally defined by considering the energy "flow" into the ram pump in unit time, $Q_w H_w$, and the work done, $Q_d H_d$, where

Q_w is the working flow
H_w is the working head
Q_d is the delivery flow
H_d is the delivery head.

Hence, Efficiency $E\% = \frac{Q_d H_d}{Q_w H_w} \times 100$

eff = 60%

For most installations E is in the region of 60% although efficiencies as high as 90% are attainable.

8. Most ram pumps will work at their best efficiency if the working head is about one third of the delivery head, but often the site will not allow this, in which case the working head should be made as large as possible. For example, this will be necessary if the source is a slow moving stream or river which has a small fall. The working head can be increased by conveying the water from the supply source along a channel or pipe to a feed tank placed over the entry to the drive pipe, see Figure 3.

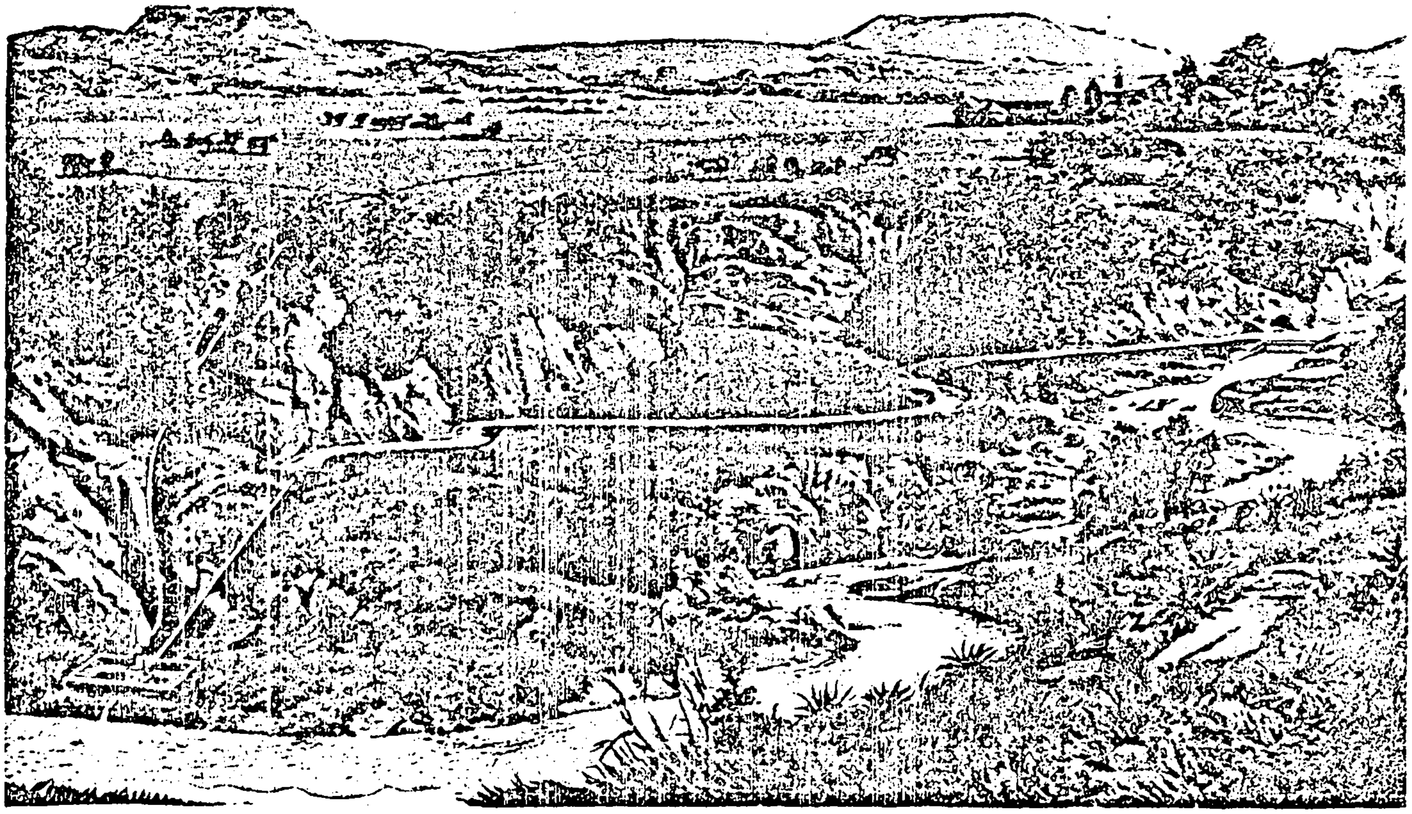

Figure 3

Potential for further development

9. The foundations of engineering science relating to small and medium scale ram pump technology are well established. Present day commercially available machines have limited capacities which severely restrict their use for irrigation water pumping. The only possible area for further development would seem to be the design of high capacity versions with drive pipe diameters of 0.6 to 1.2 metres. However, by definition such large-scale development is unlikely to be suitable for the individual small-scale irrigation farmer. At present the only country reported (3) to be conducting serious scientific research is the USSR, where three institutions are specialising in ram pump development.

10. Where good quality iron and steel pipe is available, ram pumps can be manufactured in small workshops with basic facilities. There is a growing interest in this area and information has been published about a number of designs developed especially for local manufacture (see References). As with any piece of equipment, attention should be given to inspection and quality control to ensure satisfactory performance.

Location and Installation

11. Before a ram pump is installed it is necessary to ascertain if the site is suitable for such an installation, and if so, what size will be needed to pump the amount of water required. Simple measurements can be made to provide the necessary information.

12. The first factor to be measured is the flow of water at the source to see if this is sufficient to operate the ram pump. Allowance must be made for seasonal variations, otherwise the pump delivery may prove to be inadequate.

13. Secondly, the working and delivery heads should be measured as accurately as possible. Most ram pump installations have a ratio of H_d/H_w in the range of 3 to 30. A rough estimate of the theoretical volume of water which a ram pump can deliver (Q_d) can be made by rearranging the efficiency formula:

$$Q_d = \frac{Q_w H_w}{H_d} \times E$$

and using a value of 0.6 for E. This is only an approximate check, and if the result indicates that a ram pump installation may be worth considering, further site measurements and calculations should be made. Measurements of the distance in which the supply head can be obtained and the distance through which the water must be delivered are needed to allow determination of the optimum diameter and length of drive pipe, the size of ram pump, and the length and size of the delivery pipe.

Operation and Technical Details

Tuning:

14. The efficiency and output of a ram pump is primarily a function of its impulse valve frequency, other factors being equal, and this can be changed by two adjustments - increasing or decreasing the weight or spring tension, and increasing or decreasing the stroke length. This "tuning" to obtain maximum delivery is done on site by coarse adjustment of the weight or spring tension in combination with fine adjustment of stroke length. Typical figures for frequency of commercial pumps are in the range of 20 to 100 beats per minute and stroke length in the region of 1.5 to 6.5 mm.

The Drive Pipe:

15. The drive pipe is a crucial part of the ram pump installation - it carries the water from the feed tank to the ram body, and contains the pressure surge of the water hammer. It must be made from good quality steel or iron water pipe- plastic and concrete pipes are useless for drive pipes. The diameter and length of the drive pipe is very important, although the pump will work satisfactorily if the ratios of pipe length (L) to diameter (D) are between the limits $\frac{L}{D} = 150$ to 1000. These are very broad limits and it is recommended to install drive pipes with an $\frac{L}{D}$ ratio of 500, or a length that is four to five times the working head, whichever is smaller.

Pipe Quality for Local Fabrication:

16. Working heads in excess of 7 metres may be beyond the capacity of ordinary seamed galvanised iron pipe used for fabricated ram pumps (4). Most commercially manufactured models have cast bodies which may be beyond the manufacturing capability of developing countries to reproduce.

The Delivery Pump:

17. Unlike the drive pipe, the delivery pipe can be made from any material provided it can stand the pressure of water leading up to the header tank. The water from the ram can be pumped great distances provided the delivery head is small enough. For long delivery pipes it will be necessary to select a pipe diameter that keeps the friction head to an acceptably low figure.

Starting:

18. Ram pumps are not self-starting. They are generally started by manually operating the impulse valve until the pump cycle can take over itself. Automatic starting and stopping can be engineered but this is a costly extra. Once started, ram pumps are capable of operating continuously, 24 hours a day, for long periods without attention. It is not unusual for commerical ram pumps to give good service for 30 years or more with minimal attention to the two valves.

Unintentional stopping:

19. If the flow of water in the drive pipe is impeded, or air allowed to enter, the operation of the pump will be seriously affected and it may eventually stop. Blocking of the intake with leaves can be a major problem where the source is a stream or river,

and measures should be taken to guard against this eventuality, such as by fitting an intake-strainer, constructing a settling well and operating a regular cleaning routine.

Sediment:

20. If the intake water carries any suspended solids these will tend to accumulate in the ram pump body. They should be cleaned out by flushing the pump every few months.

Valve wear:

21. The constant opening and closing of the two valves will eventually lead to wear on the valve washers. This should be inspected at regular intervals (see next sub-section).

Vibration:

22. The repeated shock loading caused by the water hammer pulse each cycle can easily loosen any bolts or other components which are not fastened securely.

Flooding:

23. The pump must be installed on a site where the impulse valve will remain above any possible flood level.

Freezing:

24. If the ram pump is installed in an area where freezing temperatures occur there should be no problems so long as the pump is operating. Should it stop, water must be drained from the pipes and pump body.

Sociological considerations

25. The following special considerations apply to the use of ram pumps as distinct from other types of pump:

- they have only two moving parts requiring inspection every few months. Special tools and training will be needed for this work and a financial incentive to do it conscientiously.
- if replacement spares are unavailable the pump can be made to work tolerably well with improvised parts. If this is done the periodic inspection interval should be shortened to every few weeks
- they are very tolerant to variations in operating conditions but have to be tuned correctly to work efficiently over a wide range of flows
- they are very robust and not particularly tempting to thieves
- the impulse valve, whose correct performance is crucial for satisfactory operation of the pump, is an exposed working part. In certain situations this may arouse curiosity and this may take the form of tampering. It may therefore be desirable to construct a pump house for security - this building should be large enough to allow the maintenance operations to be carried out in comfort.

Costs

26. Ram pump installations consist of four main components

- the ram pump body
- the drive pipe
- the delivery pipe
- storage

The ram pump itself probably represents approximately one-third of the total cost (5), depending on the particular site. Indicative 1979 prices of ram pump bodies only are given in Table 2.

Manufacturer	Model	Price(US $)
John Blake Ltd	No.1(1¼")	300
	No.2(5")	200
Green & Carter Ltd	1½"	360
	4"	700
Rife Hydraulic Engine Manufacturing Co Ltd	1¼"	300
	6"	2600
Development Technology Centre, Institute of Technology, Bandung, Indonesia	1"	22
	2"	37
	3"	74
	4"	170

Table 2

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12. Brochure. Water Supply by Blake's Hydrams.

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14. Brochure. The Billabong Hydraulic Ram. John Danks & Son Pty. Ltd., Sydney, Australia.

3.

WATER WHEELS

Mechanical Power Generation

Introduction

1. Horizontal and vertical axis wooden water wheels and bucket wheels have been used in many parts of Europe and Asia since long before the Industrial Revolution, 2000 years or more in some places. The Chinese, Persians, Romans and Norsemen all exhibited considerable skill and ingenuity in harnessing the energy of water with wheel devices to provide them with mechanical power.

2. The most significant modern development took place in Europe from the late 18th century onwards following John Smeaton's influential waterwheel experiments in 1752-1753, and being spurred on by the growing demand for power to drive the new industrial machines. Smeaton proved conclusively that the reaction overshot wheel was far more efficient, about 60%, than the impulse undershot wheel with flat paddles about 20%. Assisted by the experiments of Rennie, Morin and Poncelet, and using cast and wrought iron to replace wood, water wheel technology was developed to a fine art with efficiencies approaching 80% for the best machines.

3. In parallel with these waterwheel developments, steam engines (Newcomen and Watt) were actively being developed, and by 1800 the demand for power was such that the new engines were gaining acceptance in all areas where coal was cheap and water power unreliable. However, water power continued to be preferred until the middle of the century when the now greatly improved steam engine took the lead to meet the enormous increase in the demand for power.

4. During the first half of the 19th century, when water wheels were at their height of popularity, M. Fourneyron began experimenting and erected his first machine in 1827 which was to herald the arrival

of a new device, the water turbine. As the century progressed, improvements in metallurgical skills, the demand for higher speed devices to generate electricity, and a better understanding of fluid led to the development of turbines which supplanted the water wheel and eventually the steam engine too.

5. Although thousands of waterwheels were installed, in their heyday they were primarily used for ~~powering~~ factory machines in the cotton, plate and grinding mills and the forge of iron works. Their application to water pumping was limited to overshot wheels coupled to mine dewatering equipment. The only two water wheel devices known to be widely applied to irrigation water pumping are the ancient Chinese wheel and the Noria. Small water wheels coupled to reciprocating lift pumps are reported from Pennsylvania where the Amish people use a reciprocating wire to transmit the power from the water wheel site to the well site at the farmstead.

Water wheels
for irrigation
. Chinese wheel
. Noria

European Types of Water Wheel, their Performance and Efficiency

Illustrations of these wheels are shown in fig. 1

The Overshot Wheel:

6. This wheel simply receives the water from a supply channel, rotates due to the weight of water and empties the water at the bottom. The bucket design is critical and should be such that the water flows freely into them without causing hammering or trapping of air. The mouth of the bucket should be several centimetres wider than the stream of water, and the water should be retained as long as possible. The wheel must be clear of the tail-water and these is little likelihood of blockage with leaves or sticks. The efficiency is usually between 60% and 65%, and rotational speeds vary from 6 rev/min for large wheels up to 20 rev/min for small ones.

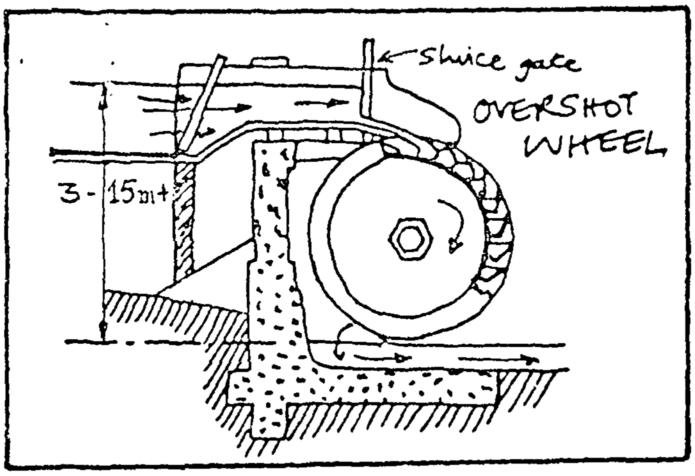
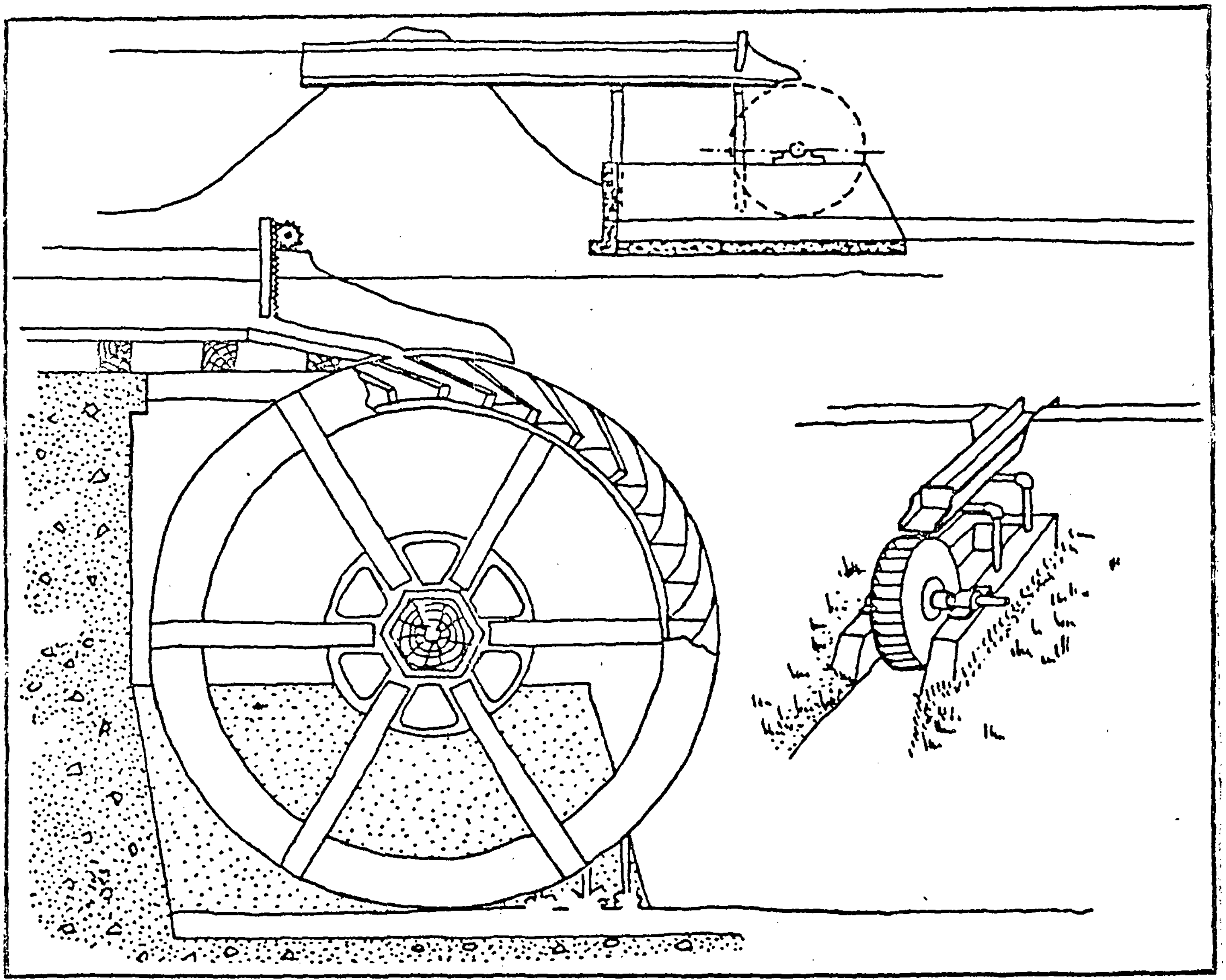
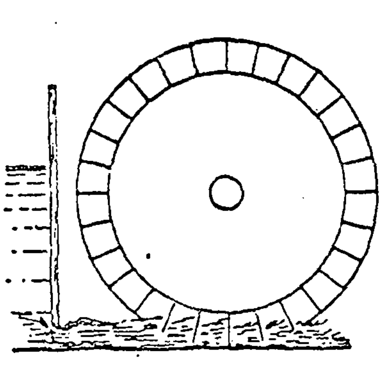


Figure 1

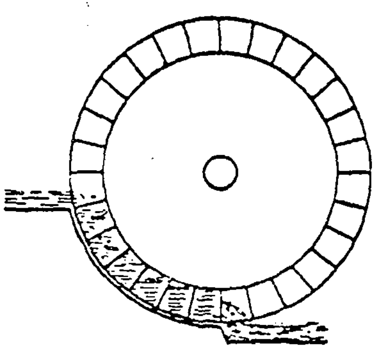
this is no water lifting device

yes it is -

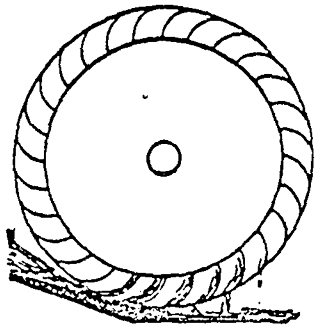




The undershot wheel.



The breast wheel



The Poncelet wheel.

7. There are three other main types of water wheel which can operate on heads too small for use with an overshot, but they have low power outputs and do not compare favourably with their turbine successors.

The Breast Wheel:

8. This is similar to the overshot wheel, but it takes its water from about ½ to ⅔ way up the periphery of the wheel and rotates towards the supply channel. It is less efficient than the overshot wheel.

The Undershot Wheel:

9. This wheel can be in the form of a simple paddle wheel running in a stream, in which case the effective head is approximately 0.3 metres or the water may run down between the wheel and the curved masonry. Leakage reduces the efficiency a lot, and there is a danger of logs damaging the buckets if they become jammed in between the wheel and the masonry. Maximum efficiency is about 25%.

The Poncelet Wheel:

10. This is an improved undershot wheel of fairly high efficiency, 50% to 60%, even when working on part flow. The water flows out from under the sluice, down a 1 in 10 race and up the curved floats (buckets) without any shock. Gliding up the floats it comes to rest, falls back, and acquires, at the point of discharge, a backward velocity relative to the wheel, such that the water falls dead into the tail race water, having given up all its kinetic energy. The wheel rotates "against" the water direction. It is suitable for use on any head of under 1.8 metres. Due to the fine clearance required, it is liable to damage from wood or stones carried along with the water.

The Bakti Wheel:

11. This wheel deserves mention although it is fairly unusual, in that it can work on a head many times its diameter and is principally of the cross-flow impulse type. The water is led to the wheel in a pipe or flume and is given considerable velocity (kinetic energy) by constricting the outlet. The water enters the floats (vanes) at the top of the wheel and is deflected across the axis to where it strikes the inside of the floats on the opposite side, which deflect the water forward at a velocity approximately equal and opposite to that of the periphery of the wheel, so that the water falls dead into the tail race. The main advantage of this type of wheel is that it is fast running and eliminates the gearing problem. The wheel could run submerged as a reaction type wheel, if enclosed in the right kind of case, but the speed and efficiency will be greatly reduced.

Ancient Types of Water Wheel

The Chinese Wheel:

12. As the name implies this device is thought to have originated in China. Sometimes known as the stream wheel or float wheel, it is basically an undershot water wheel with water lifting containers attached directly to the rim. As the wheel is turned the impact of the stream current on the paddles, the containers dip below the surface and fill with water, then, rising to the top, tip their contents into a wide trough which feeds the irrigation channel.

13. Traditionally the device is made almost entirely from bamboo (see fig. 2), with the wheel being from 6 to 12 metres in diameter

depending on the stream velocity and the elevation to which the water must be raised.

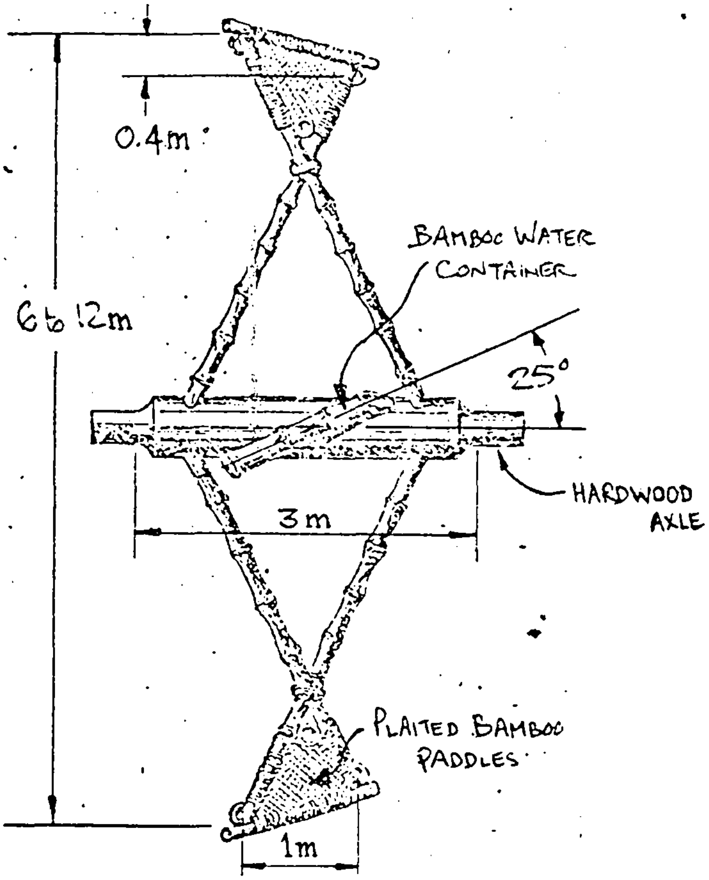


Figure 2

The hardwood axle is supported on bearings which are adjustable to allow lifting or lowering of the wheel so that satisfactory performance can be maintained with fluctuating stream levels. A 9 metre diameter wheel is reported by Joseph Glynn in "Power of Water" to carry twenty bamboo containers of 1.2 metres length and 0.05 metres inside diameter. Installed in a stream of moderate velocity the wheel makes four revolutions/minute and lifts 220 litres/minute, or approximately 13000 litres/hr. Assuming the 9 m wheel raises the water 6 m, then the output power of the wheel is approximately 220 watts.

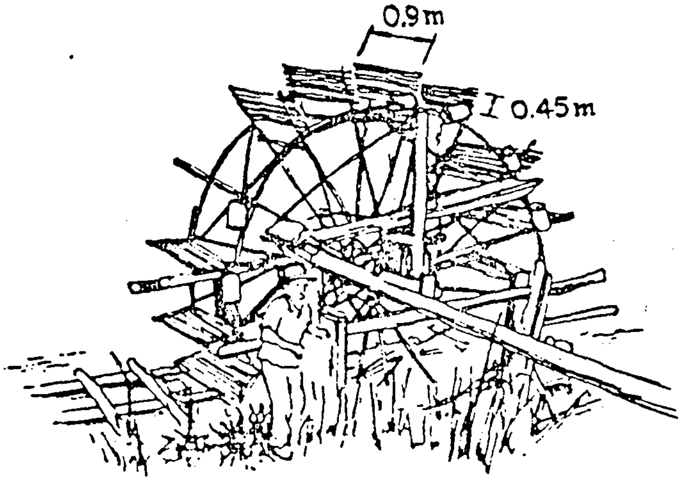
13 m^3/hr

14. Although the device only utilises a small part of the power available in the stream it has the advantage of being cheap to construct and simple to maintain and repair, requiring only periodic attention to the paddles, containers and bearings. Modifications

to improve performance by directing the water through a close fitting channel are sometimes added but this involves extra structural work and gives rise to blockage and damage problems. There are a number of variations on the traditional bamboo Chinese Wheel which bear close resemblance to undershot wheels of the Industrial Revolution with the addition of buckets, troughs or scoops to the rim. Such wheels typically have diameters of 4 to 6 metres and paddles up to 1.5 metres wide. Many such water wheels are in use for supplementary irrigation in Northeast Thailand where they can water areas up to 3 hectares.

15. A floating installation of such a wheel is reported from Sudan (AT Journal, Vol 2 No.4) where a 4 metre diameter wheel is supported on a pontoon to naturally compensate for the seasonal rise and fall of the river Nile. Lightweight plastic containers are used for buckets - a suggested modification is for the buckets to be attached to both sides of the wheel for balance with the collecting through extended to both sides to convey the water ashore. The device, carrying 9 buckets each of 2.25 litres capacity and turning at 2 rev/min will deliver about 40 lit/min or approximately 2400 lit/hr.

2,4 m^3/hr



Water wheel on the Nile near Juba, Sudan

The Noria:

16. Huge diameter wooden undershot water wheels known as Norias have been used from early to modern times in China and the Middle East. They can still be found performing important duties in countries such as Syria where they provide water for town supply and orchard irrigation as well as power for grinding corn (see fig. 3). Large wheels can have diameters in the order of 18 metres and water is typically lifted distances of 6 to 12 metres.

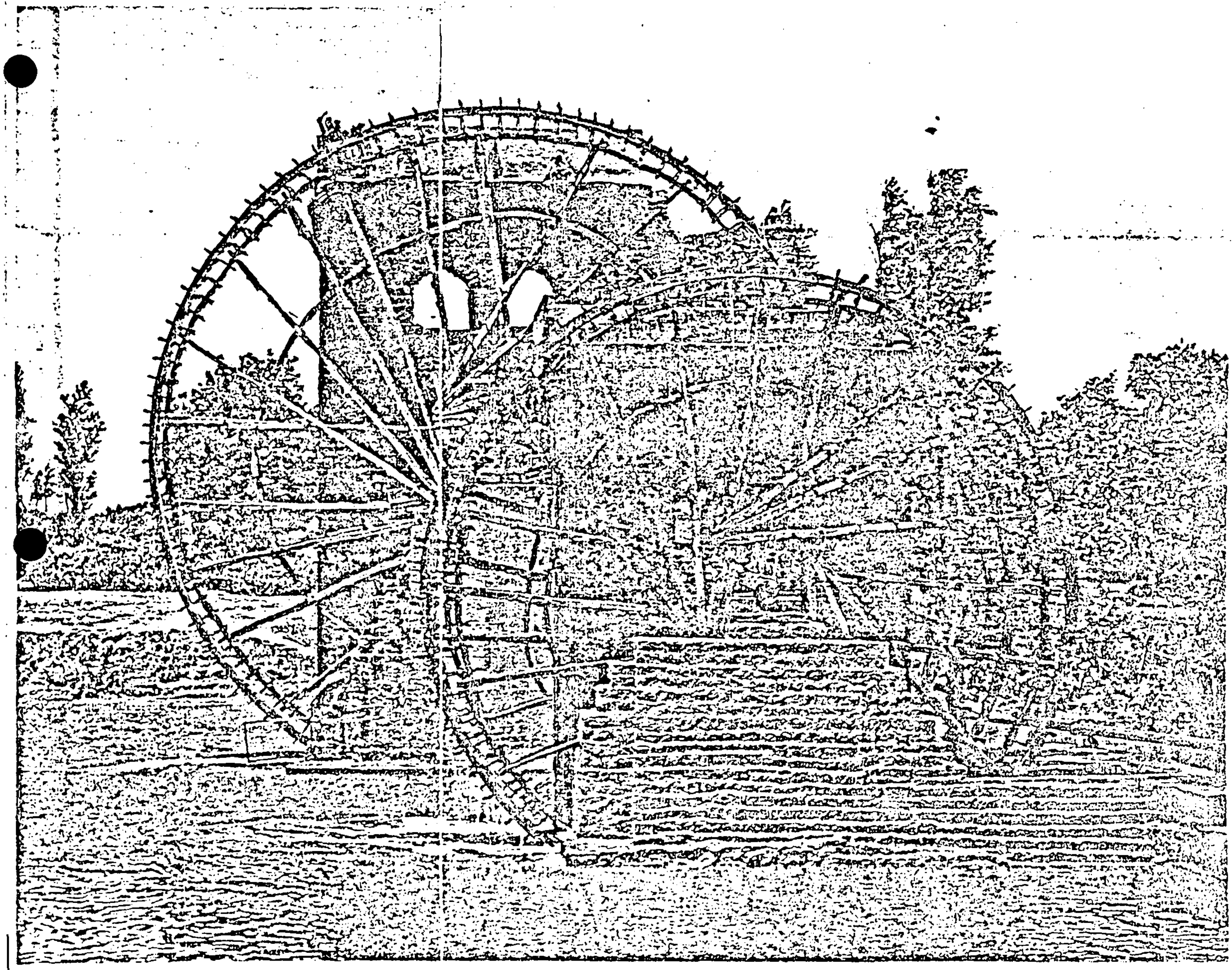
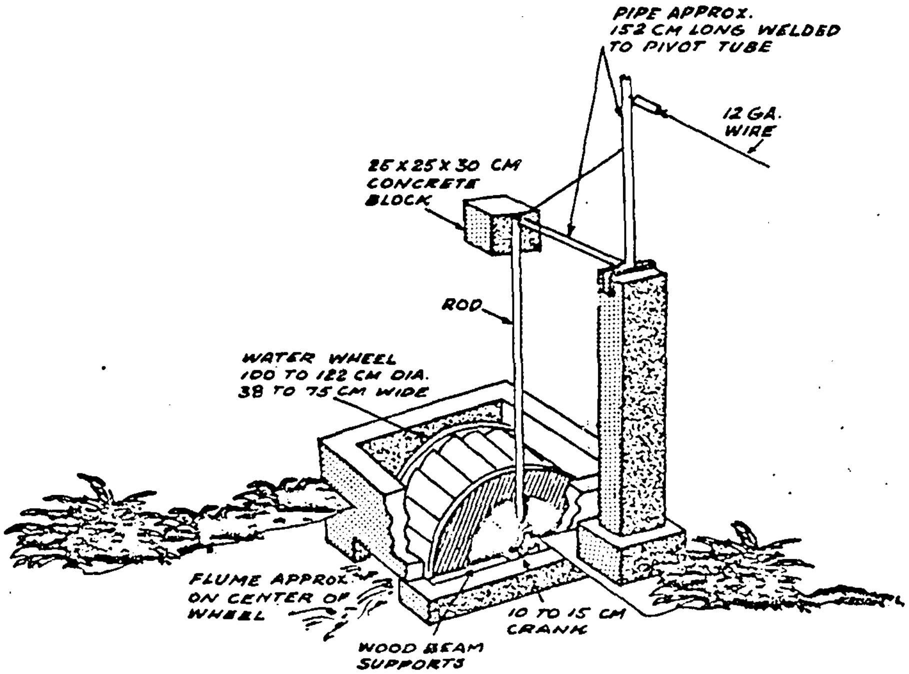


Figure 3

17. As the wheel is turned by the action of the flowing water on the paddles, water is raised in pots or "norias", which are attached to the paddles. The device is usually constructed from wood and bamboo and the largest machines are considerable feats of structural engineering (see fig. 3). In addition to the wheel, massive piers are needed to support the wheel axle bearings and the troughs which collect and convey the water.

The Amish Pump:

18. The Amish people of Pennsylvania use a reciprocating wire to transmit mechanical power from small water wheels to the farmstead up to almost a kilometre away, where the motion is used to pump well water for domestic and farm use. The water wheel is typically a small undershot wheel 0.3 to 0.6 metres in diameter. The wheel shaft is fitted with a crank, which is attached to a triangular frame which pivots on a pole. A wire is used to connect this frame to another identical unit located over the well. Counterweights keep the wire tight. As the water wheel turns, the crank tips the triangular frame back and forth. This action pulls the wire back and forth. One typical complete back and forth cycle, takes 3 to 5 seconds. Sometimes power for several transmission wires comes from one larger water wheel. Unlike the Chinese Wheel and the Noria, the cyclic nature of the power required by the pump in this arrangement is not well suited to the steady power output of the water wheel, particularly if the wheel is operating only one single-acting pump.



The Amish Pump

Some General Considerations, Technical Problems and Limitations

19. For satisfactory operation a water wheel requires a fairly constant flow - rivers or streams running with velocities between 0.3 to 1.5 m/sec that are at least 1 m wide and 0.3 m deep can be used.

20. The energy of the water which the wheel converts to power on a rotating shaft is not always in a useful form because shaft speeds are low, typically between 5 and 30 rev/min. In order to speed up to the higher speeds needed for driving modern machinery such as centrifugal pumps, heavy gearing will be necessary to cope with the high torque, and this will involve additional high costs and further inefficiencies.

21. The only type of pump which is reasonable to use at the slow speed of a water wheel is a positive displacement reciprocating plunger pump. In order to achieve satisfactory operation without stall, speed surging can be minimised by matching the pumping torque to the wheel torque. This may be done by using a double acting pump or two single acting pumps mounted 180° out of phase. More detailed accounts may be found in standard texts on pump design.

22. The method of coupling the pump to the shaft of the wheel has to take into account the desirability of achieving straightline motion of the piston rod and the need to allow for any relative movement between the water wheel pump installation and the system conveying the water to land. If the pump has to be located some distance from the wheel, the drive may be transmitted by solid shafting, which will require expensive bearings and careful alignment, or by a reciprocating wire.

23. In addition to the water wheel and pump installation expensive civil engineering works may also have to be constructed such as weirs, channels, sluices and races. For large water wheels, the great size, weight and cost of components makes them unattractively expensive compared with high speed water turbines.

Conclusion:
Match water power
to
1 double-acting
or 2 single acting
positive displacement
pumps.

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4.

WATER TURBINES

No direct relation to water lifting

Introduction

Rules out application in small-scale irrigation

1. It was more than fifty years after Fourneyron's pioneering work in the 1830's that the water turbine started to gain a degree of popularity as the provider of high speed shaft power. The rapidly increasing demand for electricity led to further development efforts by Pelton, Crewdson, Mitchell, Banki, Francis and Kaplan over the period to 1880 to 1920, which ultimately led to vast megawatt machines to power the generating equipment of the major hydroelectric schemes around the world. As it is Impossible ~~unusual~~ to find water turbines coupled directly to drive water pumps, this paper will not pursue the subject beyond a very brief summary of the different types of turbine. The reader is directed to any standard text on the subject for detailed information.

Summary of Equipment

2. Water turbines are classified into impulse and reaction types. The former, which include pelton and turgo-impulse wheels, utilise the kinetic energy (or momentum) in a jet of water which impinges on the buckets of the runner. The buckets are so shaped that they turn the flow of water through as near 180° as possible and move at a speed which results in the spent water falling straight to the bottom of the case, which is mostly full of air. Reaction turbines can be sub-divided according to the flow of water through the machine, into inward, outward, axial and mixed flow types. Most machines have a set of guide vanes (deflectors), and the runner from which the power is derived. Unlike the impulse turbine, the case is completely filled with water and the continuation of the outlet (draft pipe) below the

machine results in the formation of a slight vacuum, which both increases the total head and reduces turbulence.

3. The final classification is with regard to the casing. Those which have no exterior case and run submerged in the inlet channel are generally referred to as "open case". Some of these devices are shown in Fig. 1.

Propellor turbines:

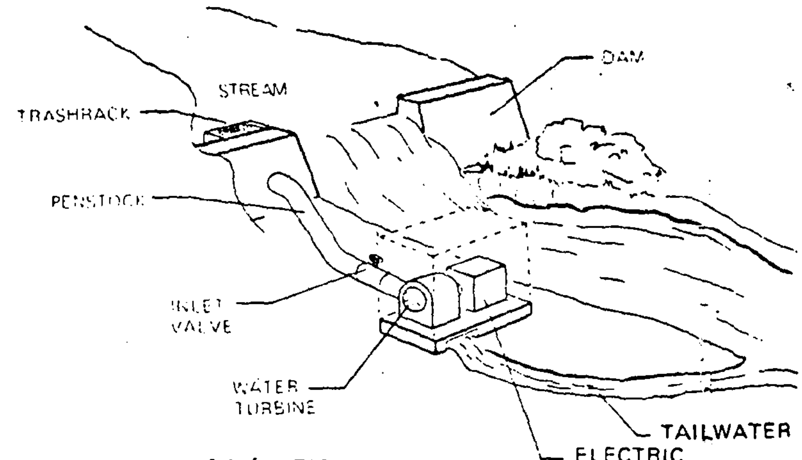
4. These axial flow high speed reaction machines may be fixed bladed or the variable pitch Kaplan type and are used on low heads in the range of 1 to 10 metres. Precision engineering is required for the manufacture of the runner in order to attain its efficiency of 80% plus. The main disadvantage with the fixed blade type is its very low efficiency on part flows, making it an unwise choice for sites which do not have a constant flow. Both types of propellor turbine are liable to cavitation problems.

Francis turbines:

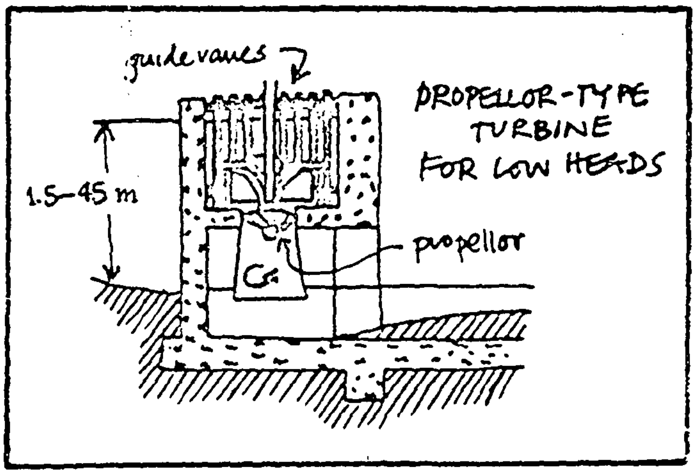
5. These impulse turbines are suited to a wide range of heads from 1.2 m upwards. They are generally complex, expensive machines requiring precision engineering and fine tolerances on the moving parts. They may be mechanically governed through adjustable guide vanes. Efficiency on full flow can be 90% plus, but this decreases under part-flow conditions. The turbine can be severely damaged by suspended solids in the water, and cavitation is always a possibility. Repairs can be very expensive as a damaged runner involves replacement of the complete unit.

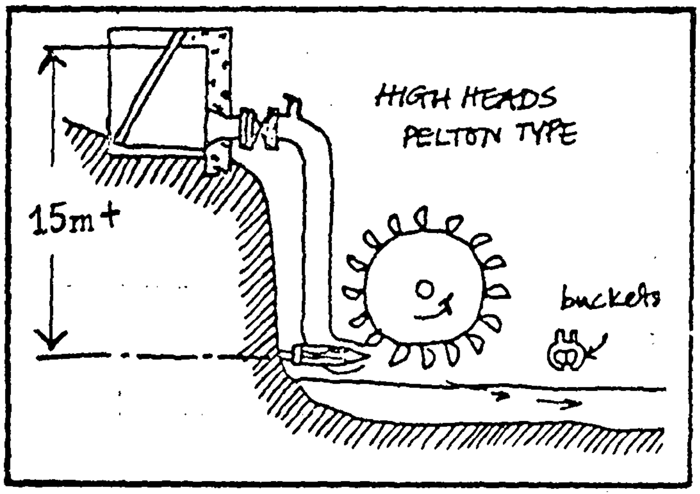
Cross-flow (Mitchell, Banki, Ossberger) Turbines:

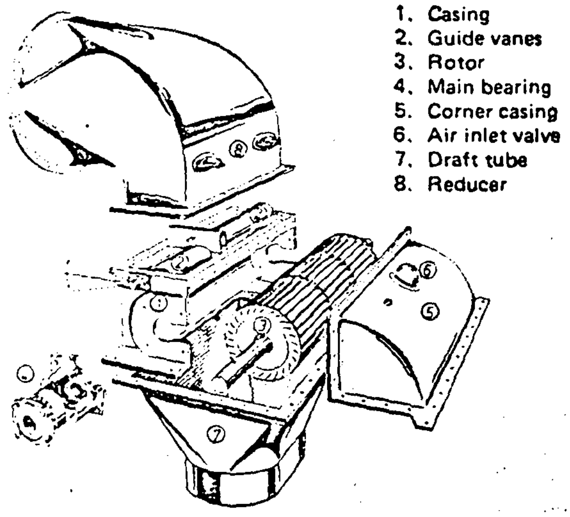
6. This radial flow impulse type turbine is suitable for use on a wide range of heads, 1 to 180 metres and for flows of 30 to 7000



WATER TURBINE INSTALLATION







Ossberger Turbine

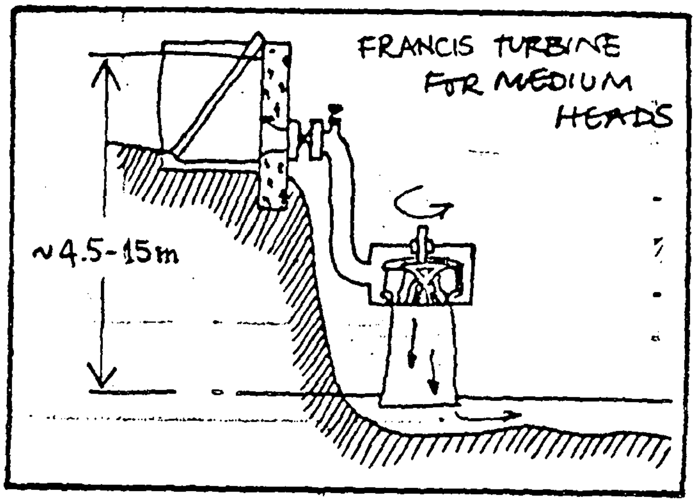


Figure 1

litres/sec. In its range it is similar to the Francis turbine but has the important advantage of being far simpler to construct and repair, has a higher efficiency on part-flow, and is not subject to cavitation. Also, leaves and other "soft" trash can pass through the blades without causing damage.

Pelton and Turgo Impulse Wheels:

7. The Pelton wheel has been called a developed undershot wheel. Essentially it depends on the impact of a high velocity jet of water upon curved buckets mounted on the wheel rim. It is suitable for use where high heads can be obtained, at least 15 metres, and can operate with flows as low as 5 litres/sec. Efficiency is in the range of 60% to 90% depending on the size of installation.

8. The Turgo wheel was the result of development efforts to increase the speed of Pelton wheels. By redesigning the runner and setting the jet at an angle to the face so that water entered one side and exited on the other, shaft speeds were doubled and wheel diameter halved. It is suitable for use on heads of 12 m or more and has an efficiency of over 80%. Both Pelton and Turgo wheels have high part-flow efficiencies.

Some General Considerations

9. In addition to the turbine machinery itself the installation involves considerable civil works and expense for items such as dams, channels, spillways, sluices, silt traps by washes, trash racks and pipelines, all of which must be carefully designed.

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X

1 l/sec
to head of 8 metres

THE PLATA PUMP

interesting

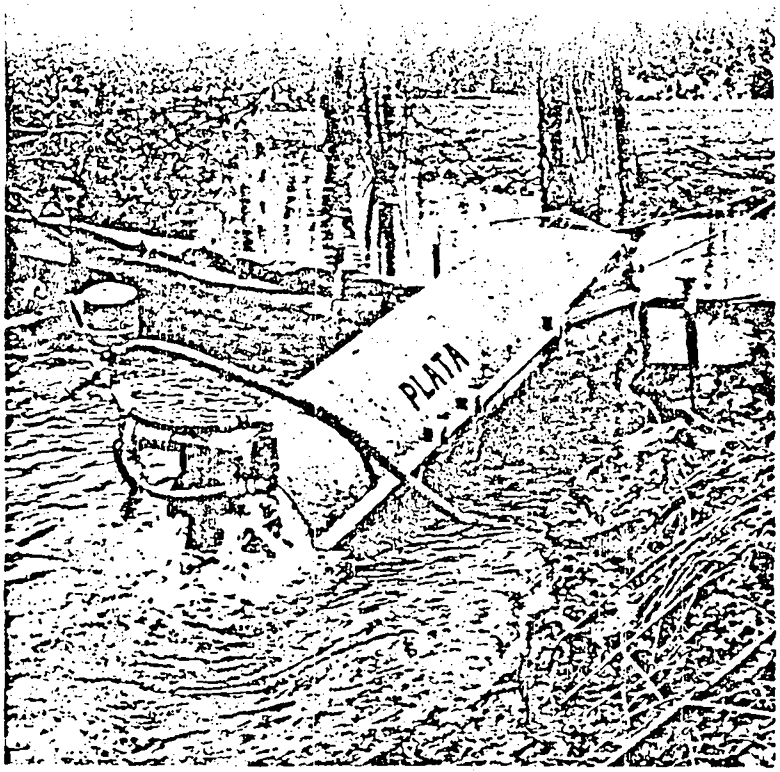
Introduction

1. The Plata pump was invented in the mid ~~1790s~~ 1970s by a New Zealand engineer, Roy Martin. It consists of a water driven turbine coupled directly to two reciprocating force pumps. Development work has been conducted by the University of Canterbury, New Zealand, and the pump is presently being marketed by Natural Energy Limited, of Hamilton, Bermuda.

Description and Principles of Operation

2. The Plata pump is derived from the low-head version of a water turbine. This traditionally uses a propeller runner mounted axially on a shaft in an inclined tube-like casing to convert the kinetic energy of water falling from a small height into power output delivered as torque on the shaft.

3. Where the Plata pump differs is its unorthodox arrangement of six eight-bladed propeller runners mounted in tandem on the shaft. Water flowing through the casing causes the propellers to rotate the shaft which is connected by a crank disc to two opposed single-acting reciprocating force pumps. A choice of six settings on the crank disc and two different pump sizes allows a degree of matching between the available power output at a given site and the duty (head and discharge capacity) of the pumping installation. The device is shown in Fig. 1



1 l/sec
to a head of 3 metres

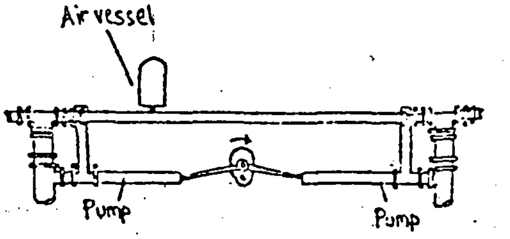
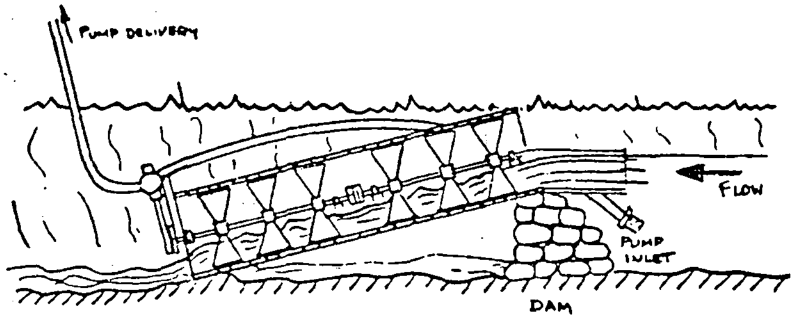


Figure 1



Performance and Efficiency

4. The limited performance data for this device is presented in Table 1. Experience to date indicates that the maximum delivery volume of a Plata pump installation is less than 1 litre/second to a head of 3 metres. (BHRA Test result using a working head of 0.23 m and a working flow of 85 l/s). The pump operates off a working head in the range of 0.2 to 0.6 m and with working flows in the order of 30 to 85 l/s. It is reported that recent tests at Canterbury University, New Zealand, have been investigating performance of the unit under higher head conditions, 0.7 to 1.2 m and higher working flows, 85 to 195 l/s, but at the time of writing, results are not available.

The only additional performance data known to the author are some discharge versus head curves which have been produced by the manufacturers

5. The overall efficiency of the Plata pump may be defined as for the hydraulic ram pump, by considering the energy flow into the device in unit time and the work done. From the limited data available, overall efficiencies calculated according to the above definition are in the range of 10% with an unexplained maximum figure of 31% (see Table 1).

eff = 10%

6. The power output of the device, calculated from the product of delivery flow and delivery head, is very small being in the region of 6 to 60 watts. In reports on the pump some general statements have been made, such as:

- "Maximum power is developed when the turbine is running just over half full of water but it will operate quite satisfactorily over a range of water depths from three-quarters full to almost empty".

and

- "An operating speed between 40 and 120 revs/min appears best".

The only additional performance data known to the author are some discharge versus head curves which have been produced by the manufacturers who supply the reciprocating pump components. These curves (see Fig. 2) are in general agreement with the results presented elsewhere.

7. Although the pump will work tolerably well with variations in working flow at any particular site, there is no possibility for increasing delivery flow to meet an increase in demand. The only way of providing this flexibility would be by the multiple installation of units either in parallel or in series depending on site characteristics (see Fig. 3).

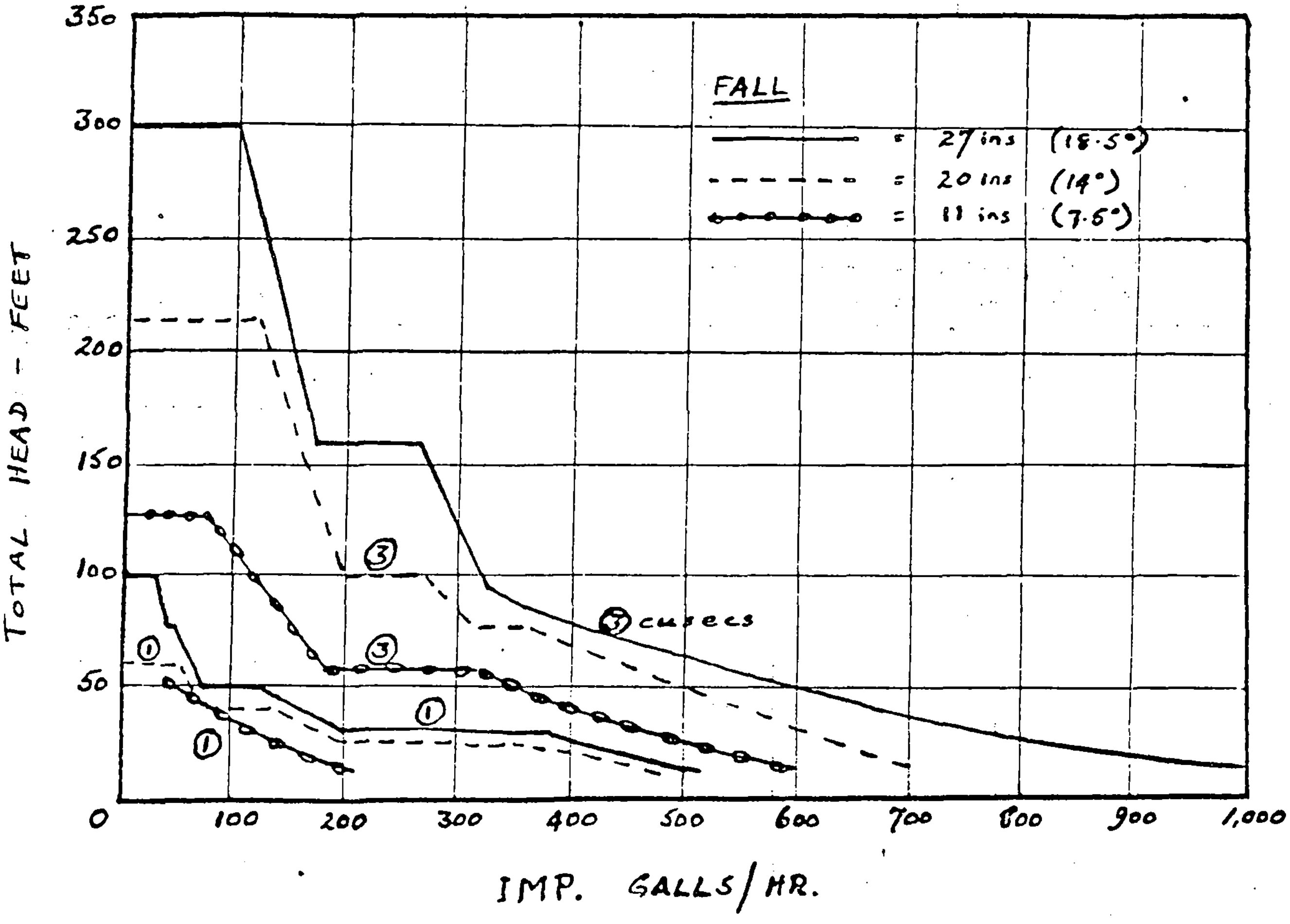
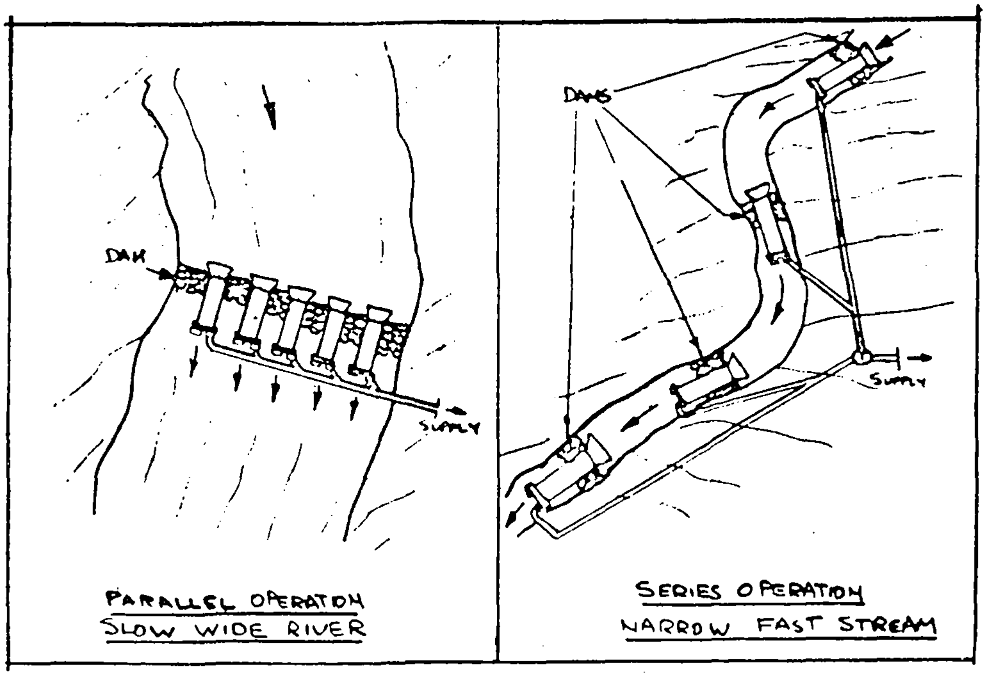


Figure 2



PARALLEL OPERATION
SLOW WIDE RIVER

SERIES OPERATION
NARROW FAST STREAM

Figure 3

Location and Installation

8. The Plata pump can be used in situations on streams, rivers or irrigation channels where there is a sufficient natural fall to give a vertical drop of 0.2 to 0.6 metres over the length of the turbine runner assembly, about 2 metres. On rare occasions it may be possible to place the unit directly on the stream bed with little or no site preparation. However, more often the natural fall will be insufficient and the necessary drop has to be engineered by digging a small channel to accommodate the downstream end of the turbine and/or erecting a low dam of wooden planking or sandbags to elevate the turbine intake. Measurements of bed slope on site will indicate the extent of site modification required.

9. For satisfactory performance the installation requires at least 28 litres/second to pass through the casing and measurements of flow velocity and cross-section have to be made at potential sites to establish if stream flows are sufficient. Seasonal variation of flow should be taken into account since minimum flows may be inadequate for the pumping duty required and maximum flows may present hazards such as flood debris.

10. Finally an estimate must be made of the water demand and measurements taken to allow calculation of the total head against which the pump must operate, including friction losses. Also because of the system's limited rate of pumping it will usually be advantageous to include some water storage facility in the installation so that the total volume of water delivered in 24 hours can be utilised.

Plata pump
Sensitive to
blockage

Operation and Technical Problems

Blockage:

11. Any piece of equipment mounted directly in a river or stream will be susceptible to blockage or damage by floating debris. There are three potential trouble spots with the Plata pump - the turbine intake the turbine unit itself, and the pump intake.

12. In order to prevent debris getting into the turbine unit of the Plata pump, the intake section is fitted with a delta shaped grid, which when it becomes blocked will have to be cleared - possibly a daily operation. Even with the precautional grid there is always the likelihood of floating material blocking up the turbine in which case it must be unblocked. Finally the screen fitting over the pipe intake to the pump section is also liable to blockage. Clearing operations for these three potential trouble spots must be as simple as possible to ensure that they are performed regularly.

Silt accumulation:

13. If the river or stream carries a large amount of suspended solids there will be a tendency for these to accumulate on the upstream side of the low dam used to raise the turbine intake and increase the head of water. Provision must be made for the periodic removal of these deposits. Again, this must be an easy procedure or it will not be done.

Turbine bearings:

14. All moving surfaces in contact with another surface will be subject to wear. The three water-lubricated bearings which carry the turbine shaft are of the plain bush variety and will have a limited life. In the event of failure the consequences could be

Plata pump

damaged propellor runners or turbine casing at the least, and total seizing at the worst.

Pump components.

15. The pumping unit consists of two conventional reciprocating force pump cylinder assemblies connected to the turbine shaft by a crank disc so that they work in horizontal opposition. Provision for adjustment is made by a choice of holes in the crank disc for the fulcrum position, which alters the pump stroke. Once the values of working flow, working head, delivery flow and delivery head are known, the size of pump and required stroke is selected and the hole position specified for the particular installation duty.

16. Any abrasive material suspended in the water will be easily drawn into the pump cylinders where it will cause wear of the piston cups and valves. Wear of these components is a serious problem with all types of plunger pump even when they are handling clean water. Also, as with any reciprocating force pump, a further point of wear necessitating periodic adjustment is the packing gland through which the pump rod passes.

Floods:

17. Flash floods can easily wash away structures erected in their path. Wherever hydrological data is scarce it is difficult to estimate peak flows accurately and potential sites require careful study to assess the risk of consequence of possible flooding.

Potential for Further Development

18. The idea of using a propellor runner mounted on a shaft to convert the energy of falling water into power is not new. The device presented in this section is one possible arrangement but

Performance results so far showing overall efficiency of about 10%, indicate that there is scope for further research to develop a more powerful unit at lower cost. As there is no wirl of the water at the moment of entry to the turbine and yet there is no wirl at the exit, indicating energy "lost" from the system, one possible line of investigation may be to reverse this tendency. By creating wirl on entry to the turbine some of this energy may be recovered by the propellor runners to generate torque and water leaving the downstream end of the turbine will do so with reduced wirl - indicating energy "gained" by the system.

19. Another possibility worth considering could be the development of a single propellor unit - this would greatly simplify the system and lower the cost. Simple methods for varying the power output to meet changing demands could also be investigated - for example the head above the propellor could be raised or lowered by an adjustable flash-board arrangement.

Working Head (metres)	Working Flow (litres/second)	Delivery Head (metres)	Delivery Flow (litres/hour)	Pump Spec.	Reference	Power Output	Overall Efficiency %
	30 to 120	18	1350		New Zealand Farmer		
		90	450		Apr. 1976		
0.60		36	680		Theoretical		
0.23	30	9	260	Two x 38 mm diam.	Test data Canterbury Univ	6 Watts	9.5
0.60	30	38	180		)Theoretical)figures)		
0.60	30	9	680				
0.23	60	18	210		)Theoretical)figures))		
0.60	60	38	470				
0.60	60	12	1430				
0.23	85	3	2500		BHRA Test	20 Watts	10.5
0.23	85	24	909		Results	60 Watts	31.0
0.68	85				)Canterbury)Univ latest)test data	0.34BHP Shaft	45.0 Turbine
1.22	195					1.20BHP	38.0

Table 1 (Metric units)

low working heads

Working Head (inches)	Working Flow (gallons/second)	Delivery Head (feet)	Delivery Flow (gallons/hour)	Pump Space	Reference	Power Output	Overall Efficiency %
	6 to 25	60	300		New Zealand Farmer Apr. 1976		
	(1 to 4 cusecs)	300	100				
24		120	150		Theoretical		
9	6 (1 cusec)	30	57	Two x 1½ diam.	Test data Canterbury Univ	0.008 WHP	9.5
24	6	125	40		Theoretical figures		
24	6	30	150				
9	12.5(2cusec)	60	47		Theoretical figures		
24	12.5	125	103				
24	12.5	40	315				
9	18.5	10	550		BHRA Test Results	0.03WHP	10.5
9	18.5	80	200			0.08WHP	31.0
27	18.5(3cusec)				Canterbury Univ latest test data	0.34BHP Shaft	45.0
48	43.5(7cusec)					1.20BHP	38.0

Table 1 (Imperial units)

6.

THE RUN-OF-THE-STREAM TURBINE

Energy harnessing
Power generation

Introduction

1. An underwater equivalent of a vertical axis windmill rotor that has emerged in recent years is presently being investigated by the Intermediate Technology Development Group for harnessing the energy of river currents. An obvious application of the device could be water pumping for irrigation from large rivers such as the Nile, Niger and Indus, whose plentiful waters cannot be fully utilised for irrigation because conventional power sources for driving pumps are becoming increasingly uneconomic. A modest experimental programme using a 1metre diameter rotor has demonstrated that the device provides a simple, efficient means of harnessing the energy present in rivers. It is planned to field test a 3 m diameter version for pumping irrigation water. As the device exploits the energy of the flowing current and does not require site engineering to create an artificial head of water, it is sometimes called the zero-head turbine. By avoiding the need for the expensive civil engineering works which are associated with other types of water turbine, the run-of-the-stream machine is comparatively simple and is also portable. Preliminary economic data indicates that X the device should be highly competitive with diesel pump sets, especially where fuel is scarce or expensive.

Engineering Summary

River currents as an Energy Resource: (1)

2. Useful power densities are obtained in river currents of around 1 metres/second (2 knots) or faster. A 1 m/s current corresponds to a power density of about 500 watts/square metre. On the basis of

Reynolds number comparisons, dynamic conditions in water are similar to those in air at a speed about ten times higher. So it seems reasonable to apply wind-turbine experience to the design of a water knietic energy turbine. There is extensive literature and considerable contemporary effort in the wind energy field which provide a useful starting point for studying analogous water-based systems. However, the extent to which data on wind turbines may be directly applied to similar turbines is limited by the effects on the latter of:

- splashing and wave-making
- the possibility of cavitation
- the reduced rotor intertia, relative to the power rating
- the much lower rotational speeds, and
- proximity to the riverbanks, beds and surface.

The Choice of Turbine: (2)

3. The most promising rotor configuration for use in rivers appears to be the cross-flow vertical axis turbine, generally attributed to Darrieus (3) but which remained obscure until Rangi and South (4) demonstrated, as recently as 1971, that it could achieve a coefficient

eff = < 30%

of performance in excess of 0.3, i.e. fully comparable with horizontal axis turbine designs. A vertical axis rotor has the following advantages in river current energy applications:

- it has high efficiency (25 to 35%) compared with drag-dependent devices (5 to 10%)
- it sweeps a more convenience rectangular cross-section, than the circle swept by propellor-type rotors, so allowing a larger swept area for a given depth of river.
- the vertical shaft avoids the need for a right-angled transmission drive, as would be needed for a horizontal axis rotor

- it has a low solidity, i.e. only a small part of the rotor swept area is occupied by blades. This reduces the weight and cost, compared with high solidity devices.

Description and Principles of Operation

4. The basic vertical axis rotor design used for the experiments is shown in Fig 1. The full-size prototype planned for irrigation water pumping will have a diameter of about 3 m and a blade length of about 1.4 m. It will be supported in a submerged position with the top of the blades about 0.8 m below the surface from a floating pontoon which will be moored to the bank by a single cable and maintained in position by rudders. It is planned to drive a rotary pump via a belt step up and alternative pumping arrangements will be considered once the turbine has been proved, and the water will be conveyed to shore by pipe. The installation is shown diagramatically in Fig 2.

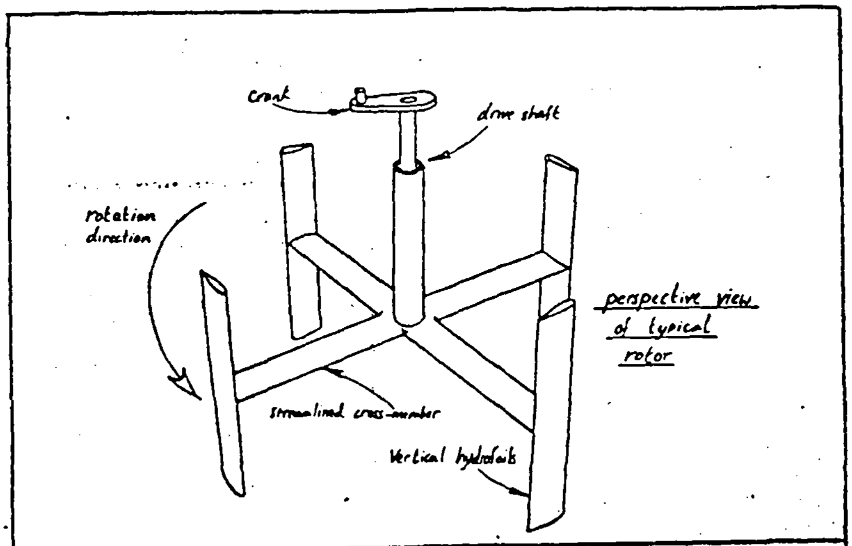


Figure 1

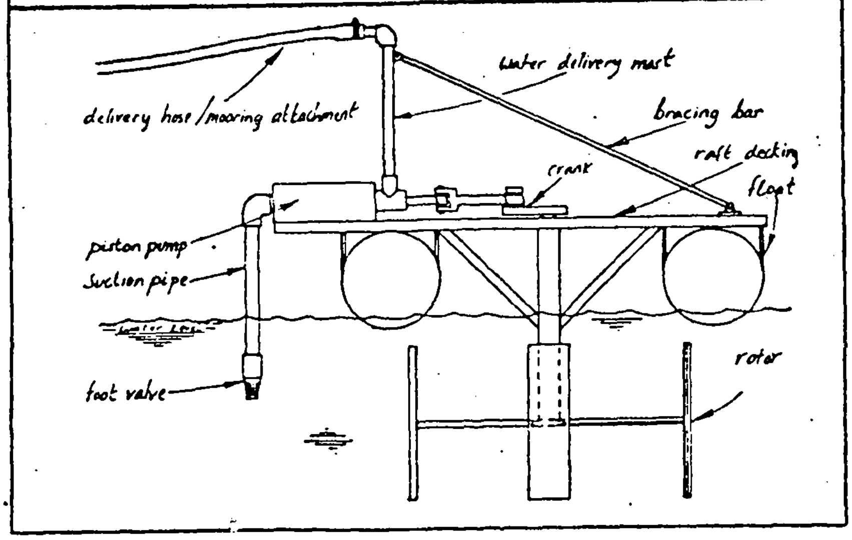


Figure 2

5. The turbine has hydrofoil sections which make it perform as a lift machine capable of recovering 25 to 35% of the available current energy. This is considerably better than the 5 to 10% recoverable with differential drag machines. The principle which is exploited is shown diagramatically in Fig 3 where it can be seen that the lift exerted on the blade (due to the relative velocity of attack of the water on the blade) always has a resulting turning moment in the same direction regardless of position. With several blades these turning moments are additive and give the turbine its motion.

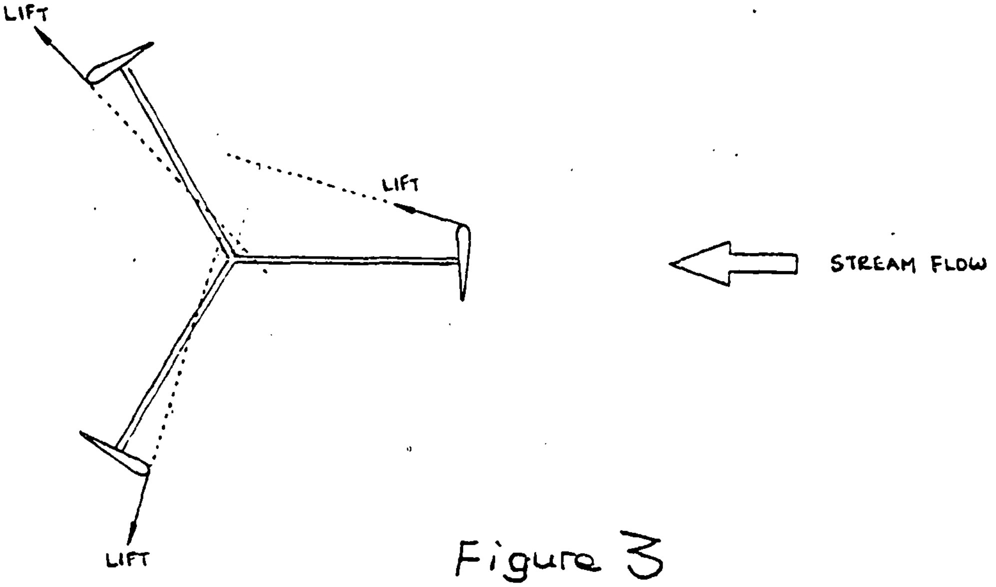


Figure 3

Performance and Efficiency

6. The size of the rotor tested was dictated by the need to operate at Reynolds numbers in excess of 100,000, so as to achieve an acceptable lift/drag ratio from the vertical hydrofoils. The four bladed, 1m diameter rotor shown in Fig 1 has a solidity of 0.33, a swept area of 0.47m^2 and a symmetrical blade section approximately to NACA 0015, through the curvature near the leading edge was reduced in an attempt to reduce pressure minima and so delay the onset of cavitation. The experiments investigated the effect of varying number of blades, solidity (number of blades x blade chord length/rotor diameter) and blade aspect

ratio (blade length/blade chord) on performance characteristics such as power, torque variation and efficiency.

7. For the tests the rotor was suspended over the bow of a small motor boat and a series of runs was under taken to simulate current velocities ranging from 0.84 m/s to 1.8 m/s in increments of 0.16 m/s. Rotor speeds of up to 20 rev/min were achieved. Values of the Coefficient of performance C_p ($C_p = 2P/\rho V^3 A$) were plotted against the tip speed ration (WR/V) to give the characteristic shown for example in Fig 4 where

P is the output power

ρ is the density of water

V is the current speed

A is the swept area

R is the rotor radius

W is the rotational speed in rads/s.

The outer envelopes of points in Fig 4 represents runs at the lowest speeds. Higher speed runs resulted in a progressive reduction of C_p and WR/V and it seems probable that this was due to the progressively increasing effects of cavitation at speeds above 1m/s. However, the tests confirm that a vertical axis turbine can be designed to operate at high efficiency in river currents, despite the small size of the test model and the consequent low Reynolds number. Cavitation effects may be largely eliminated by increasing the solidity (5); this reduces the optimum speed ratio by a factor of about two and so allows operation in currents of up to 2 m/s before the onset of cavitation. A larger rotor operating at more favourable Reynolds numbers could use a thicker and bluffer blade section which would further delay cavitation

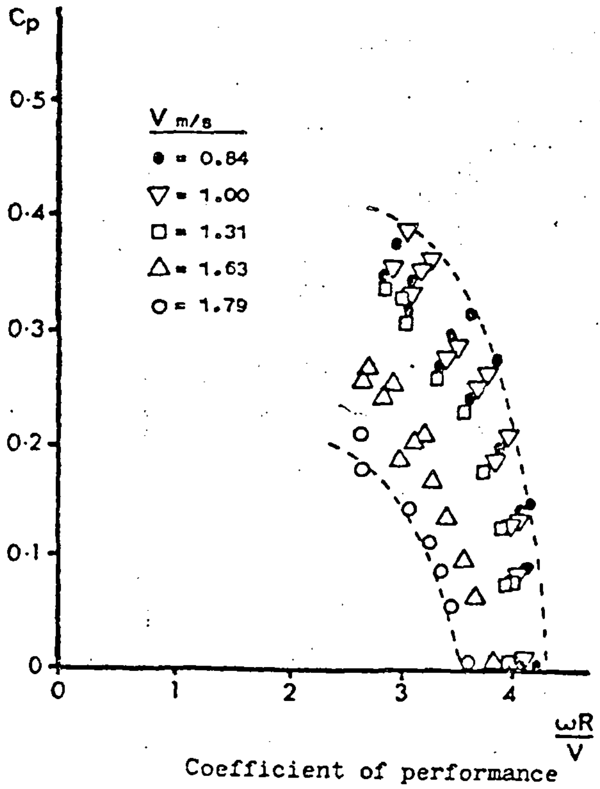


Figure 4

Coefficient of performance versus tip-speed ratio measured at various current velocities

Location and Installation

8. For irrigation water pumping applications it is planned to support the device in a submerged position from a floating pontoon. The turbine will be directly coupled to a reciprocating pump or pumps. To reduce the risk of damage or blockage by floating debris medium depth sites should be chosen provided there is sufficient velocity on the inside bank and slightly downstream from a river bend so that most debris is kept away by the faster current along the opposite bank.

Preliminary tests with a third-scale model have shown that the pontoon can be moored in an operating position using a single cable attached to the bank and rudders to maintain poisition in the stream. Pressure difference across the rotor also assists this positioning.

Operation and Technical Problems

9. At the present stage of development it is not possible to make any statement based on practical experience with full-size units power water pumps. However, it is possible to predict certain problem areas, some general, and some specific to the run-of-the-stream turbine:

- blockage or damage by floating debris
- starting and stopping
- Corrosion and erosion
- manufacturing accuracy needed for hydrofoil blades
- pumping unit
- conveyance of water to shore
- interference by river wild life

ITDG's proposed field test programme should help to provide some practical data so that the implications of the above listed problems can be more accurately assessed.

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7.

THE COIL PUMP

Introduction

1. The coil pump was described by A. Rees in The Cyclopedia of Arts, Sciences and Literature published in 1746, where attention was drawn to its similarity to the Archimedean screw. The inventor was said to be Andrew Wirtz of Zurich and it was reported at that time that a Dr. Young had produced a head of over forty feet with a one inch diameter lead pipe coil. The same device is later referred to as the spiral pump by Philip R. Björling (Water Raising Methods, Old and New, circa 1900), and no further reference is known until 1973 when A.E. Belcher conducted some tests with a fibre glass version which he called a hydrostatic pump.

2. Since this revival of interest, research projects have been carried out at the University of California, Salford University (U.K.) Los Andes University, the University of Dar es Salaam, and Loughborough University of Technology (U.K.) but there has been little progress. Research and development work is continuing in Colombia, Tanzania and the U.K. where it is believed that the main application of the pump could be a steam-driven version for raising water, for irrigation or domestic supply.

Description and Principle of Operation

3. The pump is shown in fig. 1. It consists of a length of flexible pipe wound round a frame or cylinder to form a coil which is placed horizontally or at an angle so that it is partially immersed in the water. The coiled pipe is connected to the tubular axle and as the coil is rotated, water is pumped into the fixed delivery pipe through a rotary seal arrangement. In operation, as the coil rotates in the opposite direction to the coil winding as viewed from the inlet end, a plug of water enters the pipe during the part of the cycle when the inlet is submerged. This plug then

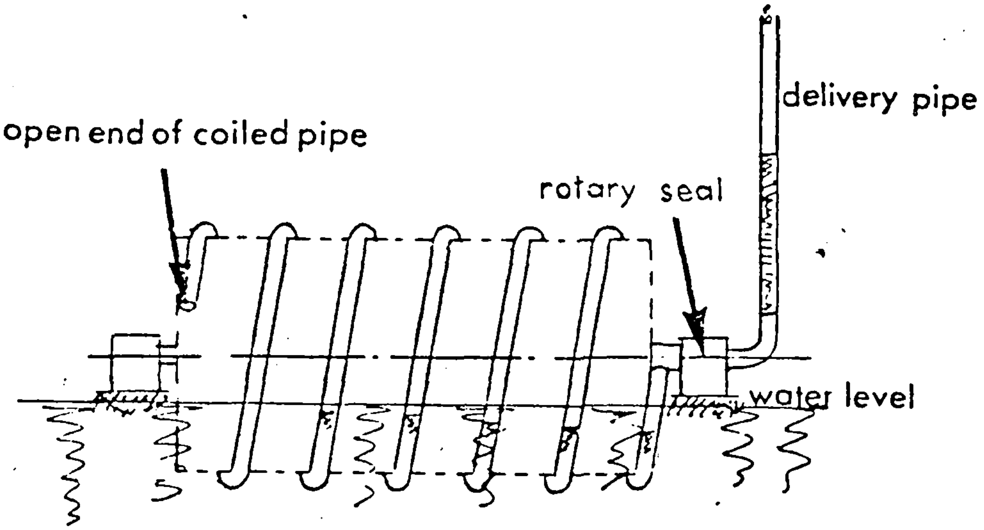
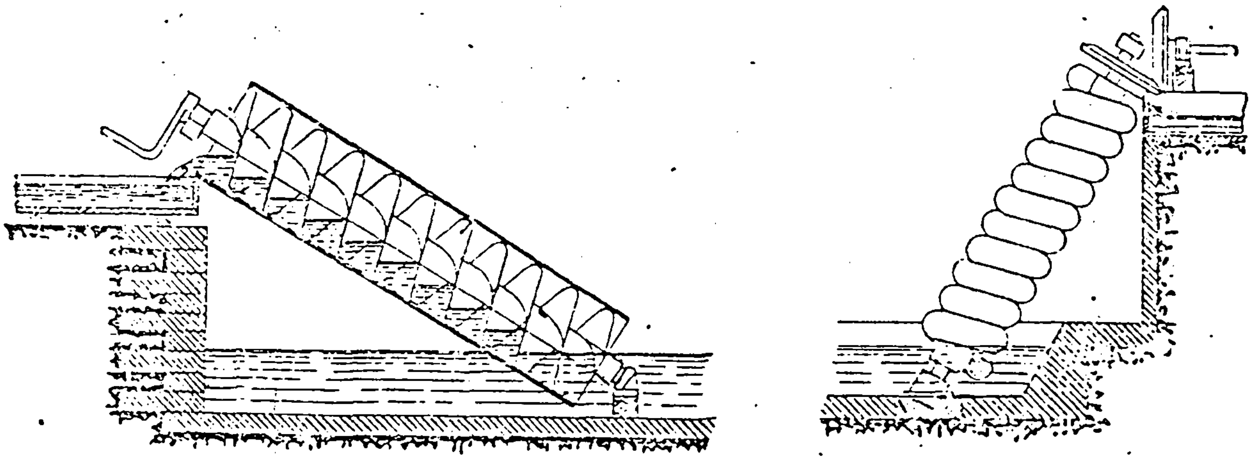


Figure 1

passes along the pipe and is followed by another plug of water separated from the first by a plug of air. In this way, a series of plugs of water and air pass along the coiled pipe and up the delivery pipe. The pump is known to raise water to a height of at least seven metres and possibly much greater heads can be obtained. Although in principle the pump may be driven by any prime mover, research workers are concentrating their efforts on systems which would raise water from a stream or river using the current flow to rotate the coil. It is anticipated that there may be great potential value for application in this way, particularly for developing countries.



...its similarity to the Archimedean Screw

Performance and Efficiency

4. The data available on the coil pump's performance is restricted to Ohlemutz's study at the University of California and the results of limited tests carried out at Loughborough University between 1976 and 1978. Small coil Pumps with diameters of 300mm and 500mm have been investigated and within the scope of the experiments the discharge was found to fall increasingly below the theoretical value as the speed of rotation and pipe diameter increased. See fig. 2.

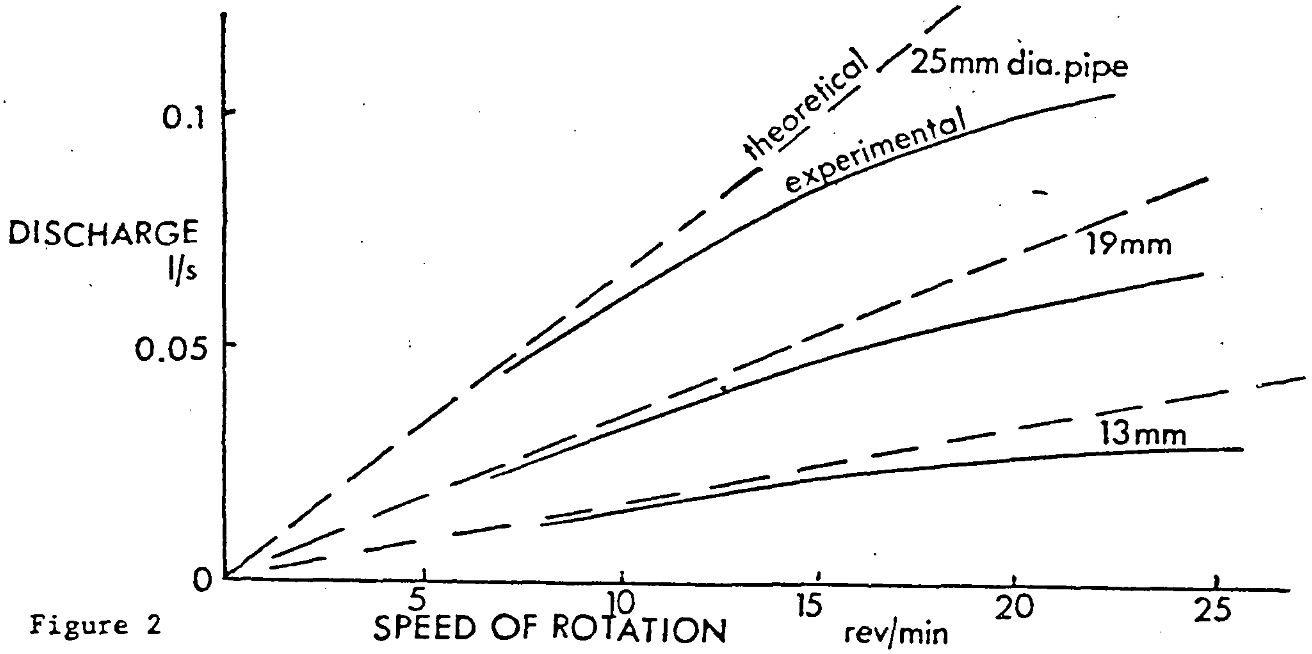


Figure 2

It should be noted that the discharge obtained in these tests is very small (below 0.1 lit/sec) and that for irrigation applications the device would probably need to be scaled up considerably.

5. Preliminary investigation of the pressure head developed by the coil pump has shown that water can be raised to at least seven metres. Two phenomena have also been observed for which there is no explanation. It appears that pressure build up does not occur until after the fourth coil (see fig. 3), and that

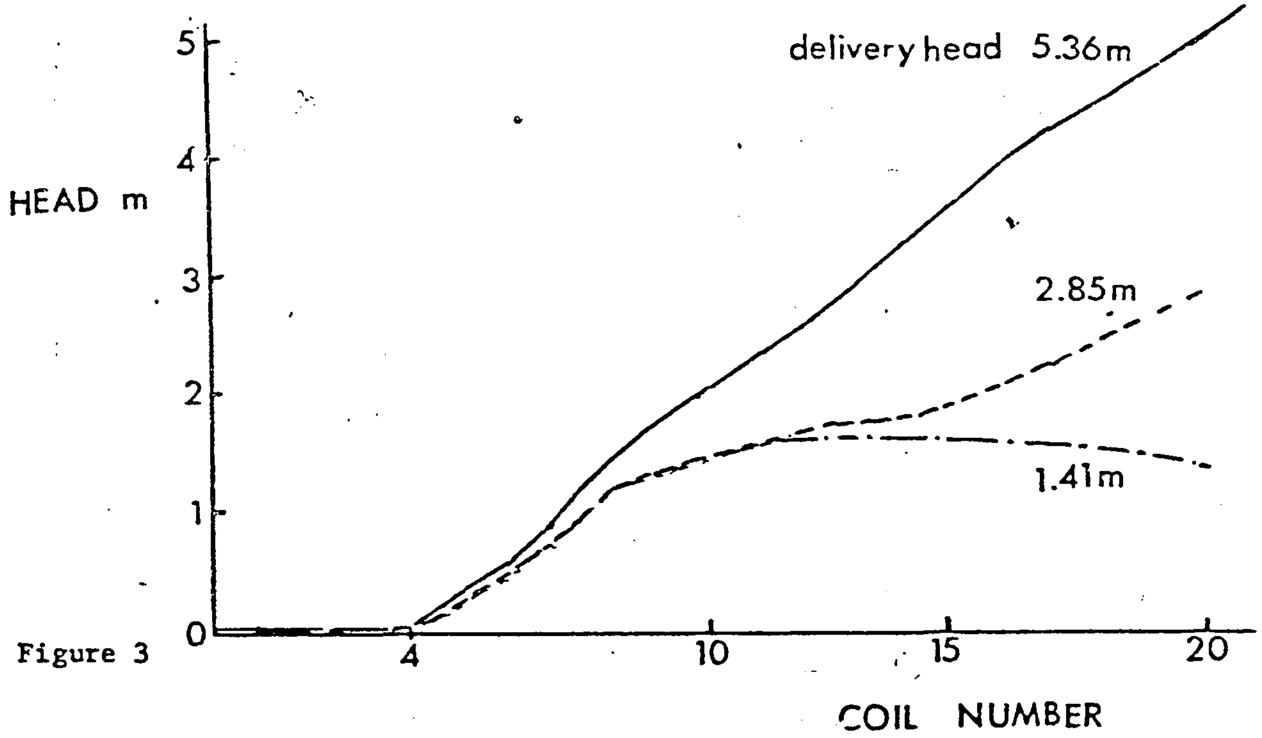


Figure 3

blow-back occurs when trying to obtain high flows against high heads. During blow-backs, water passes backwards over the top of the coils with resultant temporary reversal of flow.

Potential for Further Development

6. It is apparent from the previous section that there is a need for further investigation to ascertain the relationship between the variable factors influencing the performance of the pump. A list of the main variables would include: internal diameter of pipe, the depth of immersion, the speed of rotation, the rate of discharge and the pressure head produced.

7. To examine the relationship between all these variables would be a complex exercise. Perhaps the most rewarding area for investigation would be the determination of the head/discharge curves for a range of pipe diameters and a number of coils, the

other factors being kept constant at values chosen to represent a stream or river powered installation. Other potential areas for investigation might be the effect of a multi-stage coil and low-cost alternatives to the coiled pipe.

8. Although reasearch work is presently being conducted by the University of Dar es Salaam, Los Andes University and Loughborough University of Technology, significant contributions to the state of the art remain to be accomplished.

Location and Installation

9. From information available at the time of writing it appears that few examples of the coil pump have been field-tested as water-powered installations. This makes it difficult to report any factual data relevant to the location and installation of coil pumps. In general terms, however, the most appropriate mechanisms for converting the water energy into power for driving the pump will depend on the site characteristics. For example, if the device is to be a floating installation on a slow-moving river, a propellor is likely to be more efficient than a water-wheel arrangement and a zero-head turbine may be better still.

Operation and Technical Problems

10. A water-powered coil pump could be supported by buoyancy chambers so that it would float with optimum immersion irrespective of the river level. It would have to be moored to the bank or bed of the stream and the pumped water conveyed to the land by pipeline. As with any stream or river-mounted installation it would be vulnerable to damage by floating debris.

11. It is not known at present how large the coil pump must be made to supply a useful volume of water at a particular head for irrigation. If it is found necessary to construct a coil of several metres diameter and many turns, then the essentially simple concept will become overshadowed by the engineering work needed for the supporting and driving part of the structure. For high head pumping it may be necessary to have a quality-made rotary seal which is both liquid and air-tight. If this is found to be the case then this component presents complications in an otherwise simple device. Provided the pump can operate satisfactorily at low rotational speeds then bearings should not present any problems - in fact a wood bearing should prove quite acceptable.

Costs and Economics

Initial Cost high

12. At the present stage of development it is not possible to make any economic analysis of the coil pump. However, it appears that if the device has to assume a large size in order to pump a satisfactory quantity of water for irrigation, then the material costs could become very high. This may be off-set to a certain extent by the total absence of running costs for fuel or electricity although it should also be noted that periodic attention will be needed and a pump operator may have to be paid to perform the necessary duties.

X

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WORKSHOP ON WATER LIFTING DEVICES
FOR ASIA AND THE NEAR EAST

MANUAL PUMPING OF WATER FOR COMMUNITY WATER SUPPLY AND SMALL-SCALE IRRIGATION

BY
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WHO INTERNATIONAL REFERENCE CENTRE
FOR COMMUNITY WATER SUPPLY
VOORBURG (THE HAGUE), THE NETHERLANDS

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5. IRC'S PROGRAMME ON MANUAL PUMPING DEVICES

6. NON-TECHNICAL ASPECTS

7. IMPLICATIONS OF COMMUNITY WATER SUPPLY IN IRRIGATION DEVELOPMENT

1. INTRODUCTION

For lifting water, a great variety of devices exist. Indeed, one may say that our first ancestor who cupped his hands and fetched water from a stream chose the best water lifting technology available to him.

Water pumping technology provides a rich and varied spectrum of techniques and innovations. Those that had merit, survived, many perished. To indicate the wide range of water lifting devices, one could mention the following (Watt, 1975):

- Archimedean screw;
- Tabout, a hollow wooden wheel pierced with small holes which is used where the water table is virtually constant;
- Paddle wheel;
- Sagia or bucket wheel which is driven by draft animals;
- Noria (used to a great extent on the rivers of Syria); flowing water drives turning paddles fixed on the noria wheel.

In addition to these, there is the skin bucket fixed on a rope moving over a pulley and pulled mostly by draft animals. This device has been used, and is still being used extensively in many countries, mainly for medium-deep open wells, but also for lifting water from rivers. Normally the bucket is of leather, or of metal and leather, with a capacity of 10-60 litres.

History shows that water pumping technology developed in parallel with the available power supplies. Centrifugal, axial and turbine pumps have reached a high state of development, and are used widely in industrial countries, only because suitable power sources such as internal combustion or electrical power became available (Ewbank, 1972). In most countries, however, animal and human power are the principal sources of energy for pumping water. For community water supply and small-scale irrigation, manual* pumping is the mode of water lifting most widely used.

Manual pumping of water has certain important advantages under the conditions prevailing to many developing countries:

(a) The human energy requirements for pumping can be provided from within the users' group in a rural village, or even at the smallest farm; the costs of other energy sources continue to rise sharply, electricity often is simply not available, and there is a continuing shortage of fuel particularly in rural areas; in these areas labour typically is in surplus.

(b) The capital costs of manual pumping units are low; depending on the cost of the well and the number of people served per pump, a manually pumped water supply may be provided for an initial capital cost of as little as US \$ 0.05 to \$ 3.00 per capita (McJunkin, 1977).

(c) The discharge capacity of manual pumping units can readily meet the water requirements for domestic purposes and small-scale irrigation.

This situation, of course, provides justification for the unnumerable manual pumping devices which have been built over the centuries.

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* A manual pumping device, as used herein, is any simple device powered by human energy, for lifting relatively small quantities of water; this includes devices operated by foot.

Manual pumping of water has been practised in Asia and the Near East since times immemorable. These regions have a long history in the development and use of small-scale water lifting devices. It is the purpose of this paper to discuss the existing (traditional) types and to assess the potential of innovative designs.

Whilst the technology of manual pumping is important, the successful design and use of these devices depends to a large extent on non-technical factors. The involvement of the users in maintaining their pumping units, and the possibilities of manufacturing the pumps locally are examples. The implications of community water supply and small-scale irrigation in connection with overall irrigation development are of great importance. In fact, they combine and are both essential elements in the overall process of improving the quality of life of the vast rural populations (WHO, 1978).

2. TECHNOLOGY OF MANUAL WATER PUMPING

2.1. HISTORY

Although many manual pumping devices exist, the type used most frequently for community water supply and small-scale irrigation is the reciprocating (positive displacement) plunger pump.

This type of pump has an ancient history. A study of literature (Eubanks, 1971) reveals that a certain Ctesibius invented, around 275 B.C., a reciprocating pump. His pump was a twin cylinder lift type, with external valves and without any packing between the plunger and the cylinder wall. It was used for fire fighting. Hero (2nd Century B.C.) and Vitruvius (1st Century B.C.) were familiar with this pump. Archeological remnants of reciprocating pumps from later Roman times are occasionally found. They were in wide-spread use in medieval Europe.

Ewbank (1972) states that a reciprocating pump of wood was used as a ship's pump in the early Greek and Roman navies. The construction of these pumps is uncertain, but they may have been similar to those described in old books.

Agricola (1950) clearly shows that the design used in Saxony in the sixteenth century. At this time, in addition to the conical leather plunger or bucket, plungers in the form of perforated wood or iron disc were commonly used, the perforations being covered by a disc of leather which acted as a valve.

The foot valve typically was a hinged metal flap and was attached to a metal seating. The pump was usually made in three sections, the middle being the working barrel, while the short bottom section contained the suction valve. These early wooden pumps were of the lifting type, but when made in metal, in order to economise material and cost of manufacture, the working barrel was usually placed at the top and a narrow suction pipe used. The suction valve was placed at the bottom of the barrel.

In 17th-century England, reciprocating pumps made of wood or lead and with the plunger packed with leather were in common use. It was not until about the middle of the nineteenth century that improved transport and communication made it economical to manufacture cast, machined, metal handpumps for distribution over a wide area.

In the late 19th and early 20th centuries, a tremendous number of different pump models were produced. Perhaps 3000 manufacturers produced handpumps in the U.S. alone. They were primarily used on farms by single families and their livestock. Windmills were increasingly used to drive pumps.

All these pumps were designed on the basis of the same operating principles, and they differed little from the traditional models. In the period since Ctesibius (some 2250 years) little was done to improve the manually operated reciprocating pump. In the industrial countries, interest in this type of pump virtually disappeared, when they found less and less use. Over the last few years, it has been recognized that manual pumping units have an important role to play in providing adequate supplies of water for domestic use and small-scale irrigation in rural areas of developing countries. Water supply authorities in these countries and the international organizations and bilateral agencies providing development assistance, are now pursuing the improved technology of manual water pumping with vigour.

2.2. FUNDAMENTAL HYDRAULICS

The theoretical discharge capacity of a reciprocating handpump (single acting) is a function of the cylinder volume swept by the plunger during its upward, pumping stroke, and the number of strokes per unit of time. This is illustrated in Figure 1.

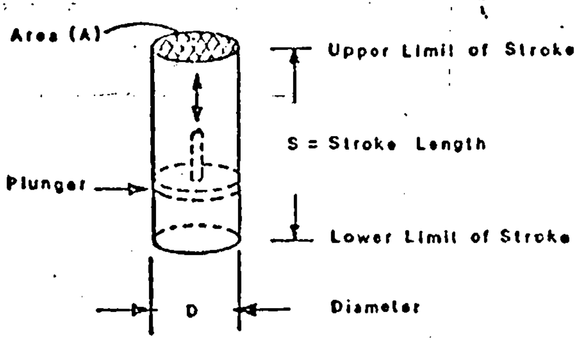


FIGURE 1 SWEPT CYLINDER VOLUME

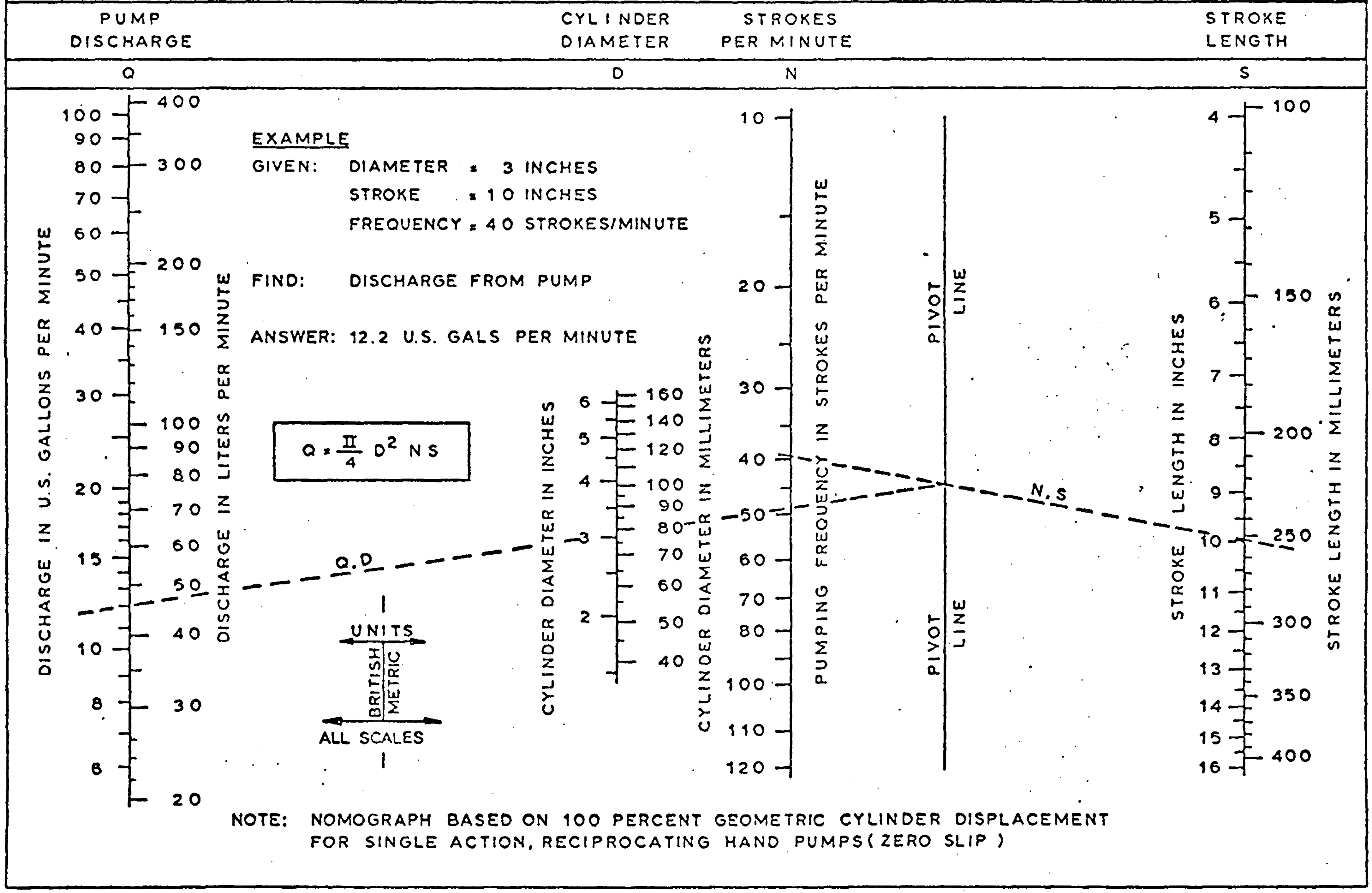
The swept cylinder volume (V) is the product of the (horizontal) cross sectional area (A) and the length of the plunger stroke (S). The cross sectional area (A) can be written in terms of the cylinder diameter (D):

$$A = \frac{\pi}{4} D^2$$

The discharge capacity (Q) for a given number of pumping strokes per unit of time (N) may be calculated with the equation:

$$Q = \frac{\pi}{4} D^2 . S.N.$$

FIGURE 2. NOMOGRAPH FOR HAND PUMP DISCHARGE



EXAMPLE

GIVEN: DIAMETER = 3 INCHES
STROKE = 10 INCHES
FREQUENCY = 40 STROKES/MINUTE

FIND: DISCHARGE FROM PUMP

ANSWER: 12.2 U.S. GALS PER MINUTE

$$Q = \frac{\pi}{4} D^2 N S$$

NOTE: NOMOGRAPH BASED ON 100 PERCENT GEOMETRIC CYLINDER DISPLACEMENT FOR SINGLE ACTION, RECIPROCATING HAND PUMPS (ZERO SLIP)

The nomograph shown in Figure 2 can be used to determine the theoretical discharge capacity of a particular pump in terms of litres per minute or U.S. gallons per minute.

The actual rate of discharge normally varies slightly from the theoretical discharge due to failure of the valves to close instantly when the plunger changes direction and to leakage between the plunger and the cylinder wall during pumping. This difference is known as slip and is defined as the difference between theoretical discharge (Q_t) and actual discharge (Q_a) as a percentage of the theoretical discharge, that is:

$$\text{Slip} = \frac{Q_t - Q_a}{Q_t} (100)$$

Slip should not exceed 15 percent, preferably 5 percent, in a well designed and maintained pump. Under certain conditions, (e.g. a long suction pipe of small diameter, below the cylinder) the flow velocity may be sufficiently high to keep the plunger discharge valve open during part of its upward movement. In such cases the actual discharge may exceed the theoretical discharge capacity; this phenomenon is called 'negative slip'. Although beneficial in terms of the hydraulic efficiency of the pump, it may lead to excessive 'pounding' and even cavitation.

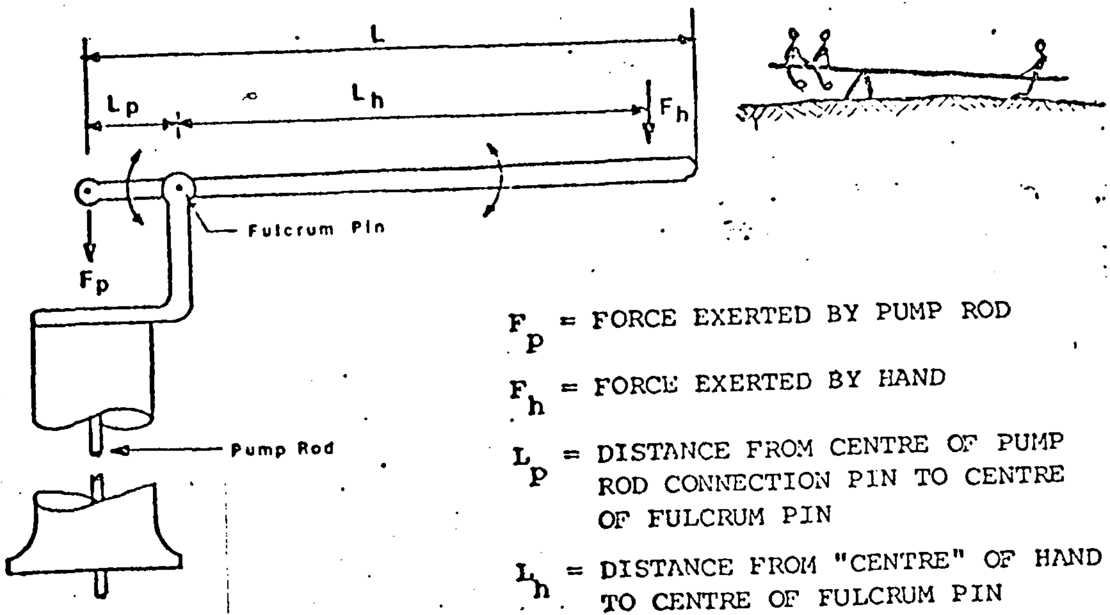
Hydraulic efficiency in terms of swept cylinder volume should not be confused with mechanical efficiency which can never exceed 100 percent.

2.3. FORCE AND ENERGY REQUIREMENTS

2.3.1 *MECHANICAL ADVANTAGE*

The force exerted on a pump rod and, through the rod to the pump handle may be as high as 50 kgf (110 lb). However, the muscular force available for continuous pumping by an individual person is generally limited to 10 - 18 kgf (20-40 lb). Through the pinciple of mechanical advantage, muscle power can be multiplied to successfuly operate handpumps in wells up to even 180 meters (60 fee) in depth.

The principle of mechanical advantage is illustrated in Figure 3.



F_p = FORCE EXERTED BY PUMP ROD

F_h = FORCE EXERTED BY HAND

L_p = DISTANCE FROM CENTRE OF PUMP ROD CONNECTION PIN TO CENTRE OF FULCRUM PIN

L_h = DISTANCE FROM "CENTRE" OF HAND TO CENTRE OF FULCRUM PIN

FIGURE 3: MECHANICAL ADVANTAGE OF PUMP HANDLE AS LEVER

Consider the lever-type pump handle shown in Figure 3. It pivots about the fulcrum pin. At one end, L_p distant from the fulcrum, the handle is connected by a pin to the pump rod. Through this pin the force exerted by the pump rod, F_p, pulls on the handle. At the other end of the handle, L_h distant from the fulcrum, the hand pushes down the handle with a force, F_h.

If the distances L_p and L_h were equal <u>and</u> the forces F_p and F_h were equal, the handle would be in balance or 'equilibrium' and would not move. If the distance L_h were twice the distance L_p but the force F_h only half the force F_p, then the handle would continue to be balanced. Indeed any combination in which the product (or 'moment' as it is termed in mechanics) of the distance and force on one side of the fulcrum is equal to the product of distance and force on the other side of the fulcrum would be stable. That is, at equilibrium, $F_h L_h = F_p L_p$. The ratio of the handle distance L_h to the pump rod distance L_p is known as the mechanical advantage.

$$\text{Mechanical Advantage} = \text{MA} = \frac{L_h}{L_p}$$

By similar analysis, the mechanical advantage MA for a rotating crankshaft with crankhandle or wheel can be shown to be:

$$\text{MA} = \frac{\text{Radius of Handle Rotation}}{\text{Radius of Crankshaft Rotation}}$$

EXAMPLE

Given a pump rod force of 88 kgf (190 lb). What handle force is needed if the mechanical advantage of the pump handle is 4 to 1.

$$F_h = \frac{F_p}{\text{MA}} = \frac{88\ \text{kgf}}{4} = 22\ \text{kgf}\ (48.5\ \text{lb})$$

A typical mechanical advantage for a shallow well pump is about 4 to 1. This means that a pump rod force can be balanced by a handle force about one quarter as large. For deep wells a greater mechanical advantage may be chosen, even 10 to 1 (McJunkin, 1977).

The mechanical advantage cannot be increased without limit. As distance L_h from the fulcrum to the hand is increased, the arc swept by the end of the handle increases. Too large an arc makes for difficult operation. Decreasing the pump rod to fulcrum distance L_p increases the mechanical advantage but it simultaneously decreases the stroke length S of the pump rod and its attached plunger.

2.3.2 *FORCES: CONVENIENCE AND EASE OF USE*

Where the required force on the handle for operating the pump is too high, especially for handpumps operated by women and children, improvement may be obtained by extending the handle for greater mechanical advantage or reducing the pump rod force by using a smaller diameter pump cylinder.

If R represents the allowable (average over pumping cycle) force required to operate the pump conveniently and easily and MA the mechanical advantage of the handle assembly, then the actual pump rod force (F_a) must not exceed the product of R and MA:

$$F_a \leqslant R \times MA$$

For an allowable average handle force of 18 kgf (40 lb), a conventional mechanical advante of 4 to 1, and a steel pump rod of normal diameter, the relationship between pumping head and cylinder diameter for comfortable operation of deepwell handpumps may be tentatively calculated as tablulated in Table 1.

TABLE 1: MAXIMUM HEAD FOR COMFORTABLE OPERATION OF DEEP WELL HAND PUMP

CYLINDER DIAMETER		HEAD (LIFT)	
Inches	mm	Feet	Meters
2	51	Up to 75	Up to 25
2½	63	Up to 60	Up to 20
3	76	Up to 45	Up to 15
4	102	Up to 30	Up to 10

2.3.4. *ENERGY REQUIREMENTS*

In handpumps, the energy requirement (or rate of work), is an important parameter.

$$\text{Energy requirement} = \frac{Q.H}{\eta} \quad \text{(watt)}$$

Q = rate of discharge (l/sec)
H = pumping head (m)
η = mechanical efficiency of pump (%)
g = gravitational constant (m/sec^2)

The above equation shows that the energy requirements for operating a pump have an inverse relationship with the pump's mechanical efficiency; the lower the mechanical efficiency, the higher the energy input required.

The appropriate SI unit of energy (watt) should preferably be used. However, energy is frequently expressed as horsepower (h.p.) 1000 watts = 1 kilowatt = 1.34 hp.

By definition man (or woman or child) is the motive force that drives the handpump. Most pumps used for domestic water supply are operated by many users, ecah pumping only a few minutes at a time. Usually many of the users are women and children.

The power available from the human muscle depends on the individual, the ambient environment, the efficiency of conversion and the duration of the task.

Very fe measured data of human energy output for work such as water pumping have been obtained under field conditions. The power available for long term useful work, for example 8 hours per day, 48 hours per week, by healthly young men is often estimated at 60 to 75 watts (0.8 to 0.10 horsepower). This value must be reduced for individuals in poor health, malnourished, of slight stature, or aged. It must also be reduced for high temperature of high humidity of the work environments. Where the man and his work are poorly matched - for example pumping from a stooped position - much of the energy input is wasted.

The power available during short work periods is much greater. There are examples of well trained athletes generating up to 2 horsepower for efforts of 5 to 10 seconds. Table 2 summarizes data obtained from Krenkel (1967).

TABLE 2: MAN GENERATED POWER

AGE OF MAN	USEFUL POWER BY DURATION OF EFFORT (in H.P.)					
Years	5 min	10 min	15 min	30 min	60 min	480 min
20	0.29	0.28	0.27	0.24	0.21	0.12
35	0.28	0.27	0.24	0.21	0.18	0.10
60	0.24	0.21	0.20	0.17	0.15	0.08

Modified from Krenkel (1967).

Using an assumed effective energy output of 75 watt (0.10 HP) for operating a pump, a tentative measure of the pump's mechanical efficiency can be obtained from the equation:

$$\text{Mechanical Efficiency } \eta = 13.3\, QH \text{ (in percent)}$$

Q = rate if discharge (l/sec)
H = pumping head (m).

2.3.4. *ANIMAL POWER*

Draft animals are a common and viatal source of power in many developing countries. Animal power is poorly suited to direct drive or reciprocating pump devices. In Africa and Asia, they are widely used for pumping irrigation water from large diameter, open, shallow wells. The most efficient use of animals is at fixed sites to pull rotating circular sweeps or by pushing treadmills. Both methods require gears and slow moving, large displacement pumps. A horse of 700 to 800 kg (1500 to 1900 lb) can work up to 10 hours per day at a rate of 1 horsepower (about 750 watts). For short bursts of 5 to 30 minutes a horse can work at about 4 horsepower (3 kilo watt) (McJunkin, 1977).

2.3.5. *WINDPOWER*

Direct drive of a pumping device by a windmill requires matching the characteristics of:

(1) the local wind regime
(2) the windmill
(3) the pump.

By far the commonest type of wind pump is the slow-running wind wheel driving a piston pump. The pump generally is equipped with a pump rod extending through a pump stand assembly and upper guide with a hole for connection with the drive axis of the windmill. Provision may be made for pumping by hand during calm periods without wind.

2.4. ECONOMIC ANALYSIS

Manual pumping of water represents an intermediate level of technology which can be higly cost-effective. When evaluating different types and models of pumping devices in terms of costs (economic costing), all relevant costs should be analyzed; these include capital costs, and any costs for operation, maintenance and replacements.

The purpose of economic analysis (costing) of handpumps is to determine an equivalent figure for each pump under consideration. In this way, a common denominator is provided in order to objectively compare the pumps.

It is a common error to use in the economic evaluation of handpumps as the paramount criterion the initial capital outlay only. This is not correct. The initial capital cost of a pump may be not more than 15-25% of its total "life-cycle" costs.

The "life-cycle" costs of each handpump involve costs (expenditures) at different points of time. In order to make any valid comparison it is necessary to convert the relevant (future) cost figures at different points of time into equivalent figures based on the principle of "time value of money".

The different costs involved in the entire "life-cycle" of a handpump can be expressed as a single figure in either of the two following ways:

(1) Present worth of costs
(at initial year of installation of the pumps);
(2) Annual equivalent costs.

The first method is generally used by economists whereas the second method is often preferred by engineers.

COST DATA TO BE USED IN ECONOMIC ANALYSIS

Economic costing should use *real economic costs*. However, in developing countries market prices or observed prices often have little relation to real economic costs (viz. opportunity costs to the national economy). Shadow pricing may be necessary to arrive at meaningful component costs in the economic comparison of handpumps. Shadow rates to be used in such analyses should preferably be obtained from economists and water supply agency staff in the country concerned.

Data on *maintenance and replacement costs* are sparse. These costs are difficult to predict, as they depend to a large extent on local circumstances. Very often they are underestimated. Sometimes, cost estimates are based on historical data without recognizing that these may represent the cost of an inadequate level of maintenance.

SERVICE LIFE EXPECTANCY OF PUMPS (n)

The service life expectancy of various handpump models is difficult to predict with accuracy, as it varies with the conditions of service and levels of maintenance*. The difficulty of course is to establish the relative level of long term maintenance required for various pumping devices.

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* Theoretically, the useful life of a handpump could be extended over a very long period of time by simply replacing worn out or damaged parts one by one as required. One could argue that when every part has been replaced at least once, the technical life span of the original pump has come to an end.

It is common for a pump manufacturer or supplier to claim that the pump will last for 15-20 years under 'normal' operating conditions. This is far too simplistic approach. Each pumping device has a number of components. Several of these may last many years with little or no maintenance. Others have a limited life span because of wear, or vulnerability to breakage. As with any mechanical device, a pump has wearing parts which require replacement periodically in relation to the intensity of use. Vandalism and accidents result in the need to replace damaged units from time to time.

In economic analysis, the 'life span' of a pump does not refer to the longest lasting component but to the pump as a functional unit.

Some parts may be replaced economically only once, others may justify replacement several times during the service life of the pump as a whole. In fact, this would imply a separate economic costing of each pump component over the design period. An estimate may have to be made of the number of times that individual components will need replacement taking into account the operating conditions.

The total cost of spare parts and replacement (purchase and installation), over the service life of the pump, can be quite substantial compared with the initial capital cost of the pump.

COST COMPARISON OF PUMPS

It should be clear that unit prices of pumps, as given in manufacturers' documentation, tender documents and bids should not be the sole criterion in comparing pumps. Obviously, the pump with the lowest initial cost, few wearing component parts, and requiring the least maintenance, would be the most economical unit. However, the situation seldom is so straight forward.

Regardless of the handpump selected, some maintenance will always be involved in keeping it in satisfactory operating condition. Some of the most significant costs associated with maintenance, do not pertain to the pumps themselves, but to the trucks, motor cycles, fuels and personnel required for inspection, servicing and repair of pumps.

The extent to which maintenance will be required, and what resources are needed, is related to many diverse factors. Many value judgements must be made. Field testing of pumps will assist in determining the performance (reliability, durability) of component parts, and so result in more meaningful value judgements than if no test data are available.

3. MANUAL PUMPING DEVICES FOR COMMUNITY WATER SUPPLY

3.1. GENERAL

By their very nature, manually operated water pumps have to fit within narrow limits regarding rotating or oscillating speeds, particularly if expensive gearing is to be avoided.

Most manual pumping devices used in community water supply are of the reciprocating type. They represent the evolutionary, often empirical product of many years (sometimes several centuries) of design modifications.

Reciprocating pumping units can be divided into type types: The shallow well and the deepwell pump.

In the shallow well pump, the plunger and its cylinder are located above the water level - usually within the pump stand itself. This pump relies on atmospheric pressure to lift the water to the cylinder; thus it is limited to water lifts of about 7 metres (22 feet).

In the deep well pump the cylinder and plunger are located below the water level in the well. This pump can lift water from wells as deep as 180 metres (600 feet). The forces and wear created by the hydraulic head increase with the depth to the water table. Also, the maintenance and repair problems associated with reaching the cylinders set deep in the well are much more difficult than in shallow well pumps. Thus the design and costs of pumps for deep well use are more critical than for shallow wells.

While this section focuses on reciprocating plunger pumps, the fundamental principles outlined also apply to other types of pumps, particularly other positive displacement types.

The hydraulic design of the pumps is concerned with the rate of discharge, the head to be overcome in lifting the water, the structural forces generated by the lift, the energy input required, and the length and frequency of the plunger strokes transmitted by the handle. These factors affect the design of the handle assembly, the pump stand, the bearings at handle pivot points, the pump rod connection to the handle and the plunger assembly, the cylinder, and the water seal ("cup" or "bucket") between the plunger and the cylinder wall.

3.2. SHALLOW WELL PUMPS

Figure 4 shows a manually operated shallow well lift pump. The body of the pump (see B) containes a plunger or piston which moves up and down, i.e. reciprocates. The principle of operation is illustrated in Figure 5.

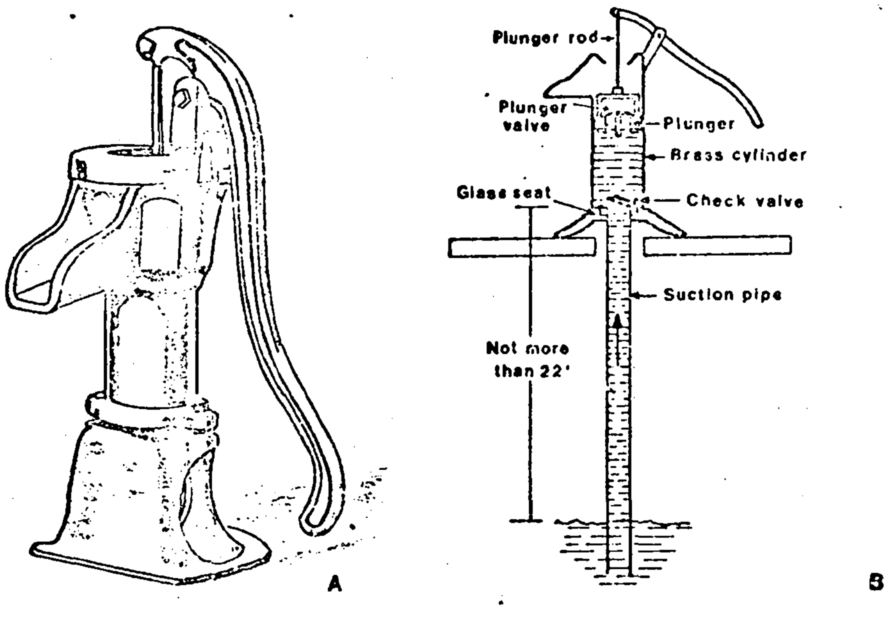


FIGURE 4: TYPICAL SHALLOW WELL PUMP

Contrary to popular opinion, pumps do not "lift" water up from the source. Rather the pump reduces the atmospheric pressure on the water in the suction pipe and the atmospheric pressure on the water outside of the suction pipe pushes the water up and onto the pump. The principle is the same as that of drawing soda water through a straw of filling a syringe.

Because of its reliance on atmospheric pressure to push water up the suction pipe, use of shallow well pumps is limited to conditions where the water table during pumping is within 7 metres (22 feet) of the suction valve even though atmospheric pressure typically is about 10.4 metres (34 feet).

3.3. DEEPWELL LIFT PUMPS

This pump is shown in Figure 5.

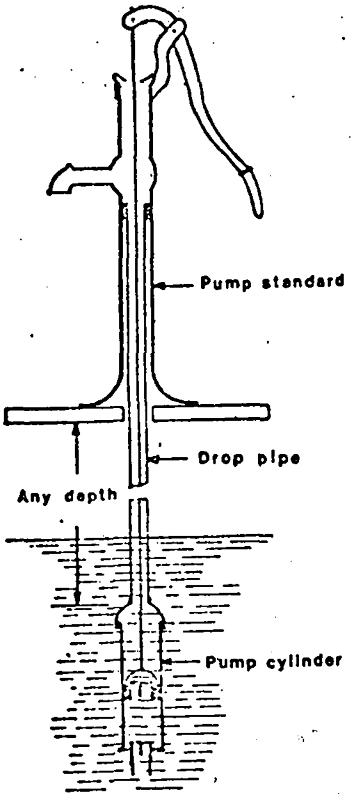


FIGURE 5: DEEPWELL LIFT PUMP

Deepwell pumps operate in the same manner as described in the foregoing. The principal difference is the location of the cylinder. The cylinder is usually submerged in the water as shown in order to prevent loss of priming. This pump can be used to water from depths greater than 7 metres below the pump spout.

Deep or shallow well in terms of handpump selection refers to the depth of the water level in the well, not the depth of the borehole or the well casing. For example, a well drilled 90 metres (about 300 feet) deep but in which the water table is 5 metres (16 feet) below the surface may use a shallow well handpump. Or a deepwell handpump. Conversely, a well drilled only 12 metres (39 feet) but whose water level is 11.7 metres (38 feet) below the surface will require a deepwell pump with its cylinder set at least 11.7 - 7 = 4.7 metres below the surface. On the second well shallow well pumps would not work.

3.4. BUCKET PUMPS**

Another type of positive displacement, hand operated pump is the bucket pump. An example is shown in Figure 6

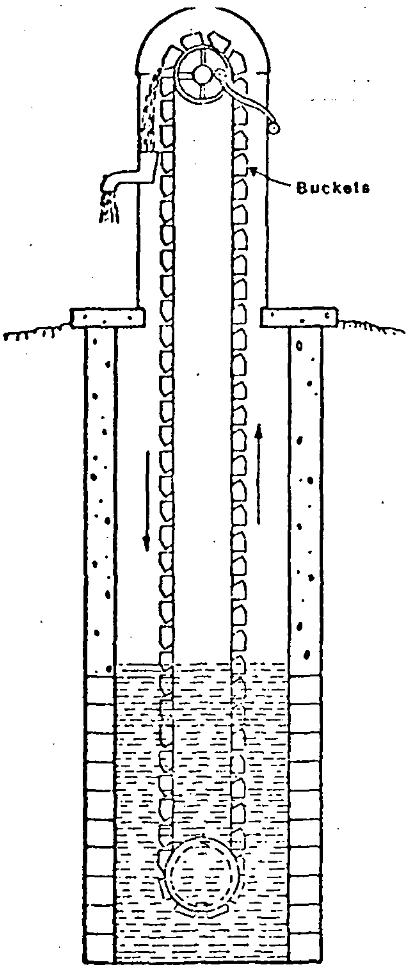


FIGURE 6: BUCKET PUMP

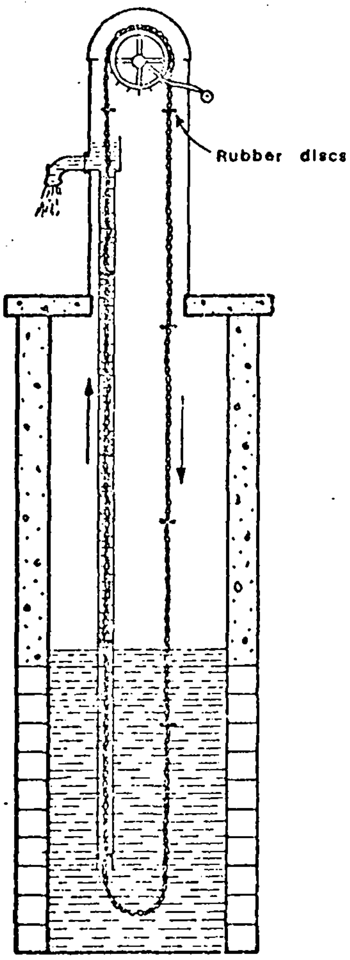


FIGURE 7: CHAIN PUMP

** Not to be confused with the name "bucket pump" sometimes given reciprocating well pumps whose plunger to cylinder seals are sometimes called "buckets".

Small buckets attached to an endless chain are rotated over sprockets as shown so that each bucket dips water from the source at the bottom, carries it to the top, and empties it into the spout as it passes over the top sprocket. At least one manufacturer makes a pump using a sponge-like belt in lieu of the buckets with a squeegee at the top to remove the lifted water. Another handmade version uses a rope driven by a bicycle wheel with a sharp bend at the top to discharge the water by centrifugal force. These pumps are used mostly on cisterns and shallow dug wells.

The same operating principle is used in "traditional" animal-powered low-lift irrigation pumps such as the Persian wheel, sakia, noria, and others in which the buckets may be replaced by earthenware jars, wooden or metal boxes and the circular, horizontal movement of the animals converted by beveled or toothed gears to rotary vertical motion to drive the endless chain.

3.5. CHAIN PUMPS

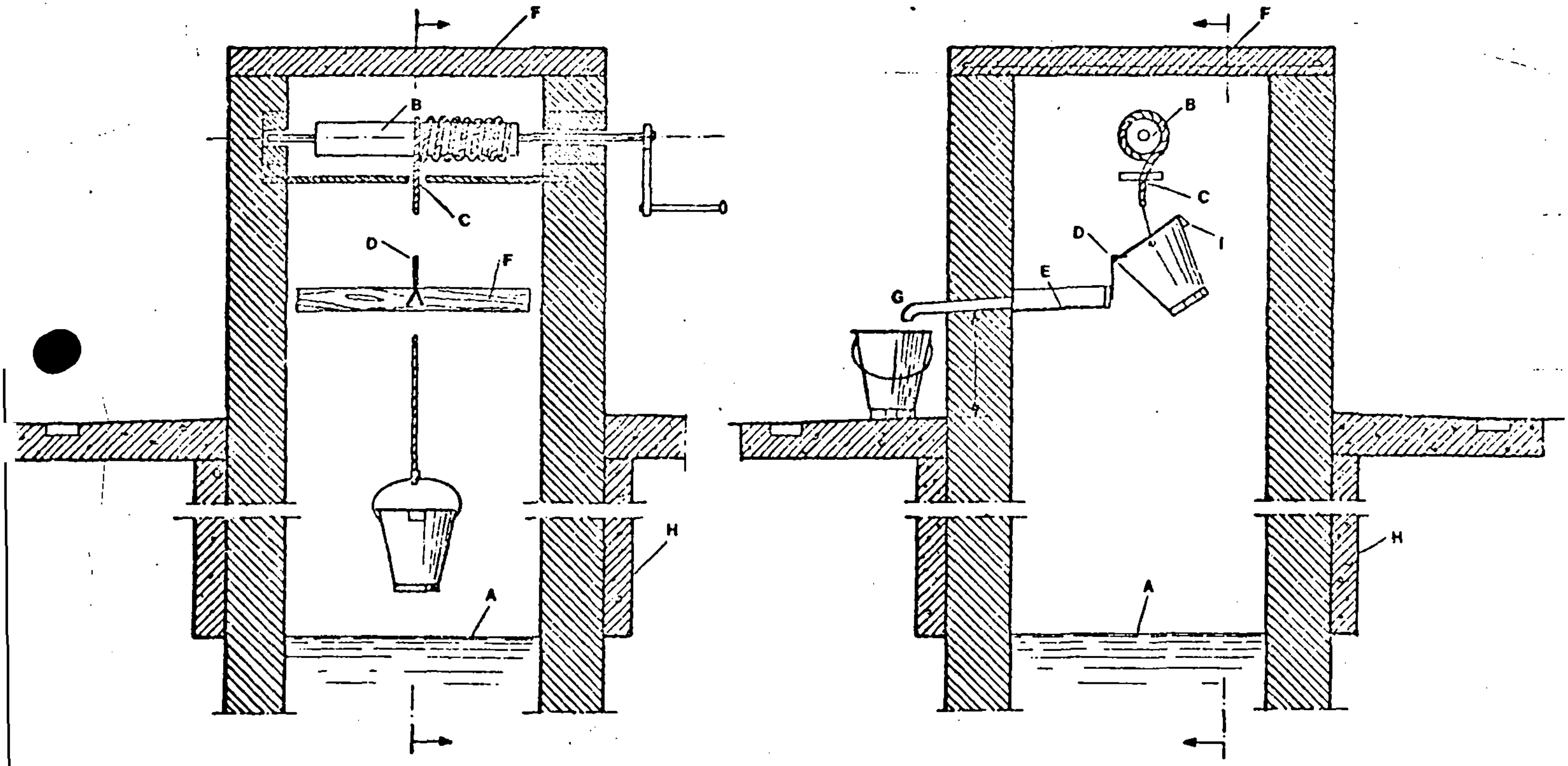
In the chain pump, rubber discs attached to an endless chain running over a sprocket at the top are pulled upward through a pipe to lift water mechanically up to the spout. Like the bucket pump, it is used mostly on cisterns and shallow dug wells. This type of pump is readily adaptable to manufacture by village artisans. See Figure 7.

Chain pumps using rags and balls in lieu of discs were commonly used for draining mines in Agricola's time (1556). Animal-powered chained pumps are apparently widely used in China for irrigation pumping (Watt, 1975).

3.6 SANITARY ROPE AND BUCKET MECHANISM

The design developed by WHO (Wagner and Lanoix) and shown in Figure 8 should not be overlooked. This design, for use with dug wells, is simple to maintain. When carefully built, this simple pumping arrangement gives good service, and will protect the well from pollution. Because it is fairly simple, details can be easily changed to fit local conditions. For ease of maintenance, the cover should be removable. A reinforced concrete slab four inches thick and three feet in diameter can be moved by two men.

The obvious disadvantage of this type of water-lifting arrangement is its low rate of discharge. But as a village community water source, it will perform satisfactorily.



A = Water level in well
B = Windlass
C = Guide hole for rope
D = Stop hook
E = Trough

F = Tight cover, removable
G = Discharge opening
H = Compacted clay, or concrete grout

I = Weight attached to top side of bucket to make it tilt when bucket is lowered onto water surface

FIGURE 8: A SANITARY ROPE AND BUCKET INSTALLATION

3.7. RESEARCH AND DEVELOPMENT

International efforts to develop pumps for water supplies in rural areas of developing countries have stimulated over the last 10 years several major research and development projects. These include (McJunkin, 1977):

(1) The AID/Battelle Pump. A comprehensive programme to develop a sturdy, dependable pump for shallow and deep wells for universal application in developing countries. While never placed in mass production, its research findings have stimulated and influenced most other handpump development programmes.

Field testing of the AID/Battelle handpump is proceeding in Costa Rica and Nicaragua under an agreement involving the governments of those countries, the Central American Research Institute for Industry (ICAITI), and the Georgia Institute of Technology (U.S.). The AID Battelle pumps under test were manufactured in Costa Rica and Nicaragua. Thirty AID/Battelle pumps deepwell and shallow well handpumps are being evaluated in the field. For comparative purposes, four other, imported pumps are also being tested.

(2) New No. 6 Pump. A shallow well pump developed in Bangladesh with UNICEF assistance, this pump is now in mass production. It incorporates many Battelle features. Plastic (PVC) seals have replaced the leather seals used previously. Considerable experimentation and prototype testing was done. The pump improvement work evolved over several years through many design modifications based on field experience.

(3) India Mark II Deepwell Pump. This pump has been developed by the Government of India with major assistance from UNICEF and WHO. The "Sholapur" pump design was adopted as the basis for the development. Design improvement first concentrated on the handle mechanism, failure of this component being the pricipal factor in breakdown of pumps. The original cast iron pedestal mounting to the well casing pipe was re-designed into a pedastal to be grouted into the pump platform, completely independent of the well casing.

(4) Hydro Pompe Vergnet. A newly developed pump using a novel operating mechanism. The pump is foot-operated; a hydraulic piston drives a diaphragm pump immersed in the tubewell. With WHO and UNICEF assistance, prototypes of the Vergnet pump were field testing in Upper Volta. The pump can be used as a lift pump or force pump, not as a suction pump. Further development for depths over 15 to 20 meters seems to be required.

(5) Petro Pump. An interesting new variation of diaphragm pump, suitable for use in deep wells. The pumping element of "cylinder" consists of an elastic rubber hose, reinforced by two layers of spirally wound piano wire, and equipped with a ball-type check valve at each end - fixed by a metal bracket. The lower end of the hose is fixed within the well by expander jaws wedged against the casing; the upper end of the hose is attached to a string of ¾- inch (19 mm) pipe which serves as both the pump connecting rod and the drop pipe.

(6) Shinyanga Pump. This pump has a wooden pumping head which closely resembles the Kenya Pump manufactured in Nairobi and widely used in East Africa. However, whereas the Uganda pump uses a brass cylinder, the Shinyanga pump has a polyvinyl chloride (PVC) plastic cylinder. A rubber double ring cupseal with an internal shape retaining stainless steel ring is used. The cup must be imported and is relatively expensive (about $10 each). However, it is expected to last perhaps as long as 10 years.

(7) Kangaroo Pump. This a foot-operated pump. The pump head consists of two pipes sliding over each other, with a spring fitted in between. The outside sliding pipe is connected to the pump rod, and operates the piston in the pump cylidner. The downward stroke serves to compress the spring, which is then left to produce the water discharge upward stroke.

(8) The International Development Research Centre (Canada) has a pump development project underway which concentrates on use of new materials, particularly plastics; improvement of valves and seals, and wooden bearings.

(9) A comparative testing project for handpumps is being carried out by the Harpenden Rise Laboratory (U.K.) funded by the Overseas Development Ministry (U.K.). Some 12 different pump models are tested under a scientific protocol, probably the most complete used sofar. The pumps

under test include most of the pumps earlier mentioned, several with wheel-type drive, a helical rotary type, the DPHE/UNICEF "New No. 6", developed in Bangladesh, the AID/Battelle, and four of the novel pumps on the market.

(10) The extensive comparative field tests of handpumps undertaken in northern Ghana by the Ghana Water and Sewerage Corporation, assisted by the Canadian International Development Agency and Wardrop Associates, Consulting Engineers, are completed and a final report has been prepared.

The results of pump research and development should be used with caution. Pump improvements that seem obvious in the office or laboratory do not often work in the field. A corollary is that successful performance in the laboratory does not guarantee success in the field.

4. MANUAL PUMPING DEVICES FOR SMALL-SCALE IRRIGATION

4.1. GENERAL

Manual pumping of water for irrigation purposes can only be effective if there is a balance between the amount of energy expended by a (often not very well nourished) man, and the quantities of water required. For many crops, particularly rice, the water requirements can be substantial.

In order to be worthwhile, energy wastage in manual pumping of irrigation water should be minimal. If much energy is used in overcoming friction, or lost altogether when lifted water is permitted to slip back down the well, then manual pumping will clearly be unsatisfactory for any irrigation application.

It is in this respect that most of the currently available hand-pumps are unsuitable. They were designed primarily for community supplies of drinking water, and conservation of human energy input was never an important consideration (Journey, 1976).

So, whereas man-powered pumps are widely used to lift the small amounts of water needed for domestic purposes and stockwatering, for large-scale irrigation the quantities of water required will rule out manual pumping; other sources of power will have to be used.

However, man-powered pumps may be a valid proposition for small-scale irrigation, They normally have a capacity suited to small fields, they are usually cheap to make, and are small and easily transported. Moreover, in many parts of the world, farmers and their families are the only source of power readily available.

Manual pumping of irrigation water need not be so ineffective as might appear at first sight. Under certain conditions, relatively small amounts of water pumped over a few weeks can save a crop or double the yield of the farmer's land. In Bangladesh, for instance, handpumps (MOSTI-pumps) are widely used for irrigating land to achieve an extra crop.

Under the pressure of rising food costs and severe unemployment, it is important to bring out the potential of manual pumping for irrigation purposes. Ingenious mechanical design, coupled with the use of new materials where appropriate, should make for suitable pumping units (Journey, 1976).

To maximize mechanical advantage and conservation of energy expended in pumping a simply supported pendulum or similar device may be useful.

The most effective use of manpower for pumping work of long duration (several hours per day) is through the legs, not through the arms. Leg muscles are stronger than the muscles in the upper part of the body. A healthy man should be able to develop comfortably about 0.10 horsepower (75 watts) over long periods, by pedalling. Many low-lift pumping devices employed for small-scale irrigation, use leg power.

4.2 TRADITIONAL PUMPING DEVICES

There are numerous water lifting devices which could be mentioned: The Archimedes screws; rope and bucket devices such as the mohte, charsa, ramioko, daly, delu, and mota; counterpoise lifts known variously as the shadouf, shaduf, shadoof, chadouf, khetara, kerkaz, kheeraz, guenina, cigonal, bascule, dhenkali, dhenkli,

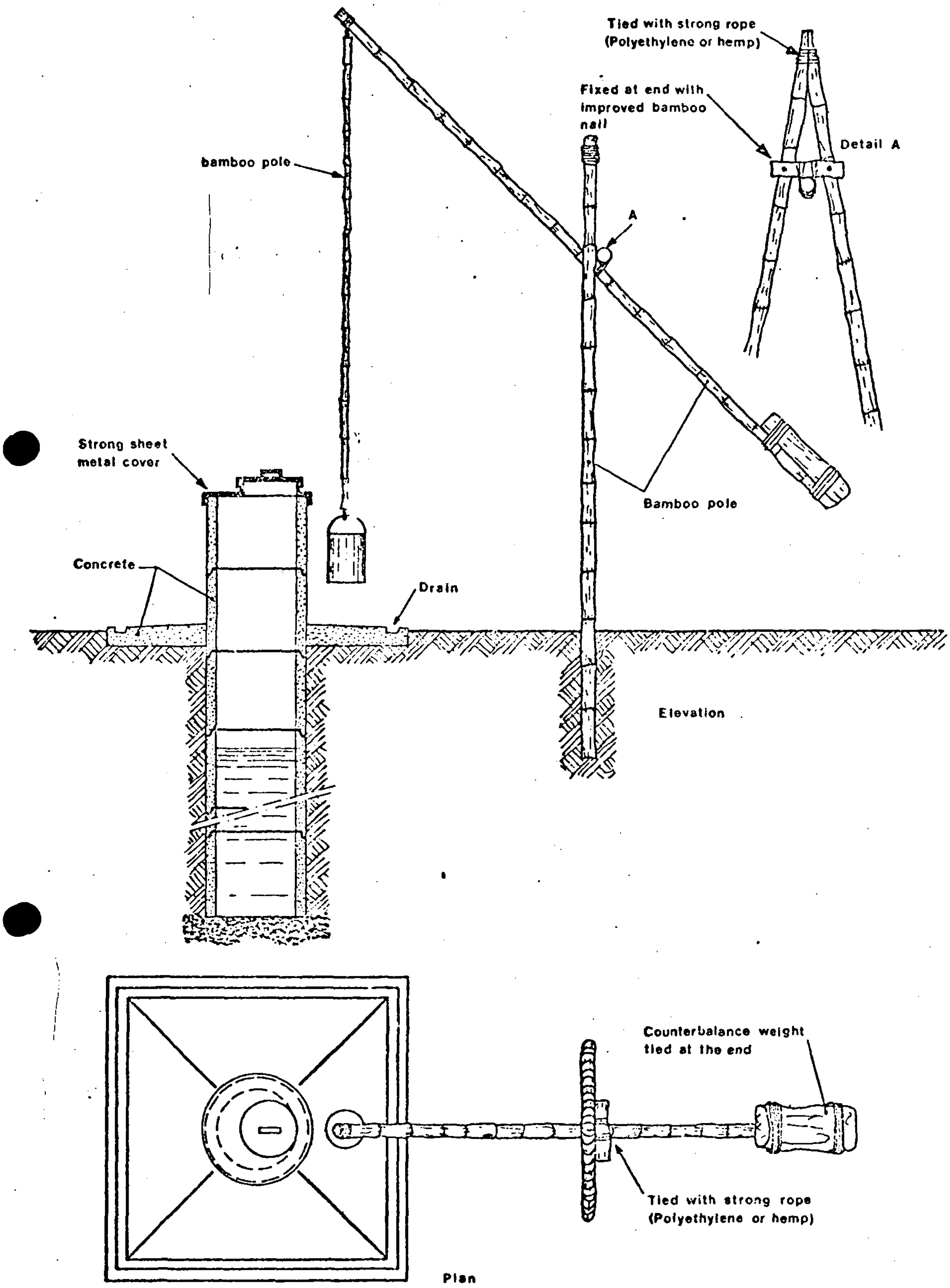
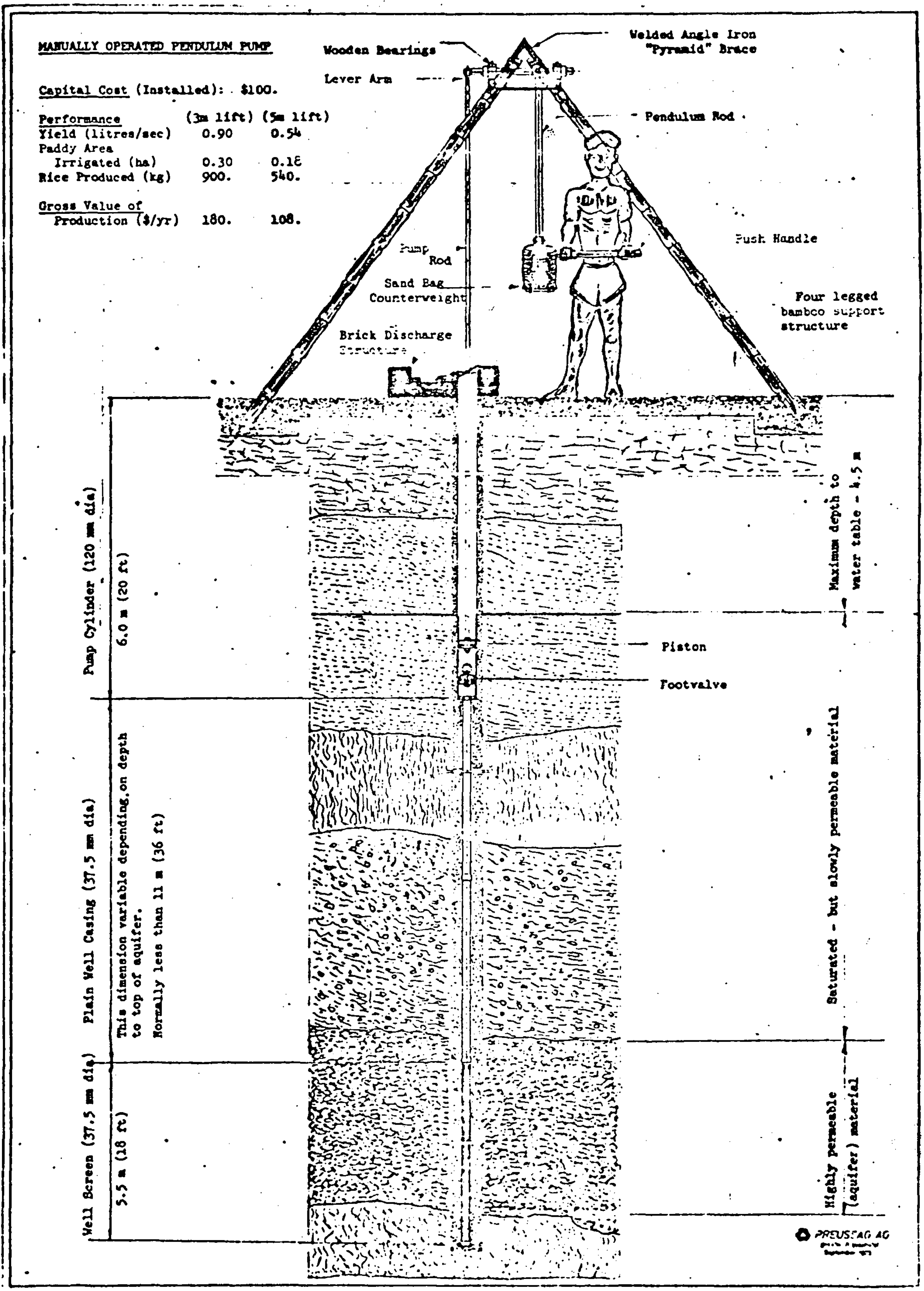


FIGURE 9: IMPROVED DUG WELL AND COUNTERWEIGHTED BAILER USED IN THE PHILIPPINES



Performance	(3m lift)	(5m lift)
Yield (litres/sec)	0.90	0.54
Paddy Area Irrigated (ha)	0.30	0.18
Rice Produced (kg)	900.	540.
Gross Value of Production ($/yr)	180.	108.

FIGURE 10: MANUALLY OPERATED PENDULUM PUMP

dhingli, picottah, lat, picotas, guimbalete, swape, sweep, et al.; the hinged channel or gutter, doon, baldeo balti, and jantu; paddle wheels; water ladders; and the various chain pumps and wheel pumps previously mentioned.

These are widely used for low-lift irrigation pumping, many are animal powered.

The shadouf, or counterweighted bailer, was modified and effectively used for community water supply purposes in a recent WHO choleria project (Rajagopalan and Schiffman, 1974) See Figure 9.

4.3. NEWLY-DEVELOPED PUMPING DEVICES

4.3.1. *PENDULAR PUMP*

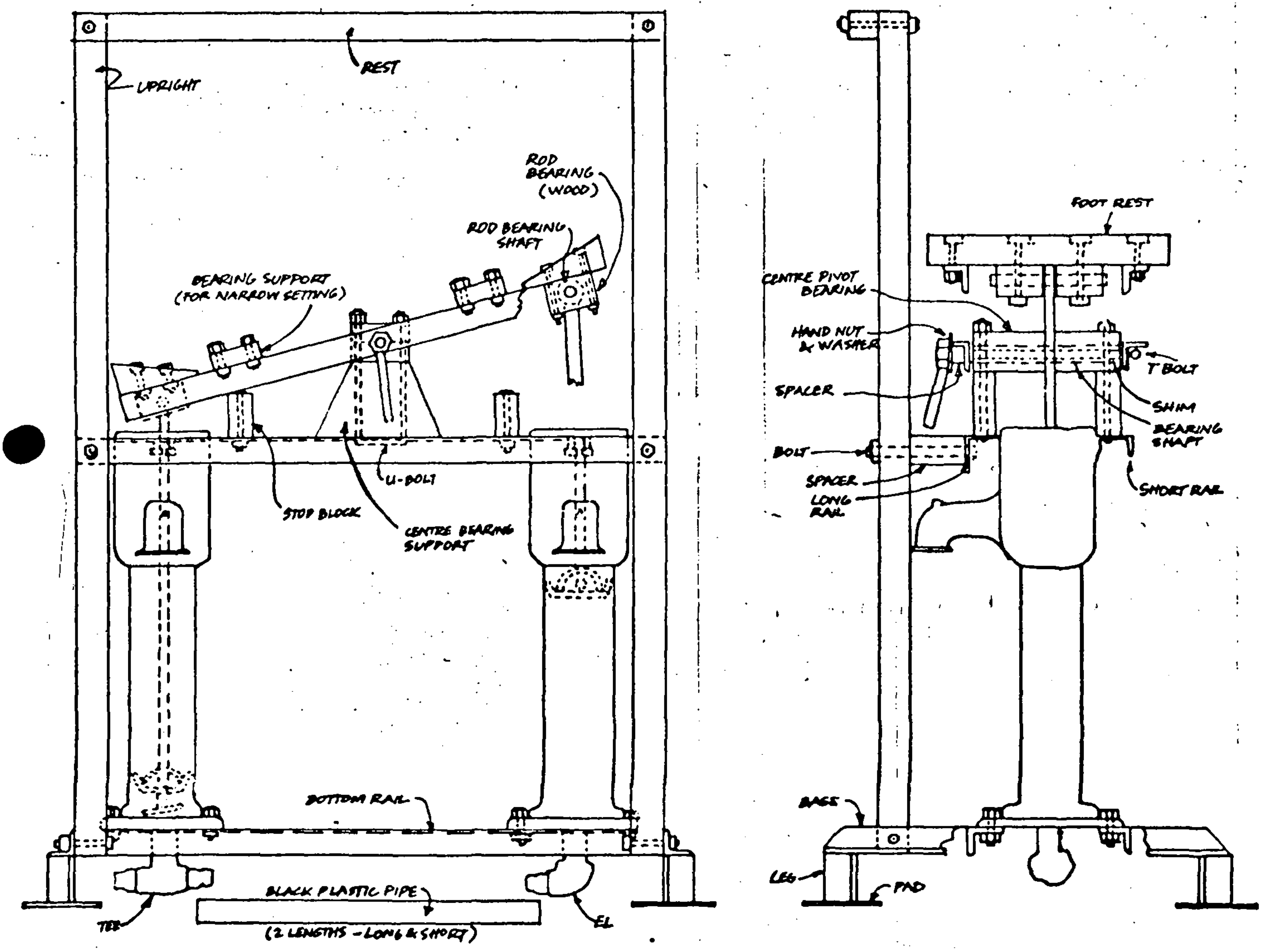
This pumping device has been designed for manual operation using energy at a rate which can be easily sustained up to 5 hours a day, under tropical conditions, i.e. about 2/3 of 0.10 hp = 0.067 hp. The actual horizontal force which has to be applied to the push handle is between 7 and 10 kgf, when lifting water 3 and 5 m respectively. See figure 10.

4.3.2. *LINKED LIFT PUMPS*

The reciprocating movement to manually operate a lift pump, can be tiring and reduces the suitability for irrigation purposes.

In Nepal, a design has been developed for a simple frame which links two lift pumps and enables a single operator to work the linked pumps at the same time using his feet. This is less tiring and, because two pumps are working, provides a greater and continuous flow of water (up to 3500 litres per hour). Figure 11 shows how the pumps are linked. The treadle is centrally pivoted and the input connections are joined by a plastic pipe.

Two alternative settings are provided for the pump rod connections to the treadle. At the wide setting the pumps work quite well at low lifts but for lifts above 5 m it is an advantage to set the pumps closer together to make pumping easier, with a reduced output. Output is satisfactory to around 6-7 m but all pipe joints must be airtight.



Design supplied by: Willard Unruh,
United Mission to Nepal
Developing and Consulting Services,
Butwal, Nepal.

FIGURE 11 LINKED LIFT PUMPS

The frame and the working parts can be made from steel angle (or even wood) with hand tools and the construction should be within the power of a village craftsman. However, as with all mechanical devices, it is the maintenance and care after installation which ultimately decides how useful this machine will be and the users should be carefully trained in simple maintenance (which is in this case only a matter of regular lubrication of the pivots and care of the valves and washers in the pumps).

4.3.3. *INERTIA PUMP*

The inertia pump consists of a long pipe with a check valve and a discharge spout located near the top end. The main pump body (riser) is connected to a prime mover assembly. Part of the function of water lifting by this device is believed to be due to the inertia of the mass of water held in the riser (Dawson, 1970).

Operation of the inertia pump requires a steady up and down motion of the main pumping body with the lower (suction) end of the riser immersed in the water. A bicyle drive with flywheel has been developed for operating the pump (Thanh et al, 1977).

When the pump body moves down a portion of water or air flows through the check vlave (typically a flapper valve). During the upward stroke the valve closes and a suction is created inside the riser so that water is drawn into it from the source.

Volumetric output of an inertia pump can be increased by chosing a larger riser diameter or valve opening size. Pump discharge can also be increased by higher spped of operation, or greater length of stroke. The discharge discreases for greater pumping head.

For a bicyle-type drive assembly, a pumping speed of some 150 strokes per minute has been found suitable for extended periods of operation (Thanh et al, 1977).

4.3.4. *BELLOW PUMP*

This is a simple water lifting device using a pair of flexible bellows as the pumping element. The idea was originally evolved at the International Rice Research Institute (IRRI), Philippines, where a prototype design was developed for use in irrigation. A modified design was developed and tested at the Aaran Institute of Technology (Thanh et al, 1977).

The main components of the bellow pump are:

- pair of flexible bellows
- supporting frame and base plate
- discharge box
- suction lines with check valves, and
- foot rests.

The bellows constitute the basic pumping element; they are supported at the bottom by the base plate fixed to the wooden frame. The suction lines deliver the water to the bellows, and these discharge into the discharge box which is connected to the delivery pipe.

The bellow pump is easy to operate. The operator stands on the foot rests and merely shifts his weight from one foot to another thus expanding one bellow while compressing the other. The expanding bellow sucks in water from the source, while water is forced from the compressing bellow out into the discharge box. Operating the pump in a rythmic manner produces a continuous flow of water.

4.3.5. *INCLINED PVC PUMP (Rower Pump)*

This is a simple PVC handpump developed for irrigation purposes in Bangladesh by Mennonite Central Committee (voluntary agency) with CARITAS assistance.

PVC pipe, 2-inch in diameter, 4 feet in length, is used as the pump cylinder. This cylinder is inclined at an angle of approximately 30° from the horizontal and the operator pushes and pulls directly on a "T" handle at the end of the piston rod. There are no pins or levers in the handle. The pump is operated with a rowing action, hence the name "Rower".

The piston valve consists of a rubber disc secured at the centre. This disc seals on a perforated metal disc on the pumping stroke and folds up on the return stroke. The footvalve is a rubber flap (with stiffener) closing a 1½-inch diameter opening. Both piston and footvalve can be removed and replaced by sliding through the cylinder - no dismantling of the pump is required.

At first, the leather cuff (on the piston) softened up and tore quickly. After changes in size and curing method, however, the leather cuffs have stood up very well. Only minimal signs of wear are seen after a month of daily pumping, and their life has yet to be determined.

Comparative testing showed that at a suction lift of 5 - 6 metres, two men pumping alternately (and paid according to output) averaged a 50% higher pumping rate (based on 5-hour averages) with the Rower pump than with the New No. 6 cast iron pump. The same tubewell was used in both cases, and consisted of 110 feet of 1½-inch pipe and 12 feet of PVC filter. Most of this output difference can be attributed directly to the use of the suction chamber, which has also been used successfully in tests with the No. 6 pump.

The pump has also been tested for durability. Three pumps have been operated on tubewells for 5 hours daily for four months without significant wear problems.

It is estimated that this pump can be produced for less than 60% of the cost of producing the New No. 6 pumps in Bangladesh.

FIGURE 12 THE ROWER PUMP (Bangladesh)

4.4. PUMPING GROUNDWATER FOR SMALL-SCALE IRRIGATION

Traditional water lifting devices for irrigation purposes usually take water from rivers, streams, canals or other sources of surface water. However, in the dry season these sources may be not available for a prolonged period of time.

The use of groundwater may have great advantages. In many cases, extraction of groundwater can be continued long after drought conditions have depleted surface water sources.

Manual pumping of water from tubewells can, under suitable circumstances, prove an effective means of providing the quantities of water required for small-scale irrigation. The water must be pumped from shallow depth and manpower has to be readily available because it is a labour-intensive methods.

Deep tubewells have little application for irrigation purposes. Such tubewells can sometimes provide large quantitites of water (2 cubic feet/second or more; sufficient to irrigate 30 - 40 acres of land) but this requires high-capacity pumps, e.g. vertical turbine pumps driven by diesel engines or electric motors. The common problems of the use of motorized deepwell pumps for irrigation are:

- they are capital intensive;
- schemes take a long time to organize; as they are normally shared by a number of farmers; social and political problems are encountered in siting the wells;
- maintenance and fuel supply are difficult.

USE OF HANDPUMPS IN SMALL-SCALE IRRIGATION

The use of handpumps for pumping water for small-scale irrigation purposes in fact represents a recent development of traditional irrigation techniques. This may be classed as "intermediate technology" (Shawcross, 1976; Stern, 1979).

The handpumps used are practically the same as those used in community water supplies, with such adaptations as appropriate. For instance, in Bangladesh the MOSTI (manually-operated shallow tubewell and pumps for irrigation) was evolved on the basis of the New No. 6 pump used by the Department of Public Health Engineering and UNICEF in drinking water supplies. The MOSTI is a standard package consisting of the pump, two 20 foot (6 metres) sections of 1½-inch (40 mm) galvanized steel pipe, and a brass wrapped steel screen 6 feet long. It can be used where the table is not more than 6-7 metres below ground level. This is the case for a large part of Bangladesh. The output is about 0.5 litre/second suitable for irrigating small plots of about ¼ hectare. Such small fragemented land holdings are common in Bangladesh (Stern, 1979).

Through irrigation in the dry season, an extra crop can be achieved. The value of the crop depends on market conditions, but should easily gross two times or more the total cost of the MOSTI package. It is therefore not surprising that numerous small farmers have spontaneously adopted this method of small-scale irrigation using handpumps. The rapid extension of the use of the MOSTI has been spectacular (Stern, 1979).*

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* In 1972, there were 2000 MOSTIs' in Bangladesh. By mid-1976 the number had increased to 40 000, and by the end of 1979 to 60 000.

One interesting feature of handpump tubewell irrigation is that the whole family shares the burden of labour. Men, children and women, take a turn at pumping. Maintenance of the pumps and wells does not seem a great problem. The main moving pump parts all last the season. Only the leather buckets must be replaced frequently, about every two weeks on average.

5. IRC'S PROGRAMME ON MANUAL PUMPING DEVICES

5.1. BACKGROUND

Several hundred million people already depend on manual pumping devices (handpumps) for their drinking water supplies. Major handpump programmes are underway or planned in many countries. There is a growing awareness of the important role handpumps will realistically play, for a long time to come, in providing an acceptable community water supply particularly in rural areas of developing countries.

Experience shows that the use of handpumps in community water supplies present serious problems with regard to handpump design and selection, quality of manufacture, and maintenance. The problems have a world-wide dimension, as they are encountered in all countries where handpumps are used extensively.

The IRC Programme on Manual Pumping Devices for use in community water supplies (further referred to as "Handpumps") was started in early 1976. It has received financial support from the UN Environment Programme UNEP)* and is being developed in close collaboration with WHO. The Programme is closely attuned to authoritive statements and recommendations.**

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* UNEP Project No. (462) 010-74-002.

**The UN Water Conference (March 1977) in its Action Plan recommended, inter alia, that international organizations and other supporting bodies should, as appropriate and on request, support research development and demonstration particularly on low-cost groundwater pumping equipment (I/Cof. 70/29 Recommendation 17).

The Meeting of Directors of Institutions Collaborating with the WHO International Reference Cnetre for Community Water Supply in April, 1973, recommended a project (no. 17) "designed to evolve reliable handpumps for rural communities"

The following areas are covered:

- handpump technology
- research and development
- maintenance, and
- local manufacture of handpumps.

5.2. HANDPUMP TECHNOLOGY SURVEY

Under the auspices of WHO, and with financial support form UNEP, the IRC has carried out a worldwide survey on handpump technology. In July 1976, the International Workshop on Handpumps was held in The Hague, the Netherlands. The Meeting reviewed the state of handpump technoloyg, research and development work, handpump maintenance, administration of handpump installation programmes and local manufacture of pumps. Guidelines for use of handpumps in water supply programmes were developed.

Under the joint sponsorship of UNEP and WHO a comprehensive handbook was prepared; it was published in July 1977. This publication provides a state-of-the-art survey of handpump technology, with description of various types of pumps, fundamental hydraulics, installation and maintenance practice, research projects and studies.

A Spanish edition of the handbook has been prepared by CEPIS in Lima, Peru, and was distributed. The handbook has been translated in French by the Institut du Genie de l'Environnement at the Ecole Polytechniquw Federale, in Lausanne, Switzerland. Distribution of the French edition will start in December 1979.

The IRC has accumulated an extensive information base relating to handpumps and their use in rural water supplies in developing countries. Information and assistance is provided to organizations involved in the planning and implementation of water supply programmes with handpumps. This includes groups such as:

- international organizations and bilateral development agencies
- national public health and water supply agencies
- field project staff
- research and testing institutes
- handpump manufacturers and suppliers.

5.3. TESTING AND EVALUATION OF HANDPUMPS

The purpose of handpump testing and evaluation both in the field and in the laboratory, is to provide objective information in support of the selection or development of handpumps for use in rural water supply programmes. This information should include data about the overall performance of pumps, as well as their important characteristics.

Several projects for field testing and evaluation of handpumps, field trials or laboratory testing, are currently underway of being planned. Some are undertaken under the sponsorship of international organizations, others with active support from bilateral development agencies.

Comparison and evaluation of handpumps on an international basis require common criteria, definitions, methods, procedures and reporting format.

The IRC promotes the development of a widely accepted methodology for handpump testing and evaluation. A manual has been prepared based on the results and recommendations of international meetings held at The Hague, the Netherlands, in November 1978, and at Harpenden, England, in June 1979.

This document provides guidelines for testing and evaluation of handpumps, so that all organizations and agencies involved in this type of work, can use the same approach.

The IRC has been requested to provide internationl coordinative functions to support the various countries and organizations active in thefield of handpump testing and evaluation.

5.4. HANDPUMP MAINTENANCE

Many rural water supply programmes will need an improved system of maintaining the installed pumps, if the impact of these programmes is to continue.

In 1977, the IRC arranged for a consultant to initiate a comprehensive study of strategies and organizational set-ups for handpump maintenance. A draft report describes a step-by-step procedure for analyzing the maintenance requirements of national organizations, international and bilateral agencies involved in handpump water supply programmes.

5.5. LOCAL MANUFACTURE OF HANDPUMPS

The promotion of local manufacture of handpumps is included in the Programme. Experience from several countries indicates that indigenous manufacture of handpumps is possible at competitive prices and at an adequate level of quality.

In collaboration with other organizations active in this field, (i.e. UNIDO) an "assistance package" will be developed for use in the improvement or expansion of existing plants for production of handpumps. Guidelines are given to determine the market potential, and production techniques, together with pertinent information for the upgrading of the manufacturing facilities.

5.6. DEMONSTRATION PROJECTS

In partnership with institutions and organizations in developing countries, projects will be set up for demonstration of selected handpump designs, handpump testing and evaluation methodology, maintenance systems, and, where appropriate and feasible, local manufacture or assembly of handpumps.

The purpose is to demonstrate, and test concepts, knowledge, methods and procedures for large-scale use in the national handpump installation programmes. The IRC promotes international cooperation among the institutions/organizations of the countries involved in this work.

6. NON-TECHNICAL ASPECTS

6.1. GENERAL

A manual water pumping unit for community water supply or small-scale irrigation is a small technical device in a complex economic and socio-cultural system.

Water supply alone, whether by handpumps or otherwise, cannot be expected to bring the desired health benefits unless accompanied by personal hygiene training, health education, and sanitary excreta and waste disposal. To optimize the chances of achieving the goal of better health conditions or improved agricultural yields requires that attention is given to the non-technical aspects.

Such factors may be difficult to define, but they are inherent in every installation programme of manual pumping devices, and become especially manifest in the operation and maintenance of the pumps.

6.2. ACCEPTANCE BY USERS

Water supplies, being a vital need, are often vested with deep cultural meanings and traditions. Many pump installations in rural areas have failed, or have been abandoned by their users, either because they did not have the skill and resources to keep them going, or because of mistrust in the agencies providing the pumping devices. The users' preferences must be one of the most important considerations if the pump is to perform its desired function. In practice, the reliability and durability of a manual pumping device interact with the social environment in which the pump operates. In this respect, a "bottom-up" approach should be followed involving the local people, to the maximum extent possible, in the design and installation of the pump. The social factors influencing the acceptance of the pump by its users, should be recognized so as to avoid frustration, sabotage and pilferage.

It is the obvious failure of pumping equipment, particularly in rural areas, that is forcing engineers and economists to consider more carefully the available manual pumping devices. Gaining the confidence of the users, training local people and organizing maintenance must be an integral part of the community water supply components in any irrigation development scheme.

6.3. LOCAL ORGANIZATION

An effective pump installation programme is a conglomerate of technology, institutions and people - individuals who must plan, design, manufacture, finance, purchase, install, operate, maintain, supervise and use the pumps. In addition to the central agency, some organizational structure should be developed at the local level in the form of a committee or some other netity that is usual in the country. The importance of a local committee is that it represents the users, directly involves the community leadership in the day to day operation and administration of the system, and hopefully, helps motivate the users of the pumping devices.

Convenience to the user population

The ultimate success of the handpump installation will depend on user acceptance. Thus site selection should consider also such factors as community preferences for the pump, proximity to users, ethnic or caste differences among users, and exposure to vandalism or pilferage. An extensive number of users per pump with long waiting lines or long distances to walk may discourage users particularly if alternative sources are nearby. Where usage is heavy, provision of two or more handpumps should be considered. This also provides a standby pump in the event of one breaking down.

Access of users and for maintenance

Manual pumping devices should preferably be readily accessible for pump inspection and maintenance and, where applicable, for vehicles.

6.5. MAINTENANCE

When selecting or developing a pumping device for use in community water supply or small-scale irrigation, it should be carefully considered whether the expected involvement of the users in the maintenance of their pump is realistic. The envisaged division of responsiblity for maintenance tasks should be clearly stated.

Without adequate information, the users cannot be expected to be cooperative in ensuring the proper maintenance of their pumps. Without support, i.e. supply of spare parts, it will be impossible for them to contribution their part to the servicing of the pump. Certain requirements are simply beyond the local capacity, at least under present conditions.

The high rate of abondoned or defective manual pumping units is not simply a reflection of poor quality pumps but also of inadequate maintenance and repair. Many authorities contend that maintenance is the critical element of pump installation programmes. The possible causes of poor maintenance may provide some insight into possible improvements. They are:

(1) Poor quality of pump design and manufacture. To a considerable extent this condition is also the result of many years of trimming weight, bearing sizes, etc., in seeking low bids (tenders) in the absence of strict speficiations. Much pump procurement has an inherent bias towards low initial capital cost and ignores the total costs over the life-span of a pump.

(2) The usual technology makes frequent lubrication mandatory. Iron and steel journals and bearing, poor fits and large clearances, lack of lubricant stocks, exposure to weather, etc.

(3) Underestimates or lack of appreciation of the structural and bearing loadings in deep well pumps.

(4) Large variety of pumps in use with accompanying need for many different spares. Limited interchangeability of spare parts, sometimes even between different pump models of the same manufacturer.

(5) Little feedback from maintenance to design engineering, and procurement personnel. Little analysis, for example, of the most common failures. Record keeping is often inadequate.

(6) Poor maintenance skills, lack of training, inadequate tools (for example, few village maintenance men have a clevis for pumling up pump rod, drop pipe, and culinder), lack of transport, and lack of supervision are characteristic of many programmes.

Most pump maintenance systems can be characterized as a one or two level system. The one level system is one where all maintenance is the responsibility of the central organization. In the two level organization, maintenance is shared with local communities or individual users.

In both systems the central organization usually installs the pump. The well may be the task of another central agency. For dug wells the village may provide labour under central agency supervision. The central agency usually handles major repairs or replacement of the pumps in both systems. It maintains stores of parts and lubricants and provides transport, warehousing, and training. When the central agency provides routing maintenance, it often employs a roving maintenance man or team with a vehicle and who services from 20 to 200 pumps on a repetitive basis.

In the two level system, the local community or a resident employed by the central organization assumes responsibility for all lubrication and minor repairs, for example, replacement of cup seals ("leathers"). Where villagers deal only with the basic maintenance tasks requiring frequent attention, the backup service could visit the pump at regular intervals (e.g. every three months) for a thorough servicing. This system is found in parts of India.

In some programme certain users may be given a thorough training in pump maintenance and cirtually all responsiblity left in their hands. These approaches are being tried, for instance, in Kenya and Tanzania. Each village is required to nominate a person before the well is sunk who will go to the district office for two weeks to learn about well construction and particularly for maintenance of the pump. He will then be responsible for the well once it is sunk, and will keep a small stock of leather components and other spare parts in his house. If a mjor breakdown occurs he will call upon the district office and either get the parts neede to carry out the repairs himself, or else get the district's mechanics to do the job.

Some people have argued that if a pump could be designed capable of being made by a village craftsman using simple tools and off-the-shelf local materials, then the maker of the pump would always be on hand to repair it when necessary.

This argument is supported by the observations that many low-lift irrigation pumps of "tradition" design are built and maintained by village craftsmen. These pumps are not suitable for community water supplies. They have been designed, built, and used in small-scale irrigation with varying success. Most have been unsuccessful in intensive community use.

7. IMPLICATIONS OF COMMUNITY WATER SUPPLY IN IRRIGATION DEVELOPMENT

7.1. GENERAL

The implications of community water supply for domestic purposes and stockwatering in irrigation development schemes tend to be neglected, particularly in small projects.

In the paper "Water for Agriculture" prepared by FAO for the U.N. Water Conference, mention is made of the basic two approaches to increased agricultural productivity:

1. the expansion of cultivation to new land (thus extending the productive area); and
2. increased yield per unit of land by improving environmental conditions and by the application of additional agricultural inputs.

Both in the new and improved irrigation schemes, the return on invested capital, and indeed the very livelihood of the beneficiaries depend largely on the way the scheme is operated and maintained. This very much determines the agricultural productivity and health benefits. Even where irrigation development works have been well-designed and constructed, the overall efficiency of the scheme may be poor when health aspects and community water supply implications have been overlooked or not adequatly considered.

Any irrigation development scheme imposes upon its beneficiaries the need for application of new technology, organization, cooperation and discipline. The provision of safe drinking water supplies is no exception, on the contrary it usually has a considerable impact on the actual improvement of the living standards and health in the area of the irrigation scheme.

7.2. THE WATER SUPPLY COMPONENT IN IRRIGATION DEVELOPMENT

The provision of safe water for domestic purposes and stockwatering hardly represents an appreciable quantity of water, when compared with the substantial flows of water provided in any irrigation scheme for agricultural production. The paramount criterion for the drinking water supply, is the bacteriological safety of water, and its quality parameters, such as purity, clarity, taste and odour.

One should realise that community water supply is only one element in the integrated development of the infrastructure required in an irrigation development scheme. Many other factors are of relevance: housing, communications, credit facilities, storage of agricultural products, and their absorption by markets. However, in many respects, the provision of drinking water for domestic purposes and stockwatering has a catalyst function in the overall development of the irrigation area and its communities.

For an integrated planning of the community water supply sources within an irrigation development scheme, the technical options have to be considered in combination with the economic, sociological and health aspects.

The possible sources of water for providing a continuous supply of safe water to communities within irrigation schemes, may be divided into groundwater, impounded surface water, or flowing water in streams and canals.

The availability and quality of groundwater are largely determined by the geohydrological characteristics of the ground formations and aquifers of the irrigation scheme area. The storage and use of surface water is usually only a practical proposition for settlements near to large impounding reservoirs. Sometimes dispersed small reservoirs can be fed by gravity flow of water from impounding reservoirs or rainwater catchment areas. Whether pipelines for transporting water to dispersed settlements are technically feasible depends on topographical and geological factors. However, such pipelines are costly and capital investment for their construction can hardly ever be justified in terms of a simple analysis of costs and benefits.

The suitablility of a water source for community water supply is largely determined by its various quality parameters of which bacteriological safety, purity and clarity are the most important. In many irrigation schemes the water from the open canals or courses is not safe without treatment. For instance, in the Gezira Irrigation Project in the Sudan slow sand filtration units are used to make water from the irrigation canal fit for domestic purposes and stockwatering.

7.3. PLANNING IMPLICATIONS

The supply of safe water to communities within an irrigation scheme is greatly influenced by the nature of the settlements. For scattered farm communities or dispersed villages, it is far more costly than for a more concentrated habitat.

For irrigation development schemes to be successful, the settlements in the area must, within a relatively short period of time, succeed in offering the farmers and their families acceptable living standards and health conditions. Only then can rural settlements in irrigation schemes have any chance of opposing the migration trend of rural people to urban centres in search of employment, and improved living conditions. This implies that, in planning irrigation development, the objective must be to provide a standard of services, housing and facilities far beyond the near-subsistance conditions found in many rural areas where irrigation schemes are attempted.

A tubewell fitted with a handpump, or a small piped supply providing a daily rate of 20 litres per person, may be acceptable in the initial stage or for temporary settlements. However, basically, it should be regarded as an intermediate step towards a higher level of community water supply service.

At the earliest possible stage in the development of an irrigation scheme, a full investigation should be carried out to identify suitable sources of community water supply. This may include the provision of pipelines for transport of water, and where necessary, even treatment works. Moreover, the requirements for operating and maintaining the water supply systems, have to receive full consideration.

Often, this will mean increased cooperation with the national or district water supply and health authorities. The ultimate goal being to arive at proper planning, construction, operation and maintenance of the community water supply services within the irrigation scheme.

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Agenda Item 6

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

DEVELOPMENT OF PRIVATE TUBEWELLS IN PAKISTAN
USING LOCALLY MANUFACTURED EQUIPMENT

by

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DEVELOPMENT OF PRIVATE TUBEWELLS IN PAKISTAN USING LOCALLY MANUFACTURED EQUIPMENT

by

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1. INTRODUCTION

Water is the most critical factor of Pakistan's agricultural production which contributes 45 percent of the gross national product. Land is not a limiting factor to increasing agricultural production as there is more cultivable land than can every be properly irrigated (1). Of the total area of 81 million hectares (MH) nearly 30 MH are cultivable and include 13.5 MH under canal commands; 5.1 MH cropped under Barani (rainfed) and riverine conditions; 1.2 MH are forests and 9.6 MH are cultivable wastes. Out of the canal command area of 13.5 MH only 8.2 MH are perennial and the remaining 5.3 MH are seasonal and receive supplies primarily in Kharif (summer season). Moreover, the designed water allowance for the canal system is hardly sufficient for 75 percent cropping intensity as compared to the envisaged intensity of 140 percent for agricultural development by the year 2 000 which would require 135 million acre feet (16.8 million hectare metres) of water at the water course head. This has been proposed by consultants to be met through conjunctive use of surface and groundwater as shown in Table 1.

In Table 1 the values in column 7 are derived from those in column 4 assuming conveyance efficiency of 73 percent. The values in the denominators in column 4 and 5 are the actual values of surface and groundwater supplies in 1965 and 1975. It is evident from Table 1 that one third of the total irrigation demand is to be met through the

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TABLE 1

WATER REQUIREMENTS AND SOURCE OF SUPPLY IN MILLION ACRE FEET (1)

(values in brackets are in million hectare metres)

Year (1)	Cropping intensity% (2)	Water Requirements at Water Course Head (3)	Proposed Source of supply at Water Course Head (4) Canal Estimate/Actual	(5) Groundwater Estimate/Actual	Total (6)	River supplies at Canal Head Estimate/Actual (7)	Storage required (8)
1965	97	66 (8.2)	56/63 (6.9/7.8)	8/9 (1/1.1)	64/72 (7.9/8.9)	77/86 (9.5/10.6)	-
1975	110	93 (11.5)	61/67 (7.5/8.3)	29/30 (3.6/3.7)	90/97 (11.1/12)	85/94 (10.5/11.6)	9.3 (1.1)
1985	126	117 (14.5)	77 (9.5)	40 (4.9)	117 (14.5)	101 (12.5)	13.3 (1.6)
2000	142	135 (16.7)	91 (11.2)	44 (5.4)	135 (16.6)	124 (15.3)	21.5 (2.7)

development of groundwater potential in the country. In fact, greater reliance is placed on groundwater during the Rabi season (October - March) because of shortage of surface water supplies as shown in Table-2.

TABLE 2

PROJECTED CANAL HEAD SURFACE WATER REQUIREMENT FOR REFERENCE YEARS AND COMPARISON WITH MEAN YEAR RIVER FLOWS IN MILLION ACRE FEET PER YEAR (2)

Note: (values in brackets are in million hectare metres)

	Month	1975	1985	2000	Total inflow of Indus Jhelum and Chenab	
Rabi	October	7.51 (0.9)	8.16 (1.00)	9.85 (12.3)	5.51 (0.7)	Shortage
	November	3.71 (0.40)	4.40 (0.54)	5.52 (0.68)	3.20 (.39)	
	December	3.50 (0.43)	3.90 (0.48)	4.57 (0.56)	2.81 (0.35)	
	January	4.00 (0.49)	4.52 (0.56)	5.24 (0.65)	2.77 (0.34)	
	February	5.90 (0.73)	6.40 (0.79)	7.33 (0.90)	3.01 (0.37)	
	March	5.58 (0.69)	6.09 (0.75)	6.91 (.85)	5.07 (0.63)	
Kharif	April	5.09 (0.63)	6.71 (0.83)	7.96 (0.82)	8.24 (1.02)	Excess
	May	7.07 (0.87)	8.26 (1.02)	10.26 (1.27)	14.22 (1.76)	
	June	10.45 (1.29)	13.25 (1.64)	16.42 (2.03)	22.73 (2.81)	
	July	10.97 (1.36)	13.64 (1.60)	16.85 (2.09)	32.04 (3.97)	
	August	11.22 (1.39)	14.03 (1.74)	17.39 (2.15)	29.39 (3.52)	
	September	9.92 (1.23)	12.06 (1.10)	15.25 (1.87)	13.19 (1.63)	
	Total	84.92 (10.5)	101.42 (12.5)	123.65 (15.4)	141.10 (17.6)	

Inadequate and unreliable irrigation supplies together with the waterlogging and salinity problem have acted as the major constraints in low agricultural yields. To control salinity from spreading further it is also necessary to supply additional water for soil reclamation. This necessitated large scale development of groundwater resources for irrigation.

2. PUBLIC TUBEWELLS

The first practical step in this direction was taken by the Water and Power Development Authority in the form of Salinity Control and Reclamation Projects (abbreviated as SCARPS) on the recommendation of World Bank Experts (3). The major Government effort in SCARPS was the development of large capacity deep tubewells with discharge varying from 2-5 cusecs (56 - 140 litres/sec). In addition, development of private tubewells by farmers were also anticipated. Total pumpage of groundwater in Pakistan was estimated (2) as shown in Table-3.

TABLE 3

GROUNDWATER DEVELOPMENT BY PUBLIC
AND PRIVATE TUBEWELLS IN MILLION ACRE FEET (2)

(Values in brackets are in million hectre metres)

Description		1965	1970	1975	1985	2000
A.	CANAL COMMANDS					
i.	Public tubewells	2.7 (.33)	10.0 (1.24)	22.0 (2.73)	36.5 (4.52)	44.0 (5.46)
ii.	Private tubewells	5.3 (0.66)	8.0 (1.0)	7.0 (0.86)	3.5 (0.45)	Nil -
iii.	Persian wheels	1.7 (0.21)	1.0 (0.12)	1.0 (0.12)	Nil -	Nil -
B.	OUTSIDE CANAL COMMANDS					
i.	Private tubewells	1.0 (0.12)	1.8 (0.22)	1.8 (0.22)	2.8 (0.35)	5.0 (0.62)
C.	TOTAL	10.7 (1.33)	20.8 (2.58)	31.8 (3.94)	42.8 (5.30)	49.0 (6.07)

It is apparent from Table 3 that Persian Wheels have been completely eliminated as a means of groundwater development after 1975. This is because of the increased cropping intensity projected up to the year 2000. The Persian Wheels yield is 0.1 cusecs (2.8 litres/sec) to 0.2 cusecs (5.6 litres/sec) under a draw down of 2 to 4 ft. (0.6 to 1.2 metres) in an open well 10 ft (3 metres) in diameter. Higher yields are not possible as sand starts slipping into the well when the depression is increased beyond 5 ft (1.5 metres). These wheels are still in existence in most of the dryland areas where land holdings are scattered and small and the farmers use water for fruit gardens, vegetables and for animal fodder. A decreasing trend is noticeable in Table 4.

The area under wells has reduced substantially in the ten-year period from 1965-75. This is because the watertable had dropped considerably due to the development of public and private tubewells and the production of lowcost pumps in the country. Large scale rural electrification in the public sector also gave a tremendous boost to use of centrifugal pumps for low farm holdings as will be discussed later.

The strategy of SCARP development with emphasis on development of public tubewells revealed several undesirable features. Firstly priority was given to high cost of public tubewells over the low-cost private tubewell development. As such the competing demands on limited public funds did not permit full development of public tubewells and the development of drainage and reclamation facilities required for the more immediate gains in the fresh water zones.

TABLE 4

AREA IRRIGATED IN THE PUNJAB BY VARIOUS SOURCES (THOUSAND ACRES)

(Values in brackets are in thousand hectares)

Year	Total	Canals	Wells	Tubewells	Canal Wells	Canal tubewells	Others
1965-66	18,922 (7,663)	12,309 (4,985)	1830 (741)	1429 (579)	1215 (492)	1864 (755)	214 (87)
1966-67	19,975 (8,090)	12,778 (5,175)	1608 (651)	1637 (663)	1332 (539)	2241 (908)	309 (125)
1967-68	20,932 (8,477)	13,815 (5,595)	1310 (531)	1936 (784)	1125 (456)	2379 (963)	287 (116)
1968-69	21,927 (8,880)	13,432 (5,440)	1342 (543)	2512 (1007)	1338 (542)	2988 (1,210)	234 (95)
1969-70	21,905 (8,871)	12,970 (5,253)	1036 (420)	2834 (1148)	1187 (481)	3566 (1,444)	234 (95)
1970-71	21,942 (8,886)	12,261 (4,966)	904 (382)	3175 (12·8)	975 (395)	4340 (1758)	190 (77)
1971-72	22,194 (8,989)	11,842 (4,796)	818 (331)	3380 (1369)	853 (345)	5054 (2,047)	199 (81)
1972-73	22,715 (9,199)	11,794 (4,777)	685 (277)	3423 (1386)	734 (297)	5844 (2467)	184 (74)
1973-74	23,612 (9,563)	11,761 (4,763)	633 (256)	3860 (1,563)	606 (245)	6421 (2600)	288 (117)
1974-75	22,902 (9,275)	10,700 (4,334)	541 (219)	3806 (1541)	512 (207)	7104 (2877)	188 (76)
1975-76	23,809 (9,643)	11,215 (4542)	481 (195)	3658 (1481)	472 (191)	7764 (3144)	179 (72)

Taking SCARP-I as an illustration Table 5 will show how the installed capacity of public tubewells was underutilized.

TABLE 5

YEARWISE PUMPAGE FROM SCARP-I TUBEWELLS
(PUBLIC)

Note: values in brackets are in million hectare metres

Year	Installed pumpage capacity in million acre feet	Actual pumpage capacity, MAF	Percentage utilization
1962-63	3.26(0.40)	2.27(0.28)	69
1963-64	3.97(0.49)	2.51(0.31)	65
1964-65	3.91(0.48)	2.44(0.30)	59
1965-66	3.92(0.48)	2.49(0.31)	52
1966-67	3.75(0.46)	1.69(0.21)	42
1967-68	3.64(0.37)	1.86(0.23)	49
1968-69	3.66(0.45)	1.96(0.24)	54
1969-70	3.68(0.45)	1.95(0.24)	53
1970-71	3.69(0.45)	1.93(0.24)	52
1971-72	3.69(0.45)	1.67(0.21)	45
1972-73	3.66(0.45)	1.64(0.20)	45
1973-74	3.66(0.45)	1.44(0.18)	39
1974-75	3.66(0.45)	1.45(0.18)	40
1975-76	3.66(0.45)	1.37(0.17)	37
1976-77	3.66(0.45)	1.27(0.16)	35
Average	3.65(0.45)	1.86(0.23)	49

Some of the reasons for low utilization efficiency may be obvious from Table-6 which indicates the number of hours lost in the year 1976-77.

TABLE 6

TUBEWELL HOURS LOST DURING 1976-77 IN SCARP-I

1.	Total hours of available commissioned tubewells	15.10 million hours
2.	Total hours lost due to tubewells which were out of commission	2.45 " "
3.	Total hours available of net operable tubewells	12.65 " "
4.	Total hours lost of net operable tubewells	4.90 " "
5.	Hours lost in breakdowns	2.42 " "

Source: Annual Report (1976-77) of SCARP-I.

The causes for the tubewell hours lost shown in Table 5 have been listed as follows in the Annual Progress Report of SCARPS (4):

- New bore, not yet commissioned
- L.T. cable burnt
- Motor burnt up or defective
- Starter defective
- Vibration of the assembly
- Bore damaged
- Bore settled down
- Transformer burnt or missing
- Shaft broken
- Pump defective
- Electrical defect
- Obstruction in pipe
- Closed due to brackish water
- Bearing defective
- Closed due to lack of demand
- Control box defective
- Closed due to small discharge
- Main switch stolen
- Pump jammed
- Suction breaks because of lowering of water table
- Water course defective, i.e. breached or not being maintained properly with the result that the water overflows its banks.

Table 7 shows the number of tubewells, which remained out of operation for various reasons mentioned above, as a percentage of the total project tubewells in 1976-77. The largest number of tubewells were stopped because the freshwater layer lying over the saline layer had reduced considerably resulting in upconing of saltwater. The next in the list is the percentage (3.8%) of tubewells delivering small discharge because of corrosion and encrustation problem as a result of groundwater of high mineral content. Groundwater with total dissolved salts up to 1000 ppm is being directly used for irrigation without mixing with canal water. This is the minimum salt content of groundwater pumped by both public and private tubewells. This also indicates the serious problem of groundwater management in the country.

TABLE 7

TUBEWELLS OUT OF OPERATION AS A PERCENTAGE OF TOTAL NUMBER OF TUBEWELLS IN SCARP-I (1976-77)

Sr.	Cause	Percent
1.	Brackish water	7.3
2.	Bore damage	2.5
3.	Small discharge	3.8
4.	Transformer/starter defective	0.8
5.	Water course and other defects	0.2
6.	New tubewell not commissioned	0.1
7.	No demand	Nil
	Total	14.7

The distribution of tubewells according to their discharge capacity is shown in Table 8.

TABLE 8

DISTRIBUTION OF TUBEWELLS ACCORDING TO DISCHARGE CAPACITY IN SCARP-I (1976-77)

(Values in brackets are in litres/sec)

Discharge capacity in cusecs	Tubewells as percentage of total
1.0 (28)	0.29
1.5 (42)	0.48
2.0 (56)	19.70
2.5 (70)	20.57
3.0 (84)	31.77
3.5 (100)	11.60
4.0 (114)	12.80
4.5 (128)	2.55
5.0 (140)	0.24
Total:	100.00

There also resulted reduction in the rate of discharge and specific capacity of tubewells due to encrustation and corrosion problem. This is shown in Table 9.

TABLE 9

DISCHARGE AND SPECIFIC CAPACITY REDUCTION OF PUBLIC TUBEWELLS IN SCARP - I (1977-78)

a) Discharge reduction

No. of tested wells	Tubewell falling under discharge reduction with respect to design capacity		
	< 20%	21-50%	> 50%
1570	1269(81%)	247 (16%)	54(3.0%)

b) Specific capacity reduction (1977-78)

No. of tested wells	Tubewell falling under specific capacity reduction ranges		
	< 15%	16-50%	> 50%
1570	574(37%)	722(46%)	272(17%)

3. DEVELOPMENT OF PRIVATE TUBEWELLS

Inadequacy and unreliability of canal supplies and the population pressure for more food production mixed with the faults in the SCARP programme listed above gave an impetus to private tubewell development in Pakistan. As a result groundwater development went beyond the estimates presented by the World Bank Consultants. This can be judged from the fact that there were 91 000 private tubewells in Punjab alone as against 52 000 estimated by the consultants for 1972. The consultants estimated groundwater utilization of 22 MAF (2.7 million hectare metres) in the public sector and only 8 MAF (1.0 million hectare metres) in the private sector in 1975. According to the actual data, however, private tubewell development contributed 23 MAF (2.8 million hectare metres) at an average designed capacity of one cusec (28 litres/sec) and working efficiency of 25% of the time. In comparison to this the water available from public tubewells was 7 MAF (.87 million hectare metres). Thus out of 30 MAF (3.7 million hectare metres) (1975) shown in Table 1 the contribution of private tubewells in groundwater development potential has been 75% of the total groundwater exploitation. This clearly indicates the trend of private enterprise. Table 10 shows the increase in cropped acreage and the contribution that the tubewells are making in agricultural production in terms of the area irrigated. The local farmers have discovered the advantages of pumping groundwater by cheap tubewells for irrigating their farms. The long delays in electrification of public tubewells and their frequent breakdown also encouraged private tubewell development.

Private tubewells have given individual farmers an assured source of supply both in quantity and timely distribution of irrigation water by removing the critical water constraint. These have also stimulated farmers' willingness and capacity to use other farm inputs which have resulted in increased cropping intensity and crop yield. A study conducted by Yasin (5) revealed that the intensity of cropping of the tubewell farmers was 142 percent as compared with 110 percent of the non-tubewell farmers living in the same village.

TABLE 10

AREA IRRIGATED IN PUNJAB ALONE

(Values in brackets are thousand hectares)

Year	Total (Acres)		% irrigated from canals	% irrigated from wells and tubewells
1965-66	18922	(7,663)	65	35
1966-67	19975	(8,090)	64	36
1967-68	20932	(8,477)	66	34
1968-69	21927	(8,880)	61	39
1969-70	21905	(8,841)	60	40
1970-71	21942	(8,886)	56	44
1971-72	22194	(8,989)	53	47
1972-73	22715	(9,199)	52	48
1973-74	23612	(9,563)	50	50
1974-75	22902	(9,275)	47	53
1975-76	23809	(9,643)	48	52

Note: Average area covered per tubewell in acres comes to 90 acres in 1975-76.

The crop yields were also found to have increased by 13 percent for cotton and 60 percent for wheat. This was attributed to the use of larger quantities of water and fertilizer. The tubewell farmers used an average of 154 lbs of fertilizer as compared to an average of 99 lbs by non-tubewell farmers. It was calculated that a tubewell farmer then earned Rs. 200 ($20) more per acre or Rs. 500/- ($50) per hectare. Assuming tubewell intensity of 90 acres (36.5 hectares) per tubewell the total surplus net income worked out at Rs. 18 000/- ($1800) per year. If the cost of a private eletric tubewell is Rs. 15 000/- ($1500) the farmer could recover the cost of the tubewell in less than a year. The diesel tubewell owner would recover in about a year as the cost of diesel tubewells is generally 60 percent more than electric tubewells.

Table 11 shows diesel and electric private tubewells in Punjab in 1975:

TABLE 11

DIESEL AND ELECTRIC TUBEWELLS

(on 30 June 1975 in Punjab)

Year	Total	Diesel			Electric		
		Total	Private	Public	Total	Private	Public
1975	139,157	91,013	90,786	227	48,144	39,612	8,532
Percentage of total		66%	-	-	34%	-	-
Percentage of respective categories		99.7%	0.3%	-	-	81%	19%

These statistics can be taken as representative of other regions of Pakistan also, although the number of private tubewells is much smaller than in Punjab.

The capital cost of a tubewell depends on the size, discharge and kind of material used and also on the nature of the formation through which boring is done. It also depends on the type of local machinery used because there is a large variation in prices of the same machinery from one manufacturer to another. A survey conducted in 1975 (6) showed the average installation cost per tubewell to vary from Rs. 6600/- ($660) to Rs. 12,950 ($1295) for electric tubewells and between Rs. 8,320/- ($832) to Rs. 18,800/- ($1880) for diesel tubewells. This cost reaches Rs. 50,000/- ($5000) in hilly areas. The average cost of public tubewells varies with the type of strainer and discharge and ranges from 6 to 15 times the cost of private tubewells. The cost is least for coir type strainers and highest for fibre glass. Strainers with coirstring have been extensively used in private tubewells owing to their cheapness compared to other kinds of screens. The prices of coirfibre have gone up and also its quality has not been sustained. As a result the farmers have now started using P.V.C. and cement strainers. These are being manufactured within the country.

A market survey in 1975 (6) showed that 74 percent of the total cost of diesel tubewells and 84 percent of the total cost of electric tubewells are incurred in local currency. The tubewells are installed by farmers either by borrowing from the Agricultural Development Bank of Pakistan or from relatives or by mortgaging a part of their land. The survey revealed that 79 percent of the funds are provided by the Agricultural Development Bank of Pakistan, 8 percent by relatives and 13 percent by mortgaging land. Yasin in 1975 worked out the operational cost of diesel tubewells as Rs. 8.31 ($0.83) per hour which includes consumption of diesel oil, lubricants, repairs and replacement depreciation at 10 percent and interest at 8 percent on the capital investment. The operational cost of electric tubewells was Rs. 3.73 ($0.37) per hour. It would be noted that the cost of pumping water from diesel tubewell was 122.7% higher than that of electric tubewells.

The cost figures mentioned earlier have been quoted just to highlight the economics of tubewells under average conditions. It is recognized that the cost depends on a number of factors such as depth of drilling, depth of watertable, type of strainer used and the discharge of the tubewell. There has been a very rapid increase in the prices of components of tubewells in the last few years. Although there has been an increase in the prices of agricultural commodities the rate has also been comparatively slow. As such it is anticipated that the private tubewells may decline in the future. The average operation period of private tubewells in relation to land holding sizes is shown in Table 12.

It may be noticed in Table 12 that the average number of days and hours per day of operation of a tubewell varies with the size of holding. Average hours of operation are the lowest (1 491) for holdings of less than 10 acres (4 hectares) and highest (3 500) for holdings of more than 200 acres (81 hectares). It can be seen, therefore, that private tubewells are not being used to the fullest extent.

TABLE 12

OPERATION PERIOD OF PRIVATE TUBEWELLS FOR DIFFERENT HOLDING SIZES (1969)

(Values in brackets are in hectares)

one acre = 0.405 hectares

Holding size (acres)	Average days of operation	Average hours of operation/day	Average hours of operation/year
Less than 10	213	7	1 491
11 - 25	213	9	1 919
26 - 50	220	10	2 200
51 - 75	232	10	2 320
76 - 100	239	11	2 629
101 - 150	249	12	2 988
151 - 200	270	12	3 249
201 and above	250	14	3 500

Table 13 presents the distribution of private tubewells according to discharge capacity and supplements the information given in Table 12.

TABLE 13

DISTRIBUTION OF PRIVATE TUBEWELLS ACCORDING TO DISCHARGE CAPACITY

(Figures are average for the country)

Percentage of total tubewells

Discharge (litres/sec)	<7	7-14	14-21	21-28	28-35	35-42	42-56	>56	29 (average)
Percentage of tubewells	5.13	8.20	13.69	21.49	22.21	14.03	7.30	95	

electric motors, pumps and diesel engines. The selection has been mainly from whatever size of component is available with the agent in the local market. Farmers are also lured by the lower prices of cheaper products and are losers in the operational cost and durability.

Farmers generally use centrifugal pumps for their tubewells as their initial cost is low. The centrifugal pumps are installed at the bottom of wells (Fig. 1) close to the watertable to keep the suction head within allowable limits. A bore is drilled at the bottom of the well to the groundwater aquifer and a blind pipe and strainers are installed.

In Baluchistan open wells are used and since the aquifer is artesian two to three pipes with strainers are drilled and left open at the bottom of the well. The water then gushes out into the well as a fountain and is pumped out by electric diesel pumps. In areas where there is considerable artesian pressure and the pumps are installed below the maximum artesian pressure there are frequent breakdowns due to submergence of the electric motor in case of failure of electricity. This is happening because farmers install their pumps without considering the artesian pressure of the underlying aquifer. Rewinding of motor costs Rs. 800 ($80.0), and farmers have reported two to three rewindings per year in some cases. This problem is also faced in other regions when tubewells start discharging saline water because the farmer happened to drill his well in an area underlain with perched saline water.

In 1974 a study (6) was conducted to carry out a field survey of the performance of private tubewells in Pakistan and also a market survey of tubewell components with a view to suggest certain guidelines which every manufacturer would be required to follow to give farmers more efficient and durable tubewells.

The market survey showed that there are numerous manufacturers of tubewell components of varying qualities. Some firms have well established workshops and information on their products is printed in pamphlets. Some manufacturers have pamphlets but no workshop. They obtain assembled units and put their trade mark on it. Farmers have gradually identified the best products through experience. Most of the pump manufacturers specify suction and delivery size and the total operating head; there are others who show horse power in addition, while others show the discharge capacity and speed. Table 14 shows prices of centrifugal pumps of different sizes. The prices are for 1974-75 and are related to unit horsepower. As is clear, in most cases, the prices range from Rs. 50 to Rs. 250 per horsepower irrespective of the size of the pump.

TABLE 14

RANGE OF PRICES OF LOCAL CENTRIFUGAL PUMPS

Speed 1400 - 1460 RPM

Conversion rate:
Rs. 10 = one US Dollar
one ft. = 0.30 metres
one cfs. = 28 litres/sec

Sr.	Size Suction & Delivery	Rated Head (ft)	Capacity (cfs)	Price in Rs/HP (1974-75)
1.	2" x 2"	30 - 50	1-0.16	270
2.	3" x 2"	40 - 50	0.67-.18	180-320
3.	3" x 3"	30 - 70	1.00-.36	50-225
4.	4" x 3"	25 - 70	1.50-.50	50-200
5.	4" x 4"	30 - 70	1.50-0.70	75-200
6.	5" x 4"	30 - 70	2.20-0.30	50-170
7.	5" x 5"	30 - 70	1.80-0.80	50-150
8.	6" x 5"	30 - 75	2.50-1.50	50-120
9.	8" x 8"	30 - 100	4.00-3.00	70-200
10.	10" x 10"	20 - 70	9-6	120-300

The prices of electric motors vary according to speed. Table 15 shows the average prices of motors with horsepower 1-50. General purpose, three phase 50 c/s drip proof, squirrel cage induction motors 2 pole to 6 pole, are being manufactured in Pakistan. Single phase motors are not being manufactured. The starters are manufactured by SIEMENS. Motors of horse power 3-10 are normally required for private tubewells for heads of 20 - 60 ft.

TABLE 15

RANGE OF PRICES (IN RS.) OF ELECTRIC MOTORS PER HORSE POWER

(Rs. 10 = one US Dollar)

Sr. No.	Horsepower		Speed (RMP)	
		910/970	1400/1470	2800/2850
			Price in Rs.	
1.	1 - 50	300-160	350 - 130	250 - 150

Table 16 gives rated horsepower, RPM consumption in gallons/hour and the prevailing price of diesel engines per horsepower for the year 1974-75. This data is based on a survey of diesel engines manufactured by sixty three firms out of which eleven were noted to have some quality control. As a result the products of such firms were comparatively dearer than those having no quality control.

TABLE 16

RANGES OF PRICES OF DIESEL ENGINES

Horsepower	RPM	Consumption in gallons/hr	Price/HP in 1974-75
10 - 50	350 - 375	0.40-.60	650 - 900

A list of some of the well known manufacturers is given in Table 17.

TABLE 17

COMPARISON OF DIESEL ENGINES FROM DIFFERENT MANUFACTURERS

(Values in brackets are in litres/hr)

Sr.	Manufacturer	Fuel consumption in gallon/hr	Rated HP
1.	Batala Kisam Eng. Co.	0.40(1.8)	10 - 20
2.	Modern Engineering Works	0.40(1.8)	15 - 30
3.	Muhammad Bakhsh & Bros.	0.44(2.0)	10 - 30
4.	Muhammad Ashraf	0.45(2.0)	10 - 30
5.	New Mujajid Foundry	0.45(2.0)	10 - 50
6.	Naseem Eng. Works	0.45(2.0)	10 - 30
7.	Nawab Tubewell Services	0.45(2.0)	15 - 30
8.	Pakistan Eng. Co.	0.45(2.0)	10 - 50
9.	Zahid Nazir	0.45(2.0)	10 - 30

5. CHARACTERISTICS OF PUMPS

Characteristics tests were carried out on six selected standard pumps in laboratories. Some of the characteristics at maximum overall (wire to water) efficiency are given in Table 18.

TABLE 18

COMPARISON OF PERFORMANCE OF PUMPS

Sr.	Manufacturer	Maximum efficiency	Discharge in Imperial GPM	Head in ft.	Input HP
1.	Nawab	67	550	45.0	11.0
2.	A.T.S.	70	450	42.5	8.0
3.	K.S.B.	78	400	45.0	7.0
4.	NICE	68	400	57.5	11.0
5.	B.S.P.		400	57.8	11.0
6.	S.K.F.	57.0	400	55.0	11.0

There is a sharp decrease in efficiency on either side of the maximum efficiency as shown in Table 18. Fig. 2 shows typical characteristic curves of some of the above pumps. For example, at a head of 50 ft. (15 metres) the efficiency of the above pumps is reduced by 10 percent. The reduction is comparatively greater for K.S.B. pumps and the least for B.S.P. pumps. The farmer has, therefore, to be very careful in selecting pumps for low and high heads. For this purpose he has to consider the maximum fluctuation in water table that is anticipated during the lift of the tubewell. The average groundwater depth below ground level was observed in the range 12-62 ft. (3.6 to 19 metres) in 1971 in the Punjab region of Pakistan. In the submontane districts it goes to 60 - 80 ft. (18 to 24 metres) below ground level.

6. FIELD SURVEY

A field survey of 1874 private tubewells distributed in the following order was carried out in various regions of the country:

Type	Punjab	Sind	NWFP	BALUCHISTAN	Total
Electric	703	131	162	21	1017
Diesel	770	29	18	40	857
Total	1473	160	180	61	1874

The overall efficiency of electric tubewells was computed by determining the input to the motor and water horsepower of the pump. Table 19 shows average overall efficiencies of electric tubewells in various regions of Pakistan.

TABLE 19

EFFICIENCIES OF ELECTRIC TUBEWELLS

Sr. No.	Regions	Overall efficiency range
1.	Punjab	30 - 60
2.	Sind	30 - 35
3.	N.W.F.P.	20 - 55
4.	Baluchistan	25 - 55

Lower efficiencies have generally been observed in areas with shallower watertable depth. During the survey some of the electric motors were found working over-limits. A frequent drop in voltage was also reported. This was causing the burning of motors. Power breakdown and lack of protective devices were also causes of most repairs and replacements.

In the case of diesel tubewells, the mechanical operation is done at the expense of diesel oil. The fuel consumption rate was determined volumetrically by timing the fuel levels in the cylindrical supply tank. The average rate of diesel consumption varied from 2.7 to 5.2 litres/hr. These values are high as compared to the rated consumption shown in Table 17. It was observed during the survey that some engines were not run at the rated speed with the result that revolutions of the pump were not developed according to the prescribed speed of the engine. The pump speed, in certain cases, was observed to be 1000-1200 RMP as compared to the rated speed of 1400 RPM. The horsepower was found to vary from 10 - 30. The efficiencies of diesel tubewells were found to vary from 30 to 45 percent. These efficiencies are low as compared to electric tubewells. This may be due to extra loss through belt transmission.

Some of the apparent defects in private tubewells causing low efficiency are damaged impellers shaft, bore vibrations, leaky seals, tight glands and low speeds of prime movers. In many cases excessive suction head was also one of the causes. The survey data showed 70 percent of the pumps had water horsepower in the range 0 - 5; 25 percent in the range 5 - 10 and only 5 percent in the range greater than 10. Contrary to this most of the prime movers had horsepower greater than 15. Figs. 3, 4 and 5 show WHP, watertable depths at the selected tubewell sites and discharge. It may be noticed that 80 percent of the tubewells had WHP less than 5, watertable depth less than 30 ft. (9 metres), and discharge less than 1.25 cusecs (35 litres/sec).

The private tubewell development has led to an uncontrolled growth of manufacturers of tubewell components in Pakistan. The Government is now providing advisory services to the farmers in the selection of tubewell sites and tubewell component through extension services of the Agriculture and Irrigation Department. Laws are being framed regarding the quality of components. Because of the importance of private tubewell development to control the menace of waterlogging and salinity in fresh water zones, the public sector emphasis is shifting to drainage and development of tubewells in marginal quality zones where tubewell water can be mixed with canal water for irrigation.

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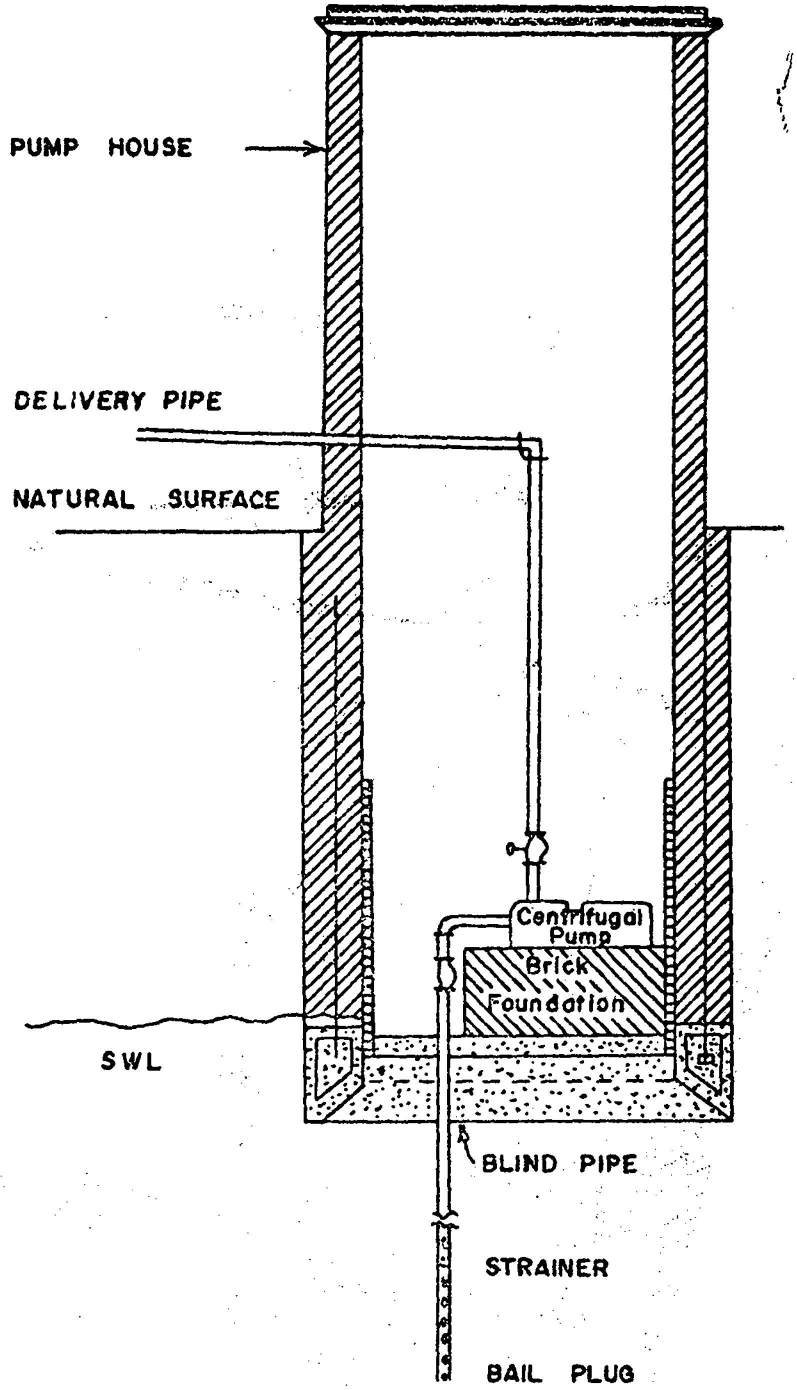

FIG. I — INSTALLATION OF PRIVATE TUBEWELLS

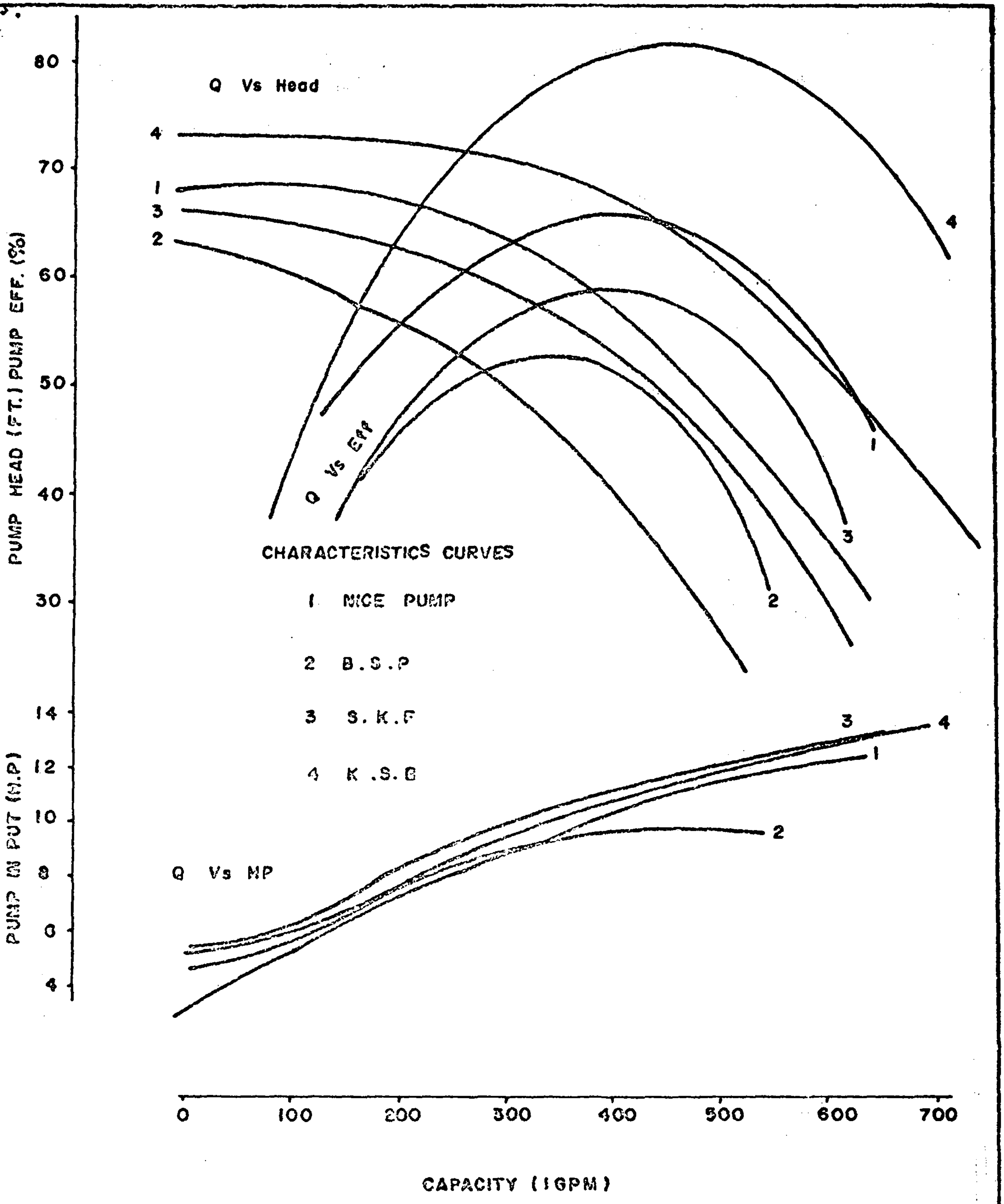

FIG. 2 — COMPARISON OF TEST CURVES

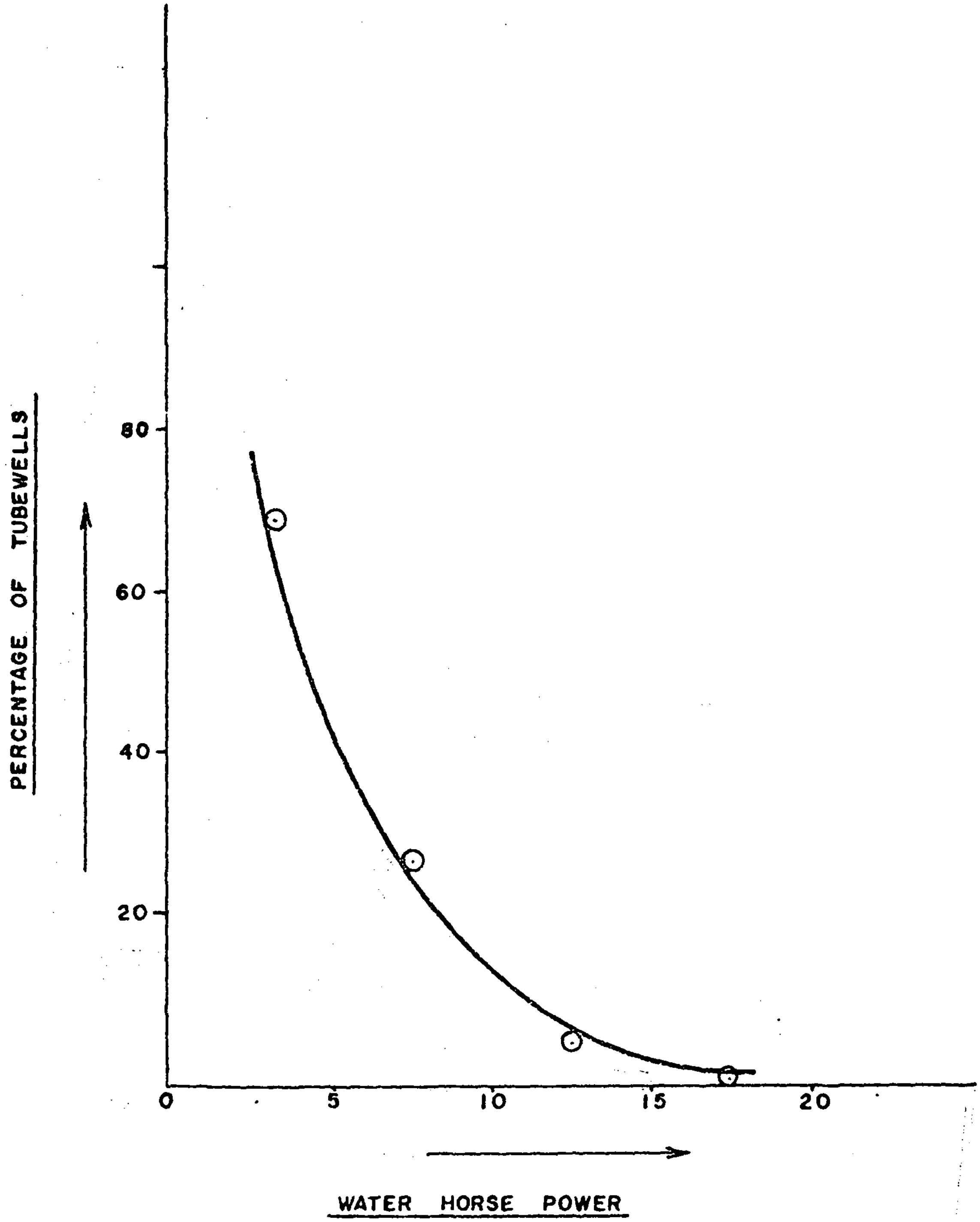

FIG. 3 – VARIATION OF WATER HORSE POWER

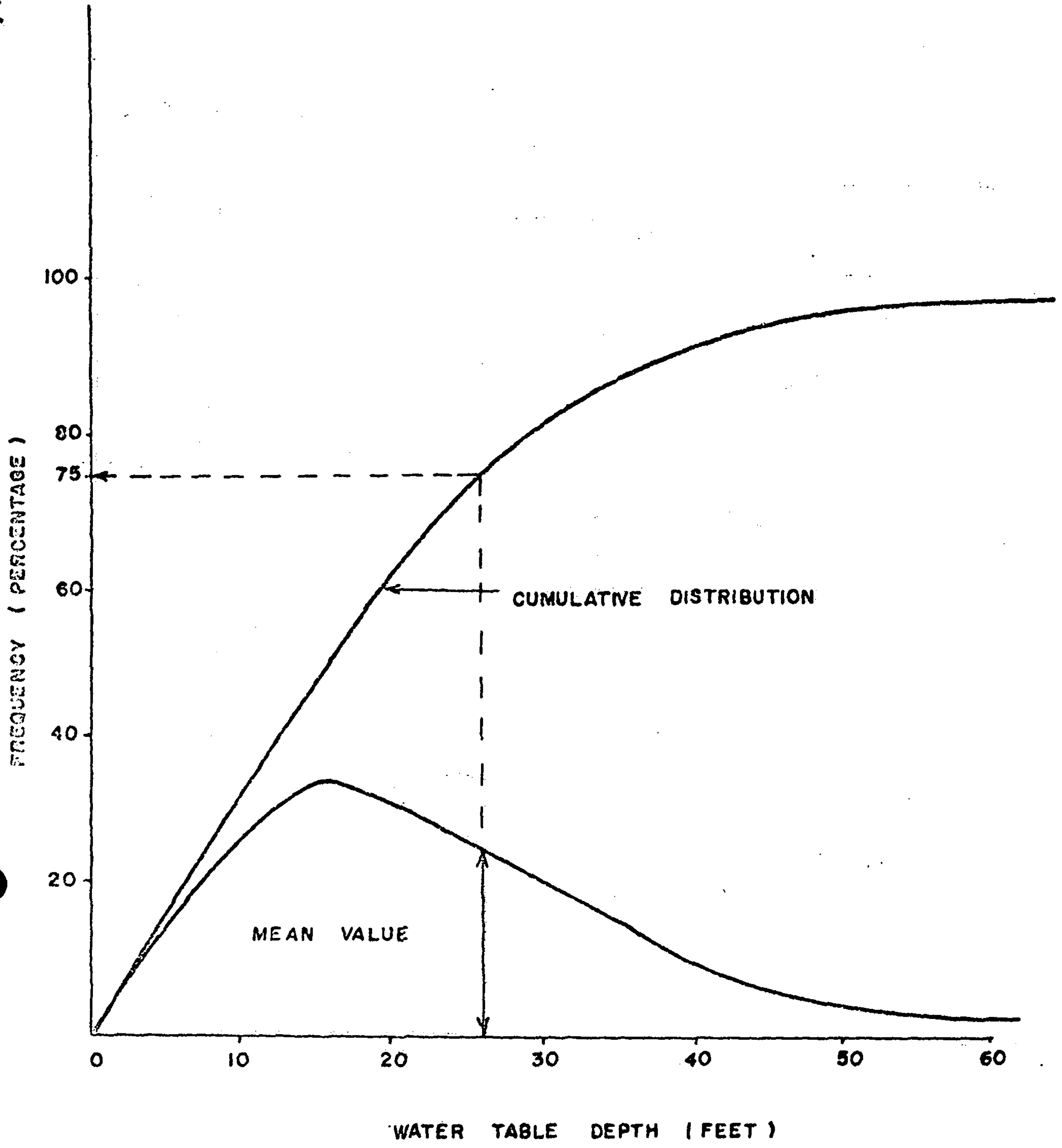

FIG. 4 – FREQUENCY DISTRIBUTION OF WATER TABLE DEPTH

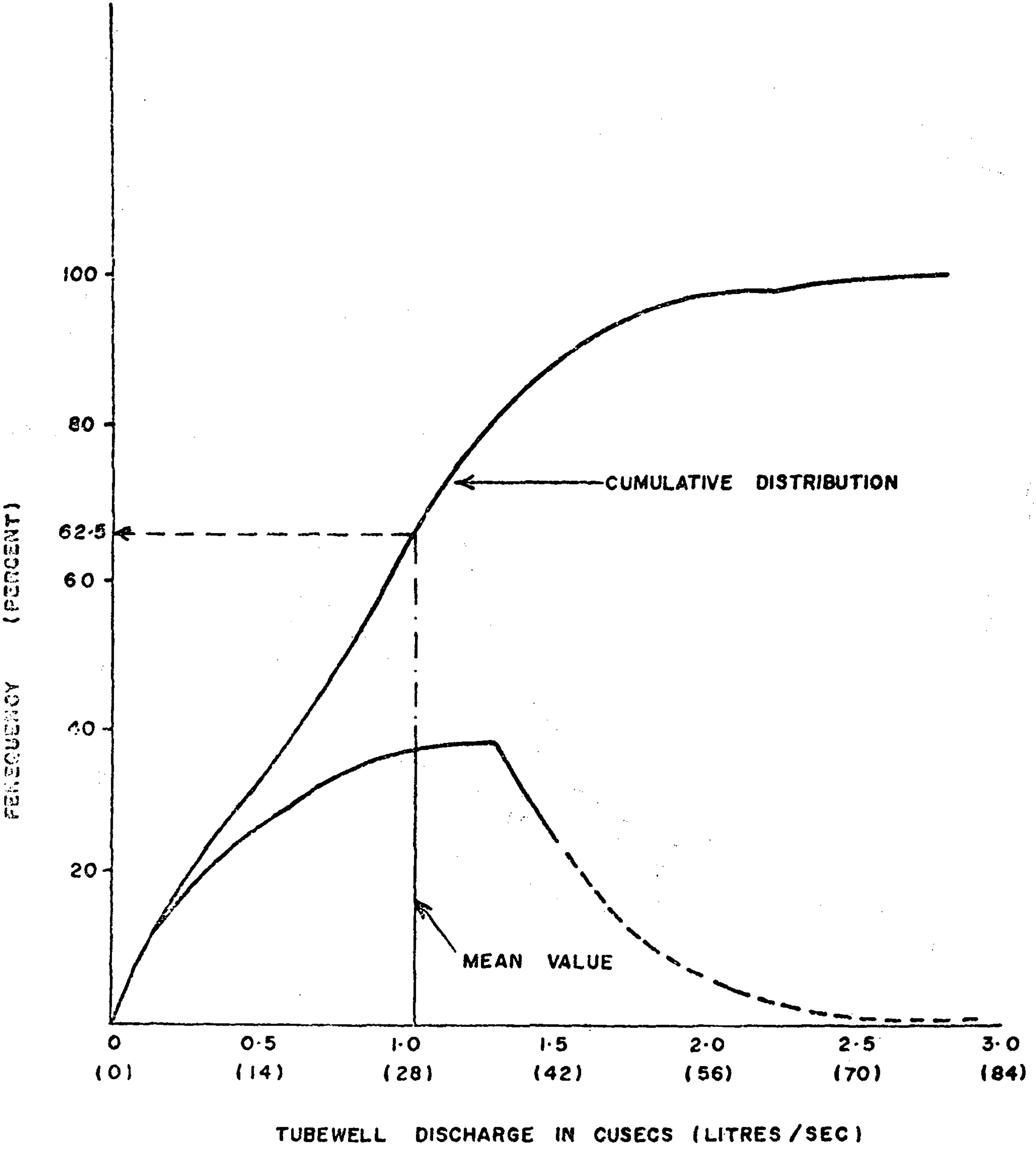

FIG. 5—FREQUENCY DISTRIBUTION OF TUBEWELL DISCHARGE

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Agenda Item 7

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

ON FARM WATER MANAGEMENT AND IRRIGATION EFFICIENCY

by

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INTRODUCTION

Agriculture is the main user of water resource on earth, and it is also indentified as a major source of wastage of the resource. Due to the rapid growth of population and development of other economic sectors besides agriculture in most of the developing countries, water is becoming a scarce resource and more costly to develop. The basic problem facing agriculturists and engineers is how to use the water efficiently so that maximum profit can be derived.

The efficiency of water utilization is an important element in planning, designing, operating and managing of an irrigation system. There are two main components of a good irrigation system; one is good design and the other is good management. For the design part, considerable experience and good engineering knowledge are required; while experience and good knowledge of basic irrigation principles are required for good management. The two components are equally important and supplement each other as well.

As this paper is intended to serve as a background paper, basic concepts of on farm water management and irrigation efficiencies will be covered and supplemented with field data whenever possible. Some practical problems as well as technical problems which impede the efficient water use will be raised in this paper for further discussion.

I BASIC IRRIGATION CONCEPTS

Crop production can be viewed as a production system which the inputs are soil, crop and water; with the farmer or his management skill and resource, the output is crop yield. The three main inputs are interrelated and without basic knowledge of their interrelationship, the farmer cannot manage the system properly in order to obtain optimum yield. In this section, soil-water-plant relationship will be discussed by presenting some basic terminologies which relate them one way or another.

1.1 *Irrigation*

The main objective of applying irrigation is to increase yield. Irrigation can be in the form of supplementary irrigation to sypplement natural rainfall during wet season or dry season full irrigation.

1.2 *Soil-water relation*

Soil is a porous medium which consists of inorganic and organic particles having a wide range of particle size. The composition, size distribution and arrangement of particles determine the other soil properties, especially the void in the soil. Soil which consists of large particles will generally have larger pores but less total void volume, and the opposite is true for soil with small particles.

1.3 *Classification of soil water*

Soil water can be classified as gravitational, unavailable and available. Gravitational water drains quickly from the root zone under normal drainage conditions. Unavailable water is held too tightly by the soil and is generally not available for plant use. Available water is the difference between gravitational and unavailable water.

1.4 Soil moisture deficiency

It is expressed as a depth indicating the dryness of the root zone at a particular time. This depth is numerically identical to the depth of water to be replaced by irrigation under normal management. This term is also referred to as available moisture.

1.5 Management allowed deficiency

It is expressed as the allowed soil moisture deficiency used to schedule irrigations so that net crop returns are maximum. The management allowed deficiency is first related to soil moisture and crop stress and is expressed as the percent of the total available soil moisture that can be extracted from the root zone between irrigations to produce the best economic balance between crop returns and irrigation costs. Secondly, it is expressed as the corresponding depth deficient for a given root depth and soil having a specific available moisture content. This term is also referred to as readily available moisture.

1.6 Crop water requirement

The amount of water used by the crop in order to maintain normal growth is commonly referred to as 'consumptive use' or 'evapotranspiration', it includes the water transpired by plant leaves and evaporated from the wet soil. Part of the consumptive use requirement may be satisfied by rainfall during the growing season. However, rainfall that runs off the surface or penetrates below the root zone depth cannot be used, only the part that is retained within the root zone is considered as 'effective rainfall'.

The consumptive use rate varies with the type of crop, the season when the crop is grown and the corresponding climatic conditions. There are numerous empirical equations used for calculating consumptive use of crop from climatological data. Some of them have been proved to be quite accurate in predicting consumptive use and can be applied to most of the areas with some modifications. FAO irrigation and drainage paper no.24 presents four methods of calculating consumptive use of crop. The Pan Evaporation method as outlined in the mentioned reference is a very practical and suitable method for most of the developing countries according to the author's opinion. Because Pan evaporation records are more readily available and can even be measured concurrently at the irrigation site in case no previous records are available, while other climatological data which are necessary for the empirical equations are not easy to obtain in many of the areas. One can also make direct measurement of the consumptive use, but it is time consumming and quite complicated, further more this method is more suitable for research work rather than practical work.

1.7 Irrigation interval

It is the time span which the crop used up the stored moisture in the root zone, and can be calculated based on management allowed deficiency and consumptive use. It is also the time span between two irrigations.

1.8 Soil moisture stress

When the soil moisture drops near or equal to the permanent wilting point, the plant no longer can use the remaining moisture in the soil. Whether the soil moisture between field capacity and wilting point is readily available to plant or only part of it is readily available is debatable. Researchers have done numerous work to answer the above question, and the general conclusion is that the availability of soil moisture is dependent on the variety of crop, root zone depth and stage of growth. Crop with deep root and at mature stage can withstand moisture stress better than crop with shallow root or same crop but at younger stage. However, if a crop is subjected to moisture stress, the growth will be affected and consequently yield will decrease when the moisture stress continues for a considerable period or when the crop is subjected to frequent short stress periods. How much will be the reduction in yield is again depending on at what growth stage when the crop is subjected to moisture stress, generally the flowering stage or tesselling stage is the most critical stage. When the crop is subjected to moisture stress at the critical stage, the reduction in crop yield will be much more in comparison to moisture stress at other stages. In order to illustrate some of the points, results of field experiment on sweet corn will be discussed in the following paragraph.

1.8.1 *Comparative study of sweet corn yield*

Sweet corn of same variety were grown near the Experimental Farm at Kalasin (Northeast of Thailand) in 1978 and 1979 in order to study its water utilization. Although the experimental plots for the two studies were not on the same location, but they were very close and the growing period is almost the same. In both studies, there were combinations of irrigation and fertilizer treatments. Figure 1.1 shows the effects of moisture stress, root distribution and root depth on sweet corn yield. Soil moisture depletion was estimated from effective root zone, and the root zone of sweet corn measured at the end of the growing season in both years showed that the roots were concentrated in the top 40 centimeter, except in the 1978 experiment which a very small percentage of root penetrated below 40 centimeter. The soil moisture were measured by neutron probe at each 15 centimeter-layer. The yield of sweet corn obtained in 1979 was much less than that obtained in 1978, eventhough the same amount of fertilizer (750 kg/ha of 15-15-15) and nearly equal amount of irrigation and rain were accounted in both experiments. The large decrease in yield of the 1979 experiment is due mainly to moisture stresses which occurred during tesselling and silking stages.

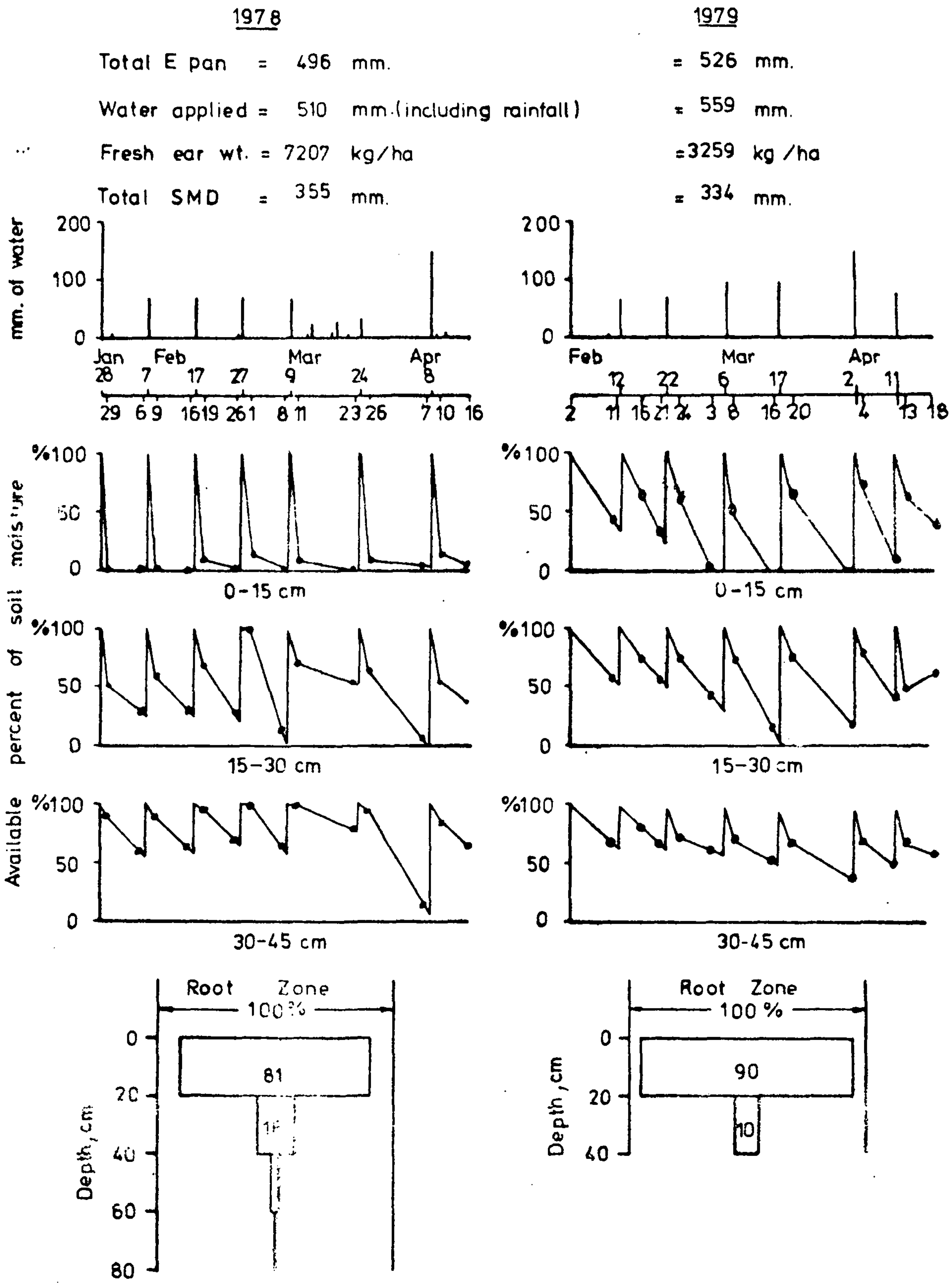


Fig 1.1 Effect of Moisture Stress , Root Distribution and Root Depth on Sweet Corn Yield

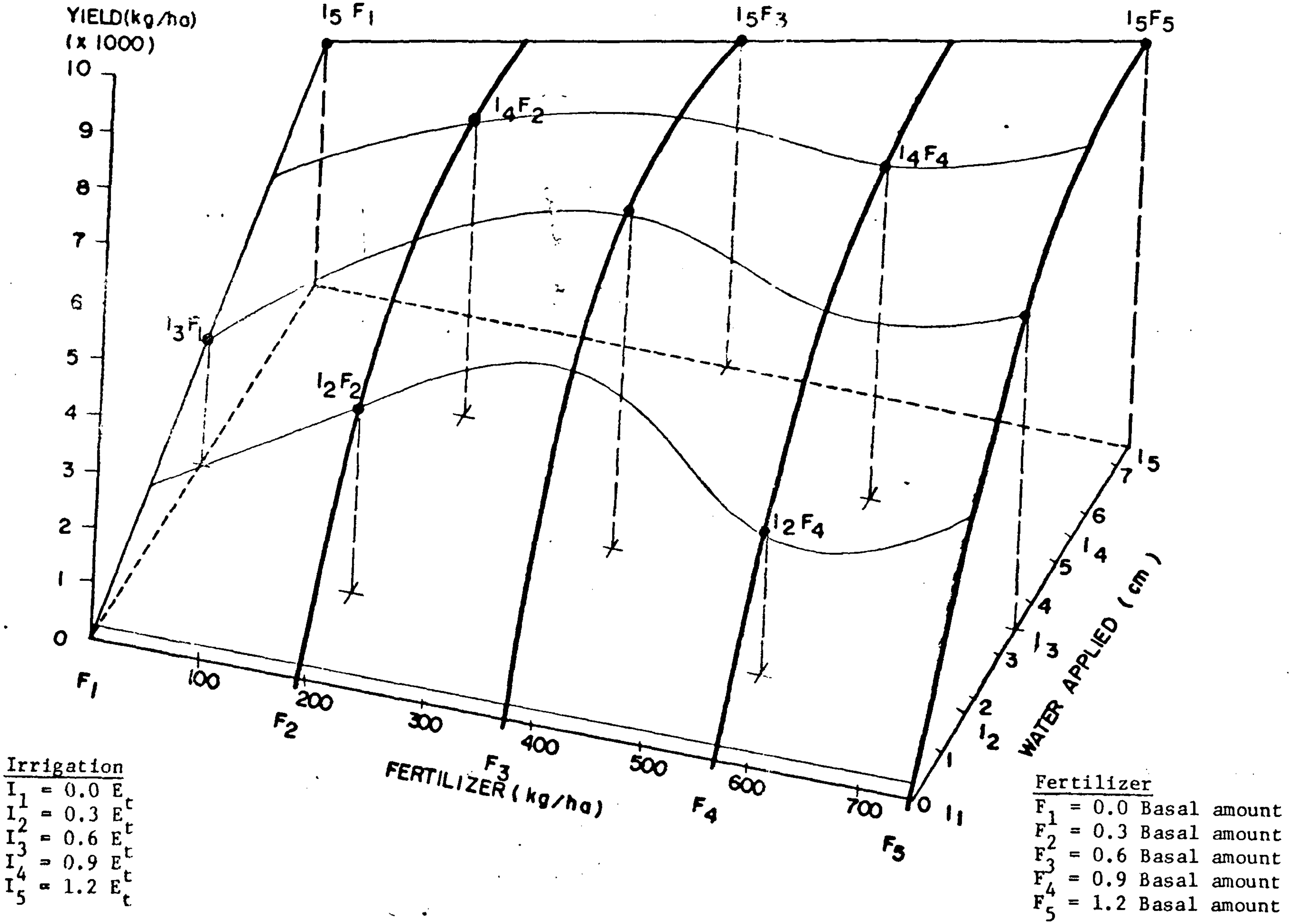
As can be seen from Figure 1.1, soil moisture content in the upper 15 centimeter of the 1979 experiment fell below permanent wilting point for as long as 3 days in the 2nd, 3rd, 4th and 5th irrigation intervals, while it never happened in the 1978 experiment. In addition, there were about 78 millimeter of rainfall during the tesselling stage of the 1978 experiment, and no rainfall during the same period of the 1979 experiment. The presented results emphasize the need to have irrigation water at the critical stage of crop growth in order to attain an optimal yield. It also must be pointed out that the results were drawn from small experimental plots and hence must be considered as a qualitative indicator.

1.8.2 *Crop production function*

This term is generally referred to the relationship between crop yield and amount of water applied, and it is used for predicting crop yield in case of moisture stress. However, crop yield is not depending on amount of water alone, it also depends on the growing stage when moisture stress occurs, fertilizer level, pest and diseases control etc. But for practical purpose, it is customary to assume that pest and diseases control remain a fixed input and two main variables, namely water and fertilizer were considered in the crop production function. With the interrelationship of water and fertilizer on yield, a production surface can be constructed. Figure 1.2 shows the production surface of sweet corn for the 1978 study.

1.9 *Intentional Under-Irrigation*

Generally, irrigation systems are designed or managed to fill the soil moisture deficiency throughout the entire root zone of each irrigation; however, this may not always be the objective. Sometimes the irrigation interval is extended to reduce the water use rate below peak values. This practice is utilized to aid other cultural practices, reduce system capacity



Irrigation
I_1 = 0.0 E_t
I_2 = 0.3 E_t
I_3 = 0.6 E_t
I_4 = 0.9 E_t
I_5 = 1.2 E_t

Fertilizer
F_1 = 0.0 Basal amount
F_2 = 0.3 Basal amount
F_3 = 0.6 Basal amount
F_4 = 0.9 Basal amount
F_5 = 1.2 Basal amount

Fig. 1.2 Production Surface for Sweet Corn.

requirement, and to obtain maximum yield per unit of water. This intentional under-irrigation may be imposed rather uniformly throughout the field, or selectively.

Maximizing water-production efficiency is very important and necessary when the water supply is inadequate and the value of water is measured by productiveness per unit of water. By operating at high management allowed deficiency, irrigation interval is extended. Such a practice, which is termed stress irrigation may reduce yields per unit area but may produce more total crop per unit of water on an increased area and a greater net return.

1.10 *Prevailing problems*

Agricultural engineers and agronomists know well the basic concepts, but to the farmers and even some zonemen or water tender, the understanding of the concepts is still lacking. Further more, most of the outlined parameters are not easy to determine, and require field measurement. Hence for most of the farmers in the developing countries, both the basic concepts and their practicallity still remain a predominant problem. There is also problem in the reliability of water supply to the farmers, i.e. whether the management program of the irrigation system can supply the required quantity of water at the right time to the farmer is often questionable.

II PROBLEMS OF EFFICIENT WATER USE

Available information based on field experience and field studies indicates that for many irrigation systems especially gravity method, less than 50 percent of water diverted from the source finally reaches the field. The low efficiencies encountered are due to losses at various stages of the transport of water from the source to the field. Some of the losses are unavoidable and the rest are due to management and technical problems. There are many definitions and formulae which were proposed as basic concepts of irrigation efficiency for consideration in the design and evaluation of irrigation system.

The process of transporting water from the source to the field can be divided into 2 phases; firstly when water is diverted into the main canal up to the farm gate,and secondly from the farm gate to the root zone of the crop. The first phase involves more of the engineering aspects of hydraulic design and operation of distribution system while the second phase involves more of the on farm management skill and basic irrigation concepts. The defined efficiency terms of various stages of the two phases are discussed below.

2.1 *Irrigation efficiency*

It is the percentage of delivered irrigation water that is stored in the soil and available for consumptive use by crops. When the delivered water is measured at farm gate, it is called 'farm irrigation efficiency'; when measured at the field, it is called 'field irrigation efficiency', and when measured at the point of diversion, it is called 'project efficiency'.

2.2 *Conveyance efficiency*

It is defined as the ratio of water received at inlet to a block of fields to that released at the project head works. Conveyance efficiency can be divided for main canal, lateral and sub lateral. Several factors affecting conveyance efficiency, namely, size of the irrigated acreage, method of water delivery, areas under different crops, canal lining and the technical and managerial facilities of water control.

Based on a literature study, average conveyance efficiency of surface irrigation with respect to method of water delivery and irrigated area are summarised in Table 2.1.

Table 2.1 Average conveyance efficiency

Irrigation Method	Method of Water Delivery	Irrigated Area (ha)	Efficiency (%)
Basin for rice cultivation	Continuous supply with no substantial change in flow	-	90
Surface irrigation (Basin, Borders and Furrow)	Rotational supply based on predetermined schedule with effective management	3000-5000	88
	Rotational supply based on predetermined schedule with less effective management	<1,000 >10,000	70
	Rotational supply based on advance request	<1,000 >10,000	65

2.3 *Farm ditch efficiency*

It is defined as ratio of water received at the field inlet to that received at the inlet of block of fields. Farm ditch efficiency is affected primarily by the method and control of operation, soil type , length of the farm ditch and size of the irrigation block.

Based on a literature study, average farm ditch efficiency under various conditions are summarised in Table 2.2.

Table 2.2 Average farm ditch efficiency

Irrigation Method	Method of Delivery	Soil Type and Ditch Condition	Block Size (ha)	Efficiency (%)
Basin for rice	Continuous	Unlined: Clay to heavy clay lined or piped	up to 3	90
Surface Irrigation	Rotation or Intermittent	Unlined: Clay to heavy clay lined or piped	<20 >20	80 90
	Rotation or Intermittent	Unlined: Silt clay lined or piped	<20 >20	60-70 80
	Rotation or Intermittent	Unlined: Sand, loam lined or piped	<20 >20	55 65

Conveyance and farm ditch efficiencies are sometimes combined and termed ' distribution efficiency ', which can be defined as the percentage of water released at the head work that is received at the field inlet. A summary of study conducted by ICID on water distribution study can be shown in Table 2.3.

Table 2.3 Average distribution efficiency of rotational supply under optimum conditions

Adequate organization and communication	65%
Sufficient organization and communication	55%
Insufficient organization and communication	40%
Poor organization and communication	33%

2.4 *Water application efficiency*

It is the ratio of the minimum depth of water stored in the root zone to the average depth of water applied.

This term merely shows the fraction of the applied water that is stored within the root zone and potentially accessible for crop use, but with the absolute minimum value, it may be exaggerately low. Instead of the minimum depth, it was suggested to use the average of the lowest quarter. This efficiency is dependent on irrigation method, soil type, crop and water availability.

Based on a literature study; average application efficiency of various irrigation method can be summarised in Table 2.4.

Table 2.4 Average application efficiency

Irrigation Method	Method of Delivery	Soil Type	Depth of Application (m.m.)	Efficiency (%)
Basin	Continuous	Clay Heavy clay	>60	40-50
Furrow	Intermittent	Light soil	>60	60
Border	Intermittent	Light soil	>60	60
Basin	Intermittent	All soil	>60	60
Sprinkler	Intermittent	Sand, loam	<60	70

2.5 *Potential water application efficiency*

It is the ratio of the minimum depth infiltrated just equaling soil moisture deficiency to the average depth of water applied. This term gives a measure of irrigation system performance attainable when applying a full irrigation.

2.6 *Distribution uniformity*

It is the ratio of minimum depth infiltrated to the average depth infiltrated. This term gives an indication of the uniformity of infiltration throughout the field, and is useful as an indicator of the magnitude of the distribution problems. For surface irrigation, in order to get a high distribution uniformity, the field has to be properly levelled or graded.

2.7 *Overall or project efficiency*

The project efficiency is determined by considering the various stages of water conveyance and application, or it is the product of all efficiencies starting from the diversion head work upto the water stored in the root zone depth. Some average farm, conveyance and project efficiencies are shown in Table 2.5.

2.8 *A case study*

A study was conducted to evaluate the performance of the Lam Pao Irrigation project in the Northeast of Thailand. The study includes the determination of conveyance, farm ditch and field application efficiencies. Field water use efficiency, seepage and percolation losses from low land paddies were also estimated.

Table 2.5 Average farm, conveyance and project efficiencies with respect to method of delivery

Method	Efficiency in percent		
	Farm*	Conveyance	Project
Continuous block supply with small changes discharge for paddy fields	27	90	25
Rotational supply based on predetermined schedule	41	70	29
Rotational supply based on advance request by farmers	53	53	28
Supply on demand, supply by pipelines system under pressure, sprinkler irrigation	70	73	51

* Farm efficiency is the product of the application and farm ditch efficiency.

2.8.1 *Description of the project*

Topography. The project area is part of a flat, mildly undulating, old alluvial plain with a longitudinal slope of 1:5000 and shorter traverse slope of similar magnitude. The Lam Pao River is a major drain of the Northern hills of the Korat Plateau, and in the part vast area of the project area was inundated as a result of high flow of the river. However, the inundation has been reduced greatly after the construction of the Lam Pao Dam. Figure 2.1 shows the Lam Pao irrigation project.

Climate. The project area is located in the warm tropical zone and its climate is influenced by monsoon cyclonoic storms. Rainfall is irregular; about 85 per cent of total annual rainfall occurs in the rainy season (April to September) and the remaining 15 per cent in the dry season.

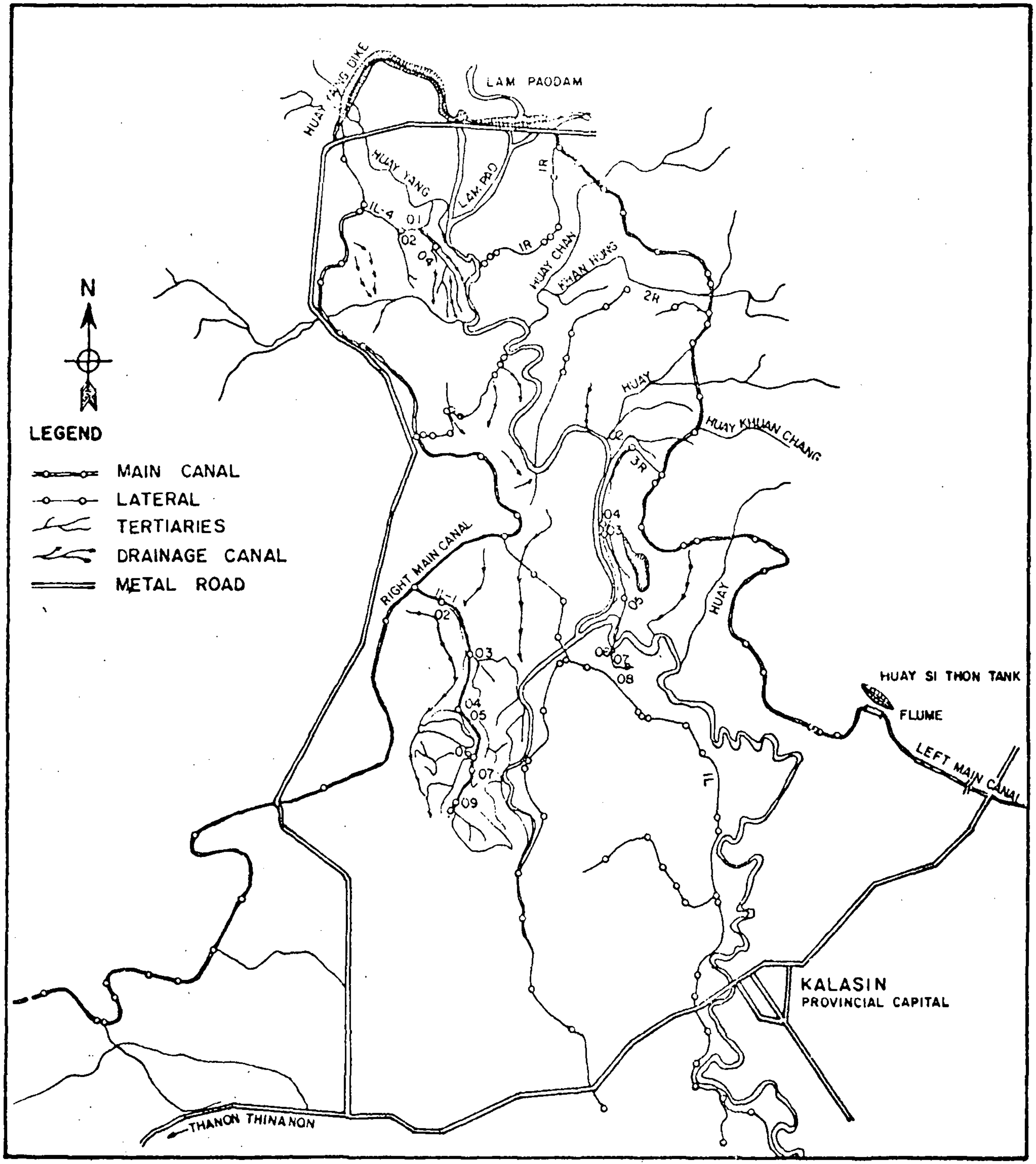


FIG. 2.1 LAM PAO IRRIGATION PROJECT (STUDY AREA 1L-4, 1L-1, 3R)

Mean annual temperature is 26 °C and mean relative humidity is 71 per cent.

Soils. The soils of the project area are the weathering products of Korat Plateau. The soils are of mostly light to medium textures, except in some low lying areas which are of heavy texture.

2.8.2 *Irrigation*

The Lam Pao Dam is an earthfill dam with a normal reservoir capacity of 1,350 million cubic meters. The irrigation development was divided into two stages, first stage with irrigated area of 18,880 hactares and second stage with an additional irrigated area of 12,600 hactares. Two main canals (one on the right and the other on the left), laterals, sub-laterals and tertiaries supply water to the field. At the time of the study, the project was still in the development and improvement phase of the first stage, not all parts of the command area were provided with irrigation supply. The study was choosen along three laterals with a command area of about 26 per cent of the total irrigated area during the dry season in 1978.

2.8.3 *Results*

Main canal conveyance efficiency. Flow measurements were taken at two points, one near the head regulator and another at 4.6 kilometers downstream, and based on the loss rate obtained, the main canal conveyance efficiency was determined. For the length of about 11 kilometers, the conveyance efficiency was estimated as 80 per cent.

Lateral conveyance efficiency. Cutthroat flumes were used for measuring flow in the laterals. The conveyance efficiencies on a lined and an unlined laterals were found to be 53 per cent and 59 per cent respectively. The lower efficiency of the lined lateral was mainly due to operational losses, whereas most of the losses of the unlined lateral was due to seepage and percolation losses.

Farm ditch efficiency. Short sections along an unlined tertiary were selected at random for the determination of farm ditch efficiency, and flow measurement was done with the use of cutthroat flumes. The values obtained range from 50 to 70 per cent with an average of 63 per cent.

Application efficiency. Field measurements were carried out on 32 field plots spreading across 3 laterals and cultivated with 3 crops; namely, ground nut, sweet corn and cucumber. The mean values obtained ranges from 40 per cent to 80 per cent, and it was found that higher efficiency is closely related to deeper root zone depth. The average value for the study area was taken as 51 per cent.

Project efficiency. The product of the conveyance, farm ditch and application efficiencies represent the project efficiency. In this study, the project efficiency is only 14 per cent which is very low. The immediate questions are why it is so low and how it can be improved; and they will be discussed in the next section.

Seepage and percolation. Seepage and percolation losses of low land paddies were estimated by substracting the estimated consumptive use from the total water use which was determined by using the water subsidence method. An average value of 3.3 mm per day was estimated as seepage and percolation losses at the study area.

Figure 2.2 shows the various efficiencies obtained for the Lam Pao Irrigation project.

2.8.4 *Discussion*

The conclusion of the study should be qualified in recognition of difficulties in carrying out the field observation. As all the data collected from the field are subjected to certain degree of inaccuracy with respect to the proper selection and installation of instrument, measurement, record

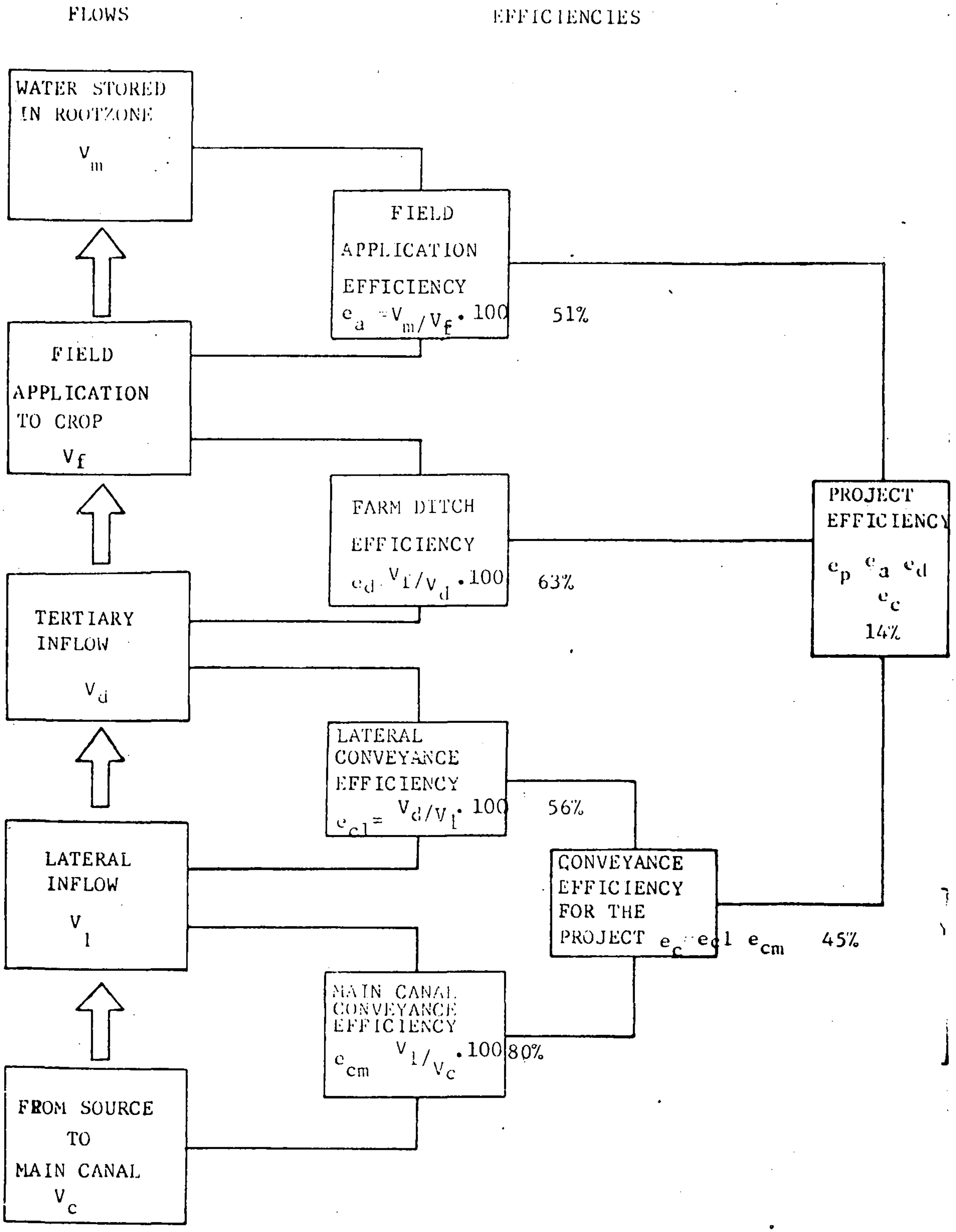


FIGURE 2.2 VARIOUS EFFICIENCIES OF THE LAM PAO IRRIGATION PROJECT

keeping and finally human errors. Nevertheless the general conclusions will present the picture of the performance of the project and the associated problems.

The main conclusions are:

(i) The overall project efficiency is very low, which is due to both operation and management of the project. In all catagories of efficiencies of the project, they are below average. Hence improvement in operation and management are necessary.

(ii) No significant difference between conveyance efficiencies of lined and unlined lateral was observed. Although the seepage losses as determined in the study for unlined canal is higher than lined canal as expected, but the difference is not significant. This is due to cracks and breakage in the canal lining. For this particular project, field engineers are faced with the problem of breakage and sliding of canal lining due to high ground water table which results in high back water pressure on the canal lining. There is also problem with flow regulation due to inadequate flow control devices and negligence of the operators.

(iii) The existing regulating structures were not properly maintained, in addition,at all laterals and tertiaries inlets no flow measuring devices were provided. So proper allocation of water for the entire project cannot be accomplished.

(iv) Canal and ditch systems were not properly maintained,weed and silt were not cleaned prior to irrigation season. This is due to lack of manpower and lack of participation on the part of the farmers.

(v) The farmers and the project field personnel still do not have good understanding of basic irrigation and water management concepts. Training programs and extension service are required in order to attain higher project efficiency.

2.9 *Some of the prevailing problems*

Irrigation can be divided into two components, each dependent on the other for attaining satisfactory results. The first is the harnessing and distribution of water which involves mostly engineering expertise, including geology, hydrology, hydraulics, design and construction. The second is the utilization and management of the distributed water which requires a sound knowledge of engineering as well as basic irrigation concepts, farm irrigation system design and operation, drainage and on farm water management. The coordination of these two components and integration of the other disciplines in both components are necessary to ensure a successful irrigation scheme. It is very common to find in irrigation development that major emphasis has been placed on the first component "the engineering aspects", while the second component "water utilization and management" which is directly related to farmers and agricultural production has been overlooked or its importance minimized. One of the reasons in that major engineering works, such as dams and canals are impressive while the proper utilization of water is less spectacular.

One of the bottlenecks hindering the coordination between engineering activities and water use practices is the intitutional and organizational set-up in the government circle. It is no surprise to find irrigation and agriculture fall under different administrations and that engineering undertakings and agricultural activities of water resource programs are unrelated. The agencies responsible for the engineering part of irrigation development concentrate their efforts on the design and construction of major civil engineering facilities. An outstanding example of this is in the provision of on-farm water facilities. The design and construction of on-farm irrigation systems is a relatively simple engineering exercise, but the engineering agency's undertaking is usually terminated at the secondary or even primary canals and the link between these canals and the farmers'field may not be given due attention.

Very few developing countries have the organizational and institutional apparatus required to construct, implement and operate agricultural development projects on a fully integrated basis.

Some of the major causes of low water utilization efficiencies can be summed up as follows:

(i) Lack of appropriate farm irrigation distribution facilities such as ditches, regulatory structures, gates and measuring devices. This inturn hinders the control of flow and usually results in wastage of water.

(ii) Lack of proper land preparation which results in uneven water distribution.

(iii) Conveyance and distribution canals are often not lined probably due to high initial cost, consequently seepage loss is very considerable and can cause salinity problem in some areas.

(iv) Lack of information on soil moisture content and crop water requirement at different stages of growth which leads to untimely irrigation.

(v) Lack of experience in drawing up agricultural development programs with adequate provision for water management and control at the farm level.

(vi) The transfer of knowledge on water management and irrigated agriculture to farmers is lacking. There is also the tendency to oversimplify the problem of scientific water management.

III MEASURES TOWARD BETTER WATER UTILIZATION

On-farm water management requires good knowledge of basic irrigation concepts, or in simple terms it requires good answers to the following three questions; when to apply water?, How much water to be applied? and How to apply the water? On-farm water management phase is usually arbitrarily taken as from the farm ditch inlet to the root zone of crops. Though the path of flow is relatively short, but proper water management is not simple especially for the farmers of the developing countries. As pointed out in the previous section, some basic informations concerning soil and crop are required, and they have to be measured as well. At the present stage, farmers in the region (Asia and Near East) still do not have the resource, experience and skill to handle this problem, and it will take time and effort to transfer some of the basic concepts to them. In addition, the zone men and water tenders also need training in this respect; besides, they are also overloaded in the sense that they are usually given too large an area to do a satisfactory job. The modern technology cannot do much yet until pre-development programs such as training programs and extension service were implemented, and only then can one expect significant improvement in water utilization.

The water management aspects of large scale or small scale irrigation projects differ only in magnitude but same in principle. The large project offers more flexibility in comparison to small project due to larger quantity of water and larger area. The large projects are planned for growth or increase in net return, while small projects are planned to satisfied the basic need which is mainly domestic water requirement. The impact of small irrigation project on social-economic status of farmers is difficult to determine. Khon Khaen University, in the northeast of Thailand has carried out a study on the impact of small irrigation tank on social-economic status of farmers; and the main conclusion is that for tanks of the size less than 100,000 cubic meter capacity no significant impact can be determined (1978-1979). A study was also conducted at the Asian Institute of Technology to determine the financial aspect of small scale tank, and it was concluded that in order to have a benefit to cost ratio of 1.0, the tank should have a capacity of 100,000 cubic meters(Nguitragool, 1979). Further more, most of the benefit derived from small tank is from growing fish, and it can be proved that in terms of water use efficiency, fishery is more efficient than crop cultivation. Anyhow, there are still questions on the definition of small scale irrigation and the limit of benefit to cost ratio to be considered as satisfactory.

In order to improve water use efficiency, the irrigation management has to be looked at in a broader context. All elements have to be considered together and multi-disciplinaries or integrated approach has to be followed. Some of the general guidelines or measures to achieve better water utilization will be discussed in the section.

3.1 *Technical*

Planning and design of irrigation project must be based on water conservation and optimal land use. Because water is becoming a limiting factor in agricultural production, the return per unit of water is more important than the return per unit area. Also it is desirable to achieve equity in water distribution to farmers, the higher the system efficiency the more land can be put under cultivation. As the cost of water resource development is increasing, optimal land use or alternate cropping pattern has to be planned in order to justify the investment whenever possible.

Planning and design of irrigation scheme must emphasize on distribution. As discussed earlier, a number of irrigation schemes still lack adequate distribution systems, tertiary or even lateral canals were not constructed or designed for. This will no doubt limit the utilization of water to those farmers whose land located near the main canals or the outlet only, and the potential benefit of the scheme cannot be obtained. On-farm water management concepts should be given due attention.

3.2 *Institution*

The line agencies should adopt the policy of integrated approach toward irrigation development projects. Independent action or input from various agencies into the project do not have enough impact or improvement, and often create confusion. The integrated effort should start from the very beginning until the end of a project.

It must be the policy of government to allocate budget to project with complete distribution system only. Under certain circumstances, many projects were implemented without adequate planning of distribution system, this can be attributed to insufficient funding at the time of request or simply overlooked. In case of insufficient funding, targets must be set to complete the distribution system and necessary budget must be committed.

In most of the countries of this region, irrigation water is provided free to the farmers. Though it is true that the farmers of these countries are generally poor, and the governments have to elevate their standard of living, but at the same time it is necessary to charge them for water at a nominal price. By paying for water, the farmer will be less wasteful and tend to improve on-farm water efficiency. At the same time it is fair to charge those farmers who received irrigation water that is developed by tax money. However, it should be borne in mind that the governments of the developing countries have the obligation to elevate the living condition of the poor, so water fee must be reasonable and should not be an added burden to the farmers. If the water charge is calculated on per unit cultivated area basis, then the effect on water saving will be small and can even be negative as well, if the farmers take the attitude that they pay for water and are hence entitled to maximum usage. It is obviously preferable to charge water based on unit volume of water received, but there is a serious practical problem on how to measure and monitor the quantity used by each farmer.

In short, for the purpose of creating water awareness and water conservation on the part of farmers, it is necessary to collect water charge; and in view of the financial status of the farmers, the charge should be reasonable in the sense that it should not hinder the improvement of the standard of living at the early stage but after a given period the charge should be increased in order to return some of the invested capital so that new project can be initiated.

3.3 *Local Participation*

In most of the irrigation schemes in this region especially for Thailand, there is a serious problem in the shortage of man power to operate and maintain the system. This is primarily due to the fact that an irrigation scheme is by no means completed with the completion of construction work, the operation and maintenance phase continues until the end of the useful life of the structures. Generally, it is easier to request budget for the development phase than for operation phase, also it is financially too heavy a burden for the government to shoulder all the operation and maintenance costs. Realistically, the farmers should participate in the operation and maintenance of the system and eventually take over this responsibility.

Farmers'participation can be very effective and serious if there exists an active water user association within the project area. Such an organization not only shares the responsibility but also plays vital role in water conservation. Ideally, farmers should participate from the start till the end i.e. selection of project, planning of project, implementing and operation and maintenance. Active farmers'participation also creates the sense of ownership which is a vital key toward the success of a project.

3.4 *Training and Extension Services*

As discussed earlier, lack of experienced and skill personnel pose a serious problem in both water management and operation and maintenance of irrigation schemes. Most of the line agencies do not have enough man power to man all the projects. In addition, the farmers do not have good background of basic irrigation concepts. Thus training programs are necessary to train man power for line agencies and to train the farmers. A project can be well designed and yet the project efficiency can be very low if not properly managed and operated.

To ensure the success of a project, some kind of extension services are required. The extension service can be in the form of technical advice, provision of necessary inputs such as seeds, fertilizers etc. and marketing. A lot of technical information is still needed to be transmitted to the farmers. Because of lack of technical know-how and resources, extension workers can best serve as linkage in this respect. Again, the effort must be well coordinated, in order to ensure meaningful results.

CONCLUSION

The title of this paper may be misleading, because the subjects were not discussed in detail but instead general concepts were discussed. Perhaps the subject matter itself is out of place under the theme of this workshop. But the author believes that if our objectives are to improve water use efficiency and to increase agricultural production, then the system as a whole ought to be examined in a broader context. On-farm water management and other specific topics have been the subject of seminars and workshops for quite some time and yet the overall performance of irrigation schemes both large and small still remain unsatisfactory in our region. If proper policy guidelines or frame work have been set concerning the various phases of irrigation development schemes, and all line agencies follow the guideline and synchronize their activities, then it can be expected that better performance can be achieved.

It is by no means the intention to minimize the importance of the subject of on-farm water management and efficient water utilization, on the contrary, by raising some of the actual field problems, their importance becoming more apparent. There is still a wide gap between technology and its application under present condition, the transfer of technical know-how to the farmer is a challenging task. Unless predevelopment programs such as training of farmers and zonemen are carried out, the real impact of most irrigation schemes cannot be realised.

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FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Agenda Item 8

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

WATER LIFTING DEVICES AND WATER MANAGEMENT

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WATER LIFTING DEVICES AND WATER MANAGEMENT*

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* Paper presented in the Workshop on 'Water lifting devices in Asia and the Near East' sponsored by the FAO at Bangkok, 4-14 December, 1979.

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WATER LIFTING DEVICES AND WATER MANAGEMENT

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1. INTRODUCTION

In our planet Earth, actually less than 3 per cent of the fluid water available at any given moment occurs in streams and lakes and the other 97 per cent is available in the underground. When the demand of water is increasing day by day, more water is obtained by tapping from the underground reservoirs. In South India, about one third of the irrigated land gets water from wells. This water has to be lifted from its source to the field surface. The efficiency of the system depends on the application of sound principles on the design and construction of the utilization structures usually the well, and the characteristics of the water lifting device in relation to the source. After lifting the water, by providing all the infrastructure facilities, it should be used judiciously since energy is to be spent on recurring basis.

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Devices for irrigation water lifting range from age old indigenous water lifts to highly efficient pumps. However, in this paper importance is given for the traditional method of water lifting devices which are locally produced and repaired

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and used by farmers as the sophisticated pumps and other methods are costly and cannot be easily repaired or serviced by the farmers themselves. In view of the increasing shortage and rising cost of energy, the traditional means of lifting water by human, animal as well as biogas and solar power are also discussed. In developing countries still more than 90 per cent of on-farm irrigation is done by surface method. Therefore water saving devices in surface method of irrigation are elaborately touched in this paper under Water Management.

2. WATER LIFTING DEVICES:

The action of tapping water involves work against gravity as water is normally below the surface datum.

2.1 Concept:

The need for lifting water was recognised even before the utility of irrigation was identified. When fish-culture got into the life-system of human food habits, the necessity for regulating pond or lake water for fish-catch was greatly felt. Swing basket (Fig.1) is a device which came into existance as a first manually operated water-lift. The use of hand, foot and body weight have been found to play important role in the development of water-lift. As the animal joined the companionship of ma~~f~~n in agriculture, the concept of spreading the animal-energy utilisation for lifting water was developed. The animals include bullock, buffalo and camel. The spread of Egyptian, Persian and Greek civilization had a telling impact in the development of mechanical gadgets for water lifting purposes and the mechanical equipments became handy in dovetailing the human/animal energy to such machines for beneficial exploitation of human needs. This method is still widely used in many parts for irrigation especially when the water is to be lifted from low level areas and from channels to fields.

2.2 Classification:

The traditional water lifting devices can be broadly classified as below:

2.2.1 Manually operated water lifting devices

i) having rotary motion
ii) having linear motion
iii) having swinging motion
iv) having any of the three combinations

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2.2.2 Animal drawn equipments

i) for open dug well with container pulley system
ii) for shallow water with continuous or semi-continuous lift system
iii) with improved mechanical linkages

The manually operated water-lifts that are in existance are as follows:

2.2.1.1 Doon or improved swing basket:

It employs the principle of lever to gain mechanical advantage and contains swinging motion of an oblong shaped trough against a horizontal fulcrum (Fig. 2).

2.2.1.2 Counterpoise, Picottah, Dhenkali, Lat, Lever or Shaduf:

This device essentially consists of a straight wooden beam supported on a Y-shaped lever with a bucket dipper rope hanging on the longer arm of the beam (lever) while the other end carried a large stone to counter balance the bucket when full. Chatterton* (1912) has reported that a picottah can perform about 7.6 Kg.M of work per minute per Kg of weight and that a see-saw water-lift with provision for cattle to walk up and down an inclined plane can perform about 4.25 Kg.M of work per minute per Kg of weight. The improved power derived in the picottah is attributable to the fact that the two-men perched on the see-saw lever are engaged in guiding the bucket rod and emptying the bucket. Molenaar**(1956) has indicated that 3 to 6 cubic meters of water could be lifted per hour if the water table is in the range of 2 to 2.5 m. The efficiency of picottah has been reported to be the highest (80 per cent) as compared to the performance of other indigenous water-lifting devices. (Fig.3).

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*Chatterton, A(1912): Water-lifts, Bulletin No.35, Department of Agriculture, Madras p. 101.

** Molenaar M.Aldert (1956): Water lifting devices for irrigation Bulletin No.60 F.A.O. Rome.

2.2.1.3 Archemedian Screw:

This device consists of a drum with a concentric screw auger of appropriate pitch so as to enable the conveyance of water along the spindle to which the auger is fastened (Fig.4). The pitch is about 1.5 times the diameter of the drum and the inclination of the unit is 30 degrees to horizontal. The unit can lift 15-30 cubic meter per hour if the water table is 0.15-0.75 meter.

2.2.1.4 Bihar pump or foot operated plunger pump:

Fig. 5 illustrates the construction of the pump. A pedal actuates the plunger through mechanical lever advantage to cause positive displacement inside a cylinder. A foot valve mounted suction hose enables the transfer of water into the cylinder to be pumped through delivery.

2.2.1.5 Hand operated chain pump:

This is a positive displacement pump having an endless chain provided with leather washers at regular intervals and is passing through a vertical suction pipe. The endless chain is mounted on a sprocket wheel which is notched in such a manner that the washer on the chain fits into the corresponding notch on the sprocket wheel to avoid slipping. The first washer creates the suction while the following washer holds the water inside the pipe since the diameter of the washer is the same as that of the suction pipe. The volumetric efficiency was found to decrease with the increase in the projection ratio (which is the ratio of the projected length of the chain outside water to the total projected length of the chain) as the leakage is higher if the height of lift is more. A provision of funnel at the lower end (Figs.6,7) enables the easy entry of the washers into the suction pipe.

2.2.1.6 Pendulum Pump:

In laboratory stage

The pendulum pump consists of two columns of buckets made of a thin metallic sheet and mounted one above the other. Each bucket of one column is connected criss cross to the next above it in the second column. As the central shaft is oscillated through 30° to 45° from the vertical on either side, the liquid filling the bottom most buckets is conducted to the alternate buckets in either of the two columns and finally delivered out from the top two buckets. The working of the pump is based on the principle that any oscillatory motion has a vertical component of lift. This pump is manually operated and it does not consume any electrical power or diesel power. Though it can work theoretically to any height, in practice it is useful to lift water by up to 3 ~~[illegible]~~ as in the case of river pumping.

Animal-operated water-lifts can be grouped into two major categories, according to the direction of movement of animals. They are:

2,2.2.1 ~~a)~~ Animals move forward and backward

This category involved intermittent operation irrespective of the relative position of the animal-power and the lifting of the relative position of the animal-power and the lifting unit. Mhot is a water-lifting device which can fall in both the categories. A single leather mhot arrangement is furnished in Fig.8. The leather cracks and perishes quickly besides increasing its weight when wet. Hence leather mhot has been improved by replacement of leather with iron buckets. The mhot prevalent in the country are:

2.2.2.1.1 Leather mhot
2.2.2.1.2 Iron Sangli mhot
2.2.2.1.3 Skeen irrigation bucket type mhot
2.2.2.1.4 Circular mhot

The sangli mhot was introduced by Messrs Bhide and Sono of Sangli in the year 1910 in Bombay Presidency[*]. This is an iron mhot which is a very close imitation of leather mhot and emptying is brought about by a subsidiary rope which pulls the lip of the container on to the discharging platform and holds there. A valve is provided in this Sangli Mhot which offers the problem of leakage. The mhot supplies 160 to 250 litres

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[*] Leaflet No.7 (1927) Department of Agriculture, Bombay: Iron mhots for raising water.

of water per run when a pair of bullocks is used.

Skeen* mhot is an improvement over the Sangli mhot by making the unit valveless and thus countering the bottleneck of leakages. It is not centrally hung and when it reaches the water it fills through the mouth immediately and reaches the vertical stage when full. On the arrival of the discharge platform, the control pully exerts its influence, and the water is discharged over a bamboo tipping bar fastened just behind the usual roller. The tilting is due to the shortening of the upper rope and the lengthening of the lower rope though the control pulley, as the animal move forward. It then automatically descends for reloading due to gravity.

Mhot is operated where an earthen ramp sloping 5 to 10 degrees are available so as to take advantage of animal weight to lift the water. The device is found to be useful for deep wells when the depth of water table exceeds 30 m. In improved designs, backing up of the bullock to let the bucket move down is avoided by provision of toggle mechanism which disengages the rope from the yoke after the bucket is empty.

2.2.2.2 Animals move round and round:

2.2.2.2.1 Circular Mhot:

Circular mhot which is also known as two-bucket lift is one of these categories. It uses two buckets which alter-

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Leaflet No.7(1927) Department of Agriculture, Bombay: Iron mhots for raising water natively are raised, emptied, lowered and filled. A four-bar linkage provision with pin-joint as a rotating beam enables the alternative lifting of two buckets (Fig.9). Experimental results at Palladam (Tamil Nadu) with single mhot operated by a pair of bullock on a ramp of 1 in 5 gradient revealed that if a pair of bullock is made to walk along a platform supported on a roller to cause up and down oscillation resulting in lowering and lifting of the bucket resulting in increased quantity of water lift. The following conclusions have been derived by a series of experiments by Alfred Chatterton

a) a pair of animal weighing 636 kg will lift 8898 litres per hour from a depth of 7.5 M

b) to cover an hectare of land to a depth of 10mm one cm the application of 100,000 of litre of water is required.

2.2.2.2.2 Persian wheel:

Persian wheel falls in the category of positive displacement pump and consists of buckets mounted on an open spoked drum and a suitable driving mechanism. Two parallel loops of chain joined by spacing bars and having earthen pots or metal buckets attached to them at intervals pass over the drum and loop into the water in the well. A horizontal shaft extends from the axle of the drum to a small vertical pinion which meshes with a large horizontal gear fitted to a vertical shaft which carries on top a long horizontal beam to which

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*Alfred Chatterton, Lift Irrigation (1912), G.A.Natesan & Co., Madras, p.33

animals are yoked. Each bucket has a small hole at the bottom for draining when the lift stops working. The capacity of buckets ranges from 7 to 14 litres. The average discharge of a Persian wheel is about 10,000 litres of water per hour from a depth of 9 m. The advantages of Persian wheel over the counterpoise lift are*

a) For an equal depth the Persian wheel can lift atleast 1.5 times the quantity of water done by the "dotte" (Counterpoise). For a depth of 4.5 M the Persian wheel draws 3600 to 4000 litres of water as against 2200-2700 litres by the *dotte* per hour.

b) Persian wheel does not require much skill or strength to work, as in the case of *dotte* which can be worked continuously only by a good strong man while Persian wheel can be operated even by a woman or a boy.

c) Bullock labour which is practically idle in the fair season can be turned to use with a small extra cost of fitting a bullock gear arrangement once for all; and

d) Persian wheel can be worked up to a depth of 8 to 9 m while *dotte* can hardly work efficiently below a depth of 5 m.

3. NON-CONVENTIONAL WATER LIFTS

The sources of power to operate a water lifting device is other than human and animal, the traditional water-

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*More Economic Water Lifts for the Konkan-Leaflet No.22(1927) Department of Agriculture, Bombay p.3.

lifts require any one of the following energies:

3.1 Wind energy

3.2 Bio-gas energy

3.3 Solar energy

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3.1 Wind energy:

Conventionally wind-mill actuated a positive displacement pump. Study conducted by Alfred Chatterton* with a wind wheel geared to the pump with a reduction ratio of 10 to 3 gave the following results. The pump diameter, length of stroke and discharge were respectively 20 cm, 40 cm and 13 litres per stroke. If x represented the quantity of water lifted from 7.5 M per day in litres and y represented the wind velocity exceeding 13 Km per hour then a linear relationship between x and y were established as below:

$$x = 445\ y$$

where x is in litres/day and y in Km/hr.

It was concluded that

a) 5 M windmill was sufficient to irrigate 4 ha of land if the water to be lifted does not exceed 7.5 M in Madras region.

b) 3.6 M wind mill has an area of 10.5 sq.M. which develops 945 Kg.M of work in 16 Km wind and thus develops 0.207 horse power.

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* The value of Wind Mills in India in "Lift Irrigation" by Alfred Chatterton, G.A.Natesan and Co., Madras, 1903 p.88-109 Reprinted from the Indian Review for June, 1903.

c) The maximum work which can be done by a wind mill in a 16 Km breeze is equal to 1.5 Kg.M per sq.M of wind power.

d) While theoretically 4.8 M wind mill having 18.7 sq.M. supplies 28 Kg.M. of work per second in a 16 Km wind flow and generates 0.373 horse power, the actual work done using the relationship x = 445 y develops only 0.198 horse power. Thus maximum efficiency that can be expected of a wind-mill in Madras region is only 53 per cent.

3.2 Bio-gas energy:

Bio-gas technology is gaining its importance as an alternate source for fuel. Fig. 10 illustrates a bio-gas plant. Cellulose containing waste-materials like cow-dung releases methane gas under anaerobic digestion. Approximately 60 per cent pure methane gas can be used as a blend to the diesel fuel in an Internal combustion engine. A 5 H.P. engine has been converted into a dual fuel engine by inserting a nipple at the air-filter side (Fig. 11). The diesel engine is started with diesel fuel and as it reaches its rated speed, methane from biogas plant is released into the combustion chamber gradually through the nipple. The governor of the engine automatically switches off the diesel supply partially as soon as the methane blends with the diesel in the chamber. The diesel engine run by 60:40 diesel-

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methane fuel blend can be coupled to a centrifugal pump to lift water.

3.3 Solar energy:

The development of a solar pump is of a recent origin~~e~~. A flat plate collector can raise the water temperature to 65° C' on sunny days at tropical belts. If the steam could be generated, a steam engine can be run which in turn can run a pump. Alternately if turbine principle could be incorporated by supplying steam under pressure or as reaction, a rotar can be actuated to develop the desired torque which in turn results in translation of energy to lift water.

4. AGRO-ECONOMIC CONSIDERATIONS OF LIFTS:

Table 1 illustrates cost of lifting 4500 litres of water per unit head-assuming 10 years life for animals, prime-mover and pipes and fittings, 20 years lift for pump housing and 40 years life for well and lining.

It can be seen that where electricity is not available, it is necessary to go for South Arcot circular mhot or country mhot to lift water according to the lift range. Oil engine pump can be resorted only where labour or bullock energy are dear. Another case study made to evaluate the cost of lifting irrigation water for five out-put levels ranging from 100 to 2000 Ha.cm. revealed that the cost reduced from Rs.52.56 to Rs. 6.96 to lift one Ha.cm. of ~~cm~~ water as can be seen from Table 2.

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1 $ = Rs. 8.00

The overhead charges were observed to vary considerably between different outputs due to the variations in size and depth of well, geophysical strata conditions, quantum and duration of availability of irrigation water and investment outlays expended initially and thereafter.

The main cropping calender of Coimbatore tract, INDIA is as follows:

Month of Sowing	Crop	Month of Harvest	Water requirement in cm
February-March	Sugarcane	March	200
February-March	Sorghum	May-June	40
June	Ragi	August	40
June-July	Banana	June	200
June	Groundnut	October	65
June	Vegetables	October	65
January	Groundnut	April	65
January	Vegetables	May	65

The months having adequate wind-velocity can be identified and the wind energy can be harnessed to lift water for irrigation. "Anila" pump of wind-operated water lifting device has been recently developed by the Murugappa Chettiar Trust, Madras and is under field tests. During non-winter season namely February to October, the biogas can be used to run a pumpset. Caution is made here to point out that 0.22 cu.m of gas is required to run 5 HP engine for one hour.

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5. MANAGEMENT OF WATER:

5.1. Importance of management of water:

Once the water is lifted and brought to the surface, management of the water becomes very important factor. This water is of special importance and interest in the development and improvement of agriculture and in the social and economic life of the small and marginal farmers in the rural community. Further the cost of lifting water is much more compared to the cost of surface water especially in southern part of India since in most of the places the ground water table is more than 20 m or so. The cost of canal water is ₨.40 to 60/ha for rice, ₨. 50 to 60/ha for cotton and ₨.25 to 60/ha for sugarcane on an average, whereas the operation cost of well water in Coimbatore District, South India where the ground water table is at about 30 m and above, is between ₨.3.00 to ₨. 6.30 per ha cm of water which works out to ₨.330/ha for rice, ₨.200/ha for cotton and ₨.660/ha for sugarcane considering the minimum operation cost only and without taking into account the cost of construction of wells, installation of pump sets, their depreciation, interest, etc. This clearly shows that the water which is lifted from wells, is to be managed very carefully in irrigation in order to get the maximum benefit.

5.2 Definition:

Water management may be defined as a skill of coordination of water resource tapping, receipt, storage, conveyance, diversion, delivery, distribution and application consistent with the soil capability and the crop requirements for maximising irrigation efficiency and economic returns. This definition implies resource inventory, system analysis, decision making and project evaluation. Hence the scope of water management depends on the inter-relationship between a variety of factors including irrigation practices, land use and cropping pattern, individual and collective system of irrigation and overall economics. The definition of water management makes very critical role of risk factor a new dimension which is well defined in other business, but not in agriculture. This dimension has direct impact on nations economy. The risk factor associated with farm irrigation management is largely due to the erratic behaviour of monsoon, the imbalance created in the supply demand structure of agricultural commodities and the consequential variations in the marketing price, government price fixation policy and the overall stress the farmer being subject to by factors other than agriculture.

The increasing scarcity of water in many parts of the country and its implications for the economy have become one of the main concerns of the Government in recent years and this will increase in the coming years. The lessons derived from the study of the present situations show that only by investing a major effort in water saving, by making water use more efficient and by use of marginal waters, it will be possible to maintain a reasonable growth rate of that part of the national income dependent on irrigated agriculture in the countries/areas where water is a limiting factor. The saving of water is an extremely complex problem since development of water resources and the operation and maintenance of water supply system is the responsibility of public bodies. Saving of water can only be observed with the full cooperation of the general public (farmers) since such saving is dependent on the individual awareness of the need to conserve water and economize water use. Hence it is all the more reason that utmost attention should be given in managing this costly and scarce input in Agriculture.

5.3 Irrigation Practice:

The irrigation method practised at present in most of the developing countries is as old as civilization. Though improved irrigation practices have been developed in the last 15 to 20 years in order to utilize the available water judiciously, the same has not been adopted in the farms in many areas. This is because the farmers think that the method followed in all these years are good and if the water is reduced the yield may be reduced. It will take years to convince them by research/extension staff by organizing demonstration plots and also by meeting and explaining the technology and its usefulness to the farmers. The following are some of the methods which can be adopted on farms to increase the efficiency of water use.

5.4 Management:

Management of irrigation water from source to the field is very essential. The water lifted from the well is to be transported, distributed with control structures after land shaping. Further in order to maintain the ground water table, artificial recharge is very necessary in the arid/ semi arid regions.

5.4.1 Conveyance:

Presently the lifted water is conveyed through open unlined earthern channels by most of the farmers big or small. In some isolated cases water is taken through lined channels. Yet in some other cases, the water is conveyed through under ground pipes. Recently after knowing the value of water and its cost of lifting, the farmers are aware of the usefulness of the system, but they are not in a position to take up the work for want of finance.

The studies conducted in many places have shown that 50 per cent of the water is lost in conveyance in large irrigation projects and about 15 to 20 per cent in the field irrigated by wells. In order to prevent the losses, the customary procedure is to construct masonry channel which is costly. Scientists have evolved cheap lining materials like soil and cement, (8:1) cement, soil and granite (1:4:4) and also making the prefabricated channel with these materials. The cost of making 1 meter long channel is about Rs.5/- and these channels can be fabricated with the help of family members. By laying the precost channels, the maintenance and other repair charges can be eliminated. Further in order to prevent the loss of water by evaporation, underground pipe lines can be laid with the above mentioned materials and specifications. Since the area of irrigation and the distance to be conveyed in the lift irrigation are small, non-pressure pipe with the necessary regulating and control structures may be sufficient. (Figs.12,13).

5.4.2 Distribution and control of water:

There is no distribution and control structures in the farmers' field except in a Government/University/farm or in a progressive farmers' field; but in majority of the fields, the irrigator does the distribution by his own judgement and control with his spade. A properly designed distribution system will make irrigation easy and efficient. Several types of structures are used to divert, distribute and control irrigation water on the farm. Good structure is an essential part of an irrigation layout and will save labour and water. The different structures used for this are different drop structures, check gates, diversion boxes turnouts for open channels and gate stands, overflow stand and alfalfa valves for the underground pipe line systems.

5.4.3 Land levelling and shaping:

Conservation farmers use irrigation system designed to fit their soil, water, supply, climate, crops to be grown, etc., in order to get an application efficiency of 75-80 per cent. Equipments and methods for precise distribution and control of water are available. In order to achieve these objectives, the important pre-requisite is land levelling and shaping. It has been found that by proper land levelling and shaping alone it is possible to save about 25-30 per cent of water, though there are other advantages like labour saving, increased yield, etc. (Fig.14)

5.4.4 Artificial recharge of ground water:

The area/zones where irrigation is done by wells the experiences show that the water table is going down due to tapping more water than recharged. This is more in arid/ semi arid zones. It is therefore very necessary to maintain the level of the ground water in order to reduce the cost of lifting water. This is possible even in places where the rainfall is about 500-800 mm since flood occurs during very intense rain and the water is lost by runoff. Therefore artificial recharge can be done in order to conserve and manage the rain water on scientific basis. Experiments have shown that by construction of percolation ponds and also by suitable soil conservation measures (contour bunding) it is possible to maintain the ground water level.

5.5 Methods of Irrigation:

Once the land is levelled and the water is conveyed for irrigation, the application aspects are to be considered. Though there are many advanced methods of irrigation, still, the farmers in the developing countries follow the age old surface irrigation only namely flooding, basins and furrow systems. There are many improved techniques to save water even in the surface water application which can be adopted by the small farmers in the developing countries without much expertise knowledge.

5.5.1 Irrigation for Rice crop - (Flooding method):

Rice is the staple food crop in India and other South Eastern countries. Rice crop consumes large quantity of water compared to any other crop. In India nearly 45 per cent of the total quantity of irrigation water is utilized for growing rice and in the Southern India this figure may be 75-80 per cent. Hence management of water in the rice field is very essential. Though the evapotranspiration (ET) requirement of rice varies from 600 to 800 mm, the quantity of water used for growing rice by farmers varies from 1500-3000 mm. Studies conducted on water requirements have indicated that the water use for high yielding varieties of rice vary from 940 to 1320 mm at Coimbatore, India. Further it is established by the scientists in the countries that by practising water saving method of irrigation that is saturation or allowing to stand thin film of water upto flowering and then followed by 2.5 to 3.0 cm of standing water for high yielding varieties of rice, it is possible to save about 30 per cent of water without affecting the yield. The water use, yield of the rice crop under the conventional (farmers) method and water saving method are given in Table 3. The results given above show that though the water used in the water saving method in all high yielding varieties are less than 25 to 45 per cent, the yield has not been reduced.

5.5.2 Irrigation of fruit crops - Banana, Grapes, Papaya (Basin method):

The irrigation is given in the basins for most of the fruit crops. The size of the basins followed at present covers the entire area and equal to the spacing of the crops. For Anab-E-Shahe grape the basin size is 8 m x 4 m and for the banana and papaya it is 1.8 x 1.8 m. From the experiments conducted in many years, it is found that the basin size can be reduced without affecting the yield, thereby large quantity of water could be saved. The results obtained for Banana is given in Table 4.

The water used and yield in the case of grapes have shown that the yield in the 4 metre diameter circular plot was on par with the control plot of 8 m x 4 m, but the saving of water is more than 50 per cent.

From the table 4, it is observed that in 1.2 m x 1.2 m basin size, 20 to 30 per cent of water could be saved in banana crop as compared to control plot of 1.8 m x 1.8 m. At the same time, the growth of stem, the rate of growth, number of flowering, number of hands and fingers have not been significantly reduced and also the yield has not been reduced.

5.5.3 Irrigation of cotton, sugarcane and other row crops (Furrow method):

Different methods of irrigation namely furrow, border, strip, check basin are used for cotton cultivation. Experiments conducted to find out the best method for cotton irrigation have indicated that the furrow is very economical method and it is possible to save 20-30 per cent of water without affecting the yield as compared to other methods. Having found that furrow method is best suited to economise the water, further work was done to save water in furrow irrigation. Alternate furrow and skip furrow irrigation (Fig. 15) was introduced for row crops. Further in the intervening space in the skip furrow method short duration pulse crops could also be raised. The results obtained are given in Table 5.

The results have indicated that by adopting skip furrow and alternate furrow irrigation, water saving upto 30-50 per cent can be obtained without any reduction in the yield. These improved irrigation methods can be adopted for all the row crops including sugarcane, vegetables, etc.

5.5.4 Advanced methods of Irrigation:

Recently as Science and Technology have advanced, new systems have entered into the irrigation practices.

5.5.4.1 Sprinkler method of irrigation for all crops except rice:

In developing countries, in view of the cost of the equipment, this is not practised at present. This method can be used where the land is undulated and the cost of levelling is prohibitive. It is also very much suitable for sandy and shallow soils. The saving of water will be about 25-35 per cent compared to surface method. The experiment results obtained in India are given in Table 6.

5.5.4.2 Drip irrigation method for fruit, vegetables and other row crops including cotton, sugarcane:

This method is very new one in the developing countries. A cheap drip irrigation has been designed and fabricated with the locally available tubes at Tamil Nadu Agricultural University, Coimbatore. This system is working at low pressure with main and lateral tubings. 1 mm holes are provided in the desired interval and to avoid clogging and spray action sockets are provided in the openings (Fig.16). The results of the experiments conducted for various crops are furnished in Table 7.

From the table it is clear that the water used in the drip system is only about 25 to 33 per cent of the control method (surface irrigation). However, the yield has been increased from 10 to 25 per cent in most of the crops except chilly and papaya where the yield of the crop are still higher in percentage.

5.5.4.3 Pitcher/pot irrigation:

In sandy areas, pot irrigation was given in some parts of South India by the farmers to save water. In this method, water is given to each plant by the farmer/worker once in 2 or 3 days according to the climatic conditions. Recently scientists have designed a system in which mud pots are buried in the soil and by making small holes and inserting coconut fibres, the water is released drop by drop to the plants. The experiments conducted with Tapiaco plants had proved that in this method it is possible to reduce the water requirements of the crops. This can be introduced especially in large spaced fruit and orchard crops and tree farming.

6. WATER RESOURCE BASED CROPPING:

6.1 Selection of crops:

The water requirements on different crops not only dependent on the duration of the crop but also dependent on the critical stages at which the water should be applied. When water is a limiting factor especially in arid and semi-arid zones the tapping of the ground water through pumps is to be made which affects the net return per unit of water per unit time per unit area. The table 8 summarises the water requirements, the yield, net profit for various crops grown in South India. As the water is a limiting factor the two manageable components involved are the area that can be catered in relation to the stage of the crop besides the selection of the crop to match the availability of the water resources. Perhaps the combination of water saving technology as well as the choice of water lifting devices depending on the motive power available will have to be adopted for agricultural irrigation. Since the choice of the crop is only the farmer's discretion which again is related to the food habit or the price structure prevalent, it becomes difficult to change the cropping pattern according to the need. Hence proper selection of water lifting device to command the appropriate area and to adopt water judiciously is only the solution.

6.2 Agronomic practices:

The management of the crop involves economisation of the irrigation water which again another dimension to the management practices. The agronomic practices which involves scheduling of irrigation, phasing, water supply at the critical period in right quantities are as important as the conveyance, distribution and delivery of the water. The small and marginal farmers are faced with financial constraints which are reflected in the choice of the water lifting devices adopted in their farms. The only factor is the cost factor that decides the choice of water lifting devices to be adopted by the farmer. The source away from the electricity becomes vulnerable for the adoption of oil engines. The marginal or small farmer who owns a pair of bullocks can easily use the animal power as the source. The depth of water table and the skill involved in operating the water lifting device play a dominant role in accepting the practices. Further the selection of the crop is also dominated by the physiological agronomical variety choice and the irrigation and engineering technology suited to the land and water and also the adaptability, marketting facility, etc., in the area.

7. EDUCATION AND EXTENSION IN WATER LIFTING AND MANAGEMENT:

7.1 Extension agency:

Extension outlets are required for dessimination of water management and lifting practices. In Israel and U.S.A. specialists (Irrigation and Water Management) are available to assist the farmers in judicial utilisation of the water which contributes for substantial increase in water use efficiency. Perhaps the establishment of a cell which takes up the extension work to select appropriate water lifting devices based on the water resources available and the motive power on hand besides utilisation of the water for the better management will be a long-range solution.

7.2 Demonstration/Pilot plots on water management:

The effectiveness of the extension can be visualised only through large scale demonstrations in small and marginal farms since psychological factor is an important component which plays a major role in transfer of technology. National demonstration schemes as well as extension net work through Drought Prone Area Programme, Small Farmers Development Agency,, Marginal Farm Development Agency and other organizations can bring the farmers and the knowledge together by effective extension media. A short term and inservice training programme besides an intensive adoption of farms can throw upon a new area through which the integrated water lifting management system can penetrate into the farming community.

8. SUMMARY AND CONCLUSIONS

Water is an important input for the agricultural production. Ground water is available not only in the humid areas, but also in the arid and semi-arid regions. Open wells/

tube wells are constructed to tap the ground water. The water thus available from underground has to be lifted by way of introducing efficient water lifting devices with low energy demands or low cost, with high degree utility in cropping. Various water lifting devices which are applicable in the rural areas with the available power have been described. There is a great possibility of utilizing the bio-gas, wind energy and solar energy in future as a motive power to drive the appliances.

The lifted water has to be used very judiciously in order to reduce the cost of lifted water. In practice it is possible to achieve the above mentioned objectives and increase the yield with saving of about 20 to 30 per cent of water by introducing the various technology developed in the various parts of the world. The practical methods and the useful results obtained are presented briefly. If the above methods are followed and by introducing advanced method of irrigation, increased demand of water by the community can be met with without any difficulty. In order to achieve the same, it is necessary to educate the farmers by providing extension staff in these fields and also by demonstrating field experiments in large scale in farmers' field of the developing countries.

TABLE 1. COST OF LIFTING 4500 LITRES OF WATER PER UNIT HEAD*

Sl. No.	Water lifting appliance	Lift range metre	Discharge range gallon per day	Cost per 4500 litres Rs.
1.	Country Mhot	8-12	5850-8100	1.80-4.00
2.	South Arcot Mhot	3-7	9900-16650	0.30-0.5
3.	Oil engine pump	4-8	18000-28800	1.40-2.70
4.	Electric motor pumpset			
	a.	5-8	11700-22500	0.60-1.20
	b.	3-14	22500-45000	0.30-1.40
	c.	6-12	45000-54000	0.20-0.30

* Chatterton A.(1912) Water lifting Bulletin No.30, Madras

$1 = Rs.8.00

TABLE 2: COST OF LIFTING WATER FOR DIFFERENT OUTPUT LEVELS*

Sl. No.	Volume of water lifted per year	Overhead charges per Ha cm	Operation cost per Ha-cm	Total cost of lifting one Ha-cm of water
	Ha-cm	Rs.	Rs.	Rs.
1.	100	48.00	4.56	52.56
2.	300	16.00	"	20.56
3.	500	9.60	"	14.16
4.	1000	4.80	"	9.36
5.	2000	2.40	"	6.96

* Sivanappan R.K., Ayyasamy P.K., Cost of Well Water in Coimbatore Region, Journal of Irrigation and Power Vol. No.35, No.4, 1978.

TABLE*3: WATER USED AND YIELD OF PADDY UNDER CONTROL AND WATER SAVING METHOD

Sl. No.	Name of rice variety	Season or Period	Water used - cm		Yield kg/ha		Rain-fall in cm	Duration after trans-planting till harvest in days
			Control	Experimental	Control	Experimental		
1.	IR 22	Feb-June'72	104.23	65.53	4700	4740	15.03	111
2.	IR 24	July-Nov.'72	111.52	83.12	4273	4370	37.92	109
3.	Kanchi	Jan-Apr.'73	131.97	67.16	4990	4890	4.5	104
4.	Bhavani	Aug-Dec.'73	96.32	61.39	5500	5450	26.71	110
5.	Vaigai	Feb-May'74	100.28	73.48	5538	5000	11.20	101
6.	Co.39	March-May'75	94.00	61.49	4098	3317	9.00	76

* Sivanappan R.K. - Water saving method of irrigation for high yielding rice crop Madras Agrl.Journal 64 (11), 1977.

TABLE 4*: SIZE OF BASINS, WATER USE AND YIELD FOR BANANA CROP (1977-78)

Sl. No.	Treatment basin size	Water used in cm	No. of flowerings (end of 9 months)	Average yield of fruit Kg/plant	Average weed weight kg.	Rainfall cm.
1.	6' x 8'	169.09	117	20.6	14.70	111.20
2.	4' x 4'	100.50	78	20.2	10.60	111.20
3.	3' x 3'	72.12	83	18.3	7.85	111.20
4.	2' x 2'	55.26	102	17.4	5.91	111.20

*Research Activities of the Dept.of Soil and Water Conservation Engineering, College of Agrl. Engg., Tamil Nadu Agrl.University Coimbatore, India, 1978.

TABLE 5*: THE WATER USE AND YIELD OF COTTON (MCU5) CROP IN DIFFERENT METHODS OF IRRIGATION

Sl. No.	Treatments	Water applied in cm	Savings of water per cent	Yield kg/ha	Rain-fall in cm	Remarks
1.	Control furrow	43.00	..	2016	14.00	No difference in yield of cotton was recorded;
2.	Alternate furrow	28.32	35	2060	4.00	
3.	Skip furrow	22.07	50	1908	14.00	25 kg/ha of pulses was obtained
4.	Inter cropping with pulses in skip furrow	22.07	50	1980	14.00	

*Sivanappan R.K. *et al*., Skip furrow irrigation in cotton Indian Farming, June, 1976.

TABLE 6* : CROP YIELD AND WATER USE IN SPRINKLER METHOD

Sl. No.	Place of experiment	Crop	Water saved in (per cent)	Yield increase (in per cent)
1.	Hissar (Haryana state)	Potato Wheat Bajra	14-20	...
2.	Kharagpur (W.Bengal)	Potato	60	...
3.	Ludhiana (Punjab)	Wheat	43	...
		Maize	47	54
4.	Chiplima (Orissa)	Ground-nut	25	50
5.	Coimbatore (Tamil Nadu)	Cotton	20-30	..

*Sivanappan R.K. Sprinkler and Drip irrigation (unpulished) 1978.

TABLE*7: WATER USED AND YIELD IN DRIP AND CONTROL METHOD IRRIGATION

Sl. No.	Name of the crop	Water used in cm		Yield in kg/ha		Rain-fall cm
		Control	Experi-mental (drip)	Control	Experi-mental (drip)	
1.	Tomato	49.80	10.76	6187	8872	24.18
2.	Bhendi	53.53	8.70	10000	11310	24.18
3.	Raddish	46.41	10.81	1045	1186	..
4.	Beet root	85.76	17.73	571	887	..
5.	Chilly	109.71	41.77	4233 (wet red pod)	6088	20.75
6.	Brinjal	69.18	24.47	12400	11900	17.18
7.	Sweet potato	63.14	25.20	4244	5888	12.12
8.	Banana (12 months)	162.70	39.00	16 kg/ plant	17.8 kg/ plant	56.10
9.	Papaya (12 months)	228.50	73.38	13.88 kg/ plant	23.8 kg/ plant	81.65
10.	Cotton	70.00	13.00	2604	3255	13.00

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*Sivanappan R.K. Economics of drip irrigation methods in small and marginal farms - Madras Agric. Journal 65 (12), 1978

TABLE* : 8 WATER REQUIREMENT YIELD AND PROFIT FOR VARIOUS CROPS

Sl. No.	Crop	Duration in days	Total water requirement in cm	Yield in kg/ha	Profit in Rs./ha/day/cm of water
1.	Paddy	100-120	100-120	5,000	0.25
2.	Ragi	105	45-50	5,000	0.66
3.	Sorghum	105	35-40	5,000	0.83
4.	Bajra	90	30-35	5,000	1.27
5.	Pulses	70	20-25	1,000	0.70
6.	Maize	100	40-45	6,250	0.55
7.	Cotton	165	70-75	2,000	1.08
8.	Groundnut	105	60-65	1,500	0.20
9.	Onion	70	30-35	6,250	0.98
10.	Sugarcane	365	225-250	12~~,~~5,000	0.08
11.	Banana	365	200-225	50,000	0.18
12.	Tomato	120	55-60	25,000	1.38
13.	Bhendai	95	55-60	12,500	1.00
14.	Brinjal	140	60~~0~~-65 60-65	25,000	1.18

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* Sivanappan R.K. Water management for better living in and around Coimbatore, Seminar on Optimum Utilization of water and land in and around Coimbatore, June, 1975.

Agenda Item 11
4/12/79

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

FAO/DANIDA WORKSHOP ON WATER LIFTING DEVICES IN ASIA AND THE NEAR EAST

Bangkok, 4-14 December 1979

COST COMPARISON OF SOME WATER LIFTING DEVICES

by

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PREFACE

The cost calculations in this paper are updated extracts from the handbook "Water Lifting Devices for Irrigation" by A. Molenaar, published by FAO in 1956. The paper should stimulate workshop discussions on costs and other factors to be evaluated in the selection process. The cost figures are indicative only.

CONTENTS

1. General

The great number of different types of devices and methods of water lifting is constantly increasing with advancing technology. In general any one device has a fairly confined range of application, i.e. it is more economical if used under the set of conditions for which it has been developed. Perhaps the best example is the windmill which can be employed (and thus compared with other devices) only for areas where there is sufficient wind. In this Workshop we are predominantly concerned with / ha small-scale irrigation, usually implying small holdings, abundance of labour, shortage in capital, low water lifting heads. In this scenario it would be meaningless to compare, e.g. a persian wheel with a large motor-driven pump set. This could be done only in situations where it is technically and socially possible to replace a number of traditional lifters by one motor pump. Such scenarios are very rare and are therefore not considered here.

Many of the traditional human or animal drawn water lifting devices can theoretically be replaced by motor pumps, especially the small electrically powered ones, provided electricity is available. In many rural areas, however, electric networks, if any, are of poor operational standard with frequent capacity variations, breakdowns, etc. A study conducted in 4 states of India* showed that the average overall efficiency of eletrically driven irrigation pumps was only 42 percent. The same study also revealed that

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* Suitability of pumping systems in farmer's irrigation wells in India. Technical report by Andhra Pradesh State Irrigation Development Corporation Ltd. 1978.

no criteria guidelines for proper selection of pump.

overall pump efficiency for diesel engine driven pump sets was as low as 10%. The main reasons for this poor performance were wrong selection of pumps and engines, improper installation, deficient operation and maintenance.

Over-capacity

The most universally applicable device is doubtless the small portable fuel engine pump. Yet the capacity, even of these light sets, generally exceeds by far the capacity of any individual traditional means of water lifting, suggesting that motor-driven pumps should be shared by several farmers. Installed over-capacity does not only lower profitability but often leads to over irrigation with all the damage this may cause. In certain areas traditional equipment (persian wheels) had to be abandoned because over-pumping had lowered the groundwater table beyond reach.

For subsistence farmers, a traditional type of water lifting device, despite its higher labour input, low capacity, etc. may still rival a motor pump in terms of reliability of service. To account for this safety asset it may be necessary to estimate the savings made by preventing yield losses.

Local employment opportunities and use of local materials may also influence a final selection. Besides saving foreign exchange local manufacturing of equipment generates skills which will also be available for repair and maintenance.

When analysing the cost of traction animals one should consider not only the feed they consume but also the lost opportunity (if any) to grow staple food or cash crops on the acreage occupied to grow animal feed.

In some development projects gravity irrigation may have to be considered as an alternative to existing lift irrigation. Apart from cost, this requires an evaluation of the factors: over irrigation and subsequent yield losses as well as undue rise in watertable, and operational and maintenance cost. Also, the more farmers depend on a single installation, the greater the losses once it fails (reduced flexibility).

2. Sample cost comparison

The scenario chosen for this sample calculation is one of subsistence agriculture on small holdings with very low wages, shortage in foreign exchange and high fuel price. The calculation is purely illustrative, since capital cost, rate of interest, labour wages, depreciation rates, etc. would vary from case to case. However, when applying the procedures to specific conditions representative values can be readily inserted.

economic
analysis
country-
specific

The comparison is between a rope-and-bucket lift, a self-emptying bucket device, a persian wheel and a diesel motor driven pump. The economy of these devices is compared for a common lift head of 9 m from a groundwater well. The costs for the well are not included as they are approximately equal for all devices.

In Appendix I an example is given on the calculation of food consumed to execute a given amount of human labour required for irrigation.

2.1 Rope and bucket lift

Used to lift water from an open well and operated with two pairs of bullocks and 3 men. The lift is 9 m and water is being raised at an average rate of approx. 17 m^3 per hour. To lift a volume equivalent to 1 Ha-cm requires one working day.

Capital outlay

	US $
Equipment and installation	50.00
Bullocks (50% of value charged to water lifting)	300.00
Total Investment	350.00

Overhead charges

Interest on investment 12% on average investment of $175.	21.00
Depreciation of Equipment (5-year life) 20% of $50.	10.00
Bullocks (10-year life) 10% of $300	30.00
Total annual overhead	60.00

Operating costs per Ha-cm

Bullock feed at $0.12 per hour, per pair, 12 hours at $0.12	1.44
Man labour at $0.10 per hour per man, 18 hours at $0.10	1.80
Repairs	0.09
Total operating cost	3.33

Total cost of lifting water, see Table 1

$7 \times (9-3) = 42\ m^3/day$

2.2 Self-emptying bucket

Operated with one pair of bullocks and one man. The source of water is an open well and the lift is 9 m. The average rate of raising water is 7 m^3 per hour, which means that some 2.4 working days (including 1 hour rest for every 3 hours of work) are required to lift a volume equivalent to 1 Ha-cm.

$10^4 . 10^{-2} = 10^2 = \underline{100\ m^3}$

Capital outlay

	US $
Bucket, rope, pulleys, frame, etc.	80.00
Bullocks - 50% of value charged to water lifting	150.00
Total	230.00

Capital costs
~~Overhead charges~~

Interest on investment 12% on average investment of 115	13.80
Depreciation of equipment (5-year life) 20% of 80	16.00
Bullocks (10-year life) 10% of $150	15.00
Total	44.80

Operating costs per Ha-cm

Bullock feed (pair) 14.3 hours at $0.12 per hour	1.72
Man labour at $0.10 per hour, 14.3 hours at $0.10	1.43
Repairs	0.09
Total	3.24

Total cost of lifting water see Table 1

2.3 Persian wheel (high lift)

Used to lift water from an open well and operated with one pair of bullocks and a boy. The lift is 9 m and water is being raised at an average rate of 9 m^3 per hour which means that approximately 1.9 working days are required to lift one Ha-cm.

Capital outlay

	US $
Persian wheel, complete	320.00
Bullocks (50% of value charged to water lifting)	150.00
Total	470.00

Capital costs ~~Overhead charges~~

	US $
Interest on investment 12% on average investment of 235	28.20
Depreciation Persian wheel (10-year life) 10% of 320	32.00
Bullocks (10 year life) 10% of $150	15.00
Total	75.20

Operation costs per Ha-cm

	US $
Bullock feed (pair) 11.1 hours at $0.12 per hour	1.34
Labour (boy) 11.1 hours at $0.05	0.55
Repairs	0.09
Total	1.98

Total cost of lifting water see Table 1.

2.4 Diesel motor driven centrifugal pump

5 Hp portable set used to lift water from an open well over a head of 9 m at an average rate of 70 m^3 per hour. Time required to lift 1 ha-cm of water is 1.43 hours.

Fuel consumption: 1.1 l per hour.

Capital outlay

	US $
Pump and engine	1 000.00
Belt, discharge box, platform, etc.	50.00
Total	1 050.00

Overhead charges

	US $
Interest on investment 12% on average investment of $525	63.00
Depreciation of pump and engine (10-year life) 10% of 1 000.00	100.00
Belt, discharge box, etc. (5-year life) 20% of 50.00	10.00
Total	173.00

Operating cost per Ha-cm

	US $
Fuel cost, 1.43 hours at 1.1 l per hour and at $0.50 per l	0.79
Lubricating oils and greases	0.08
Repairs	0.18
Attendance	0.10
Total	1.15

3. Discussion

The different cost components are shown in Table 1. Figure 1 shows the graphical analysis. Table 2 compares the days of operation required to lift various amounts of water with the individual devices.

The 9 m lift had been chosen to make a motor pump reasonably comparable to the 3 traditional devices. Even then, as Table 2 indicates, the motor pump is working far below potential capacity. While, for example, the amount of 200 ha-cm takes 2 sets of persian wheels 190 days to lift, the same is accomplished by the motor pump in 36 days at 8 hours daily operation. Thus, over an irrigation season of, say 190 days, the motorpump could replace:

$$\frac{190}{36} \times 2 = 10 \text{ sets of persian wheels (=20 bullocks)}$$

As Figure 1 indicates, the 3 traditional devices are competitive only when the total volume of water lifted does not exceed 50-100 ha-cm. Curve B depicts the cost-volume relation after a 50% increase in present fuel price*. It reveals that an increase in this order of magnitude does not significantly alter the specific competitiveness of the motor pump.

In the cost comparison safety against failure and possible crop losses due to under-irrigation has not been considered. In this respect the traditional devices appear to perform much better than engine driven pumps. They have the distinct advantage of being locally manufactured. Thus both local skill and the necessary spareparts are more readily available, when a breakdown occurs. Full advantage of motor pumps can only be taken if they are properly selected for the task in question, correctly installed and maintained. In small scale irrigation motor pumps to be optimally utilized, should be shared amongst several farmers.

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* A 50% net cost rise, independent on inflation-related increases, is assumed.

In certain cases a combination of motor pumping equipment with a traditional water lifting device may integrate their individual advantages so as to become economically feasible. This, for example, could take the form of a bucket lifting device being kept as a standby to safeguard against detrimental interruptions of irrigation supplies in times of pump failure.

Similarly other lifting devices may be combined e.g. a solar powered pump (for the season of intense sunshine) with an animal-powered device (for the remainder); a wind powered pump (for the windy season) with any other suitable device.

Volume lifted per yr in Ha-cm	OVERHEAD CHARGES				OPERATING COSTS				TOTAL COSTS			
	Rope and bucket	Self-emptying bucket	Persian wheel	Diesel powered pump	Rope and bucket	Self-emptying bucket	Persian wheel	Diesel powered pump	Rope and bucket	Self-emptying bucket	Persian wheel	Diesel powered pump
25	2.44	1.79	3.01	6.92	3.33	3.24	1.98	1.15	5.77	5.03	4.99	8.07
50	1.22	0.90	1.50	3.46	"	"	"	"	4.55	4.14	3.48	4.61
75	0.81	0.60	1.00	2.31	"	"	"	"	4.14	3.84	2.98	3.46
100	0.61	0.45	0.75	1.73	"	"	"	"	3.94	3.69	2.73	2.88
125	0.49	0.71[y]	1.20[y]	1.38	"	"	"	"	3.82	3.96	3.18	2.53
150	0.41	0.60	1.00	1.15	"	"	"	"	3.74	3.84	2.98	2.30
200	0.31	0.45	0.75	0.87	"	"	"	"	3.64	3.69	2.73	2.02

[y] Two sets required

Table 1 : Water lifting costs per Ha-cm for 4 different devices in US $.

TABLE 2: Days of operation required to lift various amounts of water at 9 m head

Total annual water lifted in Ha-cm	Rope and bucket (days)	Self-emptying bucket (days)	Persian wheel (days)	Diesel 1/ powered pump (days)
25	25	60	48	4.5
50	50	120	95	9
75	75	180	143	13.5
100	100	240	190	18
125	125	150 + 150	119 + 119 2/	22
150	150	180 + 180	143 + 143	27
200	200	210 + 210	190 + 190	36

1/ An 8-hour operation per working day is assumed.

2/ Experience showed that two devices are required when annual amount of water lifted exceeds 100 Ha-cm.

Appendix 1

Conversion of manpower, used to lift water, into food consumption[1]

1. Basic parameters

   a. A man is assumed to have an average work capacity of 30 W over an 8 hour working day.

   b. Human efficiency in converting food to mechanical work (beyond basal metabolism) is about 20%.

   c. A rice crop requires about 850 mm of irrigation water for a season of 120 days.

   d. The crop yield is 3 000 kg of rice per ha.

   e. The area irrigated by a single family unit is about 2 000 m^2.

   f. The efficiency of the water lifting device is 50%.

2. Calculation

   a. Energy input = 30 W.

   b. Energy delivered to water (50% efficiency) = 15 W = 1.5 Kpm/sec.

   c. Energy required to lift 1 m^3 of water 3 m high = 3 000 Kpm per m^3.

   d. Approximate discharge:

      $1.5/3\,000 = 0.5$ litre/sec $= 1.8\ m^3$/hour.

   e. Water requirement:

      $0.85\ m \times 2\,000\ m^2 = 1\,700\ m^3$

   f. Time required:

      $$\frac{1700}{1.8} = 944 \text{ hours}$$

      With 8 hours working day total labour requirement is 944/8 = 118 days which is just about as much as the 120 days irrigation season.

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[1] Adapted from Pumps and Water lifters for rural development. Colorado State University, USA 1977.

3. Food required to generate energy

a. To work at 30 W with a 20% efficiency between energy intake and output requires a man to have an energy intake of 30 W/0.2 = 150 W. This at 14.34 Kcal per min. for 1 KW equals 0.15 x 14.34 = 2.15 Kcal per min.

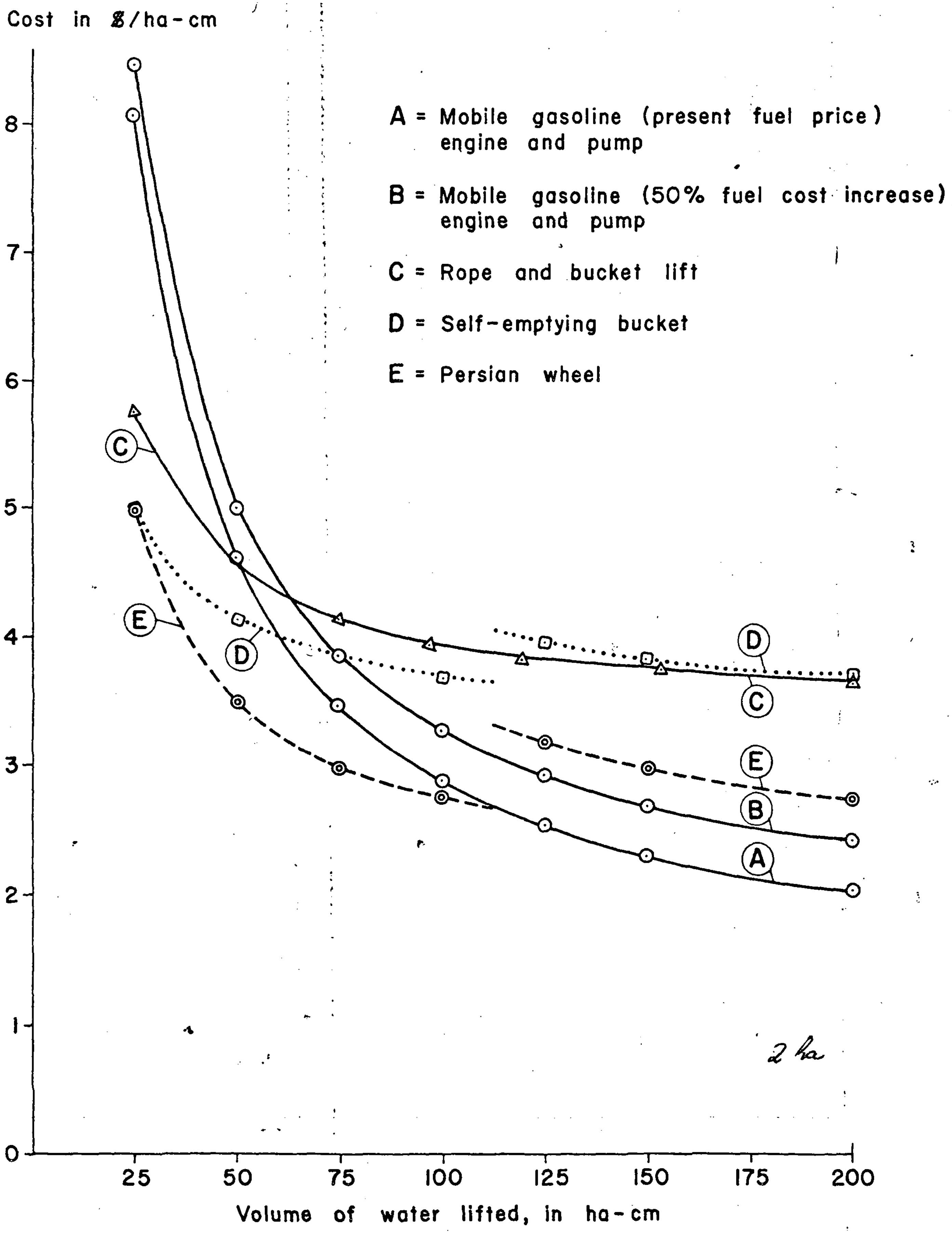
b. In 944 hours of pumping the worker will use
944 x 60 x 2.15 ≅ 122 000 Kcal.

c. At 3 500 Kcal per kg of rice this is equivalent to 122 000 : 3500 ≅ 35 kg of rice.

d. This energy input of rice for the lifting of water to grow the rice crop is thus about 6% of the expected 600 kg of rice yield.

e. The energy input required for basal metabolism is roughly the same as the requirement attributed solely to the work output, i.e. another 35 kg of rice (or equivalent).

FIG. 1: COMPARATIVE COSTS OF LIFTING WATER TO A HEIGHT OF 9m (~30 ft)



2 ha