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University of Newcastle upon Tyne
Department of Civil Engineering

Report on

WIND PUMPS -
DISCHARGE AND STORAGE ESTIMATION

Prepared by
C. PHILIP HICKLING

Submitted for the degree of
Master of Science in
Engineering Hydrology

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INTRODUCTION

It has been said that "the researcher with the appropriate problem and the ability to perceive that this or that particular tool is suited to the solution of that problem is the researcher who advances the science." (Julian, 1967). The problem to be studied in this paper is met by a farmer, rural development officer or other person who is considering the possibility of utilising wind power to provide a water supply from a nearby well or stream. He has to determine whether or not the wind is strong enough, and the technology available, to provide sufficient water at the requisite time to meet the level of demand. He needs information on the volume of storage required to ensure a dependable supply during periods of calm wind.

In this research I have studied some of the tools at present available to solve this problem, and have summarised these in Section A, with a brief discussion on the merits and failures of each method. From this basis I have developed further a suitable methodology in greater detail in Section B. The aim has been to provide a simple yet effective framework for the analysis of the wind and an estimation of storage for water pumping applications of wind power. Although the need for energy storage for wind energy utilisation is well recognised there have been few studies of methods for calculating the capacity required for a given situation. Recently a comprehensive computer model has been developed for determining the type and quantity of storage best suited for generation of electricity by wind energy (Edsinger et al., 1978) but little attention has been given by researchers to calculation of the discharge from or storage for a wind pump installation.

As will be seen only very general methods are used at present for assessing the feasibility of wind pumps. The method presented in this report has been developed by theoretical analysis and has been tested only briefly, but it is expected that the results obtained will be superior to previous work since the analysis of the wind is more detailed. Neither data nor time has been available to rigorously validate the concepts and procedures discussed in this study but most of the procedures have been borrowed from applications in other fields of research.

The most important aspect of this research has been the calculation of the pump discharge from a record of the wind regime at a site, since this is the area where most work is needed. The calculation of storage requirements from a record of discharge is well covered by many texts on water engineering and hydrology so only a very brief account of suitable methods has been included here.

C. PHILIP HICKLING
September, 1979

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My deepest love and gratitude go to Jehovah God, our heavenly Father, who provided the material for study through his beautiful creation, and who motivated and assisted me throughout this study.

SECTION A. CURRENT METHODOLOGY

CHAPTER 1. THE PROBLEM

In the developing countries of the world a large proportion of the population earn their livelihood in agriculture whilst living in small scattered villages. In such areas there is great need for small, inexpensive energy sources to increase productivity and employment in order to feed the ever growing population and reduce the migration from the rural areas to the overcrowded cities. In the wealthy nations increased energy prices, and decreased supplies and reserves are fostering a search for new supplies of energy.

Within such a background increasing attention is being given to alternative technologies to harness the potential energy of the sun, waves, wind and waste materials. In the field of windpower the wealthy nations are most interested in the generation of electricity, both on a small and large scale. In the poorer countries there is also an interest in water pumping. The years 1981-1990 have been designated the International Drinking Water Supply and Sanitation Decade by the United Nations, with the aim of provision of safe water supply and sanitation for all. Wind pumps may be one means of providing this water at a level of technology appropriate to the financial and technical constraints within the developing nations and the U.N.

The problem most often cited in the literature as the limitation to the expansion of wind energy programmes is the intermittent nature of the wind. In a comparison of a windmill in Denmark with a nuclear power station in the U.S. Sørensen has shown that the nuclear plant produces average output or more 63% of the time whilst the corresponding figure for the windmill is 40%. When the windmill data was recomputed assuming a hypothetical storage with a capacity of 24 hours average power output the power output from the windmill is distributed more evenly in time (see Figure 1) (Hinrichsen & Cawood, 1975). Thus is can be seen that the addition of even a small storage facility improves the power availability from a windmill very significantly. When using a windmill to pump water the natural method of storing energy is the storage of water.

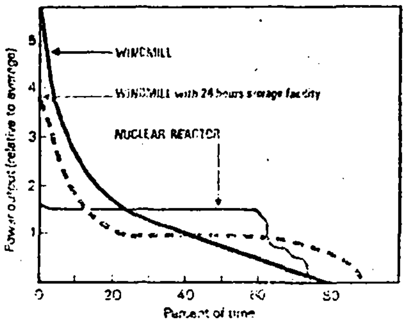


Figure 1 shows that windmills with energy storage capability can produce their "average output" as reliably as a nuclear reactor

FIG. 1 Firm power output

Having recognised the possibility of pumping water by wind power it is necessary to carry out a more detailed feasibility study for a particular location. The aims of such a study would be to estimate the demand for water during a period of time and the variable quantity of water pumped during that period and thereby to calculate the storage necessary to meet the demand by reducing variation in supply. It is impractical to design storage to meet every conceivable shortfall in supply; a balance has to be made between the cost of increasing the supply with the cost of failing to meet the demand. Similarly, in order to provide a specified supply a balance is needed between the size and cost of pump capacity and storage.

To satisfy these requirements it is not sufficient to compare average annual supply and demand, but the distribution in time must be considered since the storage requirement is a function of differences between supply and demand in real time. The time interval used in the calculation must be short enough to ensure the required degree of accuracy whilst keeping the computations within manageable proportions. A statement of the volume of storage required to balance discharge from the pump with the demand should ideally be on a probability basis. This requires the analysis of several years of wind or discharge, and demand, data.

CHAPTER 2. THE SOLUTIONS

2.1 Power in the Wind

Most of the general text books on wind power discuss windmill output in terms of power obtained from the wind (e.g. Golding, 1955; McGuigan, 1978; Putnam, 1948). The power in the wind P , can be defined as

$$P = \tfrac{1}{2} \rho A V^3 \qquad \text{(Eqn. 1)}$$

where ρ = air density

A = area swept by the blades

V = velocity of the wind (usually annual average)

Concerning units Golding has reduced the formula to:

$$P = KAV^3 \qquad \text{(Eqn. 2)}$$

by taking $\rho = 1290\ g/m^3$ and the values of K dependent on units as shown in Figure 2.

Unit of power *P*	Unit of area *A*	Unit of velocity *V*	Value of *K*
Kilowatts	Square feet	Miles per hour	0·0000053
Kilowatts	Square feet	Knots	0·0000081
Horse-power	Square feet	Miles per hour	0·0000071
Watts	Square feet	Feet per second	0·00168
Kilowatts	Square metres	Metres per second	0·00064
Kilowatts	Square metres	Kilometres per hour	0·0000137

Fig. 2 Power coefficients (Golding, 1955)

The amount of power obtained by a mill is less than that in the wind since if all the energy was extracted by the mill then the wind behind the propeller would come to a standstill. Betz (1927) showed that the maximum proportion which could be extracted is 59%. Golding claims that because of aerodynamic and mechanical losses the maximum efficiency is likely to be 40% or less whilst Dixon (1979) calculates an efficiency of 5% for windpumps from manufacturers' data.

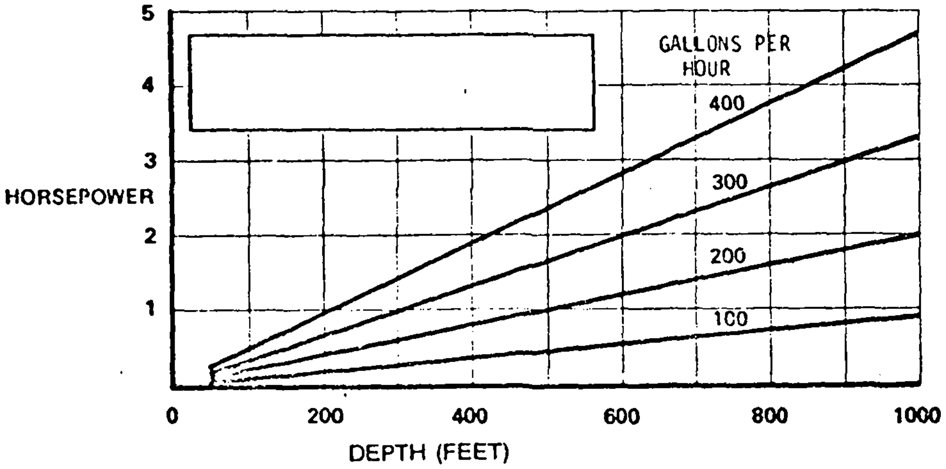
Most of the literature goes little further than this. How to calculate the amount of water pumped from the power output is not explained. The bulk of the literature written on wind power concerns the generation of electricity, and for this the power developed by a mill is sufficient.

2.2 Power to Water Yield

The Arusha windmill is designed specifically for pumping water and the construction manual (Stanley & Darrow, 1977) does describe how to match power as calculated in the previous section to water yield. They quote "a standard table for calculating the water yield that matches the horsepower being produced by a windmill", in Figure 3 but do not state how the table is derived. The authors claim that this table and a knowledge of power developed by a mill can be used to calculate the approximate size or number of mills which are required to supply a known demand.

	FLOW RATE	100	200	300	400
HEIGHT	50	.05	.10	.16	.24
	100	.09	.20	.33	.47
	200	.18	.40	.66	.94
	400	.36	.80	1.3	1.9
	600	.54	1.2	1.9	2.8
	800	.72	1.6	2.6	3.8
	1000	.90	2.0	3.3	4.7

← HORSE POWER



From bottom of well to top of discharge point for the water (top of storage tank if present).

Horsepower, Depth of Well, Flow Rate

Fig.3 Power to water yield (Stanley and Darrow, 1977)

Any known relationship of water yield to horsepower can be standard only for that particular machine since the relationship is dependent on efficiency which is affected by the aerodynamic and mechanical efficiency of design, the load matching of pump to the rotor (Dixon, 1979) and the quality of construction. A theoretical calculation of this relationship based on the potential energy of the water lifted would at the best be a very rough estimate since so many factors are involved. If matching of power to water yield is by measurement of discharge then it is more advantageous to relate this to windspeed directly than via theoretical power output.

2.3 Maximum Calm

The above method does not allow any estimation of storage requirements since it involves no analysis of the wind pattern in time, but gives only an average annual yield. Shefter (1974) gives a simple formula for calculating reservoir capacity, V :

$$V = D\,(1 + t_{calm}) \qquad \text{(Eqn. 3)}$$

where D = average daily water consumption

t_{calm} = maximum number of days with windspeed lower than cut-in speed of mill.

NB. Cut-in speed is the minimum wind speed at which a mill begins to pump.

As Shefter recognises, this method is extremely approximate and does not allow an optimisation of economic and other considerations. Neither does it guarantee that the calculated storage will be sufficient, since t_{calm} may in some locations be extended greatly by a period producing water at a rate less than demand, which would not be accounted for.

2.4 Windpump Specifications

Several of the illustrated brochures produced by the manufacturers include an unsophisticated method of selecting pump capacity, as illustrated in Figure 4. The daily water demand is estimated from a table of average water needs. The total elevation from well water level to pump discharge outlet is measured at the site. Then, using the table of mill pumping capacity, the diameter of cylinder and size of mill can be estimated. The table for the Aermotor mill in Figure 4 is based on the mill operating in a 15-20 m.p.h. wind.

The table of discharge rates for the Southern Cross mill included in Figure 5 is given with the statement:

> ". . This table applies to most districts in Australia providing that the windmill is erected on a sufficiently high tower in a good open site where the wind can reach the windwheel freely. In some districts, however, the wind is not strong, and in these positions a larger size of mill should be ordered. A larger windmill than would normally be used should be specified also where the wind does not flow for many hours a day on average. . . "

The Southern Cross manufacturers also provide a consultant's service to recommend to potential customers "the most efficient and eventually the least costly equipment for any water supply scheme." Part of the questionnaire they issue is included in Figure 5 as an illustration of the level of approach taken by the manufacturers.

The greatest failure of the procedure used by these and other companies is not to account for the actual wind speeds at the site. There is great spatial variation in wind speed and careful siting and accurate analysis of wind speed data is of great importance to ensure

HOW TO SELECT AN AERMOTOR WINDMILL

1. Estimate daily water requirements from table below. Estimate that the mill will pump the equivalent of 4 to 5 hours of full capacity out of 24, although this varies with locality.
2. Choose cylinder of diameter for required capacity.
3. Determine total elevation from low water level in well to discharge level.
4. Select size of Aermotor to handle cylinder and total elevation.
5. Select tower of height to place wheel at least 15 feet above all surrounding wind obstructions, such as buildings and trees, within a radius of 400 feet.

AERMOTOR PUMPING CAPACITY

Diameter of Cylinder (Inches)	Capacity per Hour, Gallons		Total Elevation in Feet					
			SIZE OF AERMOTOR					
	6 Ft	8-16 Ft	6 Ft	8 Ft	10 Ft	12 Ft	14 Ft	16 Ft
1¾	105	150	130	185	280	420	600	1,000
1⅞	125	180	120	175	260	390	560	920
2	130	190	95	140	215	320	460	750
2¼	180	260	77	112	170	250	360	590
2½	225	325	65	94	140	210	300	490
2¾	265	385	56	80	120	180	260	425
3	320	470	47	68	100	155	220	360
3¼		550			88	130	185	305
3½	440	640	35	50	76	115	160	265
3¾	—	730	—	—	65	98	143	230
4	570	830	27	39	58	86	125	200
4¼		940	—	—	51	76	110	180
4½	725	1,050	21	30	46	68	98	160
4¾	—	1,170	—	—	—	61	88	140
5	900	1,300	17	25	37	55	80	130
5¾	—	1,700	—	—	—	40	60	100
6	—	1,875	—	17	25	38	55	85
7	—	2,550	—	—	19	28	41	65
8	—	3,300	—	—	14	22	31	50

Capacities shown in the above table are approximate, based on the mill set on the long stroke, operating in a 15 to 20 mile-an-hour wind. The short stroke increases elevation by one-third and reduces pumping capacity one-fourth.

AVERAGE WATER NEEDS

Type	Gallons
Milking cow, per day	35
Dry cow or steer, per day	15
Horse, per day	12
Hog, per day	4
Sheep, per day	2
Chickens, per 100, per day	6
Bath tub, each filling	35
Shower, each time used	25 - 60
Lavatory, each time used	1 - 2
Flush toilet, each filling	2 - 7
Kitchen sink, per day	20
Automatic washer, each filling	30 - 50
Dishwasher	10 - 20
Water Softener	up to 150
¾-inch hose, per hour	300
Other uses, per person per day	25

WINDMILLS... LOWEST COST PUMPING POWER ON EARTH!

Fig. 4 Aermotor pump performance

The right combination of Windmill and Pump is always one which will allow the mill to work easily in light winds. The pumping table below shows the average daily supply which you can expect with each combination of windmill and pump up to the depths given. This table applies to most districts in Australia providing that the windmill is erected on a sufficiently high tower in a good open site where the wind can reach the windwheel freely.

In some districts, however, the wind is not strong, and in these positions a larger size of windmill should be ordered. A larger windmill than would normally be used should be specified also where the wind does not blow for many hours a day on the average. You will always enjoy greater efficiency from a lightly loaded mill. The easiest way to decide on the correct size windmill for your property is to use the SOUTHERN CROSS Field Service without obligation on your part.

		DIAMETER OF PUMP CYLINDER													
Size Mill		1¾"	2"	2¼"	2½"	2¾"	3"	3¼"	3½"	4"	4¼"	4½"	5"	6"	8"
6ft. "IZ"	Total Lift in Feet	73	60	51	43	37	32	27	24	19	17	15	12		
	Avg. Galls. per day	795	1040	1320	1630	1970	2345	2750	3190	4165	4705	5275	6510		
8ft. "IZ"	Total Lift in Feet	132	109	92	77	66	57	50	44	34	31	28	23	16	
	Avg. Galls. per day	875	1145	1450	1790	2165	2575	3025	3505	4580	5170	5795	7155	10305	
10ft. "IZ"	Total Lift in Feet	236	197	166	141	121	105	92	81	64	57	51	42	30	
	Avg. Galls. per day	855	1115	1415	1745	2110	2515	2950	3420	4465	5040	5655	6980	10050	
12ft. "IZ"	Total Lift in Feet	315	263	222	189	162	140	123	108	85	76	68	56	40	23
	Avg. Galls. per day	925	1205	1530	1885	2285	2720	3190	3700	4830	5455	6115	7550	10870	19325
14ft. "IZ"	Total Lift in Feet	443	370	312	265	228	197	172	151	119	107	96	79	56	32
	Avg. Galls. per day	790	1035	1310	1620	1955	2315	2730	3165	4135	4670	5235	6470	9310	16540

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.

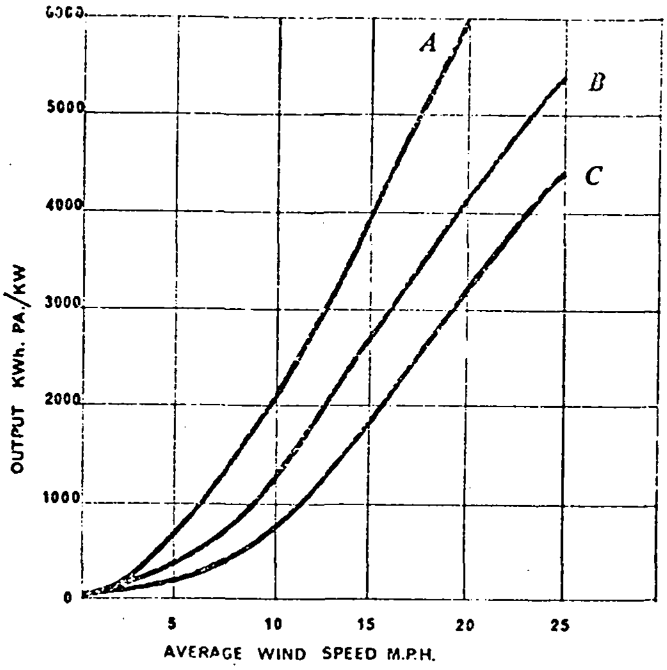
If new Windmill Head only is required—

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.

Fig. 5 Southern Cross pump performance

success of a project. Their analysis is based on one single windspeed.

McGuigan (1978) has a quick and simple method, based on windmill characteristics, which gives an approximate indication of the power potential at a site. The example is for wind generators, but the method could be adapted for wind pumps. From tests on 23 small wind generators he obtains the relationship of average annual wind speed to output for 3 mills with different rated wind speeds. Rated wind speed is the lowest wind speed for which full output is produced. The general pattern obtained is given in Figure 6, from which the estimate of the average annual output for, say, a 2 kw generator on a mill with a rated windspeed of 20 m.p.h. (curve A) on a site with an average annual wind speed of 15 m.p.h. would be 4000 KWh per year per 1 KW of generator capacity, or 8000 KWh per year for a 2 KW generator.



Annual output in kWh per generator kilowatt for various average wind speeds. Outputs for 3 wind generators with different rated wind speeds are shown. A has a rated wind speed of 20 mph, B- 25 mph, and C- 30 mph.

Fig. 6 Output from annual average wind speed (McGuigan, 1978)

The general form of these curves is controlled by the velocity duration curve. Golding (1955 B) claims it is because velocity duration curves for different sites, both at home and abroad, are of similar shape in the range of wind speeds utilised for wind power that the method is possible. The exact shape of the curve is dependent not only on velocity duration curves but also on cut-in and shut-down wind speeds, i.e. the minimum wind speed at which the mill begins to operate and the maximum wind speed at which the mill is stopped to prevent damage. Thus for the method to be accurate the actual characteristic curve of the mill being considered should be obtained.

The great advantage of this method is that one can use a cheap run of wind anemometer, read very infrequently, to measure annual run of wind and thus mean annual wind. Even so the method does not allow an estimate of the security of supply, or of the optimum size of storage required since it does not account for the temporal variation in wind speed. Thus it is only a preliminary analysis to estimate if the winds at a location are sufficient for wind power to be viable (Sencenbaugh, 1974).

2.5 Velocity Duration Curves

The wind at any location during a period can be summarised by means of a velocity duration curve, a plot of the frequency of each wind speed. The time period most frequently summarised by this process is a year or month since the calculation can then be based on hourly wind speed data. To calculate the velocity duration relationship for a period of a day or less an amenograph record is necessary.

If the velocity duration curve for a site is known it can be used to improve the estimates obtained by the methods outlined above.

The procedure is to multiply the freqeuncy of each wind speed by the discharge from the mill operating at this wind speed. This gives a more accurate estimate of the total amount of water which will be supplied during the year but, because the chronology of wind events is lost, this does not provide information on the time or length of any dry periods or the amount of storage required. If the analysis is carried out for short periods of a month or less an estimation of storage could be made (Sherman, 1976). The abstraction of data for a velocity duration curve of a short period is a laborious process and the low degree of accuracy of the results probably does not justify the work.

In the literature a velocity duration relationship is often used to calculate available power in combination with the power equation developed in section 2.1. The efficiency factor is generally kept constant but Tagg (1960), by varying the efficiency factor according to results from actual measurements on a wind generator, found that estimates of the energy produced are considerably improved and are surprisingly close to the quantity actually measured, as a total over 2,336 hours. This illustrates the advantage of using actual measured values of parameters rather than theoretical estimates.

Hutchinson (1974) has used figures of the frequency of various wind speeds and a graph of pump performance versus wind speed to calculate the annual average output per day at several different stations in Zambia. The average daily amount of water lifted over 20m ranges from 18.9 to 120m^3. He states, presumably on this evidence, that windmills are suitable for pumping water from wells, particularly since a small reservoir would usually be available. It is doubtful if such a statement could reliably be made after a general analysis of annual winds, since a more rigorous matching of supply to demand is necessary.

Wendel and Elderkin (1978) report studies which have been successful in estimating power from the Ralaigh distribution fitted to the mean annual wind as an alternative to the actual velocity duration curves when data is scarce. However, studies based on velocity duration curves, measured or synthetic, can only produce estimates of the total power produced over the period, without any indication of storage requirements, unless the period is short.

2.6 Field Study

In such a situation as Zambia where several thousand windmills are reported to be in operation (Hutchinson, 1974) a good estimation of discharge rates and storage capacities required could be made from field studies at mill sites. It is probably experience of their mills in operation in an area that allows engineers of the pump manufacturers to provide guidance to customers on the suitable size of machine and the storage necessary at a particular site. Such subjective judgement is possibly as effective as any of the above methods.

2.7 Method of Provisionability

Shefter (1974) describes a method of calculating the capacity of a reservoir based on the degree of provision of supply, as determined by

$$P = \frac{S_O + Q_T - L_T}{D_T} \qquad \text{(Eqn. 4)}$$

where P = degree of provision

S_O = volume of water stored in reservoir at beginning

Q_T = output of machine over time interval

L_T = water surplus which cannot be stored

D_T = demand during period

T = time period

The output of the machine during period T is calculated from

$$Q_T = T \int_{V_o}^{V_{max}} f(v)\, F(v)\, dv \qquad \text{(Eqn. 5)}$$

where $V_o \ldots V_{max}$ = range of wind velocities

$f(v)$ = output of pump at velocity v

$F(v)$ = chronological course of wind velocity

If the demand for water during any period T is known, then the surplus L_T can be calculated from

$$L_T = S_o + Q_T - D - S_c \qquad \text{(Eqn. 6)}$$

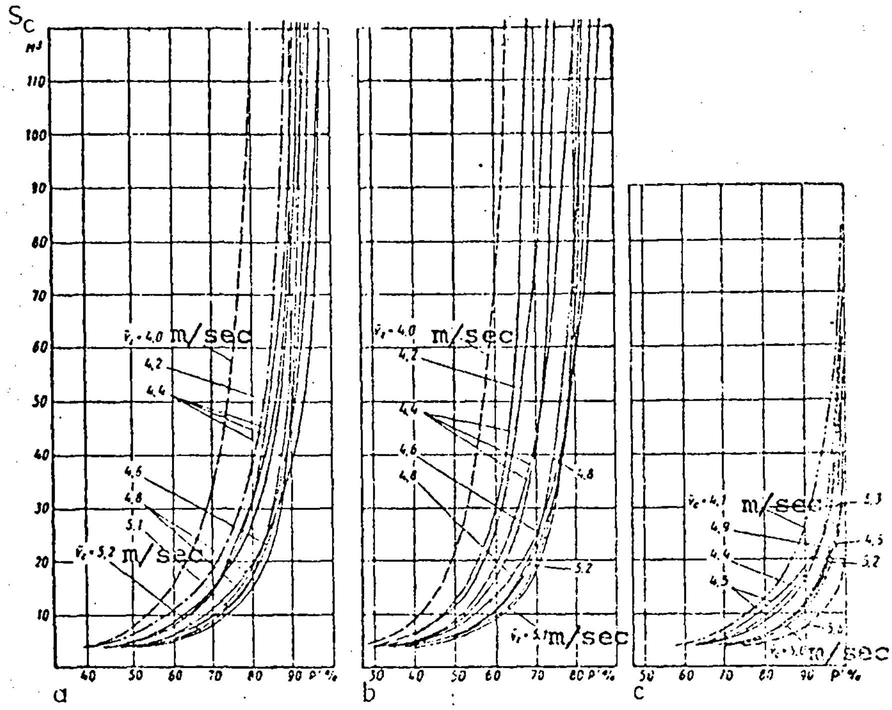
where S_c = capacity of reservoir

If provisionability as defined above is calculated for each time interval over a sufficient period then the provisionability as an average proportion can be calculated. Shefter suggests a time period T for pastoral conditions of 12 hours since stock watering and therefore complete or partial emptying of a tank, occurs twice per day.

The provisionability P has been calculated for several Russian mills under different average velocities, by varying the value of S_c with a fixed demand. Thus a relationship between S_c, P and average wind speed $\bar{V}$ has been established for each mill, as in Figure 7. Note that each graph is valid for only one value of T and D.

To estimate the reservoir capacity the following procedure is required:

1. Select T, the period of regulation.
2. Obtain information on average demand.
3. Obtain performance characteristics of the pump.
4. Obtain the mean wind velocity at mill hub height.



Required capacity of pumping wind installation reservoirs: a. VTL-3 machine (T = 1 year; D_{year} = 3800 m3); b. "Berkut" machine (T = 1 year; D_{year} = 3800 m3); c. "Vikhr'" machine (T = 6 months; D_{year} = 8.8 m3).

Fig. 7 Reservoir capacity: provisionability (Shefter, 1972)

Machine	Parameter	Period of adjustment														
		April-September v_{av} = 4.4 m/sec					October-March v_{av} = 4.8 m/sec					— Year v_{ar} = 4.6 m/sec				
		Degree of provision P' in %														
		70	75	80	85	90	70	75	80	85	90	70	75	80	85	90
TVM-3	m_w σ	8 2,4	10 5,1	15 9,7	24 21,2	40 36,3	5 1,4	6 1,9	8 2,3	10 3,9	16 8,5	6 1,6	8 4,4	11 4,5	16 8,5	26 10,0
2VPL-4	m_w σ	11 5,4	15 8,7	22 15,8	36 31,8	49 32,4	7 2,3	9 3,6	12 5,2	16 5,8	22 10,0	9 3,4	12 5,6	17 8,3	24 14,0	39 29,8
VB-3T	m_w σ	8 2,7	10 6,4	15 5,6	21 13,1	33 20,6	6 1,7	7 2,7	10 3,8	13 5,2	18 5,4	7 2,1	9 3,2	12 6,0	17 5,0	24 13,3
BNP-4M	m_w σ	6 4,2	9 3,5	12 5,9	18 10,5	29 14,4	5 0	6 1,8	8 2,5	10 3,9	14 5,0	6 1,7	8 1,7	10 4,0	14 6,3	20 11,0

DEPENDENCY OF RESERVOIR VOLUMES IN m3 ON DEGREE OF WATER SUPPLY PROVISION (ASTRAKHAN', 1950-1959)

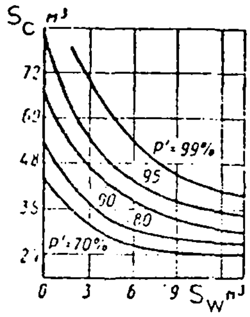
Fig. 8 Reservoir capacity: period length and degree of provision (Shefter, 1972)

5. Calculate the relationship between S, P and V as in Figure 7.
6. Determine the provisionability required
7. From the graph of (5) read off the capacity of reservoir from the mean wind velocity at the site.

There are several limitations to the method recognised by Shefter :

1. Period Length: The length of period of adjustment is of critical importance. In Figure 8 the average and variance of the calculated reservoir capacity is shown for different periods in the year, for different degrees of provision. At the 90% level for the TM3 machine the calculated capacity ranges from 40m^3 based on a 6 monthly average wind speed of 4.4 m/sec. to 16m^3 for 4.8m/sec. The capacity based on an annual average of 4.6m/sec. is 26m^3. (These 6 month and annual averages are calculated from 4 velocity readings per day).
2. Chronology: The required reservoir capacity is dependent not only on average wind speed but also on the variability of the wind in time. The sequence of working and non-working periods on a daily and seasonal basis must be studied but the method utilises only the long-term average wind speed. Note that the sequence of wind data analysed with the aid of equation 5 is only used to determine total output over the period T, which is then used to calculate provisionability (Eqn. 4). The sequence of output is not analysed as a sequence but only as a number of individual values.

3. Windmill characteristics: Each mill has a minimum wind speed at which it will begin to operate. Shefter claims, without providing evidence, that a decrease in this cut-in wind speed from 4 to 3 m/sec. decreases the required reservoir volume by 40–50%. Whilst the claim appears excessive the point is clear – the mill characteristics greatly affect the capacity of the reservoir. The analysis, however, involves only one average wind speed for the site, and not the range of wind speeds. In this respect the method is similar to that used by McGuigan, as described in section 2.4.
4. Average Value: Since, by definition, average wind velocity will only be reached or exceeded 50% of the time the norm of provisionability as calculated by the method will only be satisfied 50% of the time on average. The range of variations will however be small.
5. Losses and Well Yield: The method is the first I have described which accounts for the loss of water if discharge exceeds reservoir capacity during any period. Shefter also recognises a dependence of reservoir capacity on well yield, as affected by the reserve of water in the well S_w and shown in Figure 9, but does not include this control in his method.



Effect of water source fullness S_w and norm of mechanized water supply provision P' on the volume of a reservoir with Q_{day} = = 12 m³ and Q_{day} = = 19.2 m³ (according to the data of O. B. Khellenov).

Fig. 9 Well yield (Shefter, 1972)

Whilst the above limitations are a serious drawback to the use of the method Shefter's book is a considerable advance on any methodology currently available in the Western World since he combines a calculation of pump discharge with an estimation of reservoir capacity on a probability basis.

2.8 Chronological Analysis

The above methods using long-term average wind speeds or velocity duration relationships can only provide an estimate of the total amount of water pumped during a long period, commonly a year. The distribution of outflow during the period, of such importance in the utilisation of the water, and an optimisation of expensive reservoir capacity, is not modelled. Thus for more accurate analysis one has to study the variation of wind speed with time.

Monthly or even daily mean wind speeds may appear inadequate to operate a mill even though a considerable portion of the period may experience wind speed above the cut-in speed of the mill. It is thus necessary to use a short time interval during the analysis.

Archer (1977) carried out a chronological analysis of wind speed data for a feasibility study of windmills in Malawi. The data available was 6 mean wind speed readings per day at 3 stations and wind pump characteristics from manufacturers data in terms of work done, i.e. the amount of water lifted multiplied by the height of lift, for different wind speeds. The method of analysis was as follows:

1. A representative period of 15 months during which monthly wind speed values did not differ greatly from the mean

monthly wind speed was selected to reduce the computations being carried out manually.

2. Each of the six daily readings for the period were adjusted to wind speed at hub height (see section 4.4).
3. The wind speed values were converted to work done from the mill characteristics.
4. Values of daily and monthly work done were found by summation.
5. Storage requirements were calculated from daily work done values by mass curve analysis assuming a constant demand.

The most important limitations of his analysis, as recognised by Archer, are:

1. Only meteorological feasibility has been considered; the availability of groundwater supplies has been neglected.
2. The calculations were based on wind speed data at one station. Extrapolation of the results to distant areas is thought unwise because of local and regional variations in wind regimes.
3. The six daily readings do not define adequately the variations in wind speed and an under-estimation of the actual water pumped is expected. More detailed frequency distribution analysis is suggested as an improvement.
4. When calculating storage requirements no account was taken of other sources of inflow and outflow.

The main advantage is that chronological sequence has been retained. The methodology used by Archer has been the foundation of this present study. A more detailed critique of his method will be included in Section B in which developments and alternative techniques will be discussed.

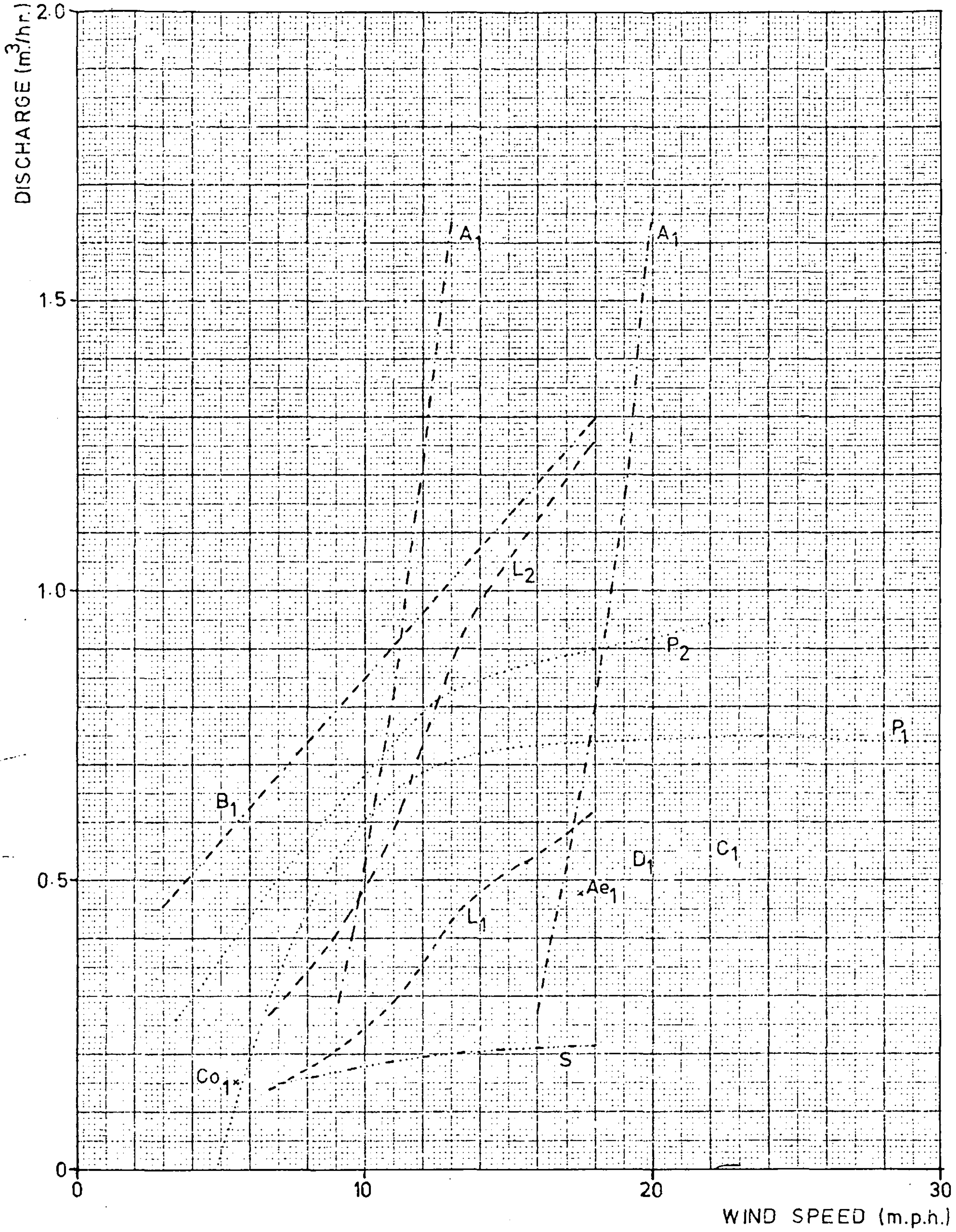
SECTION B. THE METHODOLOGY IN DETAIL

CHAPTER 3. WINDPUMP CHARACTERISTICS

The first requirement for any calculation concerning the feasibility of wind pumps is access to data. A comprehensive list of manufacturers of wind pumps, most of whom have been requested to supply data on the performance of their pumps, is included in Appendix A. The data obtained, included in Appendix B, indicates a need for a more quantitative approach to the use of wind pumps. Many manufacturers appear to be reluctant or unable to provide data on the relationship of output to wind speed which is required for a chronological analysis of wind speed variations. The majority of manufacturers provided information on the quantities of water pumped at only one wind speed - often an approximate speed averaged over an indeterminate length of time.

3.1 Variation of Discharge with Wind Speed

The data in Appendix B of variation in discharge with wind speed has been summarised graphically in Figures 10 and 11. Since power of the wind increases proportionately to the cube of the wind speed it is expected that discharge would also increase as the cube of the wind speed. This theoretical relationship can be seen in Figure 11 as the curve for the I.T.D.G. mill under 60m. head. However some mills, such as the Sparco in Figure 10, exhibit the opposite effect of smaller increases in discharge as wind speed increases. It seems likely that the relationship should be cubic at the lower velocities just above the cut-in wind speed, but should decrease at higher velocities as discharge is limited by the capacity of the pump and rotor design. The Sparco pump is efficient

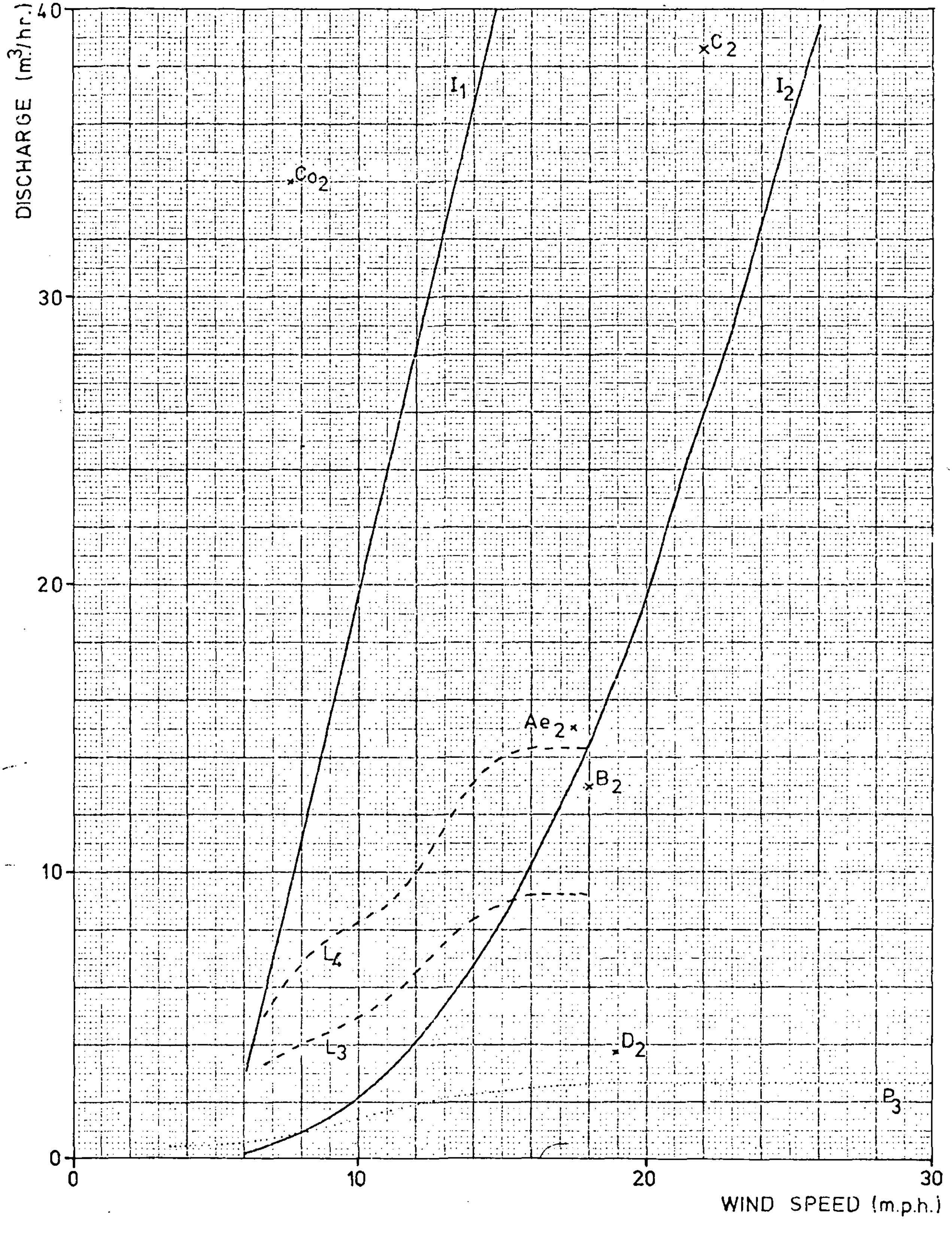


KEY

SYMBOL	MAKE	MODEL	SIZE			ELEVATION	PAGE
			MILL (ft)	STROKE (in)	CYLINDER (in)	(ft)	
Ae_1	Aermotor		6		1.75	130	11
Ae_2	"		8-16		S	14-50	11
-·-·-·- A_1	A.W.P.	12				50	105
A_2	"	16				500	105
- - - - - B_1	Ballyhale	SS1	9				106
B_2	"	SS4	18				106
C_1	Climax		6	5.75	1.75	100	104
C_2	"		18	15	15	10	104
Co_1	Comet		8		1.75	85	100
Co_2	"		30		18	12	100
D_1	Dempster		6	5	1.575	120	103
D_2	"		12	12	4	83	103

...continued

Fig. 10 Wind pump performance



KEY (continued)

	SYMBOL	MAKE	MODEL	SIZE MILL (ft)	SIZE STROKE (in)	SIZE CYLINDER (in)	ELEVATION (ft)	PAGE
————	I_1	I.T.D.G.					20	98
	I_2	"					200	98
– – – –	L_1	Lubing	P35-215				130	101
	L_2	"	P50-95				66	101
	L_3	"	P40-1.4				41	102
	L_4	"	P50-1.4				23	102
…………	P_1	Pumpoent	111,222					103
	P_2	"	9090/2					103
	P_3	"	P300					103
–·–·–	S	Sparco						97

Fig.11 Wind pump performance

in that it is operating at near full capacity for a great proportion of the normal range of wind speeds.

3.2 Effect of Mill Size

The wind has many short period fluctuations in speed and direction which can be seen on any amenograph trace. This turbulence is of small spatial extent and has little effect on a large mill with a large area swept by the blades. A large mill is also less responsive because it has greater intertia. A small mill, and especially an anemometer, will be more responsive (Juul, 1956). Thus a small mill will have characteristics which vary dependent on the gustiness of the atmosphere. Such variations are likely to be small, and can be ignored.

3.3 Effect of Head and Pump Size

Static head is defined as the depth from well water level to pump outlet plus the pressure at the outlet. Other things being equal discharge will decrease as head increases, but not as a linear relationship. The energy supply from a mill is determined by the mill and wind, whilst more energy is required to pump from a greater depth. A deep well requires a narrower diameter pump and pipe than a shallow well. The effect of pump size and head on discharge rates can be seen clearly from Figure 12. This graph has been obtained by actual measurements conducted by the University of Western Australia in the 1950's on mills manufactured by M.B.P. At high wind speeds pump size greatly affects discharge, but a difference in head of 26 feet has no effect. At low wind speeds both pumps have the same discharge rates for equal head, but rates differ for differences in head.

3.4 Summary

From the above it can be concluded that since mill wheel diameter, pump diameter and stroke length and head all affect the relationship of discharge to wind speed careful presentation of the data by the manufacturer is necessary. From the information at present available, as in Figures 4 and 5, it is very difficult to determine the effect of varying one parameter.

For any particular feasibility study the static head would be fixed according to the depth to the water table, the demand rate and the well yield. The pump diameter required is dependent mainly on well depth, but within a range set by the depth, pump diameter, stroke length and mill wheel diameter will have to be studied by means of an optimising routine balancing the cost and value of the water obtained. The present study concentrates on developing a method to calculate the discharge from a wind speed record, for any one particular pump combination whose characteristics are known. Only then can the optimum choice of parameters for a particular project be evaluated.

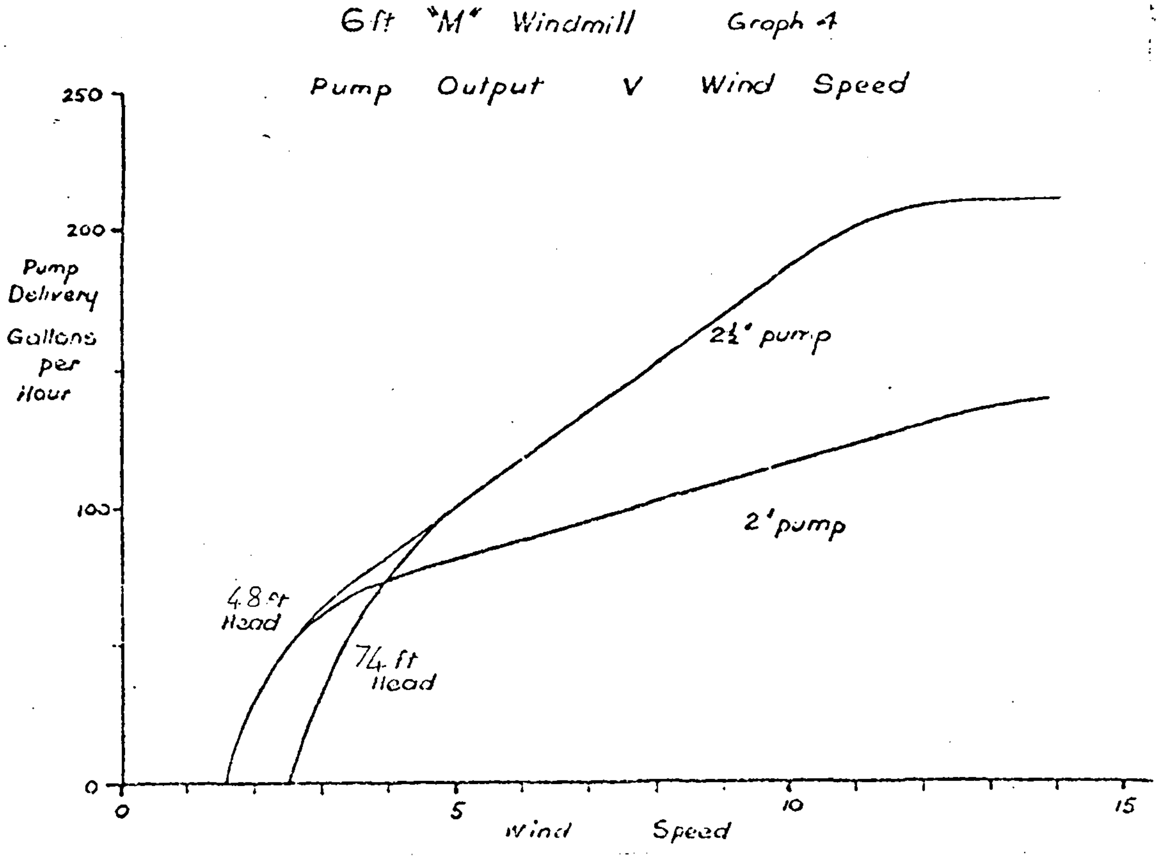


Fig. 12 Wind pump peformance - pump size and head (M.B.P. Ltd.)

CHAPTER 4. WIND ANALYSIS

4.1 Variation in Wind Speed

Two types of instruments are commonly used to measure wind speed. The most sophisticated is an amenograph which makes a continuous recording of the near instantaneous wind speed from hemispherical cups rotating with the wind or from a difference in pressure created in a horizontal tube facing into the wind. The alternative is a cup anemometer with a counter recorder from which the run of wind is read at fixed intervals. At some sites wind records are based on an estimation of wind speed from the effects on surrounding objects such as trees, water surfaces and smoke plumes, as according to the Beaufort scale.

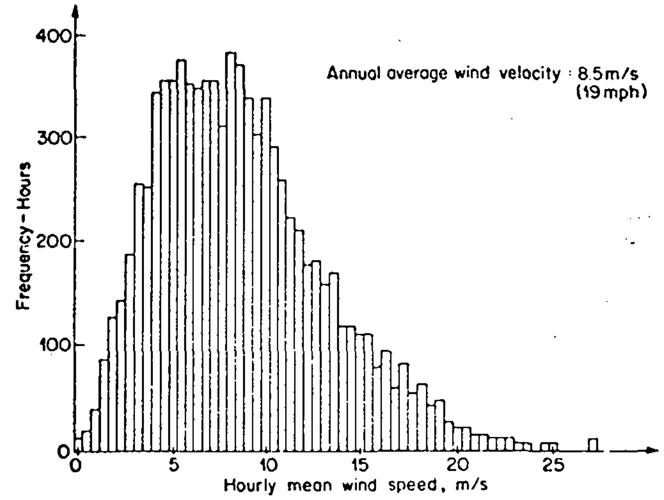
It is impractical to analyse continuous wind data for more than a few days. A gusting wind may change speed by 50-100% in 0.5 seconds (Golding, 1955b) so the abstraction of average wind speed over a period is desirable. Due to the cubic law of power in the wind, high wind speeds are of more importance than low wind speeds in power conversion by a windmill. However wind speed records are normally averaged on a linear scale with equal weights given to low and high speeds.

The period of averaging is of critical importance. A short time interval such as an hour will give greater accuracy than a period of a day or month. By analysis of the time scales associated with fluctuations of wind speed Van der Hoven (1957) showed that between 0.1 and 10 hours there are no significant fluctuations. Below 0.1 hours fluctuations known as gusts occur whilst above 10 hours fluctuations due to the passage of air masses occur. If wind speed is averaged over periods within this spectral gap the results will be reliable (Harris, 1968). The most usual period of averaging wind data is 1 hour, although many developing countries obtain averages over several hours.

The distribution of wind speed is highly skewed with infrequent high wind speeds. A typical distribution of hourly mean wind speed readings can be seen in Figure 13, the shape being similar to the frequency distribution of instantaneous readings. Thus calculations of wind power from average wind speeds are likely to underestimate the work done by the wind, if output varies with speed^3.

Several alternative approaches are available to reduce the underestimation of wind energy due to the averaging of data:

1. Electricite de France have used a wind power meter consisting of a vertical axis wind motor pulling a small AC generator whose output is recorded. Such an instrument allows direct measurement of wind power (Juul, 1956).
2. A similar solution would be to connect a computer to an anemometer to convert near-instantaneous values of wind speed to discharge and to calculate running totals. Sittler (1976) was developing an analogue computer to calculate the time integral of the cube of wind speed, thereby providing a better estimate for total energy than the one derived from estimates of hourly averages.
3. The use of average wind speed values would be of no problem if the performance characteristics used in the calculations included the relationship of discharge to wind speed averaged over the same period. There would probably be considerable scatter of the data since many different combinations of instantaneous speed can result in the same average value. At present the performance data



Wind Speed Frequency Histogram for Magdalen Islands, May 1, 1966 - April 30, 1967.

Fig. 13 Wind speed frequency histogram

provided by the manufacturers does not give any indication of the length of period of averaging.

4. Archer (1977) suggested fitting of a frequency distribution to the data to provide a basis for estimating the frequency of higher wind speeds from the mean wind speed.

5. A wind speed record is a time series, or chronological sequence of observations which can be assumed to comprise a trend component, a cyclic or periodic component and a stochastic component. The methods of autocorrelation analysis or spectral analysis are frequently used to separate the components of a time series (Price, 1976). The first method compares the time series with itself at varying lags (Box & Jenkins, 1970) and the second portions the total variance of the series into a number of frequency bands (Adamowski, 1971). Spectral analysis is the method most frequently used to analyse the turbulence of the atmosphere, and is described in detail by Lumley and Panofsky (1964). A general description of time series analysis is given by Matalas (1967).

A simple method of analysis proposed by Sittler (1976) is to assume that the periodic component has one significant harmonic which behaves as a sinusoidal variation superimposed on the mean. This suggests a relation of the form:

$$V = \bar{V} + \gamma \sin \omega t$$

where V = instantaneous wind speed

$\bar{V}$ = average wind speed

γ = amplitude of variation in speed

ω = angular frequency of variation

Sittler, by cubing and integrating this relationship, calculated total wind energy per hour. The method involves the measurement of both wind speed and amplitude of variation for each interval, but as an alternative it should be possible to use an average value of amplitude calculated from a sufficient number of hourly values.

6. Most of the variations in wind speed which are averaged to give a mean value are due to very short period fluctuations. A mill, particularly a large mill, is not fully responsive to such fluctuations and will thus tend to operate in response to the wind speed averaged over several minutes. For this reason a sixth approach to the problem is to ignore it, on the grounds that the error is of small magnitude when compared with other errors and approximations in the method.

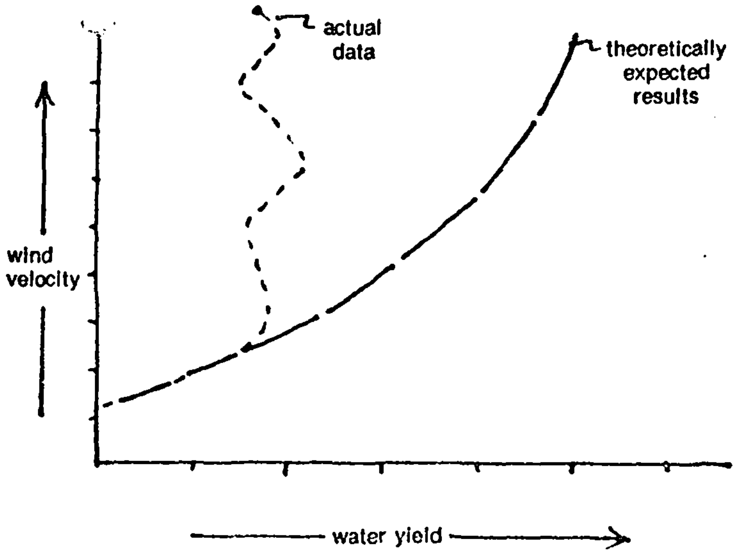
The best solution is probably to obtain the discharge to wind speed relationship for hourly average values. A test of this is required,and if successful the pump manufacturers should provide the required data. However, until contrary evidence is produced it is suggested that the sixth approach is suitable in the preliminary stages of developing the method, and thus no correction will be made for the length of averaging period.

Since a period of one hour lies well within the spectral gap, is short enough to contain the worst effects of a storm, and is the most common period of data abstration, this is chosen as the length of averaging period, when possible. Unless account is going to be taken of the effect of the cubic power law when estimating the output of mills it is not recommended that the averaging period be increased above a few hours. Rangarajan and Desikan (1978) found that analysis of mean hourly wind speed produced an estimation of energy 50-60% higher than an analysis of 24-hourly data. Further analysis of the effect of the length of averaging period is required.

4.2 Variation in Wind Direction

The direction of the wind is also a highly variable parameter. A horizontal axis windmill must be turned into the wind to extract the maximum power from the wind. This is achieved normally by means of a tail fin. Vertical axis mills do not need to be orientated into the wind since the wind blowing from any direction exerts a force on the sails.

The lag between change in wind speed direction and change in orientation of a mill is likely to be sufficient to create a significant loss of power and decrease in output. Little attention is given to this factor of wind utilisation in the literature so it is impossible to predict the magnitude of effect, which would vary as the range and sequence of direction changes vary in space and time. On site observation in Tanzania suggested that wind direction changed about 60 degrees every 15 seconds which resulted in a considerable difference between theoretical and actual discharge rates (Figure 14) (Stanley and Darrow, 1977).



Water Pumping Yield for Given Windspeeds. Data Generated by a 21' Diameter Fan-Bladed Windmill Imported Into Tanzania

Fig.14 Theoretical and actual performance (Stanley and Darrow, 1977)

It is expected that this will compensate for the underestimation due to averaging period. Further study of this important factor is necessary to verify the conclusion that its effect should be ignored to simplify calculations.

4.3 Wind Data Preparation

For a feasibility study it is necessary to obtain wind speed data averaged over one or several hours for the site under consideration. It is most unlikely that wind records will be available for the site and in developing countries where meteorological stations are limited in number the nearest station may be a great distance from the site. Extrapolation of wind data from one site to another can never be satisfactory since the surface winds are affected very greatly by the physical surroundings. When necessary the best method of extrapolation is to obtain short-term records over 6 months or less on the site and correlate these with long-term records at the nearest meteorlogical station (Pal and Parker, 1978). Care must be taken to ensure that the correlation is valid for all wind directions or is an average for all directions.

The most detailed method of correlation is to establish a relationship between average values at the site with those at the nearby station. The correlation must be established for values averaged over equal length periods. Problems will occur when the characteristics of the two wind regimes are different, as would occur when comparing flat coastal sites with a steady wind to sites in rough country with turbulent wind. Such problems can only be resolved in an actual study, but one possible method is to base the correlation on longer term averages such as over one week. Having thus obtained a long record of on-site weekly average wind speed the finer detail can be obtained by correlation between on-site weekly average and on-site hourly average.

When wind analysis is to be based on velocity duration curves a simpler method of correlation can be utilised. This can be based on the relationship of the velocity duration curves for the site and met. station based on a short period of simultaneous readings. The transformation needed to change the met. station duration curve to the site duration curve can then be applied to the duration curve from the full record of the met. station. Thus the data is reduced to a velocity duration curve before correlation, and unnecessary computation is avoided.

In addition to extrapolation of wind data interpolation is frequently necessary to fill gaps in the record due to failure of the equipment, loss of records, human errors or other causes. Allowance must then be made for diurnal and seasonal variations in the wind.

The length of data required very much depends on the method of analysis to be used. Corotis, Sigl and Cohen (1977) found that one to two years of data was sufficient to estimate the long-term seasonal wind velocity to within an accuracy of 10% with a confidence level of 90% (Wendell and Elderkin, 1978). Thomas (1949) found that annual and monthly averages of mean hourly wind speed were relatively constant and could be estimated reasonably accurately from one year of data. Although the shape of velocity duration curves will vary more than long-term averages Sørensen (1976) is possibly justified in estimating storage from a velocity duration curve based on one year of data.

However, analyses of shorter period averages must have a correspondingly longer period of data since the variance of short period averages is greater than of long period averages. Shellard (1967) found that ten years of data was necessary for probability analysis up to return periods of 200 years of very short period gust speeds used for structural design but that a longer record was of little advantage. Sherlock (1958) concluded that 40-50 years of record was necessary.

Reservoir capacity is generally determined by a probability analysis of inflow records to determine supply rates and storage requirements. The time from the start of depletion to the minimum drawdown before refill begins is known as the critical period; in Britain reservoirs are frequently designed with critical periods reaching up to 18 months. To provide a large sample of such periods for probability analysis a long record is required. Since large reservoirs are usually designed with a very small probability of shortfall in meeting demand a long record is also required to provide a large sample of extreme droughts. McMahon and Codner (1972) concluded that 34 years of record of river flow would be sufficient for estimating storage capacity, although this would increase for variable river flow.

The critical period controlling reservoir capacity for wind pumps is likely to be of the order of one week to a month, because the withdrawal rates are small, the capacity of the reservoir will be small, and the variability of supply will be small since in most localities the wind blows nearly continuously. Wind pumps are unlikely to be feasible when long-term storage from a 'wet' windy season to a 'dry' windless season or from a 'wet' to a 'dry' year is required because the supply rates during the windy season are insufficient to recharge large reservoirs whilst the losses from any reservoir due to seepage and evaporation are large. Wind pumps are most suitable for areas with a fairly continuous wind and with only short periods of low wind during the season of maximum demand. It is concluded that a record length of between three and eight years should be sufficient for estimation of storage capacity for a wind pump in most wind regimes, although a longer record record is desirable. A more precise judgement cannot be made without an analysis of a long period of actual wind records.

The possibility of synthesis of a wind record or discharge record to extend the length has not been considered in this study. For a discussion of techniques for simulating stream flow and other time series see Hurst (1965), Linsley, Kohler and Paulhus (1975) or Woolhiser (1973).

4.4 Adjusting Wind Speed for Height Variation

The atmosphere is a viscous fluid and the ground therefore exerts a frictional drag on the wind resulting in an increase in wind speed with increasing height above the ground. This effect, known as wind shear, makes it necessary to adjust wind speed measurements to the height of the mill.

Wind speed measurements are generally made at a standard height of 10m (33 ft.) above ground in an open situation. If there are surrounding obstacles such as buildings or trees disturbing the flow of air the height is increased to clear these disturbances, but an effective height of 10m is maintained if possible (Met. Office, 1969).

For smaller mills such as used for pumping it is sufficient to use the height of the centre of the rotor as the reference height for the adjustments. The variation in wind speed within the area swept by the rotor can be ignored since the effect on pump output will be negligible.

Two alternative methods are frequently used to adjust for wind shear. The earliest historically, probably originated by Archibald in 1883, is a power law of the form:

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^p \qquad \text{(Eqn. 7)}$$

where V_1 is wind velocity at height h_1, V_2 at h_2, and p is an exponent whose value depends mainly on surface roughness. The second method is a logarithmic law, proposed by Helman in 1915, with the formula

$$V_2 = V_1 \left(0.2337 + 0.656 \log_{10}(h_2 + 4.75)\right) \qquad \text{(Eqn. 8)}$$

where h_1 equals 10m. A more detailed equation for the log law has the formula

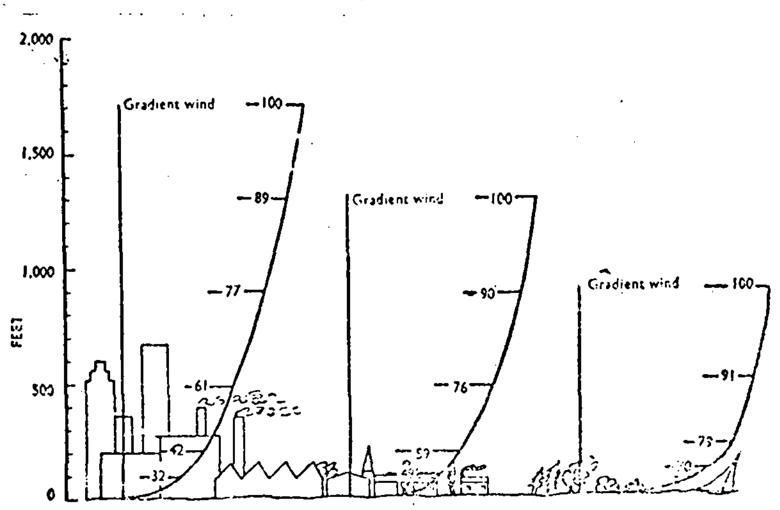
$$V_2 = V_1 \frac{\ln(h_2/z_0)}{\ln(h_1/z_0)} \qquad \text{(Eqn. 9)}$$

where Zo is the roughness length of the surrounding area.

There is no general agreement over the correct law to use to adjust wind speed at one height to that at another (Harris, 1968). The relative merit of the three methods is dependent on their ability to model the vertical gradient at a particular site with the minimum of data which is likely to be available for the location. The exact shape of the vertical gradient at a site is dependent on several factors:

1. Surface Roughness

Since wind shear is caused by friction between the wind and the surface the principal factor which has to be included in the calculations of wind gradient is the roughness of the surface surrounding the site. This effect is illustrated in Figure 15.



VARIATION OF MEAN WIND VELOCITY PROFILE WITH SURFACE ROUGHNESS

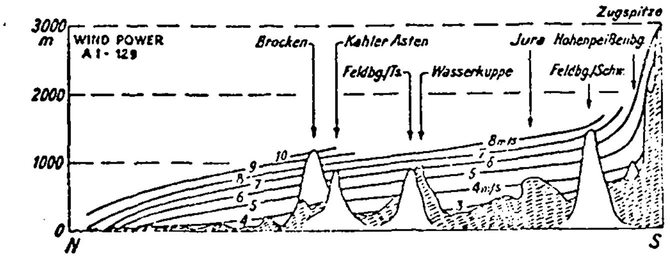
Fig. 15 (Davenport, 1960)

In the power law the value of the exponent is primarily dependent on surface roughness. Its value can be found either by on-site measurement of the gradient or more practically by reference to previous studies. In this way a value of p can be obtained which accounts for the effect of surface roughness.

In the simplified log law the wind gradient is dependent only on height and thus does not include any measure of site characteristics. Despite this shortcoming the method is used for general studies of the wind (e.g. Met. Office, 1969; U.S. Dept. of Agric., 1965) and for windmill studies (Archer, 1977).

The more complex log law includes a parameter, Zo, of roughness length whose value, like the exponent of the power law, is dependent on surface roughness. Values for Zo are well tabulated by Sutton (1953) and Deacon (1947). The relationship between values of Zo and p has been obtained by Davenport (1960) from analysis of published data for 19 different sites.

It should be noted that surface roughness in this context when discussed in the literature refers to obstruction on the scale of vegetation type or man-made features such as buildings. Roughness on the scale of topography has a considerable effect on wind-speed (Figure 16) but its effect on wind shear is not commonly discussed with reference to power studies.



Ascent of the lines of the same annual average of the wind velocity in higher altitudes in northern-southern direction from the North Sea to the edge of the Alps. (German Meteorological Service).

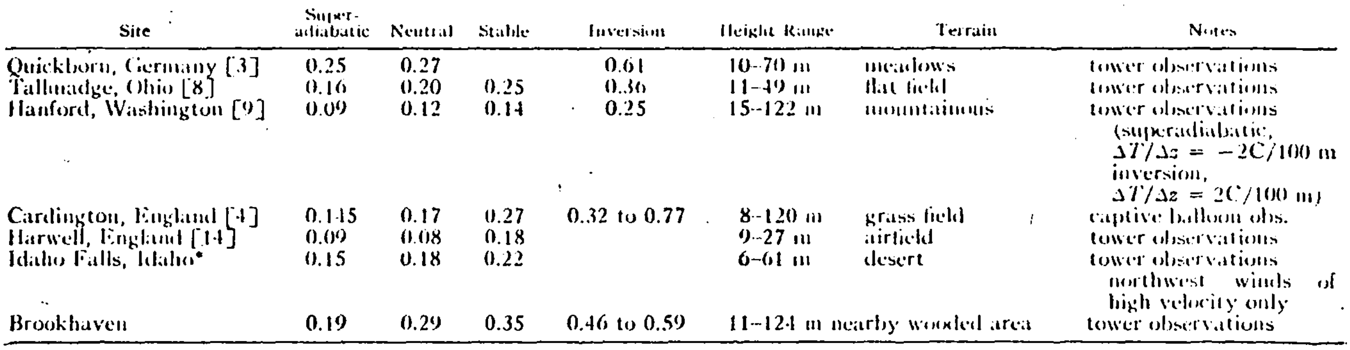
Fig. 16 Topographic effect on wind speed (Hutter, 1956)

Topographic control on wind shear will be ignored since literature is not available and actual measurements of shear are outside the scope and aims of the project. Roughness on the scale of vegetation will be considered further.

2. Atmospheric Conditions

The effect of friction slowing the surface layers of the wind is transmitted into upper layers by the process of turbulent mixing. Thus in addition to ground roughness itself the stability of the atmosphere influences wind gradient. The atmospheric terms unstable, neutral, stable and inverted are descriptions of the equilibrium of the atmosphere. If a parcel of air at a height is forced to rise, such as over a hill, it cools adiabatically, without heat being added to or removed from it. The surrounding air has an environmental lapse rate (E.L.R.), which is the rate of fall in temperature with increasing height. If the rising parcel of air cools at a slower rate than the E.L.R. then it becomes warmer and lighter than its surroundings and has a tendancy to rise. This condition is unstable and causes a mixing of the atmosphere and is said to have a superadiabatic lapse rate. If the parcel cools at the same rate as the E.L.R. it has no tendancy to move and the atmosphere is in neutral equilibrium and has an adiabatic lapse rate. If the parcel cools faster than the E.L.R. it is denser and has a tendancy to revert to its original position, and is thus stable, with a super-adiabatic lapse rate. An inversion is very stable.

The effect of lapse rate on wind shear is allowed for in the power law by altering the value of p. De Marrais (1959) analysed wind speed data from the 125m high meteorological tower at Brookhaven National Laboratory, U.S.A., and found that p decreases with decreasing stability. Representative values of p for different atmospheric conditions at several sites are given in a table by De Marrais (Figure 17).



Site	Super-adiabatic	Neutral	Stable	Inversion	Height Range	Terrain	Notes
Quickborn, Germany [3]	0.25	0.27		0.61	10–70 m	meadows	tower observations
Tallmadge, Ohio [8]	0.16	0.20	0.25	0.36	11–49 m	flat field	tower observations
Hanford, Washington [9]	0.09	0.12	0.14	0.25	15–122 m	mountainous	tower observations (superadiabatic, $\Delta T/\Delta z = -2C/100$ m inversion, $\Delta T/\Delta z = 2C/100$ m)
Cardington, England [4]	0.145	0.17	0.27	0.32 to 0.77	8–120 m	grass field	captive balloon obs.
Harwell, England [14]	0.09	0.08	0.18		9–27 m	airfield	tower observations
Idaho Falls, Idaho*	0.15	0.18	0.22		6–61 m	desert	tower observations northwest winds of high velocity only
Brookhaven	0.19	0.29	0.35	0.46 to 0.59	11–124 m	nearby wooded area	tower observations

Fig. 17 Variation of p with stability

It is accepted by many authors that the simplified log law is suitable only for adiabatic conditions (Munn, 1966). When the lapse rate is not adiabatic buoyancy forces must be considered, but the simple log law does not allow this. The more complex log law can account for the effect of atmospheric stability either by altering the roughness length as argued by Sutton (1936) or by introducing additional parameters as proposed by Sverdrup (1939).

3. Wind Direction

The vertical gradient of the wind speed at a location will vary with the direction of the wind where the roughness of the ground varies around the compass. Inclusion of this detail would considerably complicate the analysis since simultaneous study of wind speed and direction would be required. The benefits of the additional accuracy do not justify such labour, so the choice between the power or log law is not affected by this factor.

4. Wind Speed

As wind speed increases the turbulence increases and facilitates greater vertical transfer of wind shear. De Marrais analysed the effect of wind speed on the exponent in the power law. He found that during unstable conditions p increased with wind speed, but during stable conditions the effect was less marked at low wind speeds, and even reversed at higher wind speeds. Davenport (1960) cites data presented by Collins (1955) that p increases by approximately 0.02 for each 10 m.p.h. (4.5m/s) increase in wind speed. Justus and Mikhail (1976) proposed a formula for calculating the value of p which models the change with wind speed:

$$p = \frac{0.37 - 0.0881 \ln \overline{V}_1}{1 - 0.0881 \ln(h_1/10)} \qquad \text{(Eqn. 10)}$$

Using this relationship for a height H_1 of 20m.

if $V_1 = 5$ m/s, $p = 0.23$

$V_1 = 10$ m/s, $p = 0.17$

$V_1 = 20$ m/s, $p = 0.11$

This relationship has not been independently verified and gives results as calculated above in direct contradiction to those measured by De Marrais and Collins. The calculation of the value of p according to the formula above is also not compatible with an estimation of p based on roughness or stability and is not considered suitable for use until verified and further developed.

There appears to be no method developed in the literature for adjusting the log law for wind speed although it would be possible to develop a relationship to adjust the height correction of wind speed whether the log or power law is used.

However, the effect of wind speed on the vertical gradient of wind speed appears to be relatively small as compared with roughness and stability. Until further studies have been conducted, and until the different conclusions outlined above are more fully understood, it is judged both necessary and acceptable to eliminate this factor from the analysis.

5. Season

By comparing wind gradients at different seasons during periods with equal lapse rates De Marrais concluded that there is little seasonal control on the gradient other than that due to lapse rate. Other authors have not reached the same conclusion but the change of lapse rate with season is usually ignored. Figure 18 (p.49) illustrates the correlation between seasonal changes of p and lapse rate as found by Carruthers. It therefore seems suitable to exclude seasonal variation in p from the procedure.

6. Height Range

By equating equations 7 and 9 Panofsky (1977) has shown that the value of exponent can be calculated from

$$p = \frac{\ln \dfrac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}}}{\ln \frac{h_2}{h_1}} \qquad \text{(Eqn. 11)}$$

This illustrates that the exponent is dependent on the roughness length and the height interval over which the law is to be applied. However for most practical applications the variation in p with height range is not important (Davenport, 1960).

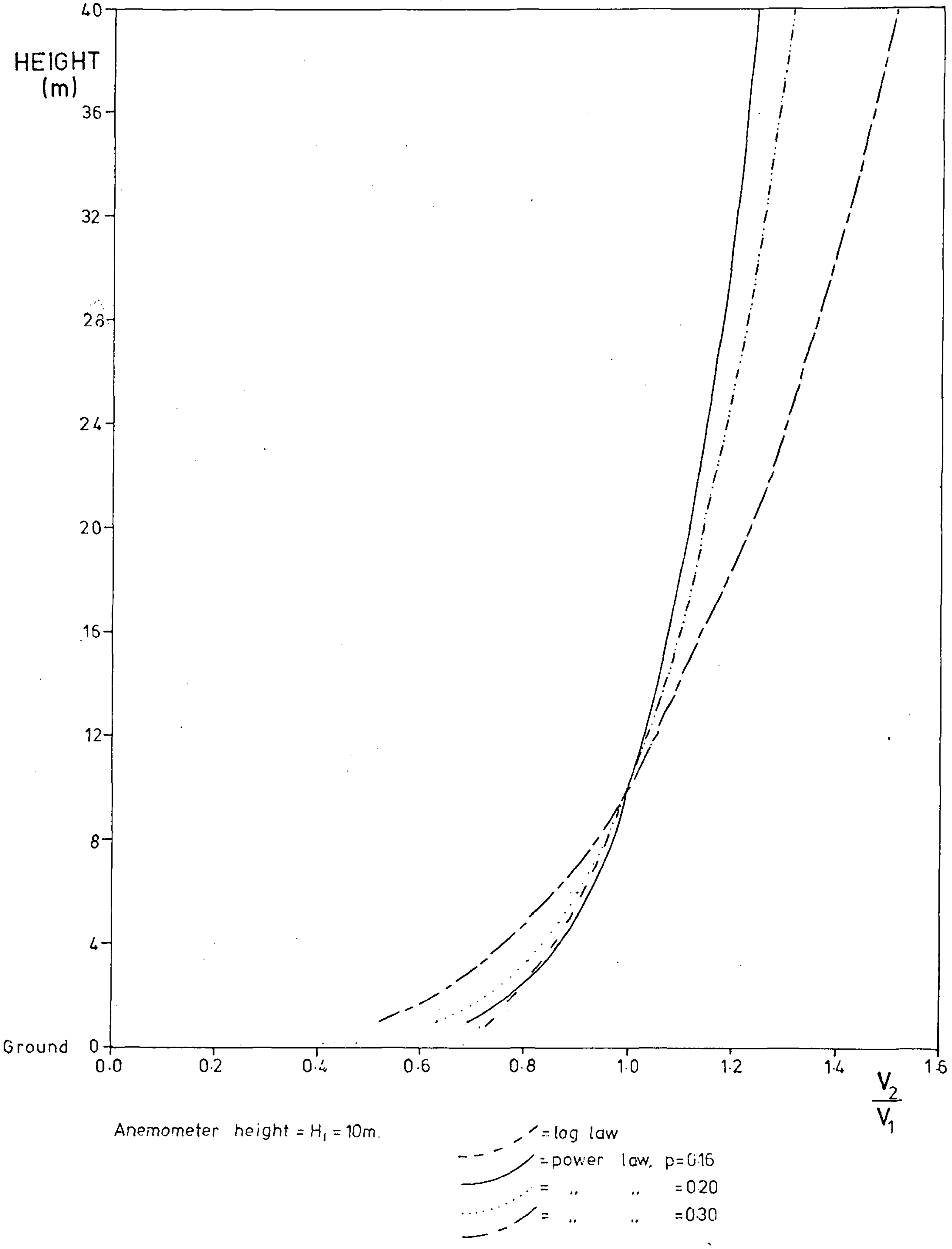
Both the log and power law can be applied for heights ranging from within a meter or two of the surface to several hundred meters.

Evaluation of the Three Methods

The main factors controlling the pattern of the vertical wind speed gradient are surface roughness and atmospheric conditions, and possibly wind speed. It is not clear from the experimental evidence and conclusions drawn in the literature which of the three methods most accurately models these controls.

The simplified log law is rejected as being too general except when no information on the site is available. The choice is thus between the detailed log law and the power law.

The greatest interest in the wind gradient is in prediction of high wind speeds for the design of tall buildings. Simiu and Lozier (1975) quote several authors as claiming that the detailed log law is a superior representation of high mean wind speed profits in the lowest few hundred metres of the atmosphere. This is because high winds most frequently occur under neutral atmospheric conditions which is the condition modelled best by the log law. Lettau (1962) however claims that neutral conditions do not always imply a log profile.

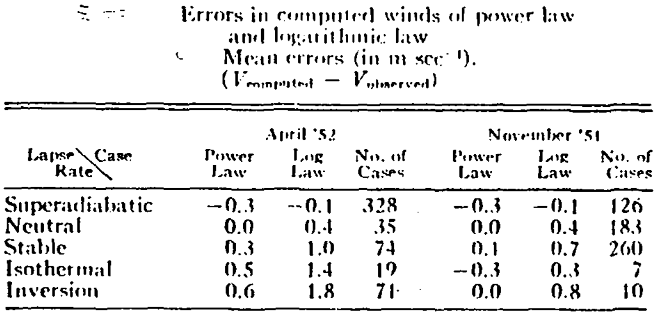


Anemometer height = H_1 = 10m.

Fig. 19 Wind speed gradient profiles

The shape of the wind speed gradient modelled by the log law, and the power low for different exponent values, is illustrated in Figure 19.

De Marrais compared observed profiles with profiles calculated by both the log law and the power law. His results (Figure 20) indicate that the power law is more accurate than the log law for all conditions except those with a super-adiabatic lapse rate. He observes that a systematic error exists in the results of the log law which could be removed by an additional parameter based on lapse rate. However the power law gives as good a representation of the wind profile with less work.



Errors in computed winds of power law and logarithmic law
Mean errors (in m sec^{-1}).
($V_{computed} - V_{observed}$)

Lapse Rate \ Case	April '52 Power Law	April '52 Log Law	April '52 No. of Cases	November '51 Power Law	November '51 Log Law	November '51 No. of Cases
Superadiabatic	−0.3	−0.1	328	−0.3	−0.1	126
Neutral	0.0	0.4	35	0.0	0.4	183
Stable	0.3	1.0	74	0.1	0.7	260
Isothermal	0.5	1.4	19	−0.3	0.3	7
Inversion	0.6	1.8	71	0.0	0.8	10

Fig. 20 Errors in power and log law

The detailed log law, with additional parameters, is used for detailed studies of the atmosphere (e.g. Lumley and Panofsky, 1964; Munn, 1966), but the power law is frequently used by engineers to approximate the wind profile (e.g. British Standards Institution, 1972; American National Standard, 1972; Sachs, 1978).

Thus the power law would appear to be the most appropriate tool for adjusting wind speed readings to the speed at mill height.

Application of the Power Law

The value of the exponent in the power law must be determined from the roughness of the surroundings and varied according to atmospheric conditions. No single value of p would suit all conditions and neither will the application of a general law model conditions at one time exactly. We seek an approximation which will provide sufficient accuracy with the minimum of labour. The actual measurement of wind gradient and values of p will not be possible at the proposed site for a windmill; values of p will therefore have to be estimated from the literature. A small change in p from 0.16 to 0.20 in a calculation based on a measured wind speed of 10 m/s at 10m would result in a 0.9% difference in calculated wind speed at 8m. For the I.T.D.G. windmill pumping under 60m head this would result in a 2.7% difference in calculated discharge. Whilst this range of error is not large when compared with the overall error in the calculations, care must be taken to obtain the best value of p.

The value of p increases as the length of averaging period of the wind speed increases; Sachs (1978) gives the empirical law that p for hourly wind speeds is twice as large as p for very short-term speeds. Thus estimations of p from the literature must be for the current length of averaging period.

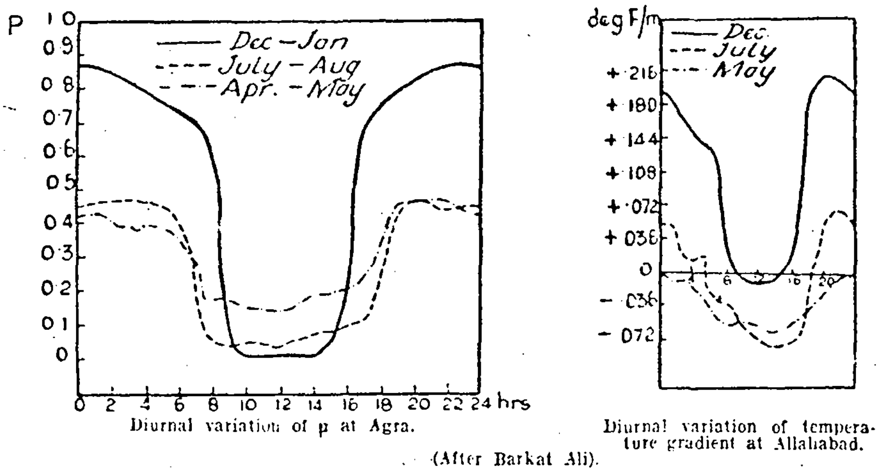
The value of p most frequently used in the literature lies in the range of 0.16 to 0.18 (Carruthers, 1953; Hardman and Helliwell, 1973; Met. Office, 1968; Shellard, 1955B). However, such low values are generally used to estimate the maximum speeds; Shellard (1967B) for example obtained values in the range 0.21-0.23 for slower wind speeds but recommended the use of p in the range 0.15-0.16 for higher wind speeds. Davenport (1961) gives a general relationship of 0.16 for open country, 0.28 for woodland and suburban areas, and 0.4 for city centres, whilst Paeschke (1937) has values ranging from 0.20 for a snow surface to 0.33 for rough crops. A value of 0.20 gives a vertical gradient closely approaching that of the general log law. It is thus suggested that a value of 0.20 be taken as the initial value for an open windmill site. This should give a good approximation over the full range of wind speeds, during neutral conditions.

Neutral, and also unstable super-adiabatic, conditions tend to prevail during the day but during the night stability increases, and therefore the value of p increases also. Typical diurnal variations can be seen in figures 18 and 21 whilst day and night values of p for various locations can be seen in Figure 22. The higher values of the Dec-Jan curve in Figure 18 are doubtful as they were observed during inversion conditions with an almost zero wind speed, but are retained to show the winter relationship. De Marrais obtained values almost as high. The average diurnal variation of the six curves in figures 18 and 21 is as follows

Time	00	2	4	6	8	10	12	14	16	18	20	22
p	.44	.44	.43	.40	.24	.10	.10	.11	.18	.34	.44	.47

Fig. 23

The mean daytime values are very low and probably relate to high wind speeds. The night values correspond well with the mean of the night values in the table of Figure 22. It is thus suggested, as a temporary measure until further research is conducted, that the above diurnal variation be adopted to account for the variation in p with atmospheric conditions. This is a very unsatisfactory procedure but is expected to provide better results than either the log law or power law when the effect of atmospheric conditions is ignored. The records of Figures 18 and 21 on which Figure 23 is based include winter and summer measurements in India, Canada and England.

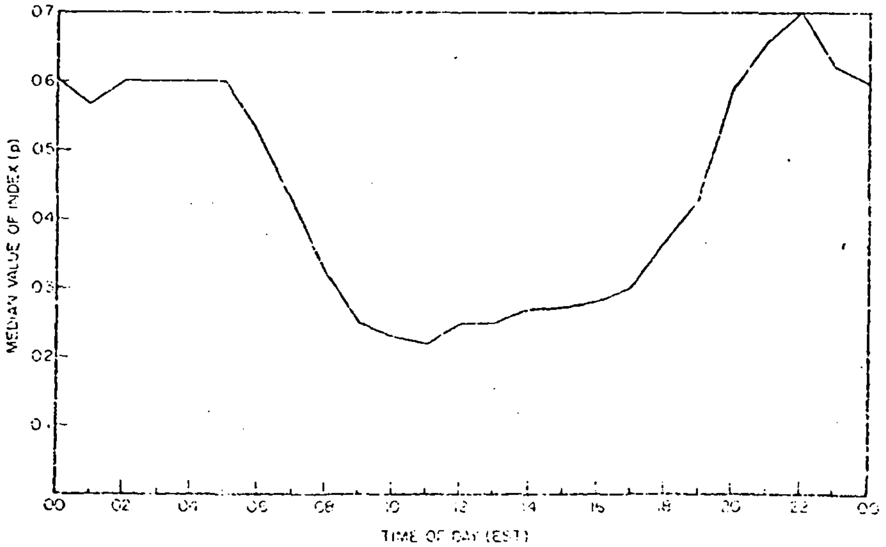


Diurnal variation of p at Agra.

Diurnal variation of temperature gradient at Allahabad.

(After Barkat Ali).

Fig. 18 Variation of p with season and lapse rate (Carruthers, 1943)



Median values by hours of the day in summer of the power law exponent *p* at Douglas Point, Canada for the 20- to 80-ft layer (Munn, 1966)

G.M.T.	0	2	4	6	8	10	12	14	16	18	20	22
April-Sept.	·17	·16	·16	·14	·10	·08	·07	·07	·08	·11	·15	·17
Oct.-March	·13	·13	·13	·13	·13	·10	·08	·08	·10	·13	·13	·13

(Carruthers, 1943)

Fig. 21 Diurnal variation in p

Site	Day	Night	Observed	Height Range	Terrain	Notes
Nauen, Germany [3]	0.06	0.31	winter	32–123 m	flat meadow	tower observations
Nauen, Germany [3]	0.11	0.60	summer	32–123 m	flat meadow	tower observations
Harwell, England [14]	0.14	–		61–152 m	constr. site	captive balloon observations
Sale, Australia [2]	0.14	0.21	fall	12–153 m	grazing land	tower observations; high speeds only
Leafield, England [6]	0.20	0.30	winter	13–95 m	grass field	tower observations
Leafield, England [6]	0.16	0.36	summer	13–95 m	grass field	tower observations
Oak Ridge, Tenn. [7]	0.24	0.71	all year	53–160 m	mountainous	pibal observations

Fig. 22 Diurnal variation in p (De Marrais, 1959)

There is no guidance in the literature on how to combine the effects of surface roughness and atmospheric stability in the application of any law to model the vertical wind gradient. It is suspected that surface roughness will have a maximum effect during unstable conditions and high wind speeds when the greatest turbulence occurs. Notwithstanding, it is recommended that the two effects be combined by simply altering the value of p for each time by the same amount. Thus the value of p equal to 0.20 for daytime conditions would give the following, annual average, diurnal variation of p:

Time	00	2	4	6	8	10	12	14	16	18	20	22
p	.54	.54	.53	.50	.34	.20	.20	.21	.28	.44	.54	.57

Fig. 24

In very flat areas with short, even vegetation p could be reduced by 0.02 - 0.04. In areas with more varied topography and increased roughness due to trees, fences, buildings, etc., it is estimated that p could be raised by 0.04 approximately, to bring the daytime values nearer to the 0.28 value recommended by Davenport (1961) for woodland and suburban conditions.

This has necessarily been a hurried and simplistic approach based entirely on an appraisal of the literary evidence. The proposed method should, theoretically, provide more accurate estimations than the methods used by previous authors such as Allen (1977) who uses the power law with a single constant power of 0.14 and Archer (1977) who uses the simplified log law. The great advantage of this method is that both surface roughness and a measure of atmospheric turbulence are both included.

CHAPTER 5. METHODS FOR DETERMINATION OF STORAGE

Rational determination of the amount of storage required for any project must be based on an analysis of either discharge records obtained from a historical wind record or a projection of such discharge records into the future. Several methods of analysis are available, some of which are discussed below.

5.1 Flow Hydrograph Analysis

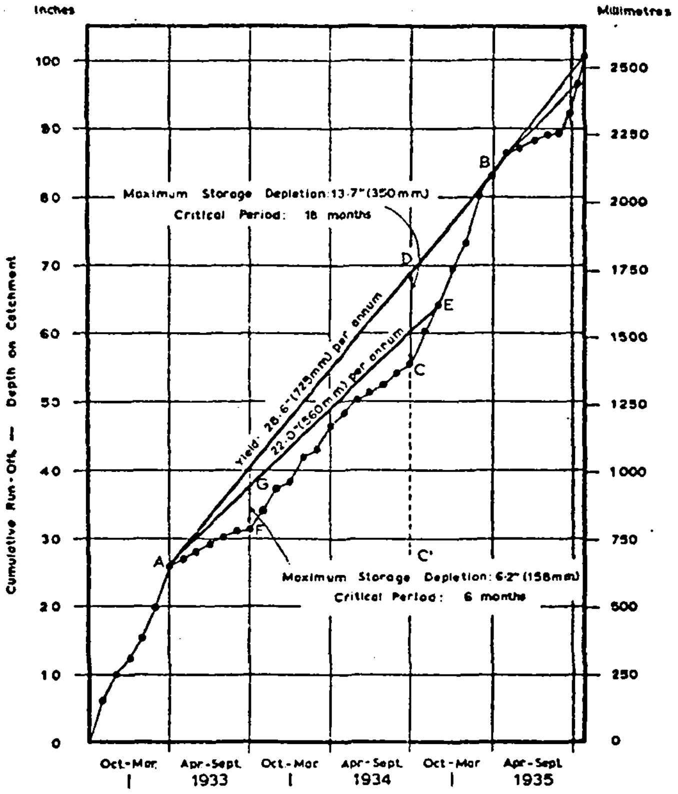
A hydrograph of daily discharge from the pump is plotted against time for the full length of record of flow computed from the wind record. If a constant demand is assumed the flow from storage required is the height of the straight, horizontal demand line above the flow line, and the volume of storage required is the maximum area of the shortfall. The method becomes difficult to operate if two periods of shortfall in supply are separated by a period of excess, since the total storage required is the area of the two periods of shortfall less the area of excess.

The main drawback to this method is that it does not allow a probability analysis or an optimisation of storage provision with other factors but gives an estimation based only on the available record without regard to whether this period is representative or not. The estimated storage is a statement of the volume of storage which would have been necessary to maintain supply during the period of historical record.

5.2 Mass Curve Analysis

The mass curve or Rippl method, which is easier to operate but has the same drawbacks as flow hydrograph analysis, is used by

Archer (1977) and by Parkes and van de Laak (1976) in their windmill studies. The cumulative flow is plotted against real time for the period of record, and a constant rate of demand is plotted as a straight, sloping line. The storage required is estimated as the vertical distance between the mass flow curve and a line drawn paralell to the demand line as a tangent through the peaks in the mass flow curve, as in Figure 25. The diagram is generally derived for monthly interval data (Collinge, 1965) but the method is equally suitable for shorter interval data if a large scale diagram, or computations are employed.



Cumulative Run-off Diagram for a Severe Dry Period

Fig. 25 Mass curve diagram (I.W.E., 1969)

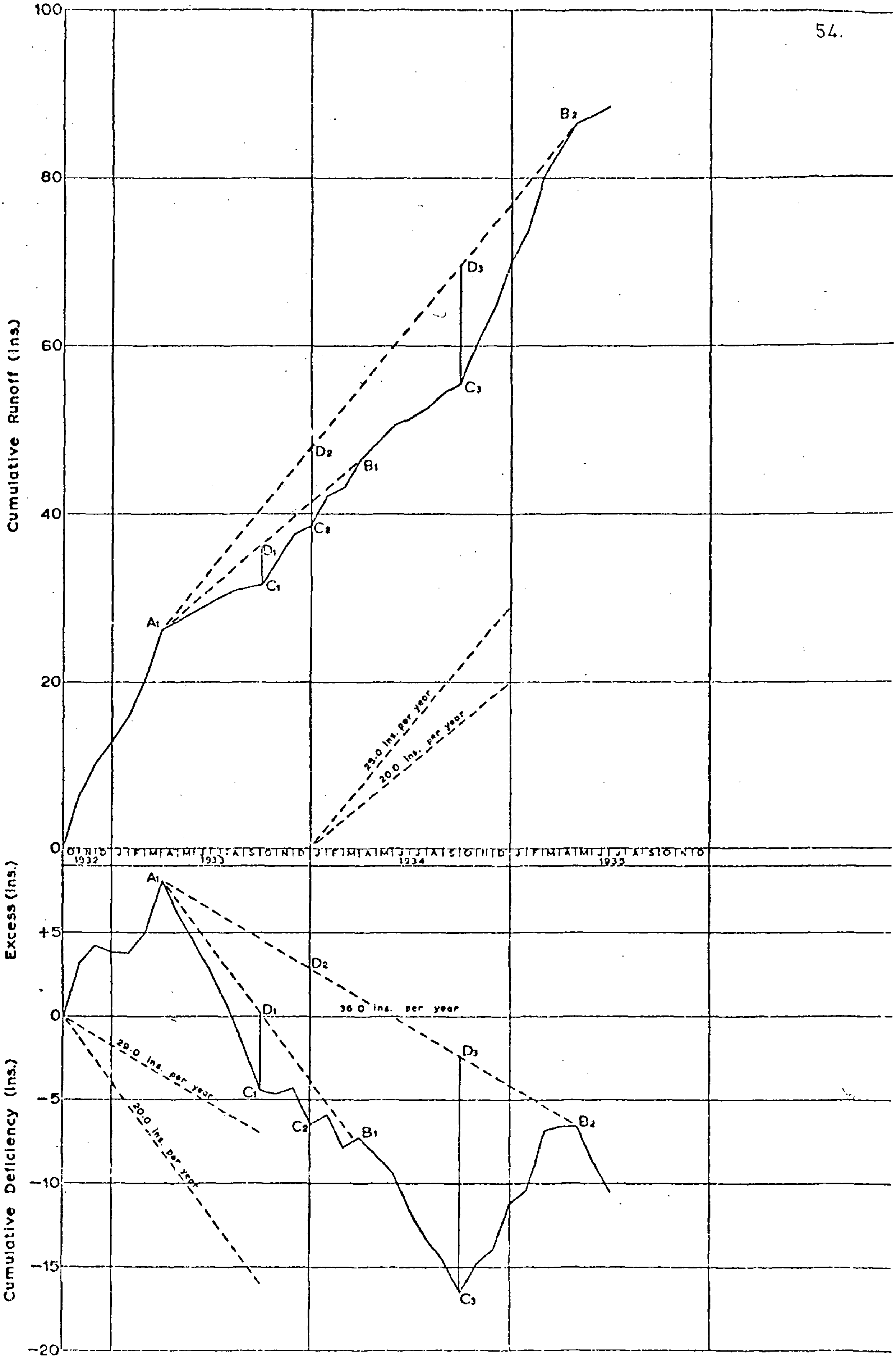
If the variation of demand with time is known, either as a record of demand during the period of flow data, or as an estimation of average daily or monthly demand, this can be plotted in both the above methods in preference to a straight demand line. Without this improvement a serious error in estimation will result if the period of maximum demand coincides with the period of minimum flow, as may often occur.

A modification of the mass curve diagram is the cumulative deficiency diagram whereby the deviations from the average flow are plotted against time (Figure 26). This allows a larger vertical scale and therefore more accurate analysis.

5.3 Flow Duration Curve

Analysis of the flow duration curve, or cumulative frequency diagram, can be a quick and useful means of estimating reservoir capacity (Lord, 1965). However, if duration curves are to be used the most expedient point to introduce them is during the analysis of the wind as velocity duration curves. Flow duration curves have the same limitations as velocity duration curves (see Chapter 2.5), and are not considered suitable for wind pump studies.

The above three methods are deterministic in that they are based on the derived historical record of sequence of flows. They have been used most frequently for determining over year storage requirements but finer analysis of within year storage is possible if short period variations in flow are analysed. The number of data points is then increased greatly and computerised analysis rather than graphical plotting becomes necessary. The methods are applicable when only a short data record of one to three years is available. Stochastic, probabilistic analysis cannot be based on such a short period although an element of probability can be introduced if the return period of the data on record can be estimated. Many reservoirs in Britain have been designed with analysis of a 3 year record of 1933-1935 (Figures 25 and 26) which covers an 18-month sequence of low river flows which



MASS CURVE OF RUNOFF FOR RIVER DERWENT. (YORKSHIRE BRIDGE) 1933-1935

Fig. 26 (Collinge, 1965)

CUMULATIVE DEFICIENCY DIAGRAM FOR RIVER DERWENT corresponds in many places to a probability of 1-2% (I.W.E., 1969). The reliability of such an estimate is uncertain, and therefore more detailed probability analysis is recommended.

5.4 Low Flow Frequency Analysis

The amount of storage required to maintain a given rate of supply to consumers is governed by the length and severity of periods of low flow into the storage and thus only low flow events need be analysed. Two methods are often used by engineers and hydrologists for abstracting low flow data from a complete chronological record of inflows. An annual duration series is obtained by removing one low flow value from each year of record for each duration under consideration, which must be less than or equal to 365 days. For a partial duration or peak over a threshold series all events under a chosen level are selected for analysis.

N.E.R.C. (1975) found that the annual maximum series was more efficient than the partial duration series for flood analysis, possibly because the annual maximum includes an indication that a certain magnitude is the extreme for a year. (Shen and Todorovic, 1976). However, use of the annual maximum series in low flow studies assumes that storage requirement is controlled by only one low flow period in each year and excludes other very low flow values if they occur in the same year. Since storage for most wind powered installations will be small and the critical period considerably shorter than a year the partial duration series is a more appropriate tool than the annual maximum series.

The procedure for partial duration series analysis, as used by McMahon (1967), is as follows:

1. Abstract series of low flow events. For each of several durations within a predetermined range running totals of the flow are calculated and for each duration the following steps are completed:

2. From each duration group of running totals the lowest values are removed and assigned a rank, from 1 for the lowest upwards.

3. The probability for each ranked flow is calculated. There are many formulae available for calculating probability but no single formula is generally accepted for use. On frequently used the the Weibul plotting position:

$$\text{probability} = \frac{\text{rank of the event}}{\text{number of events} + 1}$$

The most suitable formula is one which assistsin part 4.

4. A graph of flow versus calculated probability is drawn with separate curves for each duration. With the use of appropriate scales the points will be found to approximate a straight line. This allows the accurate estimation of the flow which will occur with a particular probability.

5. For the desired degree of security of supply the value of flow for each of the durations is obtained. These flows for the chosen probability are plotted on a graph of flow versus duration. Flow rate is represented on the graph as the gradient of a line, so the required volume of storage to maintain a given rate of flow can be estimated from a straight line with the required gradient drawn tangential to the curve.

Shortage of time has not permitted the application of partial duration series analysis to a pump discharge record calculated from an analysis of a wind record. Several problems can be foreseen:

1. Duration

Until analysis is carried out it is not possible to predict accurately the length of the critical period of reservoir operation for wind pump storage. Since the durations used in the analysis must span this critical period a preliminary analysis must include a large range of durations, probably from a week to several months.

2. Independence

When selecting the lowest flow values from the running totals independence must be guaranteed, since a false calculation of probability will occur if several values include the same period of low flow. It is common practice to eliminate from the table of running totals all values which overlap in time with each low value as it is selected (e.g. McMahon, 1967). However, this will not ensure independence since duration flows which are adjacent or separated by only a short time interval, whilst not coincident in time, may not be independent. By autocorrelation analysis Corotis et al (1977) proved that only hourly readings of wind speed separated by 8-12 hours could be considered independent. Similarly longer period data of say a day or a week may only be independent if separated by several days or weeks. Further analysis must be carried out to determine the gap necessary between values to ensure independence.

3. Number of Events

There is no logical limit to set on the number of values to be abstracted from a record. Many different arbitrary rules are applied in the literature. McMahon cites Hudson and Roberts (1955) as selecting values until the rank approximately equals the number of months of record divided by twice the duration period, and Stall and Neil (1961) until the value of the flow equals the mean flow. The U.S. Corps of Engineers (1975) terminated the series at the lower of two limits: when the calculated probability reaches 0.5 or when the rank exceeds the number of months in the record divided by the duration period. An objective rule must be used to ensure a regularity, but it is not clear which rule.

4. Probability Formulae

Numberous methods have been proposed for calculating the probability or plotting position of the ranked flow values, some of which are indicated in Figure 27.

Name	Date	Formula* for T or $1/P(X \geq x)$	Equation
California [114]	1923	$\frac{N}{m}$	(8-I-56*a*)
Hazen [14]	1930	$\frac{2N}{2m - 1}$	(8-I-56*b*)
Weibull [103–104]	1939	$\frac{N + 1}{m}$	(8-I-56*c*)
Beard [35]	1943	$\frac{1}{1 - 0.5^{1/N}}$	(8-I-56*d*)†
Chegodayev [115–117]	1955	$\frac{N + 0.4}{m - 0.3}$	(8-I-56*e*)
Blom [118]	1958	$\frac{N + \frac{1}{4}}{m - \frac{3}{8}}$	(8-I-56*f*)
Tukey [119]	1962	$\frac{3N + 1}{3m - 1}$	(8-I-56*g*)
Gringorten [120]	1963	$\frac{N + 0.12}{m - 0.44}$	(8-I-56*h*)

* N = total number of items; m = order number of the items arranged in descending magnitude, thus $m = 1$ for the largest item.

† This formula applies only to $m = 1$; other plotting positions are interpolated linearly between this and the value of 0.5 for the median event.

Fig. 27 Plotting position formulae (Ven te Chow, 1964)

Most of these have been obtained empirically and are found to produce very similar plotting positions in the middle of a distribution, but significantly different values at the extremes. It is thus important to use a formula which will fit the extremes of the distribution of low flows to a straight line when plotted on a suitably scaled graph. It appears that to the present time frequency analysis of a wind pump or wind records has not been carried out so suitable distributions and scales can only be found by trial and error.

5. Rate of Demand

This method of estimating reservoir yield most commonly assumes a constant rate of demand. Such an assumption will generally be valid for wind pump studies if the demand is for domestic uses but not for agricultural uses such as irrigation since the demand will then vary seasonally. If the maximum demand occurs during the season of low discharge then a constant rate of demand can be assumed at the maximum level. Demand of water for irrigation and other agricultural uses is a function of rainfall, growth periods and other climatic factors whilst supply from a wind pump is a function of wind speed. If the period of maximum demand does not occur during the windless 'dry' season then low flow frequency analysis is insufficient since the critical conditions may occur with maximum demand at above the lowest flow period rather than a lower demand at the period of minimum flow.

Archer found by analysis of wind records for Malawi that the maximum supply from a wind pump could be expected during the dry season when river flow is low. Under such conditions the assumption of constant demand in any of the methods of estimating storage is not valid, since the low pump flows occur during the wet season when other sources are available. Thus a method which retains the chronological sequence of inflows and outflows must be used to determine the season of critical conditions.

A graphical method is to plot a mass curve of cumulative inflows and cumulative demand; the critical period will be at the time of maximum vertical difference of the demand line above the discharge line. Computationally the critical season can be identified by calculating the function of satisfied demand from the nth month average discharge divided by the nth month average demand. Quinn (1976) suggested a similar parameter, which he normalised by dividing by the average of monthly averages, for identifying the critical season in electrical supply of power from the wind. From his results (Figure 28) for his location the critical months are July and August. He concludes that if the aerogenerator is designed to meet these requirements then the demands of all other months will be more than satisfied.

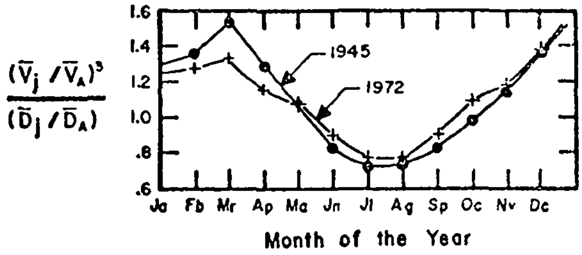


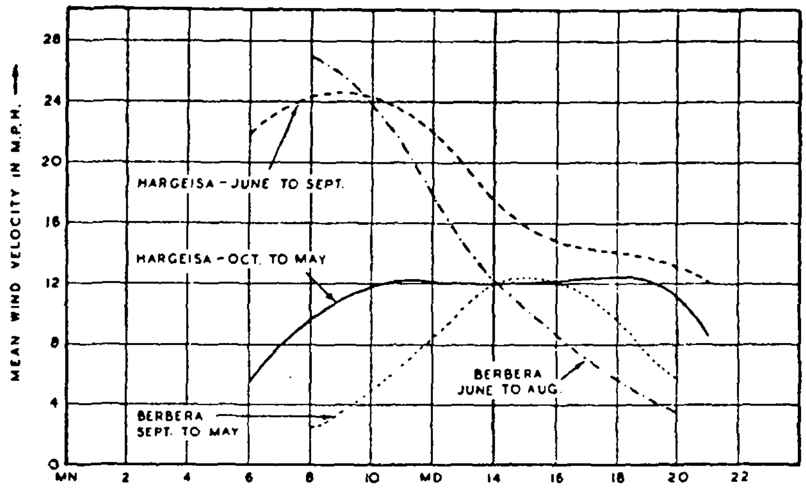
Fig. 28 Critical season of supply (Quinn, 1976)

Once the critical season has been identified a frequency analysis should be applied only to data for this critical period from successive years of record.

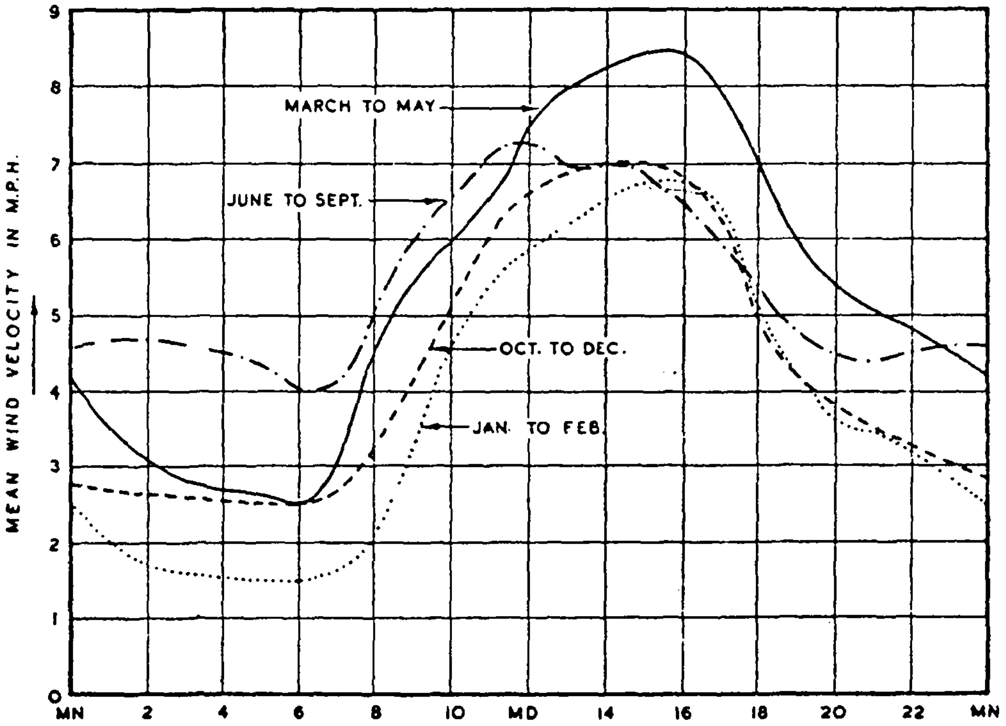
5.5 Well Yield

If the water yeild of the well or other water source is limited, as will be the situation in many developing countries during the dry season, the calculations must not assume that the pump will supply to its full capacity in response to the wind. Diurnal variations in wind speed as seen in Figure 29 are common in most areas of the world and it is during these midday periods of high wind speed that potential discharge of the pump may exceed the yield of the well. To reduce the effect of short-term limits to yield Watts (1976) recommends the use of wide wells for quick recharge and a large store of water. Tewari (1978) suggests that rice paddy can be used as a storage tank for wind pump projects, since the depth of water over a large area can be allowed to fluctuate as output from the mill fluctuates.

When the short-term variations in well yield and demand have thus been eliminated only seasonal limits to daily yield need be considered. If the maximum daily yield for each season or month can be estimated or calculated a limit can be set to the daily yield in the calculations of discharge.



Diurnal variations for Hargeisa and Berbera



Diurnal variations of wind speed in Madras

Fig. 29 Diurnal variation in wind speed (Golding, 1955)

CHAPTER 6 COMPUTER PROGRAMME

A flow diagram of the recommended procedure for examining the feasibility of using a wind pump in a particular situation is included in Figure 30.

A computer programme has been developed to carry out the calculations from stage 3 through to stage 7. The aim has been to write the programme to be compatible with any likely set of data and is written in FORTRAN IV since this is a widely available language. A description of the programme, which is included in Appendix C, follows:

1. Declaration of Variables

The values under REAL * 8 have been declared as double precision for a routine from a public library.

Arrays with dimension 24 have storage for each of 24 hourly readings per day. Arrays with dimension 40 have storage for all the points used in a regression. The dimensions need not be changed if less space is used, but must all be changed if more space is required.

CHARACTER is the type declaration of variables containing alphabetic data.

2. Description of Variables

The aim has been to make the listing of the programme and data self-explanatory and unambiguous. For this reason detailed comments are included in the programme.

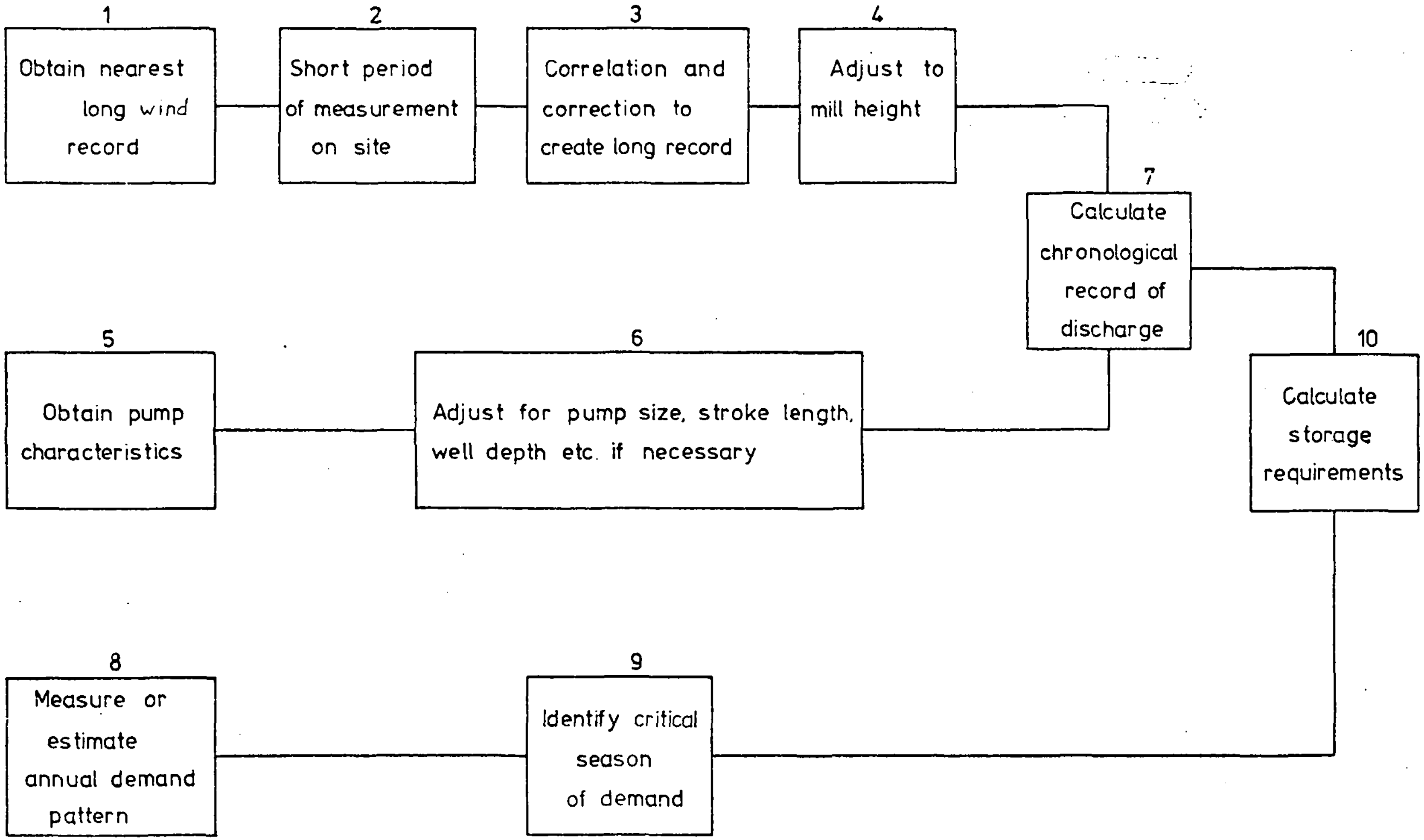


Fig. 30 Flow diagram of the recomended procedure

3. Title

The title and source of the data is read from the first line of the data as a CHARACTER string, of 72 characters.

4. Establish Pump Characteristics

The pump output at different wind speeds, obtained from the manufacturer or from measurements, is fed to the computer as separate point values and a polynomial fitted by weighted least squares regression. The relationship between discharge and wind speed is not linear and rather than compute a higher order polynomial myself a standard routine from the Numerical Algorithm Group (NAG) library was used. This involves two programmes:

E02ADF to calculate the Chebyshev coefficients (CCOEF) for the curve and E02AEF to evaluate the polynomial for given values from the Chebyshev coefficients. The data for the regression subroutine is read into the variable stores:

IFAIL is an error test for the NAG programmes which is initially set to zero. If an error is discovered by the routine IFAIL is returned with a new value to indicate the cause of error and the run on the programme is halted.

NROWS is the first dimension of the array CCOEF as declared at the start of the programme.

NR is the number of data points to which the polynomial approximation is to be fitted, and must be equal to the number of distinct velocity points.

DEGMPI is the maximum degree of polynomial required, plus one. A second or third order polynomial is sufficient in most cases to define the relationship of velocity to discharge, and DEGMPI should thus be assigned the value 3 or 4. If required the degree of polynomial to be fitted can be increased up to but not above the number of distinct velocity values.

VELYR is the array of velocity readings, each value being associted with a value of DISCHR, the array for discharge readings. Each point is given a WEIGHT which must be strictly positive and is a measure of the importance to be assigned to each point in minimising the sum of squares of deviations of the measured points from the calculated polynomial. In this exercise it is sufficient to assign a weight of 1.0 for each single point, 2.0 for two identical readings fed in as one point, etc. The lowest and highest velocity values must encompass the full operating range of the wind pump; if the discharge at these speeds is not known a DISCHR of 0.0 or the approximate value, and a positive WEIGHT of near zero can be used.

The NAG subroutine is called and NR, DEGMP1, NROWS values and VELYR, DISCHR, WEIGHT arrays are entered.

WORK 1 and WORK 2 provide working space for the routine.

CCOEF is the array of Chebyshev coefficients calculated by the routine.

SQ is the array containing the root mean square residual corresponding to each polynomial from degree 1 to DEGMPI.

If the maximum degree to be calculated, as specified by DEGMPI is large the best fit polynomial has to be searched for. This is done by scanning the residuals for the smallest, recording the value in MINSQ and the degree in DEGPI. The coefficients of this best fit polynomial are then placed in array COEF.

When operating at high wind speeds a mill is designed to furl its blades or turn itself partially out of the wind to prevent excessive speeds. Above the furling speed discharge is almost constant. The rate of QMAX is calculated by evaluating the polynomial for the highest velocity in the data, VELY(NR), with the NAG routine E02AEF. The use of this routine is described below

5. Time Interval

The programme is designed to process velocity readings taken several times per day. When hourly readings are available these should be used, but often less frequent readings, possibly at irregular intervals in the day, will have to be used. The number of time intervals per day is read into NT, and the NT intervals in hours between each velocity reading are read into TIME. Thus the programme can accept 24 hourly readings, 4 six-hourly readings, or any number of irregularly spaced readings.

6. Data for Adjustment for Height

To adjust wind speed readings to the height of the mill by the power law the height of the anemometer and mill are fed into HA and HM. Provision is made for varying the vertical gradient during the day (Section 4.4) by reading NT values of the POWER and calculating the mill factors NT time from the formula

$$\mathrm{MF} = \left|\frac{\mathrm{HA}}{\mathrm{HM}}\right|^{\mathrm{POWER}} \qquad \text{(Eqn. 12)}$$

7. Date

The number of years of data is read in and for each year the date is read by YEAR and for each of 12 months the name of the month and the number of days are read into MONTH, NDAYS. The monthly discharge, QMONTH, is initialised to zero.

For each day in the month the date is read to DAY and the daily total discharge, QDAY, is set to zero.

Although not necessary in FORTRAN each do loop for a different time period is inset 5 spaces to enhance the presentation.

8. Velocity Readings

For each of NT intervals the velocity at the anemometer is read in to VA and adjusted to velocity at the mill VM by multiplication by MF.

9. Calculate Discharge

If the wind speed VM is less than the cut-in speed of the mill, VELYR (1), then discharge, Q, is set to zero. If the speed is above the furling speed, VELYR (NR), then discharge is set to QMAX. For all other speeds the discharge is evaluated from the polynomial by the NAG routine E02AEF. This requires that the VM value be scaled or normalised to lie within the range -1 to +1 by the formula

$$\mathrm{VMN} = \frac{(\mathrm{VM} - \mathrm{VELYR}(1)) - (\mathrm{VELYR}(\mathrm{NR}) - \mathrm{VM})}{\mathrm{VELYR}(\mathrm{NR} - \mathrm{VELYR}(1)} \qquad \text{(Eqn. 13)}$$

The number of degrees and the coefficients of the polynomial and the VMN value are supplied to the routine and the discharge Q is returned to the programme.

The NT increments of flow, multiplied by the time interval are summed as a volume to give QDAY and the QDAY values are summed to give QMONTH. Note that the time interval in TIME and Q as a rate of flow must be the same, or a correction must be applied.

10. Format Statements

11. Description of Data Input

An example of the application of the programme will be included in the following chapter.

If NAG routines are not available the section on establishing pump characteristics must be changed. A simple and very satisfactory solution would be to read in a table of values of discharge for different wind speeds obtained by a graphical plot of the data and a sketch by eye of the best fit curve. Alternatively a subroutine to carry out a least squares regression could be written.

CHAPTER 7 FIELD TEST

7.1 The Equipment

A field test was conducted in order to test the validity of the method developed, to examine the accuracy of manufacturer's performance data and to demonstrate the advantages of obtaining pump characteristics by field measurement rather than by theoretical calculation.

The wind pump available was a Sparco diaphram pump designed to pump water from streams or shallow wells for cattle watering. The 0.9m diameter rotor comprises two flat metal blades, turned into the wind by means of a tailfin, mounted on a horizontal axis 3m above the base. To prevent damage in excessive winds the blades are feathered centrifugally in winds over 18 m.p.h. to spill the wind and thereby ensure a constant speed. Supply and delivery pipes have $\frac{1}{2}$ inch internal diameter and for this experiment were connected with common garden hose pipe. The agents for Sparco in Britain, Conservation Tools and Technology Ltd., supplied the discharge rates given in Appendix B.

The discharge in the test was measured as flow over a small 30° V notch wier manufactured by Tequipment Ltd. The head of water over the wier was measured with a Portadip water level recorder manufactured by Portacel Ltd. This has a metal probe which every 30 seconds is lowered until contact is made with the water surface, thereby completing an electrical circuit and causing the probe to rise slightly clear of the surface. The water level is recorded by means of a moving needle on a circular chart rotating 360° in 24 hours. The equipment was calibrated in a laboratory by passing a known discharge over the wier and recording the level indicated by the Portadip[1]. It was found that the head of water, measured 8 cm. upstream of the centre of the V notch, was recorded to an accuracy of 1 mm. The finest resolution of readings obtained in real time was 2 minutes, the values being read from the chart with the aid of a transparent plastic overlay graduated with 2 minute intervals. The response by this equipment to changes in discharge was by no means instantaneous. Storage behind the wier, the 30 second delay between measurements and the slow response in the movement of the recording needle result in an estimated time delay of greater than 1 minute and a consequent reduction in accuracy of the recording of variation in discharge. The greatest error occurs when discharge is reduced or halted completely since the water stored behind the wier continues to flow for several minutes.

Wind speed was measured by means of a cup anemometer connected to a flat bed chart recorder with the chart speed set to 100 mm/hour. The response of the recorder to the output of the anemometer at different wind speeds was calibrated by simulating a constant wind speed with a constant voltage source fed into the recorder via a wind speed meter dial[1]. Wind speed values were read from the record with the aid of an overlay graduated with the scale of wind speed from the calibration. The direction of wind was not measured.

The test was conducted at Nafferton Farm, 18 km. due west of Newcastle. The site available was the corner of a field at an elevation of approximately 115 m. (Figure 31). The exposure to the N.W., the direction of the prevailing winds was good except for a hedge approximately 12 m. to windward. To the S.E., 7 m. from the mill, was a large agricultural barn but since the wind was never observed during the test to blow from this direction it was hoped

(1 See Appendix D for calibration results)

Fig. 31 Test site

that the effect on wind behaviour would be minimal.

The installation of equipment is illustrated in Figure 32. The wind pump was erected on top of an 82 litre (18 gallon) tank and the anemometer on a nearby post at the same height as the centre of the mill wheel (Figure 33). The discharge from the pump was fed through 8 m. of hose to the V notch wier tank set up in the barn, and the overflow from the wier was fed by gravity back into the supply tank under the mill by the same length of hose. In this way a virtually constant head of 1·2 m. was maintained.

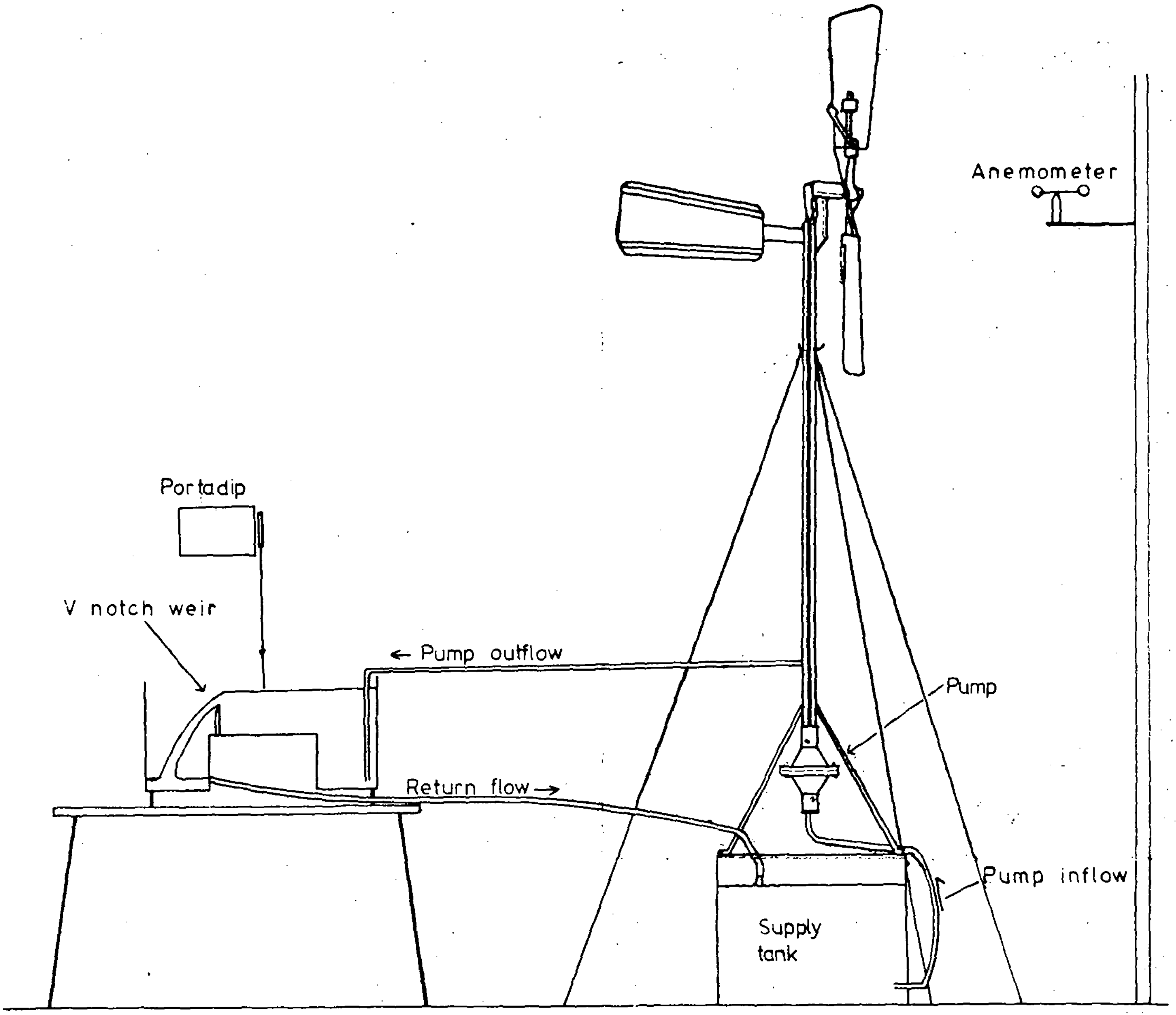
7.2 The Results

The equipment was in operation for a total of five days. A sample of the records is shown in Figure 34.

Mean hourly wind speed values were estimated for the record with the overlay according to the instructions for analysis of amenograph records issued by the Met. Office (1973). The broad trace was narrowed to a single line following the pattern of the short period average speed, and the average hourly wind speed was estimated such that equal areas were bounded above and below the average by the line of the trace. Similarly the mean hourly water levels as recorded by the Portadip were estimated and converted to mean hourly discharge rates according to the calibration results.

1. Pump Characteristics

Four sets of performance characteristics for the Sparco have been analysed using the computer programme. Each set of characteristics was read into the programme and the rate of discharge for each wind speed from 0 to 23 m.p.h. was evaluated. The characteristics were obtained from:



Vertical head from water surface in supply tank to pump outflow level is 1.2 m.

Horizontal length of pump outflow ½ inch diameter pipe is 8 m.

Fig. 32 Installation of equipment

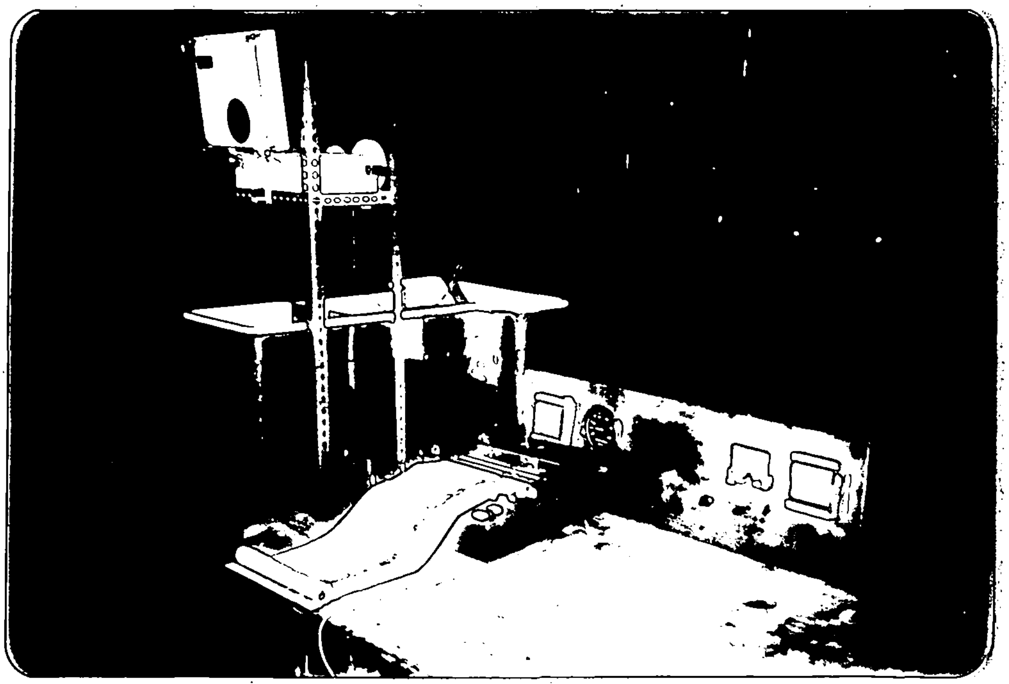


Fig. 33 The equipment

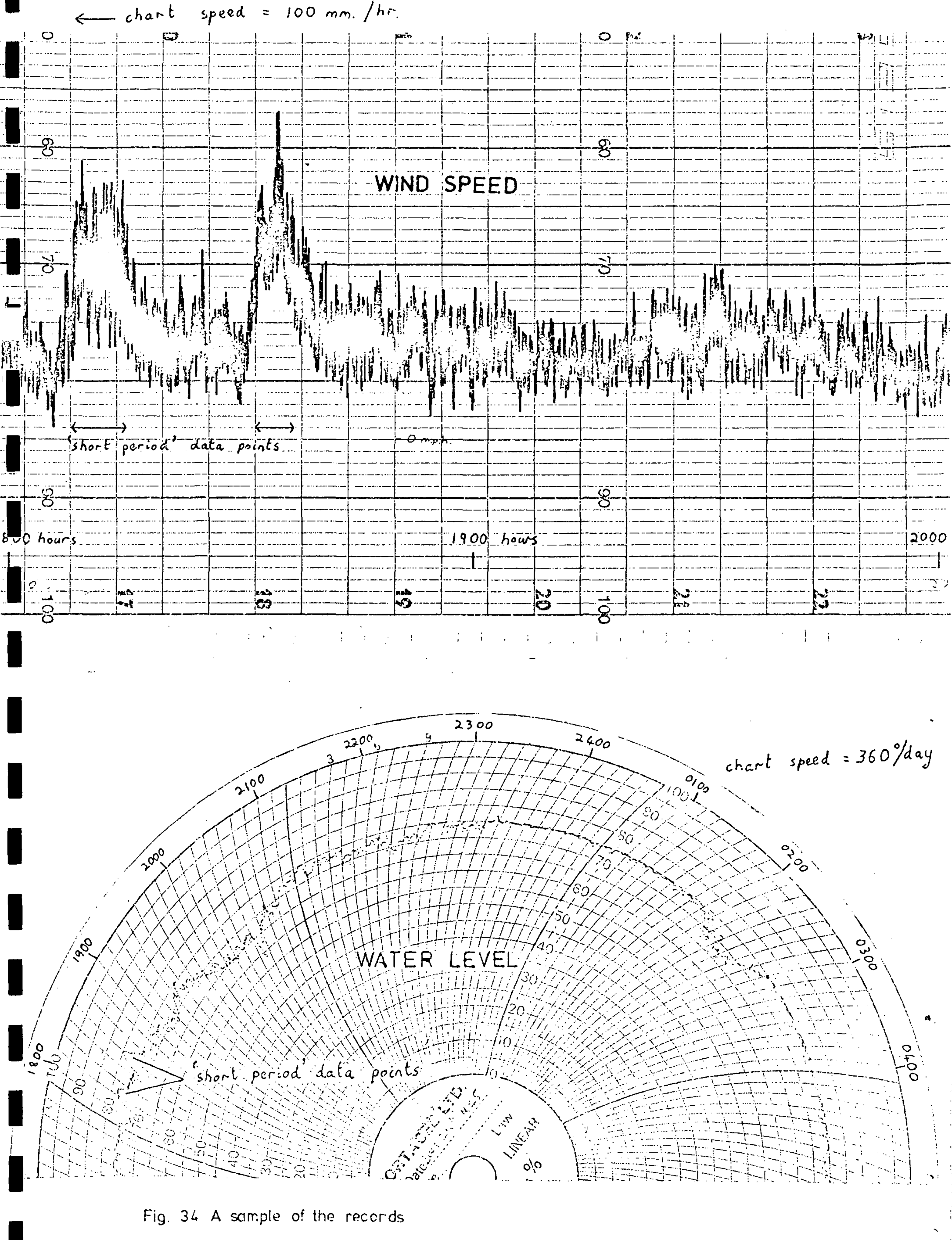


Fig. 34 A sample of the records

i) The manufacturer's data in Appendix B.

ii) All points in the five days of data record when the discharge could be clearly related to the wind speed were abstracted. Most of these readings were short periods when average wind speed was higher or lower than the average before or after, as indicated in Figure 34.

iii) Wind speed and discharge values averaged over longer periods of approximately one hour were also matched. Only periods of relatively constant discharge were chosen because of the difficulty of accurately estimating the average of a variable discharge.

iv) All the hourly readings of discharge and wind speed, but excluding those hours when wind speed was interpolated due to breaks in the electricity supply (8 hourly values).

The values of discharge versus wind speed for the regression and the calculated discharge for each wind speed from 0 to 23 m.p.h. are listed in Appendix E and the 2nd degree polynomials are plotted in Figure 35. The points for the regression have a wide scatter, and the root mean square residuals for the 2nd order curves are high, probably because of errors in estimating averages and also because of the varying pump response to varying wind speed.

Despite this scatter the curve fitted to the selected hourly averaged data corresponds remarkably with that fitted to the manufacturers data, which has been extrapolated to the measured cut-in speed of 5 m.p.h. The curve of all the hourly values has a more marked curvature which results in decreasing discharge as wind speed increases. This results from the wide scatter of points and since

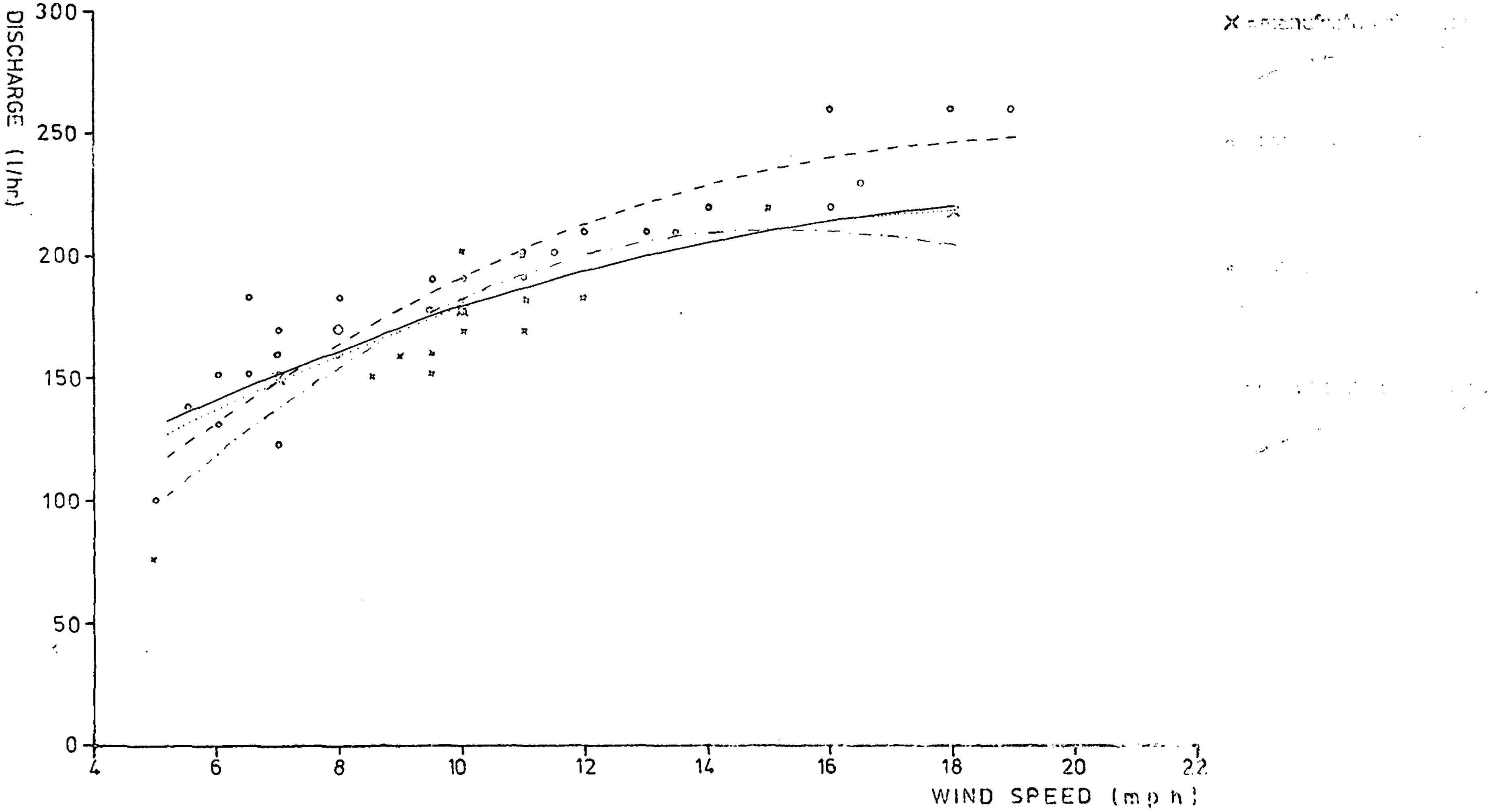


Fig. 35 Sparco performance characteristics

it is not an accurate model of expected pump performance the curve can be rejected. Subjective, visual inspection of the polynomial fitted by regression is important because the scatter of points may result in curves which are mathematically possible but not a feasible model. If 3rd degree polynomials are fitted to the hourly averaged data a steep positive curvature at high wind speeds indicates discharges of over 300 l/hr. at 18 m.p.h.

The curve fitted to short period data is significantly different from the other curves. At low wind speeds the discharge is small but this rises rapidly to a level 12% higher than that for the manufacturer's data at 14 m.p.h.

The similarity of the curves of manufacturer's and hourly data indicates that the manufacturer's data is, in this instance, reliable. It is not known what period of averaging or how long a record of measurement was used to calculate the performance characteristics provided by the agents for Sparco. Accepting that the results of this short field test are verified when compared with the manufacturer's data it would appear that 5 days of hourly data is sufficient to estimate the characteristics of a wind pump to a sufficient degree of accuracy.

The main problem in estimating characteristics from a short record of data is the small sample of extreme values. From the 5 days of record it was observed that the minimum speed of operation of the pump is 5 m.p.h. The rate of discharge at this speed ranges from approximately 80 l/hr. for an hourly average to 100 l/hr. for a short-term average. Note that the long-term average curve appears to produce a greater discharge at low wind speeds because only one point below 8 m.p.h. is used in the regression.

At higher wind speeds the long-term response could not be estimated except by extrapolation because only very short periods with high wind speeds were experienced. The Sparco mill is designed to furl its blades and maintain a constant speed of rotation at wind velocities above 18 m.p.h., whilst pumping at a rate of 218 l/hr. according to the manufacturer's data. From the short record of data it appears that the pump discharges at a rate of 220 l/hr. at a short-term wind speed of 15 m.p.h. and 260 l/hr. at 18-19 m.p.h. The discharge recorder was in operation before the wind speed recorder, and during this time, for two short periods of approximately 1 minute the discharge reached levels of 280 and 300 l/hr. Further measurements are therefore necessary to obtain the pump response at high wind speeds and to test the furling mechanism on the mill.

2. Discharge Estimation

The hourly wind speed readings abstracted from the amenograph record have been processed by the computer using the pump characteristics supplied by the agents and as calculated from the hourly averages. The results are included in Appendix E.

The percentage difference of the calculated hourly discharge above or below the measured discharge included, for a few intervals, in Appendix E, is seen to range very widely from +45% to -100%. The error in estimation of daily totals in all cases is less than 17% whilst the estimation of the total discharge over the 5 days is accurate to within 0.9% using the manufacturer's data and 0.2% using the measured hourly characteristics.

Archer (1977) stated that "Even with hourly figures there is likely to be an underestimation of water pumped due to the highly skewed frequency distribution of extreme windspeeds." This, it was assumed, would result because average wind speed values would not be an accurately scaled average of the power in the wind, which varies as the cube of the wind speed. The accurate results of the estimation of discharge from wind speed values in the Sparco test indicate that the averaging of wind speed values is not a problem if the data used for modelling pump performance are averaged over the same interval as the wind measurement. However, if the short-term averaged characteristics from the Sparco test are used to estimate the discharge with the hourly average wind speeds the discharge is overestimated by 5.3%.

It may be that sufficiently accurate results would be obtained, with less work, if the measured characterics and the wind speed record were both averaged over one day. The effect of seasonal changes in the diurnal wind regime would have to be considered but if the pump characteristics used are a measure of the average response of the mill throughout the year the results should be satisfactory. Five days of data is not sufficient to reliably test this hypothesis.

The effect of the long averaging period for wind data is seen to be an overestimation rather than an underestimation as predicted by Archer. The relationship of windmill output in response to increases in wind speed does not have a positive curvature and increasing gradient as commonly claimed in the literature, but rather a negative curvature and decreasing gradient.

In many areas of the world wind analysis is complicated because the averaging period is not constant throughout the day. The wind measurements available in Malawi for Archer's analysis varied in averaging period from 2 and 3 hours during the day to 13 hours overnight. In such circumstances an analysis based on characteristics from hourly data would not be valid; a characteristic curve based on 12 hourly or 24 hourly averages would be more appropriate. Such a method provides an easier solution than the alternatives discussed in Section 4.1.

7.3 Height Variation of Wind Speed

In the Sparco test the wind measurements were taken at the same height as the mill wheel, so corrections for the vertical gradient of wind speed were not necessary. To illustrate the magniture of the effect of altering the exponent in the power law the computer programme with the agents data was run 3 times, with different powers, assuming an anemometer height of 10m and a mill height of 3.5 m.

In the first run the exponent was constant throughout the day at 0.16 and in the second at 0.20. The mill factor $(HA/HM)^{POWER}$ was equal to 0.845 in the first run and 0.811 in the second, and the calculated 5 day discharge was 8.0% less in the second run. For the third run the power was varied during the day according to the values in Figure 24 and the calculated discharge was 30.3% less (Appendix E).

Such a magnitude of difference clearly indicates that accurate values of the exponent are of great advantage in the analysis. Note that the majority of windmills in commercial production are higher than the standard anemometer height of 10m. and the effect of the wind gradient will be to increase the discharge. If too low an exponent is used the estimated discharge will be less than reality and the estimated storage capacity will be too large thus possibly discrediting the value of windmills for pumping water, although at the same time ensuring a greater security of supply than calculated.

7.4 Errors in the Test Results

From the very brief record of measurements and calibration available it is impossible to carry out a detailed analysis of errors. The following is a brief description of the main source of potential errors:

1. Calibration of Wind Speed Recorder

The scale of the wind speed for the amenograph record was calibrated as instructed by the owners but the accuracy of the wind speed meter dial was unknown. The very slight irregularities in the calibrated scale were averaged to create a linear scale with equal intervals.

2. Response of the Water Level Recorder

The 30-second delay in measurement, the slow movement of the pen over the chart and storage upstream of the wier all combine to decrease the sensitivity of the response of the recording equipment to changes in water level. A more accurate measurement would be obtained with a more responsive turbine meter with readings every hour. A 19 hour period of simultaneous measurement with the wier and level recorder and with a water volume meter as used by water authorities indicated that the average of the sum of the 19 hourly readings of discharge over the wier was 4.3% higher than the 19 hour long average of the volume meter. Two measurements over a 1 hour and a ½ hour period revealed a difference of 4.1% and 5.9%. These measurements were discontinued because the meter became blocked with debris in the water.

The calibration of the head over the wier appeared to be correct, forming a straight line on log-log paper.

3. Averaging of Values

The averaging of values from a continuous record is subject to considerable errors, particularly due to lack of experience. Wind speed values averaged over 1 hour are probably accurate only to a maximum of 1 m.p.h., but short-term readings are more accurate. The water level averages are probably accurate to no more than 2 mm., although the chart can be read to the nearest mm. or less. This will result in considerable errors in discharge when converting on the calibration chart. The water level averages were read assuming a linear scale but the relationship of discharge to head over the wier is a log-log scale.

4. Head

The experiment was conducted with the pump lifting over a constant head by recirculating the water. The head was less than 2 m. and although the water was pumped through 8 m. of narrow diameter tubing the resistance to flow will have been less than under the normal operating conditions when pumping from a well or river.

5. Regression

The polynomials have been fitted to points with a large scatter; only 2nd degree curves could be fitted since instability resulted with higher order curves. The curves have been extrapolated outside the range of measured values to the known cut-in and furling wind speed; this is acceptable for 2nd degree curves but subject to error at higher orders.

Despite these possible errors the similarity of the hourly average curve with that supplied by the manufacturer, and the accurate estimation of discharge from the wind speed record illustrate the success of the method.

7.5 Pump Characteristics

It is considered more advantageous to obtain pump characteristics by measurement of discharge rather than by calculation from theoretical principles because:

1. Measurement is simpler.
2. Measurement produces accurate results, as illustrated in this chapter.
3. Wind speed and direction are constantly varying but theoretical calculations can only provide an estimation of mill output under a wind with a steady speed and direction, unless integrated with respect to a very complex function of wind speed and direction. Measurement of pump characteristics under a natural wind, not in a wind tunnel, will provide an estimation of output under all winds with a similar pattern of variation in speed and direction. Such an estimation is possibly accurate enough for application in all regions of the world, but this should be tested.

A sample of the variation in wind speed during the test, which was conducted between 1200 hours on 20 June 1979 and 1100 hours on 25 June 1979, is seen in Fig. 34 (page 75); detailed analysis was not carried out.

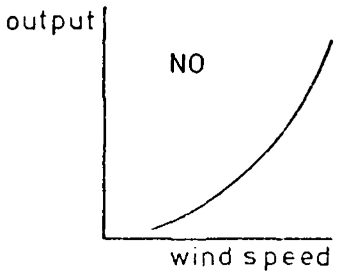
CONCLUSIONS AND RECOMMENDATIONS

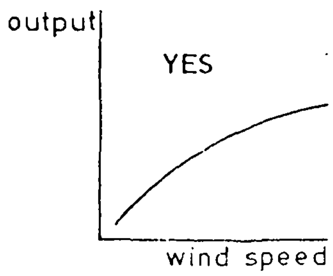
On the basis of the literature review and the results of the field test and subsequent data analysis the following conclusions and recommendations are made:

1. If the benefits of wind pumps are to be fully exploited then storage estimations based on calculation or actual measurement of discharge and demand variations over a year are required. (See Chapter 1)

2. Few detailed analyses of the chronological variation in pump yield have been conducted in the past. Many analyses have provided an estimation of the total yield in a year, but no indication of the amount of storage required which needs an analysis of the chronology of the difference between pump output and demand. (Chapter 2)

3. The power in the wind is proportional to the cube of the wind speed but the output of a windmill is not, because of the mechanical constraints to increasing output. The fallacy of output increasing as the cube of the wind speed, so common in the literature, should be ended. A plot of output versus wind speed forms a curve with a negative curvature and decreasing gradient. (2)





4. The output of a wind pump at any wind speed is a complex function of aerodynamic and mechanical efficiency, the

total system design and construction and load matching of the pump to available power. Actual measured performance characteristics of the pump under consideration at different wind speeds are therefore required. (3)

5. Pump characteristics are obtained by matching measured output to measured wind speed. The period of averaging must be constant. Because of (3) above the output at a given wind speed averaged over a long period is less than that at the same wind speed averaged over a short period. (3, 7)

6. Most manufacturers provide too little data on their pumps for detailed analyses of yield. The main requirements are:
   a) A plot of output versus wind speed for values averaged over 1 hour, and ideally a separate plot for 12 hour and 24 hour averages.
   b) A detailed report of the conditions of measurement
      - description of location and site
      - date and duration of test
      - description of the wind regime and a wind speed frequency histogram for the short-term wind speeds within an hour, to allow comparison with the wind at the proposed site.
      - head over which the water was lifted
      - details of the pump diameter, stroke length, mill wheel size, etc., if different combinations are available (3)

7. Research is needed on the effect of different combinations.

Either a general technique for analysis must be developed, or separate pump characteristics for each combination must be provided by the manufacturer. (3)

8. Research is also needed on the effect of different wind regimes on the performance characteristics. (3)

9. Performance characteristics can be obtained accurately by measurement over a period of a few days if winds over and outside the full range of the operating speeds are experienced. (7)

10. The data provided by the agents of Sparco in Britain appears to be an accurate summary of the pump performance under hourly averaged wind speeds. (7)

11. A wind record for the site is required. If this is not available correlation of a short-term on-site record (of about 6 months) with a long-term record at a nearby meteorological station can be made. (4)

12. When converting a wind record to discharge the wind and pump characteristics must both be averaged over the same time interval. (7)

13. The critical period controlling the amount of storage required will be short because wind power is available almost all the year and long-term storage between seasons is probably not feasible. Short interval data must therefore be analysed. (5)

14. Wind data averaged over one hour is appropriate because such data is commonly available, and the period is small

enough to indicate the main effects of atmospheric disturbances creating the wind whilst long enough to eliminate unnecessary 'noise' in the data. The spatial scale of fluctuations in hourly wind speed is sufficient to envelop fully the rotor of a windmill. (4)

15. If hourly data is not available longer interval data must be used. The interval must be approximately constant throughout the day. Average daily wind speed data may provide a suitably accurate result - further tests are needed. (7)

16. Variations in wind direction have to be ignored to simplify calculations although rapid, frequent changes in direction severely reduce the amount of power abstracted from the wind by a vertical axis mill. If the pump characteristics have been obtained under a similar pattern of direction variation little error should result. (4)

17. Wind speed increases with height above the ground. The most flexible tool available for modelling this effect is the power law

$$V_2 = V_1 \left(\frac{H_2}{H_1}\right)^p$$

A constant value of p of 0.20 models the vertical gradient under adiabatic atmospheric conditions for an open site but since the wind gradient varies during the day the value of p should also be varied. Until more detailed analysis is available the following variation of p is recommended as an average of diurnal variations studied in the literature.

Time	00	02	04	06	08	10	12	14	16	18	20	22
p	.54	.54	.53	.50	.34	.20	.20	.21	.28	.44	.54	.57

These values are for a moderately open site and should be increased by 0.04 approximately in areas with varied topography and rough vegetation, and decreased by 0.02 to 0.04 for very flat areas with short, even vegetation. (4.4)

18. For the estimation of storage the assumption of constant demand must not be used unless valid. If demand varies the season of critical supply must be identified. (5)

19. Mass curve analysis is a suitable method of storage estimation if an element of probability can be introduced, i.e. if the return period of the sequence of wind used in the analysis is known. If several years of wind data are available partial duration series analysis is probably better. If the demand is not constant the analysis should be based only on the data for the critical season. (5)

20. Research is needed on the application of partial duration series analysis to wind pump data. (5)

21. Knowledge and experience of the use of wind pumps in the region of the proposed new installation is possibly as useful an indication of the storage capacity required as the more detailed analyses above, because the critical period of reservoir operation is small and the range of required capacity is limited. (2, 5)

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APPENDIX A. WINDMILL MANUFACTURERS AND SUPPLIERS

Argentine Republic

- Aermotor, Fabrica de Implementos Agricolas, S.A.,
  Hortiguerra 1882, Buenos Aires.

Australia

- Metters Building Products (SA) Pty. Ltd.,G.P.O. Box 2047,
  Adelaide, South Australia, 5001.
- Southern Cross Engine & Windmill Co. Pty. Ltd.,
  39 Grand Avenue, Granville, Syndney, N.S.W., 2142
- Sidney Williams & Co. (Pty) Ltd.,
  Williams Parade, P.O. Box 22, Dulwich Hill, N.S.W. 2203 (Comet Mills)

France

- S.A. Bruno, Route du Mans, Bonchamps-Les-Laval, 53210 Argentre.
- Ets. Poncelet & Cie, Place de la Victoire, Plancy, Aube.
- Briau S.A., Boite Postale 43, 37009 Tours
- Eoliennes Humblot, 8 Rue d'Alger, A Coussey, 88300, Neufchateau

Great Britain

- Conservation Tools & Technology Ltd.,
  161 Clarence Street, Kingston upon Thames, Surrey, KT1 1QT
  (Sparco mill)
- Intermediate Technology Development Group Ltd.,
  9 King Street, London, WC2E 8HN
- Natural Energy Centre,
  2 York Street, London, W1. (AWP mill)
- P.I. Specialist Engineers Ltd.,
  The Dean, Alresford, Hampshire.

- Wakes & Lamb Ltd.,

  Millgate Works, Newark, Notts.
- Wyatt Bros. (Whitchurch) Ltd.,

  Wayland Works, Whitchurch, Salop, SY13 1RS (Climax mills)

Ireland

- Southern Steel Works Ltd.,

  Ballyhale, Co. Kilkenny (Ballyhale mill).

Malawi

- Stewards and Lloyds,

  P.O. Box 579, Blantyre.

South Africa

- Southern Cross Windmill & Engine Co. Ltd.,

  P.O. Box 627, Bloemfontein.
- Stewarts and Lloyds,

  Technical Products Division, P.O. Box 74, Vereeniging, 1930.
- Stewarts and Lloyds, Technical Products Division,

  P.O. Box 1195, Johannesburg, 2000

U.S.A.

- Aeromotor, Division Valley Industries Inc.,

  Industrial Park, P.O. Box 1364, Conway, Arkansas,72032
- Dempster (Annu Oiled Windmills) Industries Inc.,

  P.O. Box 848, Beatrice, Nebraska, 68310.
- Heller-Aller Co., Corner Perry and Oakwood,

  Napolean, Ohio, 43545.
- Windworks, Box 329, Route 3, Mukwonago, Wisconsin, 53149

West Germany

- Lubing Maschinenfabrik,
  2847 Barnstorf, Postfach 110.
- Pumpomat, Windpumpen Zentrale, H. Frees Ing. Lutthorn 51,
  D2330 Eckemforde.

- Pump body is 3 metres (10') long.
- Delivery stub 1 metre (3' 3") above stand.
- 3.6 metres (12') hose included.
- Maximum vertical delivery above stand is to the level of 4 on the diagram. To increase this the stand can be raised on a plinth, provided the diaphragm pump is not more than 4 metres from the water.
- Practical horizontal delivery limit is 100 metres (328') using a ½" delivery pipe. However, any horizontal pumping distance will reduce the vertical pumping capacity.
- Pumping rates:

Wind speed	Approx rpm of blade	Approx pump rate gal/hr
7 mph	80	33
10 mph	100	39
18 mph upwards	150	48

- Governing: centrifugally operated feathering device ensures constant speed in winds over 18 mph and safety in gale conditions.
- Spares and maintenance: CTT keeps a full range of spares although there is virtually nothing to go wrong with the Sparco. The cheap diaphragm should occasionally be replaced and grease nipples indicate where it should be greased every six months or so.
- CTT recommends the use of a Stuart Turner footvalve and strainer with this pump.

SPARCO

Practical Heads for Mill and Pumps to Efficiency

	25-ft.		50-ft.		75-ft.		100-ft.		125-ft.		160-ft.		200-ft.		250-ft.		300-ft.		350-ft.		400-ft.			
Diameter of Wheel	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Diam. of Pump Barrel	Approx. Gals per Hour	Approx. no. of strokes per minute in a 10 mile per hr. wind	Length of Stroke
	ins		ins		ins		ins		ins		ins		ins		ins		ins		ins		ins			
6 feet	3	240	2½	166	2	105	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	35	6
8 "	4	475	3	268	2½	166	2	119	—	—	—	—	—	—	—	—	—	—	—	—	—	—	30	6½
10 "	5	800	4	512	3½	392	3	288	2½	200	2	127	—	—	—	—	—	—	—	—	—	—	30	7
12 "	7	1500	5	760	4½	618	4	487	3½	373	3	275	2½	190	2	120	—	—	—	—	—	—	25	8
14 "	8	1750	6	990	5	685	4½	555	4	440	3½	335	3	247	2½	170	2¼	139	2	109	—	—	20	9
16 "	10	2720	6	1750	6	990	5	685	4½	555	4	440	3½	335	3	247	2½	170	2¼	139	2	109	20	9

WAKES & LAMB

I.T D.G.

TECHNICAL SPECIFICATION AND DESCRIPTION OF PROTOTYPE I.T.D.G. WINDMILL

PURPOSE

The developed version of this windmill is intended primarily for applications to provide either irrigation water or village water supplies.

The anticipated performance, assuming a power coefficient remaining constant at 0.25 and the blades set at a tip-speed ratio of 5 has been computed as follows (these figures are subject to confirmation by practical testing and are theoretically derived).

Wind Speed		Shaft Power		Speed	Volume of water pumped per hour			
					20ft (6m) head*		200ft (60m) head*	
mph	m/s	bhp	kW	rpm	gals.	litres	gals.	litres
6	2.7	0.12	0.09	42	700	3 150	70	315
10	4.5	0.56	0.42	70	4 600	20 700	460	2 070
14	6.3	1.55	1.16	98	8 200	36 900	1 500	6 750
18	8.0	3.29	2.46	126	12 100	54 450	3 200	14 400
22	9.8	6.01	4.49	154	15 000	67 500	5 800	26 100
26	11.6	9.93	7.41	182	17 900	80 550	8 800	39 600
machine governs at higher windspeeds					*100ft of 2½" pvc delivery pipe was assumed to estimate dynamic heads. Combined pumping + mechanical efficiency was taken as being 60%.			

The above figures cover the entire operating wind range, the 20ft static head being chosen to represent a typical irrigation application and the 200ft head a typical village water supply from a tube well or borehole.

The volumes arrived at will be proportionately worse if the power coefficient is worse than 0.25 or if the mechanical/hydraulic efficiency is worse than 60%, and vice versa. These figures were taken as probable ones and may need revision in the light of test results. A longer delivery hose would reduce the flow, particularly in higher winds, but this could be compensated for by using a larger diameter than was used for the calculation. Similarly, if say 3 inch hose was used, somewhat higher volumes of water would be delivered, particularly in the case of the lower head with higher windspeeds.

The U.K. prototype serves as a combination of a prototype and testing facility and incorporates a number of compromises introduced to permit various design options to be tested.

COMET

WINDMILL DATA SHEET

PUMPING TABLE

Duties for a Mean Hourly Wind Velocity of 7.7 m.p.h./12.39 k.p.h. — 185 miles/297.7 k.m. in each 24 hours
Windmill Diameter — Feet/Metres Total Head — Imperial Gallons/Litres each day

PUMP SIZE	8 ft. 2.44M		10 ft. 3.05M		12 ft. 3.66M		14 ft. 4.27M		16 ft. 4.88M		18 ft. 5.49M		20 ft. 6.10M		22 ft. 6.71M		24 ft. 7.32M		27 ft. 8.23M		30 ft. 9.14M		PUMP SIZE
Inches cm.	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls Litres	ft. Mt.	galls. Litres	ft. Mt.	galls Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	Inches cm.
1¾ 4.45	157 48	970 4410	270 82	1000 4550	355 108	1080 4910	508 155	1170 5320															1¾ 4.45
2 5.08	124 38	1280 5820	220 67	1320 6000	279 85	1420 6460	410 125	1540 7000	548 167	2100 9550	710 216	1880 8550											2 5.08
2¼ 5.72	100 31	1620 7370	178 54	1670 7590	225 69	1780 8090	328 100	1940 8820	454 138	2680 12180	610 186	2380 12180	795 242	2780 12640									2¼ 5.72
2½ 6.35	86 26	2000 9090	144 44	2060 9370	193 59	2200 10000	290 88	2300 10460	377 115	3300 15000	520 159	2940 13370	690 210	3440 15640	793 242	3820 17370							2½ 6.35
2¾ 6.99	75 23	2420 11000	123 38	2500 11370	162 49	2650 12050	230 70	2900 13180	326 99	4000 18180	435 133	3570 16230	595 181	4160 18910	683 208	3900 17730	903 275	4330 19680					2¾ 6.99
3 7.62	63 19	2880 13090	102 31	2950 13410	138 42	3150 14320	200 61	3400 15460	272 83	4800 21820	364 111	4250 19320	505 154	4950 22500	600 183	4650 21140	776 237	5150 23410					3 7.62
3¼ 8.26	53 16	3390 15410	86 26	3450 15680	117 36	3700 16820	173 53	4000 18180	231 70	5600 25460	313 95	4950 22500	430 131	5800 26370	515 187	5420 24640	685 209	6000 27280	885 270	6000 27280			3¼ 8.26
3½ 8.89	46 14	3940 17910	77 24	4050 18410	102 31	4250 19320	147 45	4700 21370	205 63	6400 29100	270 82	5750 21640	374 114	6750 30690	445 136	6300 28640	586 179	7000 31820	800 244	6930 31500	985 300	6450 29350	3½ 8.89
4 10.16	36 11	5100 23190	60 18	5300 24090	78 24	5600 25460	116 35	6100 27730	162 49	8400 38190	216 66	7530 34230	298 91	8820 40100	350 107	8250 37510	445 136	9100 41370	613 187	9100 41370	775 236	8260 37550	4 10.16
4¼ 10.80	31 10	5750 26140	51 16	5950 27050	70 21	6300 28640	103 31	6800 30910	143 44	9500 43190	192 59	8450 38410	264 81	10000 45460	317 97	9330 42410	397 121	10350 47050	555 169	10250 46600	715 218	9320 42370	4¼ 10.80
4½ 11.43	25 8	6450 29320	46 14	6650 30230	61 19	7100 32280	91 28	7700 35000	128 39	10700 48640	165 50	9550 43190	231 70	11200 50920	269 82	10400 47280	350 107	11500 52280	490 149	11400 51830	634 193	10450 47510	4½ 11.43
5 12.70	21 6	7500 34100	38 12	8250 37510	49 15	8700 39550	75 23	9500 43190	103 31	13200 60000	130 40	11750 53420	168 51	13750 62510	214 65	12850 58420	278 85	14200 64550	392 120	14200 64550	503 153	12900 58640	5 12.70
6 15.24	15 5	10500 47730	27 8	11500 52280	33 10	12600 57280	50 15	13700 62280	69 21	19000 86370	87 27	16900 76830	116 35	19800 90010	151 46	18500 84100	191 58	20550 93420	265 81	20400 92740	359 109	18550 84330	6 15.24
7 17.78			18 6	15500 70460	25 8	17050 77510	35 11	19750 89780	48 15	25650 116610	65 20	23000 104560	85 26	26300 119560	90 28	31500 143200	143 44	28000 127290	198 60	27800 126380	160 79	25300 115010	7 17.78
8 20.32					18 6	22400 101830	27 8	25650 116610	36 11	33850 153880	50 15	29900 135930	65 20	34000 154560	70 21	40300 183200	110 34	35900 163200	150 46	36400 165480	200 61	32800 149110	8 20.32
10 25.40							17 5	39800 180930	24 7	51400 233670	32 10	46000 209120	43 13	52700 239570	44 13	63000 286400	72 22	55400 251850	100 31	55200 250940	132 40	50000 227300	10 25.40
12 30.48											22 7	66700 303220	30 9	76200 346400	31 10	90700 402320	50 15	80600 366400	68 21	81000 368230	90 28	73800 335500	12 30.48
15 38.10													17 5	117200 532790	20 6	138500 629620	32 10	124700 566890	44 13	125600 570980	56 18	114300 521680	15 38.10
18 45.72																	22 7	183000 831920	30 9	181000 822830	49 12	164000 745540	18 45.72

COMET (continued)

PUMPING TABLE

Duties for a Mean Hourly Wind Velocity of 5.6 m.p.h./9.01 k.p.h. — 130 miles/208 k.m. in each 24 hours
Windmill Diameter — Feet/Metres Total Head — Imperial Gallons/Litres each day

PUMP SIZE	8 ft. 2.44M		10 ft. 3.05M		12 ft. 3.66M		14 ft. 4.27M		16 ft. 4.88M		18 ft. 5.49M		20 ft. 6.10M		22 ft. 6.71M		24 ft. 7.32M		27 ft. 8.23M		30 ft. 9.14M		PUMP SIZE
Inches cm.	ft. Mt.	gals. Litres.	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	ft. Mt.	galls. Litres	Inches cm.
1¾ 4.45	95 29	800 3640	160 49	850 3860	220 67	870 3960	310 95	960 4360															1¾ 4.45
2 5.08	75 22	1060 4820	130 40	1120 5090	175 53	1130 5140	250 76	1260 5730	320 98	1800 8180	410 125	1630 7410											2 5.08
2¼ 5.72	60 18	1340 6090	105 32	1420 6460	140 43	1430 6500	200 61	1590 7230	265 81	2290 10410	350 107	2070 9410	480 146	2300 10460									2¼ 5.72
2½ 6.35	52 16	1650 7500	85 26	1750 7960	120 37	1770 8050	170 52	1960 8910	220 67	2830 12870	300 91	2550 11590	415 126	2850 12960	500 152	2550 11590	650 198	2830 12870					2½ 6.35
2¾ 6.99	45 14	2000 9090	72 22	2130 9680	100 31	2150 9770	140 43	2380 10820	190 58	3430 15590	250 76	3100 14090	360 110	3450 15680	430 131	3100 14090	570 174	3430 15590	715 218	3800 17280	985 300	3360 15280	2¾ 6.99
3 7.62	38 12	2380 10820	60 18	2500 11370	85 26	2550 11590	120 37	2830 12870	160 49	4080 18550	210 64	3680 16730	305 93	4100 18640	380 116	3680 16730	490 149	4080 18550	620 189	4350 19780	840 256	3950 17960	3 7.62
3¼ 8.26	32 10	2800 12730	50 15	2950 13410	72 22	3000 13640	105 32	3300 15000	135 41	4780 21730	180 55	4300 19550	260 79	4800 21820	325 99	4300 19550	430 131	4780 21730	520 158	5100 23190	650 198	4650 21140	3¼ 8.26
3½ 8.89	28 9	3250 14780	45 14	3450 15680	63 19	3450 15680	90 27	3850 17500	118 36	5550 25230	155 47	5000 22730	225 69	5600 25460	280 85	5000 22730	370 113	5550 25230	470 143	5900 26820	570 174	5400 24550	3½ 8.89
4 10.16	22 7	4200 19090	35 11	4550 20460	48 15	4550 20680	70 21	5650 25690	94 29	7250 32960	124 38	6550 29780	180 55	7300 33190	220 67	6550 29780	280 85	7250 32960	360 110	7750 35230	445 139	7050 32050	4 10.16
4¼ 10.80	18 6	4750 21590	30 9	5050 22960	43 13	5100 23190	62 19	5050 22960	83 25	8200 37280	110 34	7350 33410	160 49	8250 37510	200 61	7400 33640	250 76	8200 37280	325 99	8750 39780	425 130	7950 36140	4¼ 10.80
4½ 11.43	15 5	5650 25690	27 8	5650 25690	38 12	5700 25910	55 17	5350 24320	75 23	9150 41600	95 29	8250 37510	140 43	9250 42050	170 52	8250 37510	220 67	9150 41600	285 87	9800 44550	370 113	8900 40460	4½ 11.43
5 12.70	12 4	6600 30000	22 7	7000 31820	30 9	7050 32050	45 14	7850 35690	60 18	11300 51370	75 23	10200 46370	110 34	11400 51820	135 41	10200 46370	175 53	11300 51370	230 70	12100 55010	295 90	11000 50010	5 12.70
6 15.24			15 5	10000 45460	20 6	10150 46140	30 9	11300 51370	40 12	16300 74100	50 15	14700 66830	70 21	16400 74550	95 29	14700 66830	120 37	16300 74100	155 47	17400 79100	210 64	15800 71830	6 15.24
7 17.78			11 3	13200 60010	15 5	13700 62280	22 7	15400 70010	30 9	22000 100010	38 12	20000 90920	56 17	22400 101830	75 23	25000 113650	92 28	22200 100920	100 31	23700 107740	140 43	21600 98190	7 17.78
8 20.32					12 4	18000 81830	17 5	20000 90920	24 7	29000 131830	30 9	26000 118200	45 14	29000 131830	60 18	32000 145470	70 21	28500 129560	80 24	31000 140930	110 34	28000 127290	8 20.32
10 25.40							10 3	31000 140930	14 4	44000 200020	18 6	40000 181840	26 8	45000 204570	35 11	50000 227300	42 13	44000 200020	52 16	47000 213660	72 22	43000 195480	10 25.40
12 30.48											12 4	58000 263670	17 5	65000 295490	23 7	72000 327310	30 9	64000 290940	38 12	69000 313670	52 16	63000 286400	12 30.48
15 38.10													12 4	100000 454600	16 5	110000 500060	19 6	99000 450050	23 7	107000 486420	32 10	98000 445510	15 38.10
18 45.72																	13 4	145000 659170	17 5	154000 700080	23 7	140000 636440	18 45.72

TOTAL HEAD

Total Head is the usual definition of the vertical height from the lowest water level whilst pumping to the discharge tee plus the pressure at the discharge tee measured in feet/metres head.

The most common windmill installations are shown in diagrams 1 and 2 where C plus N is the total head. For higher heads, as in diagram 4, C plus N added to the frictional loss in the long pipeline E is the total head.

Comet windmills allow very deep pump settings and high discharge pressures to deliver water through a pipeline over great distances and to a site much higher than the windmill.

The self priming Syphon Pump in diagrams 3 and 5 has the effective suction head limitation of all self priming pumps — about 22 feet/6.7 metres. The discharge head is the total heads shown in the Pumping Tables, less the suction head.

LUBING

The pump output increases to the square of the wind velocity up to wind speeds of 13.4 stat. miles per hour, then linear to 17.9 stat. miles per hour. From wind velocities of 17.9 stat. miles per hour up to gale force winds the output remains practically constant.

Piston pump for the M 022–3 windmill installation for draining and irrigating purposes

									E	F	D		G		
Type	Wind stat. m. p. h.	6,7	8,9	11,2	13,4	15,6	17,9	Delivery height ft.	Water level ft.	Well depth ft.	Pressure head ft.	Pressure line in.	Well dia ~ in.	Weight ~ lb.	Volume ~ cu. yd.
PE 115–28	US gal/h	360	527	824	1290	1490	1710	12,5	8.2	12,5	4,3	2	23	75	0.065
PE 115–18	US gal/h	360	527	824	1290	1490	1710	12,5	4,9	9,2	7,6	2	23	62	0.039
PE 115–13	US gal/h	360	527	824	1290	1490	1710	12,5	3,3	7	9,2	2	23	55	0.026

The pump unit consists of piston pump 14, filter 15 and delivery pipeline 13, high-grade steel piston rod.

Pision suction and pressure pumps for household water supply systems, pasture drinking units for cattle, irrigation, etc., for the **M 022–3 windmill.**

									K	H	L	M			
Type	Wind stat. m. p. h.	6,7	8,9	11,2	13,4	15,6	17,9	Delivery height ft.	Suction height ft.	Pressure head ft.	Min. in.	Max. in.	Suction pipeline in	Pressure pipeline in.	Weight ~ lb.
P 65-6	US gal/h	118	169	258	416	485	560	40	20	20	28	24	1½	1¼	15,5
P 50-6	US gal/h	71	105	163	245	290	332	66	20	26	28	24	1¼	1	8,8
P 40-6	US gal/h	45	68	105	158	184	211	100	20	80	28	24	1	1	6,6
P 35-6	US gal/h	37	53	79	121	140	161	130	20	110	28	24	1	1	4,4
P 115-6	US gal/h	360	527	824	1290	1490	1710	12,5	11,5	1	28	24	2	2	4,2
P 90-6	US gal/h	230	340	520	830	970	1120	20	19	1	28	24	2	2	26,5

Pump unit consists of suction pump 17 and surge tank 16.

Deep-well pumps for household water supply systems, cattle drinking units, irrigation, etc., for the **M 022–3 windmill.** The piston pump is always located below the water level in the well and is particularly suitable in this form for low water levels.

									R	O	P	S				
Type	Wind stat. m. p. h.	6,7	8,9	11,2	13,4	15,6	17,9	Delivery height ft.	Water level ft.	Pressure head ft.	Well depth ft.	Max. dia in.	Delivery line in.	Pressure line in.	Weight ~ lb.	Volume ~ cu. yd
P 65-35								40	9	31	13	3,4	1½	1¼	44	0.0196
P 65-65	US gal/h	118	169	258	416	485	560	40	19	21	23	3,4	1½	1¼	73	0.039
P 65-95								40	28	12	33	3,4	1½	1¼	101	0.059
P 65-125								40	38	2	43	3,4	1½	1¼	130	0.078
P 50-35								66	9	57	13	3,1	1¼	1	130	0.098
P 50-65								66	19	47	23	3,1	1¼	1	155	0.118
P 50-95	US gal/h	71	105	163	245	290	332	66	28	38	33	3,1	1¼	1	180	0.137
P 50-125								66	38	28	43	3,1	1¼	1	203	0.157
P 50-155								66	48	18	53	3,1	1¼	1	227	0.176
P 50-185								66	58	8	63	3,1	1¼	1	250	0.196
P 40-35								100	9	91	13	3,1	1¼	1	274	0.215
P 40-65								100	19	81	23	3,1	1¼	1	298	0.236
P 40-95								100	28	72	33	3,1	1¼	1	322	0.295
P 40-125								100	38	62	43	3,1	1¼	1	346	0.262
P 40-155	US gal/h	45	68	105	158	184	211	100	48	52	53	3,1	1¼	1	370	0.281
P 40-185								100	58	42	63	3,1	1¼	1	395	0.3
P 40-215								100	68	32	73	3,1	1¼	1	420	0.32
P 40-245								100	78	22	83	3,1	1¼	1	440	0.34
P 40-275								100	87	13	93	3,1	1¼	1	470	0.36
P 40-305								100	97	3	103	3,1	1¼	1	490	0.38
P 35-35								130	9	121	13	2,5	1	1	420	0.4
P 35-65								130	19	111	23	2,5	1	1	440	0.418
P 35-95								130	26	101	33	2,5	1	1	460	0.438
P 35-125								130	38	92	43	2,5	1	1	480	0.458
P 35-155								130	48	82	53	2,5	1	1	500	0.477
P 35-185								130	58	72	63	2,5	1	1	518	0.496
P 35-215	US gal/h	37	53	79	121	140	161	130	68	62	73	2,5	1	1	540	0.516
P 35-245								130	78	52	83	2,5	1	1	560	0.536
P 35-275								130	87	43	93	2,5	1	1	580	0.555
P 35-305								130	97	33	103	2,5	1	1	600	0.575
P 35-335								130	107	23	113	2,5	1	1	617	0.595
P 35-365								130	117	13	123	2,5	1	1	637	0.615
P 35-395								130	127	3	133	2,5	1	1	656	0.635

The pump unit consists of deep-well pump 20, filter 21, delivery pipeline with high-grade steel piston rod 19 and surge tank 18.

LUBING (continued)

Reciprocating suction and discharge pumps suitable for WIND-POWER DRIVE SYSTEMS M 015-6-3 and M 015-6-6.
for cattle drinking places on the pastures, domestic water supply, crop irrigation, etc.

TABLE I

								F	K					
Types	**Wind stat. m. p. h.**	**6.7**	**8.95**	**11.2**	**13.45**	**15.7**	**17.9**	**Max. Lift ~ ft.**	**Max. Water Level ~ ft.**	**Suction Connect in.**	**Discharge Connect in.**	**Min. Well Diameter in.**	**Net Weight ~ lbs.**	**Volume ~ cu. yd.**
P 50–1,4	**US gal/day**	1 320	2 060	2 380	3 275	3 800	3 800	23	23	1	¾	1½	4.4	
P 40–1,4	**US gal/day**	875	1 165	1 505	2 110	2 420	2 430	41	23	¾	¾	1½	2.2	

Extent of delivery: Suction-discharge pump 12, coarse-mesh filter 14 for suction line 13.

Deep-well reciprocating pumps suited to WIND-POWER PUMP DRIVES M 015-6-3 and M 015-6-6.
for domestic water supply, cattle drinking places, crop irrigation, etc. With this type, the reciprocating pump is always installed in the well below the water level; it is used for drainage and irrigation purposes and is suited especially for deep water levels. The reciprocating pump never lets water drop in the case of clogged valves. The suction head of these reciprocating pumps is also 23 ft. so that in case of emergency water can be delivered from a well having a water level depth of, say, 72.1 ft. through a suction pipe of 23 ft. long installed below the reciprocating pump. In this case, however, the pump will start to deliver water not until a wind velocity of, say, 11.2 stat. m./h.

TABLE II

								F	K	P	S				
Types	**Wind stat. m. p. h.**	**6.7**	**8.95**	**11.2**	**13.45**	**15.7**	**17.9**	**Max. Lift ~ ft.**	**Max. Water Level ~ ft.**	**Min. Depth of Well ~ ft.**	**Max. Diameter In.**	**Diameter Rising Main In.**	**Discharge Connection In.**	**Net Weight ~ lbs.**	**Volume ~ cu. yd.**
P 50– 32	**US gal/day**	1 320	2 060	2 380	3 270	3 800	3 800	23.0	8.2	9.84	2.95	1	¾	24.2	0.0079
P 50– 62	**US gal/day**	1 320	2 060	2 380	3 270	3 800	3 800	23.0	18	19.7	2.95	1	¾	44.0	0.0157
P 40– 92	**US gal/day**	875	1 165	1 505	2 110	2 430	2 430	42.6	27.9	29.5	2.56	1	¾	61.5	0.0236
P 40–122	**US gal/day**	875	1 165	1 505	2 110	2 430	2 430	42.6	37.7	39.4	2.56	1	¾	81.5	0.0314
P 35– 92	**US gal/day**	686	924	1 215	1 690	1 980	1 980	52.5	27.9	29.5	2.56	1	¾	61.7	0.0236
P 35–122	**US gal/day**	686	924	1 215	1 690	1 980	1 980	52.5	37.7	39.4	2.56	1	¾	79.3	0.0314
P 35–152	**US gal/day**	686	924	1 215	1 690	1 980	1 980	52.5	47.6	49.2	2.56	1	¾	99.2	0.0392

Extent of delivery: Deep-well reciprocating pump 16, coarse-mesh filter 17, rising main with piston rod 15.

SOUTHERN CROSS - Seneschal mill

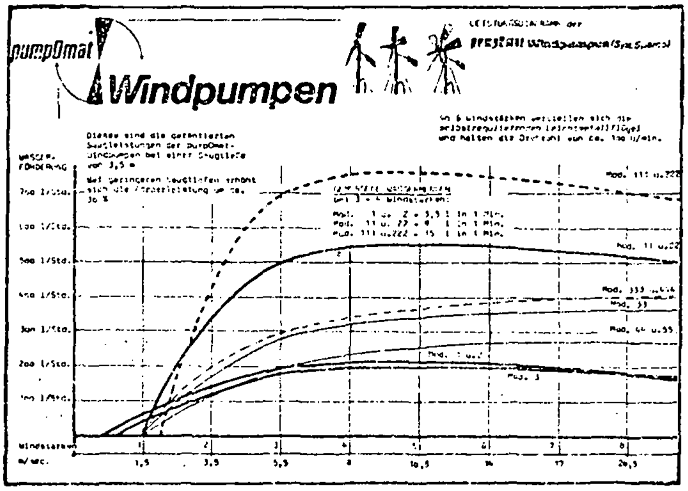
		DIAMETER OF PUMP CYLINDER															
Size Mill		**1¾in.**	**2in.**	**2¼in.**	**2½in.**	**2¾in.**	**3in.**	**3¼in.**	**3½in.**	**4in.**	**4¼in.**	**4½in.**	**5in.**	**6in.**	**8in.**	**10in.**	**12in.**	**14in.**
17ft. "R"	**Total Lift in Feet**	480	415	360	315	275	240	205	175	135	120	105	85	60	34			
7in. Stroke	**Av. Gls. per Day**	1300	1800	2300	2800	3400	4100	4800	5600	7300	8200	9200	11300	16300	29000			
17ft. "R"	**Total Lift in Faet**	420	360	310	270	240	210	180	155	120	105	95	75	53	30			
8in. Stroke	**Av. Gls. per Day**	1600	2100	2600	3200	3900	4700	5500	6400	8300	9400	10500	13000	18700	33200			
21ft. "R"	**Total Lift in Feet**			575	500	440	390	345	310	240	210	190	155	105	60	38	27	
8¼in. Stroke	**Av. Gls. per Day**			2200	2700	3300	3900	4600	5300	6900	7800	8800	10800	15600	27700	43300	62300	
21ft. "R"	**Total Lift in Feet**			470	410	360	320	285	250	200	175	155	125	83	50	32	22	
10in. Stroke	**Av. Gls. per Day**			2700	3300	4000	4700	5500	6400	8400	9500	10600	13100	18900	33600	52400	75500	
25ft. "R"	**Total Lift in Feet**				710	635	575	515	460	350	310	280	225	155	88	55	39	28
9½in. Stroke	**Av. Gls. per Day**				2600	3200	3600	4400	5100	6700	7600	8500	10500	15100	26800	41900	60300	82700
25ft. "R"	**Total Lift in Feet**				530	475	425	365	350	280	245	220	160	125	70	45	31	23
12in. Stroke	**Av. Gls. per Day**				3300	4000	4800	5600	6500	8500	9500	10700	13200	19000	33800	52900	76000	104500

PUMPING CAPACITY

These capacities are based on a 15-mile per hour wind for small mills and 18 to 20 miles per hour wind for larger mills. Capacities are based on longest stroke of Dempster mills. If short stroke used, capacities will be reduced in proportion to length stroke used.

Cylinder Size	6 Ft. 5" Stroke Elev.	6 Ft. 5" Stroke G.P.H.	8 Ft. "A" 7½" Stroke Elev.	8 Ft. "A" 7½" Stroke G.P.H.	10 Ft. 7½" Stroke Elev.	10 Ft. 7½" Stroke G.P.H.	12 Ft. 12" Stroke Elev.	12 Ft. 12" Stroke G.P.H.	14 Ft. 12" Stroke Elev.	14 Ft. 12" Stroke G.P.H.
1⅞	120	115	172	173	256	140	388	180	580	159
2	95	130	135	195	210	159	304	206	455	176
2¼	75	165	107	248	165	202	240	260	360	222
2½	62	206	89	304	137	248	200	322	300	276
2¾	54	248	77	370	119	300	173	390	260	334
3	45	294	65	440	102	357	147	463	220	396
3¼	39	346	55	565	86	418	125	544	187	465
3½	34	400	48	600	75	487	108	630	162	540
3¾	29	457	42	688	65	558	94	724	142	620
4	26	522	37	780	57	635	83	822	124	706

If the wind velocity be increased or decreased, the pumping capacity of the windmill will also be increased or decreased. Capacities will be reduced approximately as follows, if wind velocity is less than 15 miles per hour: 12 mile per hour wind, capacity reduced approximately 20%; 10 mile per hour wind, capacity reduced approximately 38%.



PUMPOMAT PUMPING CAPACITIES (L/HR)

WINDSPEED (M/SEC)	1.5	3.5	5.5	8.0	10.0	14.0
MODEL 9090/2	260	550	905	900	950	
MODEL P300	520	910	2000	2650	2660	2670

TABLE OF CAPACITIES OF CLIMAX OIL BATH WINDMILLS.

Size of Mill	Strokes per Minute	Cylinder Dia. Inches and **Actual** Gallons per Hour	Total Head in Feet.											
			10	50	75	100	125	150	175	200	250	300	350	400
6 ft.	45	Cylinder	3¼	2½	2	1¾								
		G.P.H. @ 5¾" stroke ..	420	250	155	120								
8 ft.	42	Cylinder	3¾	3¼	2¾	2¼	2							
		G.P.H. @ 5¾" stroke ..	500	380	275	182	145							
		,, ,, 7¾" ,, ..	680	510	370	245	195							
10 ft.	37	Cylinder	4¼	3½	2¾	2½	2¼	2	1¾	1¾				
		G.P.H. @ 8" stroke ..	800	530	337	275	228	177	138	138				
		,, ,, 9½" ,, ..	950	630	400	325	270	210	165	165				
12 ft.	31	Cylinder	7	5	4	3¾	3½	3	2¾	2½	2¼	2	1¾	
		G.P.H. @ 10" stroke ..	2260	1150	750	625	555	412	360	285	240	187	144	
		,, ,, 11½" ,, ..	2600	1325	860	720	640	475	415	330	275	215	165	
14 ft.	29	Cylinder	8	6½	5	4½	4	3½	3¼	3	2¾	2¼	2	
		G.P.H. @ 11½" stroke	3115	1980	1210	980	780	600	510	410	372	250	200	
		,, ,, 13" ,, ..	3600	2300	1400	1130	900	690	590	475	430	290	230	
16 ft.	21	Cylinder ..	12	8	7½	6	5½	5	4¾	4	3¾	3¼	3	2¾
		G.P.H. @ 12" stroke ..	5400	2400	2125	1330	1120	930	855	600	525	392	336	284
		,, ,, 15" ,, ..	6750	3000	2650	1660	1400	1160	1070	750	655	490	420	355
18 ft.	17	Cylinder	15	12	10	8	7	5¾	5¼	4¾	4¼	3¾	3½	3¼
		G.P.H. @ 12" stroke ..	6800	4360	3000	1920	1480	1000	920	665	544	425	368	320
		,, ,, 15" ,, ..	8500	5450	3750	2400	1875	1250	1150	830	680	530	460	400

Galvanized Steel Towers to carry "CLIMAX" Windmills are supplied in heights from 15 feet to 60 feet in multiples of 5 feet.

MANY CLIMAX WINDMILLS supplied thirty and forty years ago are still in regular service. They provide the ideal means of obtaining a water supply for farms, estates, plantations, etc., and are also widely used for irrigation and drainage work.

If erected according to our recommendations and to the instructions provided, CLIMAX windmills and towers are guaranteed for a period of one year, from date of despatch, against faulty material or workmanship—fair wear and tear excepted.

SELECTING A CLIMAX WINDMILL.

The capacities in the above table are in Imperial gallons per hour and are those obtainable in a good wind of about 20/22 miles per hour. In a wind of 12 m.p.h. these capacities will be about 65 per cent. of those listed.

After arriving at the total gallons of water required per day of 24 hours, allow for pumping this quantity in about 10 hours' time and in a 12 miles per hour wind, which should provide for the fluctuations in wind velocity, which occur in some districts. Where good winds blow regularly, a selection may be made direct from

As a general guide, a windmill of 12 ft. size and under will commence pumping in a breeze of 6 to 7 miles per hour, and the larger windmills in one of 8 to 9 miles per hour. Where light winds prevail it is advisable to lightly load a windmill by using a pump of comparatively small bore, so that pumping will occur in the lightest possible breeze.

The tower should be of sufficient height to ensure the windmill being at least 5 feet higher than any trees, buildings or rising ground within a radius of 150 to 200 yards.

PERFORMANCE CHARACTERISTICS AND SYSTEM SELECTION PROCEDURE FOR WATER PUMPING WINDMILL SYSTEMS

To select a complete pumping system, determine the depth of your well to the lowest expected water level. Then refering to the table below pick up the pump and windmill system best suited you your needs. Note that in several cases, either the AWP-12 or AWP-16 may be selected. If you are in an area of very high average wind, the AWP-12 will probably be satisfactory. On the other hand, if your average windspeed is lower, or you need more water, the AWP-16 may be needed. Actually, it is perfectly satisfactory to put the AWP-16 on a shallow well and the CPS-10 or CPS-14 pump, if water flow at a lower windspeed is desired.

Well Depth	Recommended Pump	Recommended Windmill System	Windspeed (m.p.h.) at which Pumping Begins (about 1 gallon per minute)	Windspeed For 3 gpm (180 gph)	Windspeed For 6 gpm (360 gph)
50' or less	CPS-10	AWP-12	9	11	13
50'-100'	CPS-14	AWP-12	11	12	14 to 15
100'-150'	CPS-19	AWP-12	12	13	15
	CPS-19	AWP-16	10	11	13
150'-200'	CPS-23	AWP-12	13	14	15 to 16
	CPS-23	AWP-16	11 to 12	12 to 13	14
200'-250'	CPS-23	AWP-12	14	15 to 16	17
	CPS-23	AWP-16	12	14	15
250'-300'	CPS-23	AWP-16	13	15	16 to 17
300'-400'	CPS-30	AWP-16	14	16	17 to 18
400'-500'	CPS-39	AWP-16	15	17	19
500'-600'	CPS-39	AWP-16	16	18	20

M.B.P.
(S.A.) PTY. LIMITED

PUMPING CAPACITIES OF M WINDMILLS

For the total factors involved in calculating capacities it will be noted that the M windmill shows a decided superiority. Note that the capacities listed for M.B.P. windmills are based on actual tests.

PUMP SIZE

Inches	2	2⅜	2½	2¾	3	3½	4
Millimetres	50.8	60.3	63.5	69.8	76.2	88.9	101.6
6 FEET							
1.828 m							
MAX. HEAD							
Feet	71	61	49	40	34	28	25
Metres	21.64	18.59	14.94	12.19	10.37	8.53	7.62
PER DAY							
Av. Galls.	1,100	1,530	1,750	2.110	2,475	3,410	4,400
Av. Litres	5 001	6 955	7 956	9 592	11 251	15 502	20 002
8 FEET							
2.438 m							
MAX. HEAD							
Feet	127	102	86	72	62	44	35
Metres	38.71	31.09	26.2	21.95	18.90	13.41	10.67
PER DAY							
Av. Galls.	1,320	1,860	2,090	2,540	2,970	4,125	5,280
Av. Litres	6 001	8 456	9 501	11 547	13 502	18 752	24 003
10 FEET							
3.048 m							
MAX. HEAD							
Feet	265	233	206	161	139	99	73
Metres	80.77	71.02	62.79	49.07	42.37	30.18	22.25
PER DAY							
Av. Galls.	1,540	2,145	2,420	2,970	3,465	4,785	6,160
Av. Litres	7 001	9 751	11 001	13 502	15,752	21 753	28,003
12 FEET							
3.658 m							
MAX. HEAD							
Feet	292	255	233	199	169	139	112
Metres	89.00	77.72	71.02	60.65	51.51	42.37	34.14
PER DAY							
Av. Galls.	1,650	2,287	2,585	3,180	3,700	5,115	6,500
Av. Litres	7 501	10 397	11 751	14 456	16 820	23 253	29,549
14 FEET							
4.267 m							
MAX. HEAD							
Feet	385	314	282	245	201	169	134
Metres	117.35	95.71	85.95	74.68	61.26	51.51	40.84
PER DAY							
Av. Galls.	1,705	2,385	2.668	3,285	3,823	5,280	6,820
Av. Litres	7 751	10 842	12 129	14,934	17.379	24,003	31 004

BALLYHALE

SOUTHERN STEEL WORKS LTD

BALLYHALE, CO. KILKENNY,
CO. KILKENNY,
IRELAND.
TELEPHONE (056) 28633

RANGE AVAILABLE

Model No.	Gallons Capacity Per Hour Max.	Mill-Diameter
S.S.1.	300.	9 ft.
S.S.2.	800.	12 ft.
S.S.3.	1,600.	15 ft.
S.S.4.	3,000.	18 ft.

(Maximum gallon capacity is calculated at wind-speed of 18 miles per hour.)

- The wind-mill is sturdy built, mounted on steel-lube roller bearings.
- The Tower is a welded steel construction which can vary in height to suit area location.
- The submersible piston pump, will supply water from a 200 ft. deep bore-hole, or any other sources (e.g. rivers, lakes, streams, wells etc.)
- When the wind speed reaches approx. 25 miles per hour, the wind-mill automatically swings itself out of the moving air-mass, and re-aligns itself as the velocity decreases.
- The horse-power development of these machines range from 3½ to 14 h.p.
- The unit is supplied with 1,100 gallon water storage if necessary.
- The S.S.I. model at a wind-speed of 3 miles per hour, has an output of 100 gallons per hour, increasing as wind-speed increases to a maximum of 300 gallons.

APPENDIX C. COMPUTER PROGRAMME

```
&COMPILE
C     ****************************************************
C     * PROGRAMME TO CALCULATE DISCHARGE FROM A WINDPUMP *
C     ****************************************************
C
C     ****************************
C     * DECLARATION OF VARIABLES *
C     ****************************
      INTEGER DAY,DEG,DEGP1,DEGMP1,IFAIL,M,NDAYS,NR,NROWS,NT,NYEARS,QDAY
      INTEGER QMDAY,QMEAS(24),QMONTH,R,T,TIME(24),VA(24),Y,YEAR
      REAL    HA,HM
      REAL*8  MINSQ,QMAX,VMAXN,VMN,WORK3
      REAL*8  CCOEF(40,40),COEF(40),DISCHR(40),MF(24),POWER(24),Q(24)
      REAL*8  SQ(40),VELYR(40),VM(24),WEIGHT(40),WORK1(3,40),WORK2(2,40)
      REAL*8  X(24)
      CHARACTER*10 MONTH
      CHARACTER*72 TITLE
C
C     ************** DESCRIPTION OF VARIABLES **************
C     CCOEF  =CHEBYSCHEV COEFFICIENTS FOR REGRESSION
C     COEF   =COEFICIENT FOR REGRESSION EQUATION
C     D      =ARRAY SUBSCRIPT FOR EACH DAY IN A MONTH
C     DAY    =LOOP RANGE FOR EACH DAY
C     DEG    =NUMBER OF DEGREES OF BEST POLYNOMIAL
C     DEGP1  =NUMBER OF DEGREES +1,OF BEST POLYNOMIAL
C     DEGMP1 =MAXIMUM NUMBER OF DEGREES +1, FOR REGRESSION (<= NR)
C     DISCHR =DISCHARGE POINTS FOR REGRESSION
C     HA     =HEIGHT OF ANEMOMETER
C     HM     =HEIGHT OF MILL
C     I      =ARRAY SUBSCRIPT TO PRINT COEFICIENTS
C     IFAIL  =ERROR TEST FOR NAG PROGRAM
C     J      =ARRAY SUBSCRIPT FOR EACH COEFICIENT
C     M      =LOOP RANGE FOR EACH MONTH
C     MF     =MILL FACTOR FOR ADJUSTING WINDSPEED FOR HEIGHT
C     MINSQ  =SMALLEST SQ
C     MONTH  =MONTH
C     NDAYS  =NUMBER OF DAYS IN MONTH
C     NHOURS =NUMBER OF HOURS BETWEEN VELOCITY READINGS
C     NR     =NUMBERS OF POINTS IN REGRESSION
C     NROWS  =FIRST SIZE OF ARRAY CCOEF
C     NT     =NUMBER OF TIME INTERVALS PER DAY
C     NYEARS =NUMBER OF YEARS OF WIND RECORD
C     POWER  =POWER IN EQUATION FOR ADJUSTING HEIGHT
C     Q      =DISCHARGE FROM PUMP
C     QDAY   =TOTAL DISCHARGE IN A DAY
C     QMAX   =MAXIMUM DISCHARGE FROM PUMP
C     QMDAY  =TOTAL MEASURED DISCHARGE IN A DAY
C     QMEAS  =MEASURED DISCHARGE FROM PUMP (FOR RUN ON SPARCO DATA)
C     QMONTH =TOTAL DISCHARGE IN A MONTH
C     R      =ARRAY SUBSCRIPT FOR EACH REGRESSION POINT
C     SQ     =ROOT MEAN SQUARE RESIDUAL OF REGRESSION
C     T      =ARRAY SUBSCRIPT FOR EACH TIME INTERVAL IN A DAY
C     TIME   =TIME INTERVAL BETWEEN VELOCITY READINGS
C     TITLE  =TITLE OF DATA INPUT
C     VA     =VELOCITY AT ANEMOMETER
C     VELYR  =VELOCITY POINTS FOR REGRESSION
C     VM     =VELOCITY AT MILL
C     VMAXN  =MAXIMUM VELOCITY IN VELYR, NORMALISED
C     VMN    =VELOCITY AT MILL,NORMALISED
C     WEIGHT =WEIGHT OF POINTS IN REGRESSION
C     WORK1  =WORKING SPACE FOR NAG PROGRAMME
C     WORK2  =WORKING SPACE FOR NAG PROGRAMME
C     WORK3  =WORKING SPACE
C     Y      =LOOP RANGE FOR EACH YEAR
C     YEAR   =YEAR
C     ******************************************************
C
```

```
C     *********
C     * TITLE *
C     *********
      READ  (5,901) TITLE
      WRITE (6,902) TITLE
C
C     ***********************************
C     * ESTABLISH PUMP CHARACTERISTICS *
C     ***********************************
      IFAIL=0
      NROWS=40
      READ  (5,903) NR,DEGMP1
      WRITE (6,904) NR,DEGMP1
      WRITE (6,9904)
      DO 1 R=1,NR
           READ  (5,905) VELYR(R),DISCHR(R),WEIGHT(R)
 1         WRITE (6,906) VELYR(R),DISCHR(R),WEIGHT(R)
      CALL E02ADF (NR,DEGMP1,NROWS,VELYR,DISCHR,WEIGHT,
     *WORK1,WORK2,CCOEF,SQ,IFAIL)
      MINSQ=SQ(1)
      DEGP1=1
      DO 2 I=1,DEGMP1
C          IF (MINSQ .LE.SQ(I)) GOTO 1
           MINSQ=SQ(I)
           DEGP1=1
 2    CONTINUE
      DEG=DEGP1-1
      WRITE (6,907) (SQ(I),I=1,DEGMP1)
      WRITE (6,908) DEG
      DO 3 J=1,DEGP1
 3         COEF(J)=CCOEF(DEGP1,J)
      VMAXN=(VELYR(NR)-VELYR(1))/(VELYR(NR)-VELYR(1))
      CALL E02AEF (DEGP1,COEF,VMAXN,QMAX,IFAIL)
C
C
C     ********************
C     * TIME INTERVALS *
C     ********************
      READ  (5,909) NT
      WRITE (6,910) NT
      READ  (5,911) TIME
      WRITE (6,912) TIME
C
C     **********************************
C     * DATA FOR ADJUSTMENT FOR HEIGHT *
C     **********************************
      READ  (5,913) HA,HM
      WRITE (6,914) HA,HM
      READ  (5,915) (POWER(T),T=1,NT)
      WRITE (6,916) (POWER(T),T=1,NT)
      DO 4 T=1,NT
 4         MF(T)=(HM/HA)**POWER(T)
      WRITE (6,917) (MF(T),T=1,NT)
C
C     ********
C     * DATE *
C     ********
      READ  (5,918) NYEARS
      DO 5 Y=1,NYEARS
           READ  (5,919) YEAR
           DO 6 M=1,12
                READ  (5,920) MONTH,NDAYS
                WRITE (6,921) MONTH,YEAR
                QMONTH=0.0
                DO 7 DAY=1,NDAYS
                     WRITE (6,922) DAY
                     WRITE (6,9922)
                     QDAY=0
                     QNDAY=0
C
C
```

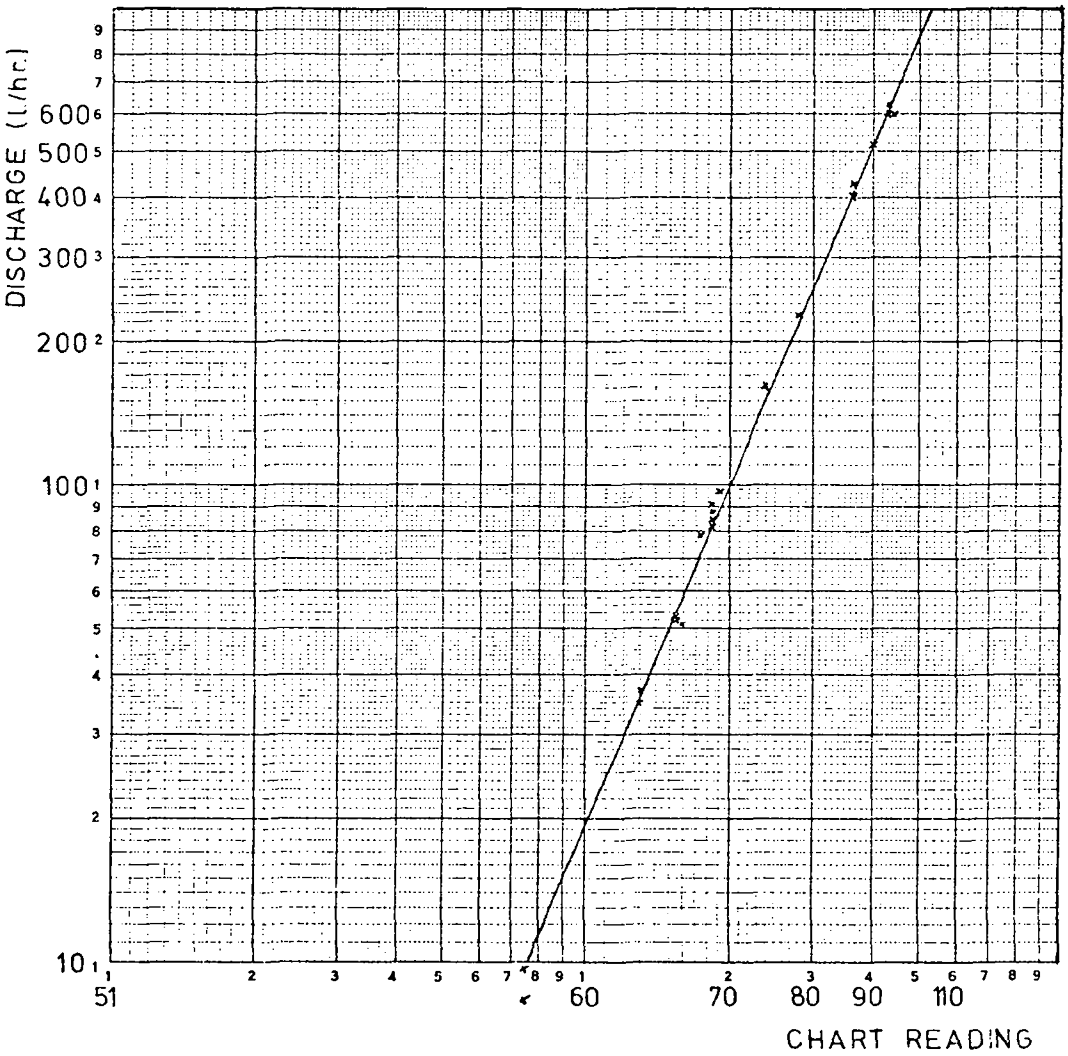
```
C                         ********************
C                         * VELOCITY READINGS *
C                         ********************
                          READ  (5,923) (VA(T),T=1,NT)
                          READ  (5,924) (GMEAS(T),T=1,NT)
                          DO 8 T=1,NT
                               VM(T)=VA(T)*MF(T)
C
C
C                              ************************
C                              * CALCULATE DISCHARGE *
C                              ************************
                               IF (VELYR(1)-VM(T) .GT. 0.001) GOTO 9
                               IF (VELYR(NR)-VM(T) .LT. 0.001) GOTO 10
                               WORK3=VELYR(NR)-VELYR(1)
                               VMN=((VM(T)-VELYR(1))-(VELYR(NR)-VM(T)))/WORK3
                               CALL E02AEF (DEGP1,COEF,VMN,Q(T),IFAIL)
                               GOTO 11
 9                             Q(T)=0
                               GOTO 11
10                             Q(T)=QMAX
11                             QDAY=QDAY+Q(T)*TIME(T)
                               QMDAY=QMDAY+QMEAS(T)*TIME(T)
                               WRITE (6,925) VA(T),VM(T),Q(T),QMEAS(T)
 8                        CONTINUE
                          WRITE (6,926)
                          WRITE (6,927) QDAY,QMDAY
                          QMONTH=QMONTH+QDAY
 7                   CONTINUE
                     WRITE (6,928) QMONTH
 6              CONTINUE
 5         CONTINUE
           STOP
C
C          **********************
C          * FORMAT STATEMENTS *
C          **********************
901        FORMAT (1H ,A72)
902        FORMAT (1H1,A72)
903        FORMAT (1H ,2I5)
904        FORMAT (5H0 NR=,I3,9H  DEGMP1=,I3)
9904       FORMAT (31H0       VELYR      DISCHR      WEIGHT)
905        FORMAT (1H ,3F10.5)
906        FORMAT (1H ,3F10.2)
907        FORMAT (10H0 SQ'S ARE,6F10.5)
908        FORMAT (31H  ORDER OF POLYNOMIAL FITTED IS,I5)
909        FORMAT (1H ,I5)
910        FORMAT (29H0 NUMBER OF TIME INTERVALS IS,I5,18H ;  INTERVALS ARE:)
911        FORMAT (1H ,12I5)
912        FORMAT (1H ,12I5)
913        FORMAT (1H ,2F5.2)
914        FORMAT (5H0 HA=,F5.1,4H HM=,F5.1,24H    POWERS AND MF'S ARE:)
915        FORMAT (1H ,12F5.2)
916        FORMAT (1H ,12F5.2)
917        FORMAT (1H ,12F5.2)
918        FORMAT (1H ,I5)
919        FORMAT (1H ,I5)
920        FORMAT (1H ,A10,I5)
921        FORMAT (9H0DATE IS ,A9,I5,1H0)
922        FORMAT (7H0DAY IS,I2)
9922       FORMAT (32H            VA       VM       Q  QMEAS)
923        FORMAT (1H ,12I5)
924        FORMAT (1H ,12I5)
925        FORMAT (1H ,I10,2F7.1,I7)
926        FORMAT (1H ,19X,12H-----  -----)
927        FORMAT (11H DAY TOTAL=,7X,2I7)
928        FORMAT (1H ,31X,I10)
C
C
C          *********** DESCRIPTION OF DATA INPUT ***********
C          TITLE                      72      CHARACTER
C          NR,DEGMP1                          2I5
C          VELYR DISCHR WEIGHT                3F10.5        NR LINES
C          NT                         1       I5
C          TIME                       NT      I5            12 PER LINE
C          HA,HM                      2       F5.2
C          POWER                      NT      F5.2          12 PER LINE
C          NYEARS                     1       I5
C          YEAR                       1       I5
C          MONTH,NDAYS                2       CHARACTER*10,I5
C          VA                         24      I5            12 PER LINE
C          ********************************************
           END
```

1. Flow Recording Equipment

The upper depth range of the Portadip recorder was set to 100 mm. Although this is below the minimum recommended range for the equipment (150 mm) the results were found to be accurate. The indication dial was set to give a reading of 50 mm at the level of the wier sill, 72 mm above the floor of the flume. The linear chart scale (Figure 34) had a range from 0 to 100%, with 50% as the sill level. Each 1% interval above this represents a 1 mm increase in head above the sill. The chart values were found to be 1 mm less than the dial so chart values (%) can be converted to head over the wier (mm) by subtracting 49.

The rate of discharge over the wier was measured as the time taken to fill a 1 litre flask whilst the Portadip was recording water level. The measured discharge rates and the corresponding chart readings, which have been plotted on a log-log graph, were as follows:

CHART READING	DISCHARGE
57.5	8.24
57.5	9.42
57.5	9.54
63	35
63	37
65.5	52
65.5	53
63	51
67.5	78
68.5	82
68.5	84
68.5	89
68.5	90
69	97
74	150
76	225
78	228
80.5	400
80.5	424
90	514
93	600
93	621
94	600

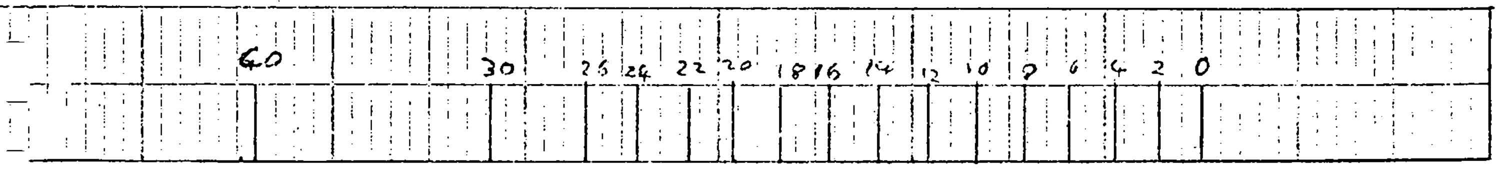


The average values read from the Portadip chart were subsequently converted to discharge with the following table abstracted from the graph.

CHART READING	DISCHARGE
64	42
65	50
65.5	54
66	58
66.5	62
67	67
67.5	72
68	77
68.5	82
69	88
69.5	93
70	100
70.5	105
71	110
71.5	118
72	124
72.5	131
73	138
73.5	143
74	152
74.5	160
75	170
75.5	178
76	185
76.5	191
77	201
77.5	210
78	220
78.5	230
79	240
79.5	250
80	260
81	280
82	300

2. Wind Recording Equipment

The single measured scale from the calibration of the wind anemometer and flat bed recorder is illustrated below. Further calibration should have been conducted to eliminate random errors.



APPENDIX E. TEST RESULTS

```
***** SPARCO CHARACTERISTICS, MANUFACTURER'S DATA *****
 NR=   4   DEGMP1=   3

       VELYR      DISCHR     WEIGHT
        5.00      128.00       0.00
        7.00      150.00       1.00
       10.00      177.00       1.00
       18.00      218.00       1.00

 SQ'S ARE   27.95632    4.72136    0.00000
 ORDER OF POLYNOMIAL FITTED IS     2

 NUMBER OF TIME INTERVALS IS    24 ;   INTERVALS ARE:
     1      1      1      1      1      1      1      1      1      1      1      1
     1      1      1      1      1      1      1      1      1      1      1      1

 HA=   3.5 HM=   3.5     POWERS AND MF'S ARE:
 0.16  0.16  0.15  0.15  0.16  0.15  0.16  0.16  0.16  0.16  0.16  0.16
 0.16  0.15  0.15  0.16  0.15  0.16  0.16  0.16  0.16  0.16  0.16  0.16
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00

DATE IS CURVE       1979

DAY IS 1
            VA       VM        Q
             0       0.0       0.0
             1       1.0       0.0
             2       2.0       0.0
             3       3.0       0.0
             4       4.0       0.0
             5       5.0     128.5
             6       6.0     139.6
             7       7.0     150.0
             8       8.0     159.7
             9       9.0     168.7
            10      10.0     177.0
            11      11.0     184.6
            12      12.0     191.5
            13      13.0     197.7
            14      14.0     203.1
            15      15.0     207.9
            16      16.0     212.0
            17      17.0     215.3
            18      18.0     218.0
            19      19.0     218.0
            20      20.0     218.0
            21      21.0     218.0
            22      22.0     218.0
            23      23.0     218.0
```

```
      *****SPARCO CHARACTERISTICS, SHORT PERIOD DATA *****
  NR= 29   DEGMP1=    3

      VELYR       DISCHR       WEIGHT
       5.00      100.00        3.00
       5.50      135.00        1.00
       6.00      131.00        1.00
       6.00      152.00        1.00
       6.50      132.00        1.00
       6.50      183.00        1.00
       7.00      124.00        1.00
       7.00      152.00        1.00
       7.00      160.00        2.00
       7.00      170.00        1.00
       8.00      160.00        1.00
       8.00      170.00        2.00
       8.00      183.00        1.00
       8.50      173.00        1.00
       9.50      191.00        1.00
      10.00      178.00        1.00
      10.00      191.00        1.00
      11.00      191.00        1.00
      11.00      201.00        1.00
      11.50      201.00        2.00
      12.00      210.00        1.00
      13.00      210.00        2.00
      13.50      210.00        1.00
      14.00      220.00        1.00
      16.00      220.00        1.00
      16.00      250.00        1.00
      16.50      230.00        1.00
      18.00      260.00        1.00
      19.00      260.00        1.00

  SQ'S ARE   59.52179   22.33923   18.66851
  ORDER OF POLYNOMIAL FITTED IS      2

  NUMBER OF TIME INTERVALS IS    24 ;   INTERVALS ARE:
     1      1      1      1      1      1      1      1      1      1      1      1
     1      1      1      1      1      1      1      1      1      1      1      1

  HA=   3.5 HM=   3.5     POWERS AND MF'S ARE:
  0.15  0.15  0.15  0.16  0.15  0.16  0.16  0.16  0.16  0.16  0.16  0.16
  0.15  0.16  0.16  0.16  0.15  0.16  0.16  0.16  0.16  0.16  0.16  0.16
  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00

 DATE IS CURVE      1979

 DAY IS 1
           VA       VM        Q
            0      0.0      0.0
            1      1.0      0.0
            2      2.0      0.0
            3      3.0      0.0
            4      4.0      0.0
            5      5.0    113.9
            6      6.0    131.5
            7      7.0    147.9
            8      8.0    163.0
            9      9.0    175.9
           10     10.0    189.5
           11     11.0    200.8
           12     12.0    210.6
           13     13.0    219.0
           14     14.0    227.1
           15     15.0    233.4
           16     16.0    238.3
           17     17.0    242.0
           18     18.0    244.4
           19     19.0    245.6
           20     20.0    245.6
           21     21.0    245.6
           22     22.0    245.6
           23     23.0    245.6
```

```
***** SPARCO CHARACTERISTICS, SELECTED HOURLY DATA *****
 NR= 18  DEGMP1=   3

      VELYR      DISCHR      WEIGHT
       5.00       77.00        1.00
       8.00      170.00        4.00
       8.50      152.00        1.00
       9.00      160.00        4.00
       9.00      170.00        2.00
       9.00      178.00        2.00
       9.50      152.00        1.00
       9.50      160.00        1.00
      10.00      170.00        5.00
      10.00      178.00        6.00
      10.00      183.00        2.00
      10.00      201.00        1.00
      11.00      170.00        1.00
      11.00      183.00        2.00
      11.00      201.00        1.00
      12.00      183.00        1.00
      15.00      220.00        1.00
    * 18.00      220.00        1.00

 SQ'S ARE  35.35010  24.95921  24.75583
 ORDER OF POLYNOMIAL FITTED IS     2

 NUMBER OF TIME INTERVALS IS    24 ;  INTERVALS ARE:
    1      1      1      1      1      1      1      1      1      1      1      1
    1      1      1      1      1      1      1      1      1      1      1      1

 HA=  3.5 HM=  3.5     POWERS AND MF'S ARE:
 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16
 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00

DATE IS CURVE      1979

DAY IS 1
           VA        VM        Q
            0       0.0      0.0
            1       1.0      0.0
            2       2.0      0.0
            3       3.0      0.0
            4       4.0      0.0
            5       5.0    123.3
            6       6.0    135.6
            7       7.0    147.1
            8       8.0    157.7
            9       9.0    167.4
           10      10.0    176.3
           11      11.0    184.4
           12      12.0    191.5
           13      13.0    197.9
           14      14.0    203.4
           15      15.0    208.0
           16      16.0    211.8
           17      17.0    214.7
           18      18.0    216.8
           19      19.0    216.8
           20      20.0    216.8
           21      21.0    216.8
           22      22.0    216.8
           23      23.0    216.3
```

* Nb. For the runs on hourly data it was assumed that the furling speed was 18mph., as claimed by the Sparco agents. If no discharge was specified for 18mph. the estimated discharge reached a maximum of 204l/hr. at 17mph., lower than that measured at 15mph. Assuming that the discharge at 18mph. would be as great or greater than that at 15mph. a rate of 220l/hr was used as an approximation.

```
***** SPARCO CHARACTERISTICS, ALL HOURLY DATA *****
NR= 37  DEGMP1=   3

      VELYR       DISCHR       WEIGHT
       5.00        50.00        2.00
       5.00       124.00        1.00
       5.00       170.00        1.00
       6.00       100.00        1.00
       6.00       105.00        1.00
       6.00       110.00        3.00
       6.00       124.00        1.00
       6.00       136.00        1.00
       6.00       170.00        1.00
       7.00       110.00        2.00
       7.00       138.00        2.00
       7.00       143.00        1.00
       8.00       105.00        1.00
       8.00       110.00        1.00
       8.00       124.00        3.00
       8.00       138.00        1.00
       8.00       152.00        3.00
       8.00       160.00        1.00
       8.00       170.00        8.00
       8.00       178.00        1.00
       9.00       152.00        5.00
       9.00       160.00        6.00
       9.00       170.00        7.00
       9.00       178.00        7.00
       9.00       183.00        1.00
      10.00       152.00        1.00
      10.00       170.00        8.00
      10.00       178.00        8.00
      10.00       183.00        9.00
      10.00       191.00        2.00
      10.00       201.00        3.00
      11.00       183.00        4.00
      11.00       201.00        4.00
      12.00       201.00        2.00
      13.00       201.00        1.00
      14.00       220.00        1.00
      16.00       220.00        1.00

SQ'S ARE   79.22987   51.68655   49.24882
ORDER OF POLYNOMIAL FITTED IS      2

NUMBER OF TIME INTERVALS IS    24  ;   INTERVALS ARE:
    1       1       1       1       1       1       1       1       1       1       1       1
    1       1       1       1       1       1       1       1       1       1       1       1

HA=   3.5 HM=   3.5     POWERS AND MF'S ARE:
0.16  0.16  0.15  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16
0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16  0.16
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00

DATE IS CURVE       1979

DAY IS 1
          VA        VM        Q
           0       0.0      0.0
           1       1.0      0.0
           2       2.0      0.0
           3       3.0      0.0
           4       4.0      0.0
           5       5.0     98.4
           6       6.0    119.1
           7       7.0    137.5
           8       8.0    153.9
           9       9.0    168.2
          10      10.0    180.3
          11      11.0    190.4
          12      12.0    198.3
          13      13.0    204.1
          14      14.0    207.8
          15      15.0    209.4
          16      16.0    208.9
          17      17.0    206.3
          18      18.0    201.5
          19      19.0    201.5
          20      20.0    201.5
          21      21.0    201.5
          22      22.0    201.5
          23      23.0    201.5
```

```
***** SPARCO DISCHARGE ESTIMATION, MANUFACTURER'S DATA *****

DATE IS JULY        1979

DAY IS .                                % difference   DAY IS 4
      VA      VM       Q   GMEAS  Q from QMEAS           VA      VM       Q   GMEAS
       0     0.0     0.0       0                          6     6.0   139.6     124
       0     0.0     0.0       0                          8     8.0   159.7     152
       0     0.0     0.0       0                          7     7.0   150.0     143
       0     0.0     0.0       0                          8     8.0   159.7     170
       0     0.0     0.0       0                          8     8.0   159.7     170
       0     0.0     0.0       0                         10    10.0   177.0     178
       0     0.0     0.0       0                         10    10.0   177.0     191
       0     0.0     0.0       0                         10    10.0   177.0     183
       0     0.0     0.0       0                         10    10.0   177.0     183
       0     0.0     0.0       0                         10    10.0   177.0     183
       0     0.0     0.0       0                         11    11.0   184.6     201
       0     0.0     0.0       0                         10    10.0   177.0     178
       0     0.0     0.0       0                         10    10.0   177.0     183
      11    11.0   184.6     201   - 8                    9     9.0   168.7     178
      14    14.0   203.1     220   - 8                    9     9.0   168.7     178
      13    13.0   197.7     201   - 2                    8     8.0   159.7     170
      11    11.0   184.6     183   + 1                    7     7.0   150.0     136
       9     9.0   168.7     152   + 11                   9     9.0   168.7     178
       8     8.0   159.7     124   + 28                  10    10.0   177.0     183
       7     7.0   150.0     136   + 9                    9     9.0   168.7     170
       8     8.0   159.7     152   + 5                   10    10.0   177.0     178
       6     6.0   139.6     100   + 40                  11    11.0   184.6     183
       6     6.0   139.6     110   + 27                  11    11.0   184.6     183
       9     9.0   168.7     152   + 11                   8     8.0   159.7     124
                   -----   -----                                          -----   -----
DAY TOTAL=          1849    1733   + 6.6     DAY TOTAL=                    4040    4102
                                                                                  +1.5
DAY IS 2                                     DAY IS 5
      VA      VM       Q   GMEAS                         VA      VM       Q   GMEAS
       9     9.0   168.7     152   + 11                   6     6.0   139.6     110
      10    10.0   177.0     170   + 4                    4     4.0     0.0      42
      11    11.0   184.6     183   + 1                    6     6.0   139.6     110
      10    10.0   177.0     178   - 1                    8     8.0   159.7     170
       9     9.0   168.7     170   - 1                    4     4.0     0.0      50
       9     9.0   168.7     152   + 11                   7     7.0   150.0     124
      10    10.0   177.0     170   + 4                    7     7.0   150.0     170
      10    10.0   177.0     170   + 4                    8     8.0   159.7     170
      12    12.0   191.5     201   - 4                    8     8.0   159.7     178
      11    11.0   184.6     191   - 3                    8     8.0   159.7     170
      11    11.0   184.6     183   + 1                    9     9.0   168.7     178
      12    12.0   191.5     201   - 5                   11    11.0   184.6     183
      10    10.0   177.0     170   + 4                   10    10.0   177.0     191
      10    10.0   177.0     178   - 1                    9     9.0   168.7     170
      10    10.0   177.0     178   - 1                    8     8.0   159.7     178
       8     8.0   159.7     110   + 45                   9     9.0   168.7     160
      10    10.0   177.0     170   - 4                   10    10.0   177.0     152
       9     9.0   168.7     170   - 1                    9     9.0   168.7     170
       9     9.0   168.7     170   - 1                    9     9.0   168.7     183
       7     7.0   150.0     110   + 36                   8     8.0   159.7     170
       4     4.0     0.0      67   - 100                  5     5.0   128.5      50
       8     8.0   159.7     138   + 16                   4     4.0     0.0      19
       8     8.0   159.7     124   + 29                   3     3.0     0.0       9
       9     9.0   168.7     152   + 11                   4     4.0     0.0     136
                   -----   -----                                          -----   -----
DAY TOTAL=          3976    3858   + 3.1     DAY TOTAL=                    3034    3245
                                                                                  -6.5
DAY IS 3                                     DAY IS 6
      VA      VM       Q   GMEAS                         VA      VM       Q   GMEAS
      10    10.0   177.0     170   + 4                    8     8.0   159.7     105
       9     9.0   168.7     160   + 5                    9     9.0   168.7      42
       6     6.0   139.6     105   + 33                   7     7.0   150.0     110
       9     9.0   168.7     160   + 5                    6     6.0   139.6     170
       9     9.0   168.7     160   + 5                    5     5.0   128.5      50
       9     9.0   168.7     160   + 5                    5     5.0   128.5     124
       9     9.0   168.7     170   - 1                    5     5.0   128.5     170
      10    10.0   177.0     170   + 4                    9     9.0   168.7     178
      10    10.0   177.0     178   - 1                    9     9.0   168.7     178
      10    10.0   177.0     178   - 1                   10    10.0   177.0     170
      10    10.0   177.0     183   - 3                    0     0.0     0.0       0
       9     9.0   168.7     178   - 5                    0     0.0     0.0       0
       9     9.0   168.7     160   + 5                    0     0.0     0.0       0
       8     8.0   159.7     160     0                    0     0.0     0.0       0
       8     8.0   159.7     152   + 5                    0     0.0     0.0       0
      10    10.0   177.0     183   - 3                    0     0.0     0.0       0
      10    10.0   177.0     183   - 3                    0     0.0     0.0       0
      11    11.0   184.6     201   - 8                    0     0.0     0.0       0
      11    11.0   184.6     201   - 8                    0     0.0     0.0       0
      10    10.0   177.0     201   - 12                   0     0.0     0.0       0
      10    10.0   177.0     201   - 12                   0     0.0     0.0       0
       8     8.0   159.7     170   + 6                    0     0.0     0.0       0
       8     8.0   159.7     170   + 6                    0     0.0     0.0       0
       6     6.0   139.6     138   + 1                    0     0.0     0.0       0
                   -----   -----                                          -----   -----
DAY TOTAL=          4042    4092   - 1.2     DAY TOTAL=             [illegible] [illegible]
```

```
***** SPARCO DISCHARGE ESTIMATION, SHORT PERIOD DATA *****

DATE IS JULY        1979

DAY IS 1
                VA        VM         Q    GMEAS
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                11      11.0     200.8      201
                14      14.0     227.1      220
                13      13.0     219.6      201
                11      11.0     200.8      183
                 9       9.0     176.9      152
                 8       8.0     163.0      124
                 7       7.0     147.9      136
                 8       8.0     163.0      152
                 6       6.0     131.5      100
                 6       6.0     131.5      110
                 9       9.0     176.9      152
                                 -----    -----
DAY TOTAL=                        1933     1733

DAY IS 2
                VA        VM         Q    GMEAS
                 9       9.0     176.9      152
                10      10.0     189.5      170
                11      11.0     200.8      183
                10      10.0     189.5      178
                 9       9.0     176.9      170
                 9       9.0     176.9      152
                10      10.0     189.5      170
                10      10.0     189.5      170
                12      12.0     210.8      201
                11      11.0     200.8      191
                11      11.0     200.8      183
                12      12.0     210.8      201
                10      10.0     189.5      170
                10      10.0     189.5      176
                10      10.0     189.5      178
                 8       8.0     163.0      110
                10      10.0     189.5      170
                 9       9.0     176.9      170
                 9       9.0     176.9      170
                 7       7.0     147.9      110
                 4       4.0       0.0       67
                 8       8.0     163.0      138
                 8       8.0     163.0      124
                 9       9.0     176.9      152
                                 -----    -----
DAY TOTAL=                        4224     3258

DAY IS 3
                VA        VM         Q    GMEAS
                10      10.0     189.5      170
                 9       9.0     176.9      150
                 6       6.0     131.5      105
                 9       9.0     176.9      150
                 9       9.0     176.9      160
                 9       9.0     176.9      160
                 9       9.0     176.9      170
                10      10.0     189.5      170
                10      10.0     189.5      173
                10      10.0     189.5      178
                10      10.0     189.5      183
                 9       9.0     176.9      173
                 9       9.0     176.9      150
                 8       8.0     163.0      150
                 8       8.0     163.0      152
                10      10.0     189.5      183
                10      10.0     189.5      183
                11      11.0     200.8      201
                11      11.0     200.8      201
                10      10.0     189.5      201
                10      10.0     189.5      201
                 8       8.0     163.0      170
                 8       8.0     163.0      170
                 6       6.0     131.5      158
                                 -----    -----
DAY TOTAL=                        4267 [illegible]

DAY IS 4
                VA        VM         Q    GMEAS
                 6       6.0     131.5      124
                 8       8.0     163.0      152
                 7       7.0     147.9      143
                 8       8.0     163.0      170
                 8       8.0     163.0      170
                10      10.0     189.5      176
                10      10.0     189.5      191
                10      10.0     189.5      183
                10      10.0     189.5      133
                10      10.0     189.5      183
                11      11.0     200.8      201
                10      10.0     189.5      178
                10      10.0     189.5      133
                 9       9.0     176.9      176
                 9       9.0     176.9      173
                 8       8.0     163.0      170
                 7       7.0     147.9      138
                 9       9.0     176.9      173
                10      10.0     189.5      183
                 9       9.0     176.9      170
                10      10.0     189.5      176
                11      11.0     200.8      183
                11      11.0     200.8      183
                 8       8.0     163.0      124
                                 -----    -----
DAY TOTAL=                        4245     4102

DAY IS 5
                VA        VM         Q    GMEAS
                 6       6.0     131.5      110
                 4       4.0       0.0       42
                 6       6.0     131.5      110
                 8       8.0     163.0      170
                 4       4.0       0.0       50
                 7       7.0     147.9      124
                 7       7.0     147.9      170
                 8       8.0     163.0      170
                 8       8.0     163.0      173
                 8       8.0     163.0      170
                 9       9.0     176.9      178
                11      11.0     200.8      133
                10      10.0     189.5      191
                 9       9.0     176.9      170
                 8       8.0     163.0      173
                 9       9.0     176.9      150
                10      10.0     189.5      152
                 9       9.0     176.9      170
                 9       9.0     176.9      133
                 8       8.0     163.0      170
                 5       5.0     113.9       50
                 4       4.0       0.0       13
                 3       3.0       0.0        9
                 4       4.0       0.0      133
                                 -----    -----
DAY TOTAL=                        3105     3243

DAY IS 6
                VA        VM         Q    GMEAS
                 8       8.0     163.0      105
                 9       9.0     176.9       42
                 7       7.0     147.9      110
                 6       6.0     131.5      170
                 5       5.0     113.9       50
                 5       5.0     113.9      124
                 5       5.0     113.9      170
                 9       9.0     176.9      170
                 9       9.0     176.9      170
                10      10.0     189.5      170
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                 0       0.0       0.0        0
                                 -----    -----
DAY TOTAL=                        1497     1297
```

```
***** SPARCO DISCHARGE ESTIMATION, SELECTED HOURLY DATA *****

DATE IS JULY        1979

DAY IS 1
          VA        VM         Q    GMEAS
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
          11      11.0     184.4      201
          14      14.0     203.4      220
          13      13.0     197.9      201
          11      11.0     184.4      183
           9       9.0     167.4      152
           8       8.0     157.7      124
           7       7.0     147.1      138
           8       8.0     157.7      152
           6       6.0     135.6      100
           6       6.0     135.6      110
           9       9.0     167.4      152
                         -----    -----
DAY TOTAL=                1833     1733

DAY IS 2
          VA        VM         Q    GMEAS
           9       9.0     167.4      152
          10      10.0     176.3      170
          11      11.0     184.4      183
          10      10.0     176.3      178
           9       9.0     167.4      170
           9       9.0     167.4      152
          10      10.0     176.3      170
          10      10.0     176.3      170
          12      12.0     191.6      201
          11      11.0     184.4      191
          11      11.0     184.4      183
          12      12.0     191.6      201
          10      10.0     176.3      170
          10      10.0     176.3      178
          10      10.0     176.3      178
           8       8.0     157.7      110
          10      10.0     176.3      170
           9       9.0     167.4      170
           9       9.0     167.4      170
           7       7.0     147.1      110
           4       4.0       0.0       67
           8       8.0     157.7      138
           8       8.0     157.7      124
           9       9.0     167.4      152
                         -----    -----
DAY TOTAL=                3962     3858

DAY IS 3
          VA        VM         Q    GMEAS
          10      10.0     176.3      170
           9       9.0     167.4      160
           6       6.0     135.6      105
           9       9.0     167.4      150
           9       9.0     167.4      160
           9       9.0     167.4      160
           9       9.0     167.4      170
          10      10.0     176.3      170
          10      10.0     176.3      178
          10      10.0     176.3      173
          10      10.0     176.3      183
           9       9.0     167.4      178
           9       9.0     167.4      150
           8       8.0     157.7      150
           8       8.0     157.7      152
          10      10.0     176.3      183
          10      10.0     176.3      183
          11      11.0     184.4      201
          11      11.0     184.4      201
          10      10.0     176.3      201
          10      10.0     176.3      201
           8       8.0     157.7      170
           8       8.0     157.7      170
           6       6.0     135.6      138
                         -----    -----
DAY TOTAL=                4019     4092

DAY IS 4
          VA        VM         Q    GMEAS
           6       6.0     135.6      124
           8       8.0     157.7      152
           7       7.0     147.1      143
           8       8.0     157.7      170
           8       8.0     157.7      170
          10      10.0     176.3      178
          10      10.0     176.3      191
          10      10.0     176.3      183
          10      10.0     176.3      183
          10      10.0     176.3      183
          11      11.0     184.4      201
          10      10.0     176.3      178
          10      10.0     176.3      183
           9       9.0     167.4      178
           9       9.0     167.4      178
           8       8.0     157.7      170
           7       7.0     147.1      138
           9       9.0     167.4      178
          10      10.0     176.3      183
           9       9.0     167.4      170
          10      10.0     176.3      178
          11      11.0     184.4      183
          11      11.0     184.4      183
           8       8.0     157.7      124
                         -----    -----
DAY TOTAL=                4018     4102

DAY IS 5
          VA        VM         Q    GMEAS
           6       6.0     135.6      110
           4       4.0       0.0       42
           6       6.0     135.6      110
           8       8.0     157.7      170
           4       4.0       0.0       30
           7       7.0     147.1      124
           7       7.0     147.1      170
           8       8.0     157.7      170
           8       8.0     157.7      178
           8       8.0     157.7      170
           9       9.0     167.4      178
          11      11.0     184.4      183
          10      10.0     176.3      191
           9       9.0     167.4      178
           8       8.0     157.7      178
           9       9.0     167.4      160
          10      10.0     176.3      152
           9       9.0     167.4      170
           9       9.0     167.4      183
           8       8.0     157.7      170
           5       5.0     123.3       30
           4       4.0       0.0       19
           3       3.0       0.0        9

           4       4.0       0.0      138
                         -----    -----
DAY TOTAL=                3000     3245

DAY IS 6
          VA        VM         Q    GMEAS
           8       8.0     157.7      105
           9       9.0     167.4       42
           7       7.0     147.1      110
           6       6.0     135.6      170
           5       5.0     123.3       50
           5       5.0     123.3      124
           5       5.0     123.3      170
           9       9.0     167.4      178
           9       9.0     167.4      178
          10      10.0     176.3      170
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
           0       0.0       0.0        0
                         -----    -----
DAY TOTAL=                1485     1207
```

HEIGHT VARIATION OF WINDSPEED

HA=10m. HM=3.5m.

Power	5 day total discharge (litres)		Average % difference from p=0.16
	Manufacturer's characteristics	Selected hourly characteristics	
0.16	16608	16381	0.0
0.20	15273	15047	-8.0
Variable	11578	11312	-30.6