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STORAGE MODEL FOR MULTIBLADED WATER PUMPING WINDMILLS WITH PISTON PUMPS

by

Ukpong D. Assam

A thesis
submitted under the supervision of
Dr. E. J. Schiller

in fulfillment of the
thesis requirement for the degree of
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in
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DEDICATION

To Annie, Lydia and Elena

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ABSTRACT

The aim of this thesis is the optimization of Multibladed Water Pumping Systems. The optimal sizing of the storage tank is determined using Rippl's mass curves and behaviour analyses. The effects of some of the input parameters on the storage tank were also examined.

Three wind speed distributions were used to calculate the storages required at given demand levels. Only daily and monthly wind speed distributions are considered.

From comparisons of the storages calculated using the meteorological data of Ottawa International Airport, it was found that the storages calculated using the actual wind speed distribution were smaller than those calculated using either the Weibull or Rayleigh distribution.

A computer model, written in FORTRAN IV, was developed. For flexibility purposes, various options are included.

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NOTATION

A	rotor swept area
B_1	formation loss coefficient
C	storage capacity
C_{HW}	Hazen-Williams coefficient
C_1	well loss coefficient
C_p	coefficient of performance (power coefficient)
C_{pm}	maximum power coefficient
C_q	torque coefficient
C_{qm}	maximum torque coefficient
c	Weibull scale factor
D	rotor diameter
D_p	internal diameter of pump
D_t	reservoir release at period t
d	internal diameter of pipe
ΔV	wind speed interval
e	absolute roughness of pipe
e_o	initial absolute roughness of pipe
f	pipe friction factor
f(V)	cumulative distribution function
$f_i(V_c)$	calculated cumulative probabilities
$f_i(V_o)$	observed (actual) cumulative probabilities
G_r	gear ratio
g	gravitational acceleration

H	total dynamic head
h_1	head loss due to pipe friction
h_s	static height
k	Weibull shape factor
L	pipe length
m, n	exponents in Hazen-Williams equation
N	total number of wind-speed observations
P_e	extractable power from the wind
P_h	hydraulic power
P_m	mechanical power
P_w	power in the wind
Prob	probability of failure
$p(V)$	probability density function
Q	flow rate
Q_t	reservoir inflow at period t
R	resistance coefficient in Hazen-Williams equation
R_e	Reynolds number
Rel	reservoir reliability
R_o	occurrence-based reliability
R_q	quantity-based reliability
R_t	time-based reliability
S	pump stroke
S_o	initial storage
S_t	storage at beginning of period t
S_{t+1}	storage at beginning of period t+1
s_w	well drawdown
T	total time period

T_m	total number of years
T_n	number of failure years
T_q	rotor torque
T_w	average water load torque
t	time
Δt	duration of a single time period
Δt_f	duration of a single failure period
U	rotor tip-speed
V	wind speed
$\bar{V}$	average wind speed
V_i	wind speed at i-th period
v	average velocity in pipe
ΔW	quantity of water not delivered during a single failure period
ρ_a	density of air
ρ_w	density of water
γ_w	specific weight of water
η_m	mechanical efficiency of pump
η_t	gear efficiency
η_v	volumetric efficiency of pump
λ	tip-speed ratio (TSR)
λ_d	design TSR
λ_m	maximum TSR
λ_{qm}	TSR at maximum torque coefficient
Ω	rotational speed of pump shaft
α	rate of growth of pipe roughness element
σ	standard deviation of wind speeds

ε	root-mean-square (rms) residual error
Γ	gamma function
Σ	summation sign
μ	coefficient of viscosity of water

GLOSSARY OF TERMS

Anemometer	instrument used for measuring wind speed
Aquifer	a water-bearing stratum of permeable rock, sand and/or gravel
Cut-in speed	the lowest wind speed below which a wind turbine produces no power
Cut-out speed	the highest wind speed above which a wind turbine produces no power
Gear ratio	ratio of rotational speed of windmill to that of pump shaft
Mass curve	a cumulative plotting of net reservoir inflow and draft
Power coefficient	the ratio of the power extracted by a wind turbine to the power available in the wind stream
Rated wind speed	the lowest wind speed at which wind turbine output power reaches maximum value
Rated output	output corresponding to the rated wind speed
Rotor	the blades and associated rotating members of the wind turbine

Solidity	ratio of the blade area to the swept area of the rotor
TSR	tip-speed ratio, ratio of tip-speed of rotor to wind speed
WECS	wind energy conversion system
Wind turbine	an individual wind powered machine

Chapter I

INTRODUCTION

1.1 WIND PUMPING SYSTEM AS A SOURCE OF WATER SUPPLY

In order to meet the water demand of our modern society, various sources of water supply which include surface, sub-surface, and rain water are currently being used. All these sources of water interrupt the natural hydrologic cycle at some point, and then collect, treat, store and distribute the water.

Most water supply systems involve pumping. The most common method of pumping requires the use of electricity or diesel fuel to drive the pump. But with the cost of energy rising, other methods are currently being investigated. These methods, which include wind and solar pumping, are commonly referred to as renewable energy methods.

The extraction of groundwater requires the drilling of wells below the water table, and a pumping method. Well waters are generally of superior quality compared to surface waters due to percolation through the ground. From the assessment study conducted in ref. [49], (vol. I), it has been found that wind pumps are economically competitive with other pumping devices if the minimum monthly average wind speed is greater than 3 m/s.

Wind pumping systems are considered economical because of the following reasons:

1. The wind is a freely available renewable energy source.
2. Generally minimum maintenance is required.
3. Little or no treatment is usually required if well water is used.
4. Small installations ~~can~~ be financed at a modest cost.

Wind pumping systems may not be able to meet all the water requirements of a community. In such a situation, other methods of water supply can be used to supplement the supply from wind pumping system. Furthermore, rationing can be implemented.

Wind pumping systems are used worldwide, especially in the rural areas of developing countries.

1.2 OUTLINE OF A WIND PUMPING SYSTEM

Fig. 1 illustrates the key water pumping terms for a multibladed water pumping windmill coupled to a reciprocating piston pump.

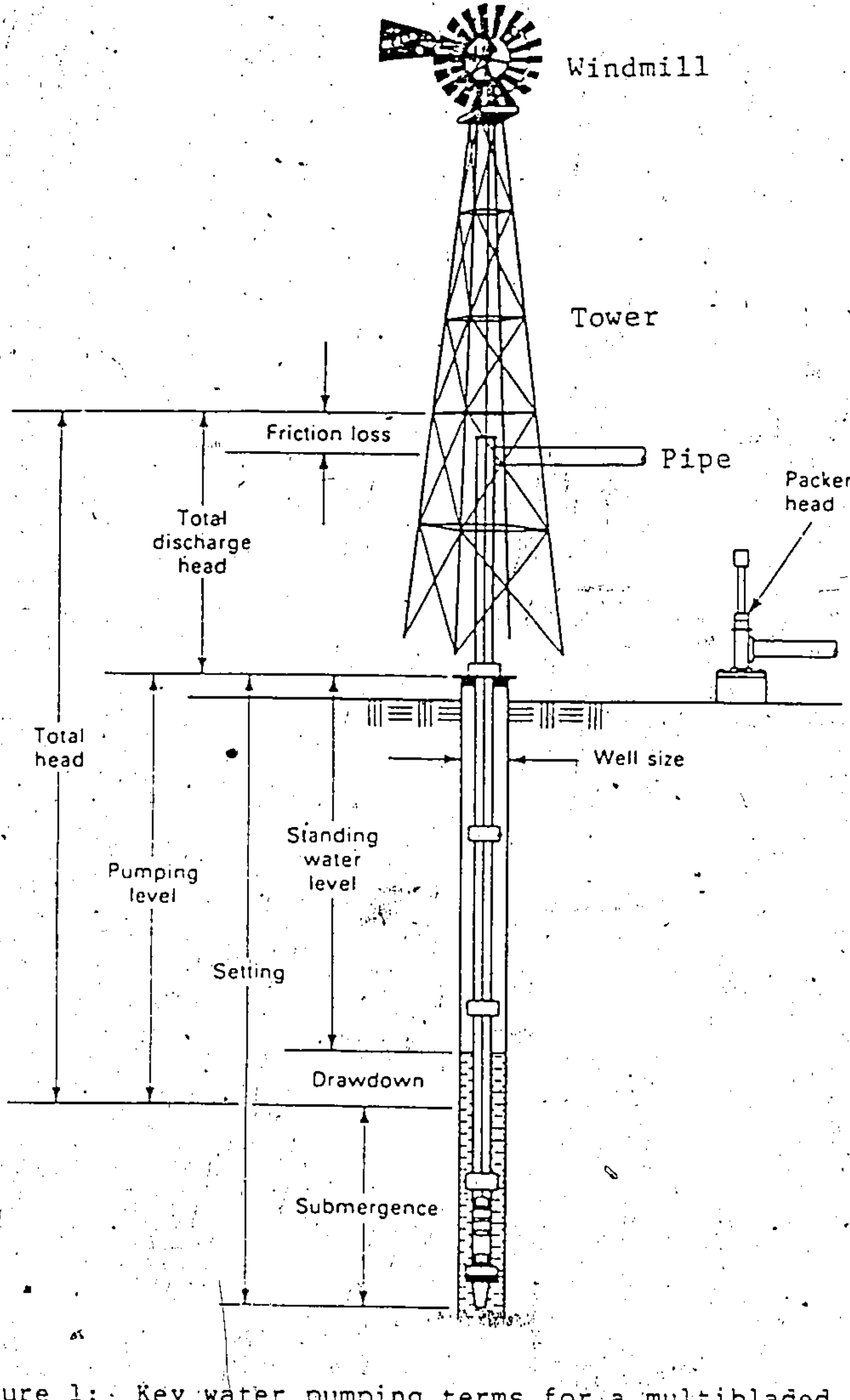


Figure 1: Key water pumping terms for a multibladed mindmill (adapted from Johnson [20])

1.2.1 Extraction

The hydrologic cycle is intercepted by drilling a well. Extraction is accomplished by using a wind energy conversion system (WECS) coupled to a pump to lift the water to the surface. A remote WECS can also be used to pump surface water if an electrical connection exits between the WECS with electrical generator and the pump.

1.2.2 Storage

Due to the variability of the wind, if water is to be guaranteed during low wind or calm periods, it becomes necessary to provide a storage facility. The form of storage considered in this thesis is an elevated storage reservoir. The height of the storage tank is determined from the hydraulic and economic factors. It is the determination of the optimum size of this reservoir which constitute the main goal of this thesis.

1.2.3 Delivery

If hydraulic and topographic conditions are favourable, gravity distribution is used from the reservoir. This means that the reservoir should have sufficient elevation so that water could be supplied to all parts of the distribution system without additional pumping.

1.2.4 Quality of Ground Water

Physically, ground water is generally clear, colorless and with little or no suspended matter. Chemically, ground water may contain large quantities of dissolved minerals due to the contact of the water with the minerals that make up the earth's crust.

Calcium and magnesium are the main causes of hardness while iron is responsible for the discoloration of ground water. If these or other unwanted minerals are present in excess amounts, then treatment may need to be applied to remove the undesirable minerals.

Ground water is generally free from bacteria if the well is not close to pollution sources, such as privies and cesspools. Thus ground water is usually considered to be of superior quality compared to other sources of water.

1.3 DESIGN OF A WIND PUMPING SYSTEM

In order to determine the optimal size of a reservoir in a wind pumping system, the following input information should be known:

1. Wind characteristics: wind speed patterns, frequencies, duration and gusts.
2. Pumping parameters.
3. Pump characteristics.

4. Windmill characteristics.
5. Well characteristics: discharge versus drawdown.
6. Demand pattern.

The most variable and unpredictable factor is the wind. Wind behaviour is governed by a combination of global, regional, seasonal and diurnal weather patterns. In some parts of the world, especially in the less developed countries, wind data are not usually available. Also the cost of collecting and processing wind data may be prohibitive if wind monitoring is done over an extended period of time. Therefore, statistical distributions are sometimes used to approximate the actual wind regime.

In order to rectify this situation, an anemometer is usually set up at the proposed site and height that the windmill will be installed, and wind data are collected over a certain period of time.

The choice of pumping parameters is important and is dependent upon choosing the most economical commercial pipe. The most difficult task is to properly match the wind turbine to both the pump and the wind regime.

Pumps and windmills have optimum characteristics for a given operating range. If any of these components operates outside its operating envelope, its efficiency will be reduced considerably and useful power would be wasted. Previous work on the matching of pumps and windmills has been done by Bragg and Schmidt [3] and in ref. [50]. Also the procedure of matching the windmill to the wind regime is given by Park [38].

If water is to be pumped from a well, the ground water potential should be investigated. Testing for well yield is normally done with pumping test units consisting of a submersible pump and measuring devices for discharge and water level or drawdown.

1.4 STATEMENT OF PROBLEM TO BE SOLVED

A storage model for multibladed water pumping windmills coupled to reciprocating piston pumps will be developed for use on computers. The model will simulate a windmill that has already been matched to the given wind regime and pump.

An optimal size of the storage tank would be determined at a particular reliability level for a given set of input parameters. If the tank is too small, it will cost less but water will be wasted by overflowing. On the other hand, if the tank is too large, construction costs will be excessively expensive.

1.5 OUTLINE OF THESIS

Chapter II deals with the literature review of WECS with emphasis on water pumping windmills. Various input data and parameters are discussed. References are made to the work of other researchers.

In Chapter III, the equations used to develop the WINDPUMP storage model are presented. All the input data and parameters required are clearly stated. This storage model is based on Rippl's method and the behaviour analysis of McMahon and Mein [33].

The meteorological data used to test the storage model are discussed in Chapter IV. Methods used to calculate the required parameters as well as the results of the three wind speed distributions considered are presented. Testing of the WINDPUMP storage model is done in this chapter. Values of all the input data and parameters used in the computations are indicated. Results are either tabulated and/or graphically presented. Results of sensitivity analyses on some input parameters are discussed.

Chapter V contains the discussions and conclusion of the work done, including the list of further work that might be conducted in this field.

Chapter II

LITERATURE REVIEW

2.1 WINDMILL CHARACTERISTICS

2.1.1 Types of WECS

The most common WECS are classified according to their axis of rotation relative to the wind direction. Cheremisinoff [7] listed the major categories of WECS as follows:

1. Horizontal-axis wind turbine (HAWT).
2. Cross-wind horizontal-axis rotors.
3. Vertical-axis wind turbine (VAWT).
4. Thermoelectric type machines.
5. Translational wind machines.

HAWT and VAWT are the most common ones in use, and both types of machines are used for water pumping. However, Burton and Pinilla [5] pointed out that windmills of high solidity are usually used for water pumping. The HAWT machines are further classified as single-bladed, double-bladed, triple-bladed or multi-bladed rotors (pp. 59-60 of [7] and pp. 66-67 of [4]). Bragg [4] stated that the fundamental advantage of a VAWT is that the usual vertical axis device is independent of the wind direction; therefore, the windmill does not need to be oriented into the wind stream.

Le Gourieres [28] pointed out that two types of installations are available: low-speed wind turbines driving piston pumps and high-speed wind machines driving helical or turbine pumps. Because of the high starting torque required by piston pumps, the most suitable windmills to use are the multibladed windmills. Multibladed windmills operate efficiently at low wind speeds (p. 151 of [28] and p. 68 of [4]).

2.1.2 WECS Performance

According to Pennell and Miller [39], the most commonly available information on wind turbine performance is the steady-state performance characteristics. It gives the relationship between the mechanical shaft power and the wind speed in a steady homogeneous flow.

From rotor theory and experimental observations, Justus [24] and Koeppl [26] stated that the coefficient of performance (power coefficient), C_p, depends only upon the tip-speed ratio (TSR) and the blade pitch angle. Pennell and Miller [39] added that C_p is also a function of blade airfoil shape and blade angle of attack.

However, C_p can be expressed as a function of wind speed only, as suggested by Pennell and Miller [39]. Justus et al. [22] and Justus and Mikhail [23] developed C_p models for constant and variable speed machines.

The preceding C_p models were developed for high-speed wind turbines having cut-in, rated and cut-out wind speeds. Multibladed windmills are not high-speed windmills; consequently, the models are not applicable for these types of machines.

Carothers and Bragg [6], Lysen [31] and Wyatt and Hodgkin [53] developed performance output models for multibladed windmills using the average load torques of the pump and windmill. A linear relationship between the torque coefficient, C_q, and TSR is assumed. However, the starting conditions of the windmill cannot be predicted with this assumption because the linear relationship is not valid for low values of TSR.

Carothers and Bragg [6] tested their model using statistical analysis of wind pumps operating in low to moderate wind regimes. They compared the predicted results with field measurements taken at a site in the Sahelian region of Niger and found reasonable agreement. Wyatt and Hodgkin [53] tested their model by comparing the predicted results to field test results for a Dempster windmill installed in Honduras and found good agreement.

Other researchers (Burton and Pinilla [5], Pallabazzer [37] and Pinilla et al. [40]) assumed a parabolic relationship between C_p and TSR.

2.2 WELL CHARACTERISTICS

In order to investigate the groundwater potential, a series of pumping tests have to be done. Pumping tests are normally carried out to determine the aquifer properties, namely, permeability, coefficient of transmissibility and coefficient of storage.

If the aquifer properties are already known, it may not be necessary to perform any pumping tests in order to determine the relationship between discharge and drawdown. McWhorter and Sunada [34] and ref. [19] have plotted the relationship between the percent of maximum yield and the percent of maximum drawdown for water-table well in a homogeneous unconfined aquifer. The preceding situation is only valid for an unconfined aquifer. However, there are other types of aquifers that may be encountered.

2.2.1 Theis Solution

The Theis formula for a non-equilibrium well is widely used in aquifer analysis. The assumptions used to derive the Theis formula are summarized in [19] as follows:

1. The water-bearing formation is uniform in character with equal permeability in both horizontal and vertical directions.
2. The formation has uniform thickness.
3. The formation has infinite areal extent.

4. The formation receives no recharge from any source.
5. The pumped well penetrates and receives water from the full thickness of the water-bearing formation.
6. The water removed from storage is discharged instantaneously with lowering of the head.

The Theis solution not only predicts the drawdown in response to a step change in pumping rate from zero at time zero to Q at time t, but it can be used to predict the drawdown due to variable and intermittent operation of wells. McWhorter and Sunada [34] pointed out that the incremental response to a change in pumping rate is independent of the previous history of discharge and that the computation is equally valid for a reduction in discharge.

2.2.2 Jacob Solution

The total drawdown is considered by Raghunath [43] to be made up of:

1. Head loss resulting from laminar flow in the formation (formation loss).
2. Head loss resulting from the turbulent flow in the zone close to the well face.
3. Head loss through the well screen.
4. Head loss in the well casing.

Jacob [17] expressed the well drawdown, s_w, in terms of the formation loss coefficient, B_1, and the well loss coefficient, C_1, as:

$$s_w = B_1Q + C_1Q^2 \tag{2.1}$$

where Q = discharge

With the values of B_1 and C_1 known, the complete relationship between s_w and Q can be determined.

From the economic point of view, Raghunath [43] suggested that three to five different rates or steps, each step being of the same duration, say 60 or 90 minutes, are sufficient for the analysis of wells. From the measured s_w, the specific drawdown, s_w/Q, can be plotted against Q. The slope and the intercept on the s_w/Q axis yields C_1 and B_1 respectively.

Jacob [17] pointed out that s_w already takes into account the type of aquifer, the effect of boundaries in the vicinity and the partial penetration of wells. Thus, the solution is equally applicable to non-uniform aquifers.

2.2.3 Yield of an Aquifer

After constructing a well, it should be tested for its yield and the corresponding drawdown. Raghunath [43] suggested that the well should be pumped at a slightly higher rate than the maximum design pumping rate, though not too much as this may adversely affect the aquifer framework.

Bear [2] stated that the yield of an aquifer is not necessarily a constant value. It may vary from time to time, depending on the state of the aquifer and also on the hydrologic constraints imposed on its operation. There are different definitions of the safe yield in the literature, but Bear [2] defined it as "the maximum annual withdrawal which will not produce undesirable results".

2.3 PUMPING PARAMETERS

The pumping parameters are considered to be essentially the static height to which the water has to be raised and the lengths, diameters and the absolute roughnesses or Hazen-Williams coefficients of the pipes. The static height is defined as the distance from the initial groundwater level to the level in the storage reservoir.

Depending on the type of inlet used for the storage reservoir, the static height may be constant or variable. The variability is due to the fluctuating water level in the storage tank.

The system-head is obtained by combining the static height, the friction-head and the well drawdown. Head loss is a function of pipe size, pipe length, number and type of fittings, discharge and the type of fluid.

2.3.1 Head Loss

There are two widely used formulae for calculating the head loss due to pipe friction.

2.3.1.1 Darcy-Weisbach Formula

Simon [46] considered the Darcy-Weisbach formula as scientific and more satisfactory from a conceptual point of view. The reason is that the friction factor, f, was subject to theoretical and experimental research. The head loss is given as a function of f, the velocity head, $v^2/(2g)$, the length, L, and internal diameter, d, of the pipe.

The friction factor is dependent upon the Reynolds number, R_e, and the relative roughness. Moody [35] derived a chart for the determination of f for new and clean commercial pipes. Moody's diagram comprises of four zones:

1. Laminar zone: R_e is less than or equal to 2000 and varies inversely with f.
2. Critical zone: R_e is between 2000 and 3000 or 4000, and f is undefined in this region.
3. Complete turbulence zone: on one hand f is only dependent upon R_e - the smooth pipe zone, and on the other hand f is only dependent upon the relative roughness - the rough pipe zone.

4. Transition zone: f is dependent upon both R_e and the relative roughness.

2.3.1.2 Hazen-Williams formula

The Hazen-Williams formula was derived empirically (Daugherty and Franzini [10], Hwang [16], Prasuhn [42] and Simon [46]). It was developed for water flows in pipes with diameters greater than or equal to 5 cm and at velocities less than or equal to 3 m/s. But Prasuhn [42] stated that it has been well verified over a wide range of pipe sizes.

It ignores the viscous effect and this corresponds to the assumption of fully rough flow. Consequently, the Hazen-Williams coefficient, C_{HW}, is independent of R_e. The value of C_{HW} ranges from 140 for very smooth and straight pipe to 90 or 80 for old, unlined turberculated pipe. For average conditions, the value of 100 is generally used.

Streeter and Wylie [48] and Vennard and Street [52] derived a relationship between f and C_{HW}. For a given C_{HW} and d, f decreases with increasing R_e. Also f is neither strongly dependent upon d nor upon the average velocity. Streeter and Wylie [48] concluded that the two equations: Darcy-Weisbach and Hazen-Williams used for calculation of losses in a pipeline can be seen to be significantly different, adding that the Darcy-Weisbach equation is probably more rationally based than other empirical exponential formulations and has received wide acceptance.

2.3.2 Minor Losses

Unlike the friction losses, minor losses are due to expansions, contractions, bends, valves and any other types of pipe fittings. The general rule is that if L/d is greater than or equal to 1000, then minor losses should be ignored. However, Streeter and Wylie [48] suggested that minor losses can be included if expressed as equivalent pipe lengths.

2.3.3 Aging of Pipes

As stated previosly, the Moody diagram was developed for new, clean pipes. A pipe deteriorates with age due to the growth of the roughness element. Dake [9], Moody [35] and Streeter and Wylie [48] concluded that the rate of deterioration depends upon both the pipe material and the fluid being conveyed.

The absolute roughness increases linearly with time according to Eqn. (2.2). Dake [9] stated that the growth rate, α, of the pipe roughness element ranges from 0.0254 mm/year for slight attack to 0.762 mm/year for severe attack by domestic water supply.

$$e = e_o + \alpha t \tag{2.2}$$

where e = absolute roughness

e_o = initial absolute roughness

t = time

2.4 PUMP CHARACTERISTICS

Various kinds of pumps are used with windmills (Bragg [4]), but the kind of pump considered in this thesis is the reciprocating piston pump. Bragg [4] pointed out that the advantage of the piston pump is its slow cycle rate, which corresponds to the low rotational speed that is required for high solidity windmills. Individual pumps operate most efficiently within a range of heads and flow rates. The operating envelopes for several types of pumps are given in Figs. 3 and 4 of [3]. Furthermore, Bragg and Schmidt [3] stated that within each operating range, there is a point at which all similar pumps have a maximum efficiency.

To select the best type of pump requires the determination of the specific speed and the specific diameter of the pump. All the parameters that appear in both the specific speed and the specific diameter equations are measured at the most efficient operating point of the pump. However, Bragg and Schmidt [3] pointed out that the concepts of specific speed and specific diameter are not so versatile for windmill design.

2.5 WIND CHARACTERISTICS

2.5.1 Speed Duration and Frequency Curves

The speed-duration curve gives the time during which the wind speed exceeds a given value, while the speed-frequency curve gives the time during which the wind speed falls within a particular wind speed interval.

Apart from yearly wind speed duration and frequency curves, monthly and daily curves can be constructed from monthly and daily wind data respectively. The frequency curve is used to calculate the energy output of a windmill by multiplying the time in each interval with the power output that the windmill generates at that wind speed interval (chapter 9 of [31]).

2.5.2 Statistical Distribution

In most instances the actual wind speed data are not available, and statistical distributions are used to generate the curves. The Weibull and Rayleigh distributions are the most common distributions used in wind power evaluations. The Weibull distribution is a two-parameter distribution while the Rayleigh distribution is a single parameter distribution.

Justus [24] preferred to use the Weibull distribution with the United States National Weather Service wind data.

Cliff [8] recommended the use of Rayleigh distribution with average wind speed greater than or equal to 5 m/s. Park [38] added that with wind speed below 5 m/s, the Rayleigh distribution has low reliability.

Hennessey [15] compared the Weibull and Rayleigh distributions using the National Aeronautics and Space Administration (NASA) 100 kW and the General Electric (GE) 1500 kW aerogenerators. He found that if the average wind speed is less than about 8 m/s in the case of the NASA 100 kW or less than about 10 m/s in the case of the GE 1500 kW, the error in using the Rayleigh distribution will be less than 10% of the full rated power density level.

Before the Weibull distribution can be used, two parameters - the shape and scale parameters must be known. These two parameters are normally estimated from actual wind speed data. Stevens and Smulders [47] presented five different methods of estimating these parameters and recommended only two for wind energy evaluation studies. Justus [24] gave six methods, and his Table 4-2 can be used to find these parameters if only the average wind speed and the variance are known.

From the study of wind speed near 10 m level at 140 sites across the continental United States, Justus [24] gave the reference distribution statistics for the shape parameter, k, for average variance, high (90 percentile) and low (10 percentile) variance in terms of the average wind speed (Eqn. (2.3)).

$$k = \begin{cases} 1.05/\sqrt{\bar{V}} & ; \text{ low variance} \\ 0.94/\sqrt{\bar{V}} & ; \text{ average variance} \\ 0.73/\sqrt{\bar{V}} & ; \text{ high variance} \end{cases} \qquad (2.3)$$

where $\bar{V}$ = average wind speed in m/s

2.6 STORAGE RESERVOIR

2.6.1 Demand

The design capacity of a storage reservoir is determined if the estimated demand which will be placed upon the storage is known. Linsley and Franzini [29] have discussed the various methods of estimating the demand.

The rate of water usage varies from city to city depending on the water characteristics of the city. Typical water demand in the developing and industrialized countries averages about 30 and 500 litres/capita/day respectively.

Because of the hourly, daily and seasonal fluctuations in the rate of water usage, it becomes necessary to provide a storage facility to store the the unused water during low demand periods for use during peak demand periods.

The term "demand" is considered by McMahon and Mein [33] to mean the same as the yield, release, draft, outflow and regulation. Demand is often expressed as a percentage of the average inflow (Klemes [25] and McMahon and Mein [33]), and rarely exceeds 90% (p. 15 of [33]) with a well designed system.

Demands are controlled in various ways known as release or operating rules. Uniform or constant demand represents the simplest release rule. In this case, McMahon and Mein [33] considered all the water demanded to be supplied, and the demand is independent of the reservoir content and season.

2.6.2 Reservoir Reliability

Linsley and Franzini [29] defined reservoir reliability as the probability that it will deliver the expected demand throughout its lifetime without incurring a deficiency. The lifetime is usually taken as the economic life.

Three different reliabilities commonly used in reservoir analyses are:

1. Occurrence-based reliability, R_o.
2. Quantity (volume)-based reliability, R_q.
3. Time-based reliability, R_t.

$$R_o = 1 - T_n/T_m \tag{2.4}$$

$$R_q = 1 - \Sigma\Delta W/(TD_t) \tag{2.5}$$

$$R_t = 1 - \Sigma\Delta t_f/T \tag{2.6}$$

where D_t = demand at period t

T = total time period

T_m = total number of years

T_n = number of failure years

Δt_f = duration of a single failure period

ΔW = quantity of water not delivered during a single failure period

Klemes [25] stated that in general $R_o < R_t < R_q$ and only if there are large seasonal fluctuations in demand may it happen that $R_t > R_q$. However, if the value of one of the reliabilities is 100%, then all three will be equal to 100%.

Linsley and Frazini [29] stated that reliability analyses are used to compare the costs of achieving various levels of reliability and to determine if an increase in reliability is necessary.

2.6.3 Storage Equation

Klemes [25] outlined the procedures to follow in order to find the relationship between reservoir storage; demand and reliability. The determination of the storage for a given draft and 100% reliability represents the simplest case, and the storage is found using the mass or the residual mass curve technique. Fiering [13], Klemes [25] and Loucks et al. [30] stated that the solution exists if the draft is less than or equal to the average inflow.

Other cases involving the determination of reliability, storage or demand (at different reliability levels) are solved using an iterative procedure. Behaviour or simulation analysis used by McMahon and Mein [33] can be applied to determine the reliability at a chosen demand level.

With the mass curve method, also called the "sequent peak procedure", it is assumed that the reservoir is initially full and that the data are representative of future inflows. Furthermore, Fiering [13] stated that the solution requires only two cycles. However, Potter [41] introduced a method in which the two-cycle results can be obtained from one cycle only.

Chapter III

EQUATIONS USED TO DEVELOP THE WIND PUMP STORAGE MODEL

3.1 APPROACH

The basic approach is to generate a pumping curve and integrate this curve with the wind histogram to compute the total water pumped over the period of the histogram. The pumping curve gives the relationship between the instantaneous discharge and the wind speed. The wind histogram can be an actual or statistically derived histogram, and gives the relationship between the amount of time that the wind blows at a given wind speed.

With the given demand level (less than or equal to the average inflow), the storage-yield functions are computed for different levels of reliability. These functions can then be used to size a reservoir for a given demand and reliability of operation.

3.2 PUMPING CURVE

By equating the average load torque due to pumping to the torque provided by the windmill, the wind speed can be calculated for a given discharge. From the literature review, torques are normally used for matching windmills with reciprocating piston pumps (Bragg and Schmidt [3], Carothers and Bragg [6], Lysen [31] and Wyatt and Hodgkin [53]). Torque and power are related as given in Eqn. (3.1):

$$\text{Power} = \text{Torque} \times \text{Rotational speed} \tag{3.1}$$

Carothers and Bragg [6] and Wyatt and Hodgkin [53] found that when the windmill is running, the average rotor output torque equals the average pump torque. But the start-up performance of the windmill can only be described by the starting or peak load torque.

3.2.1 Total Dynamic Head

The total dynamic head, H, is considered by Le Gourieres [28] to be made up of the well drawdown, s_w, the static height, h_s, and the head loss, h_l, according to Eqn. (3.2).

$$H = s_w + h_s + h_l \tag{3.2}$$

The Darcy-Weisbach or Hazen-Williams equation can be specified for the head loss calculation, given the pipe parameters:

3.2.1.1 Darcy-Weisbach Equation

The Darcy-Weisbach equation is expressed as:

$$h_1 = 0.81fLQ^2/(gd^5) \tag{3.3}$$

where d = internal pipe diameter
f = friction factor
g = gravitational acceleration
L = pipe length

The friction factor is calculated from the following formulae depending on the type of flow:

1. Laminar flow, $R_e \leq 2000$:

$$f = 64/R_e \tag{3.4}$$

2. Smooth pipe flow, $3000 < R_e < 100000$:

$$f = 0.316/R_e^{0.25} \tag{3.5}$$

3. The transition zone:

$$1/\sqrt{f} = -2.0 \log[e/(3.7d)+2.51/(R_e\sqrt{f})] \tag{3.6}$$

$$\text{where } R_e = vd/\nu \tag{3.7}$$

e = absolute roughness
R_e = Reynolds number
v = average velocity in pipe
$\nu = \mu/\rho_w$, kinematic viscosity of water
ρ_w = density of water
μ = coefficient of viscosity of water

Jain [18] concluded that Eqn. (3.6) is valid for all three zones of turbulent flow. For very large values of R_e, Eqn. (3.6) reduces to Eqn. (3.8) and for smooth pipes, Jain [18] suggested that if e is assumed to be zero, then Eqn. (3.6) will reduce to Eqn. (3.9).

$$1/\sqrt{f} = -2.0 \log(e/d) + 1.14 \tag{3.8}$$

$$1/\sqrt{f} = 2.0 \log(R_e \sqrt{f}) - 0.8 \tag{3.9}$$

3.2.1.2 Hazen-Williams Equation

Streeter and Wylie [48] represented the Hazen-Williams equation in the following empirical form:

$$h_l/L = RQ^n/d^m \tag{3.10}$$

R is defined as a resistance coefficient and it is considered to be a function of pipe roughness only. For water at ordinary temperatures, R is given in [48] as:

$$R = 10.675/C_{HW}^n \tag{3.11}$$

where C_{HW} = Hazen-Williams coefficient

n and m are 1.852 and 4.8704 respecively

3.2.2 Wind Power

The power available in the wind, P_w, is calculated from Eqn. (3.12) which is known as the "cube law".

$$P_w = (1/2)\rho_a AV^3 \tag{3.12}$$

where A = rotor area
V = wind speed
ρ_a = density of air

Some of the power available in the wind is lost because of conversion efficiency, and the extractable (shaft) power, P_e, is given as:

$$P_e = (1/2)\rho_a A V^3 C_p \tag{3.13}$$

where C_p = power coefficient

The average torque provided by the windmill is given by Eqn. (3.14), after accounting for the gear ratio and gear efficiency (Wyatt and Hodgkin [53]). For a direct drive system, $G_r = \eta_t = 1.0$.

$$T_q = (1/2)\rho_a A V^2 (D/2) C_q G_r \eta_t \tag{3.14}$$

where D = rotor diameter
C_q = torque coefficient
G_r = gear ratio
η_t = gear efficiency

3.2.2.1 Power and Torque Coefficients

A parabolic relationship between C_p and TSR ([40]) and a linear relationship between C_q and TSR ([53]) are assumed.

$$C_p = C_{pm} - C_{pm}[(\lambda - \lambda_d)/(\lambda_m - \lambda_d)]^2 \quad ; \quad \lambda_{qm} \le \lambda \le \lambda_m \qquad (3.15)$$

$$\lambda = \lambda_m - \lambda_m C_q / C_{qm} \qquad (3.16)$$

where

$$\lambda_{qm} = \sqrt{[\lambda_m(2\lambda_d - \lambda_m)]} \qquad (3.17)$$

$$C_{qm} = -2C_{pm}[(\lambda_{qm} - \lambda_d)/(\lambda_m - \lambda_d)^2] \qquad (3.18)$$

C_{pm} = maximum power coefficient

C_{qm} = maximum torque coefficient

U = rotor tip-speed

λ = U/V, tip-speed ratio (TSR)

λ_d = design TSR

λ_m = maximum TSR

λ_{qm} = TSR corresponding to C_{qm}.

The maximum power coefficient for American multibladed windmills varies from 0.30 to 0.35 [38].

3.2.3 Hydraulic and Mechanical Power

Eqn. (3.19) gives the hydraulic power required to lift the water through a total dynamic head, H.

$$P_h = \gamma_w H Q \qquad (3.19)$$

where $\gamma_w = \rho_w g$, specific weight of water

The power needed to drive the pump can be calculated if the mechancal efficiency, η_m, is known. Bragg and Schmidt [3] stated that η_m can be assumed and checked when the final operating conditions are known.

$$P_m = P_h / \eta_m \tag{3.20}$$

where P_m = mechanical power

The rate of water pumped is directly proportional to the stroke rate and hence the rotational speed of the windmill (Bragg [4], Lysen [31] and Wyatt and Hodgkin [53]).

$$Q = \eta_v (\pi/4) D_p^2 S (\Omega/2\pi) \tag{3.21}$$

where

$$\Omega = 2V\lambda/(DG_r) \tag{3.22}$$

Ω = rotational speed of pump shaft

Combining Eqns. (3.20) and (3.21), P_m is given by Eqn. (3.23), which is similar to Eqn. (3.1).

$$P_m = T_w \Omega \tag{3.23}$$

where

$$T_w = \eta_v \gamma_w D_p^2 SH/(8\eta_m) \tag{3.24}$$

D_p = pump diameter

S = pump stroke

T_w = average water load torque

η_v = volumetric efficiency

3.3 WIND HISTOGRAM

An actual wind histogram or a histogram derived from the Weibull or Rayleigh distributions can be entered in the model. The single parameter Rayleigh distribution is the simplest case since it requires only the average wind speed in order to define the distribution. According to Justus [24], the Weibull and the Rayleigh distributions become useful if a transfer of measured wind data from one site to another is required. Carothers and Bragg [6] found that a low Weibull shape factor is more suitable for low wind speed in the Sahelian region.

3.3.1 Actual Wind Histogram

If historical meteorological data are not available or insufficient, the actual wind speed frequency distributions can be derived fron wind speed measurements, usually at the same location and height that the windmill will be installed.

Measuring the actual wind speed is normally done with an anemometer. Golden [14] and Park [38] have described a number of ways of taking the required readings and how the data can be processed. What is needed for this thesis is the wind speed and the corresponding time that the wind blows at that wind speed.

3.3.2 Weibull Distribution

The probability density function (PDF) and the cumulative distribution function (CDF) are given respectively as:

$$p(V)\Delta V = (k/c)(V/c)^{k-1} \exp[-(V/c)^k]\Delta V \qquad (3.25)$$

$$f(V) = 1 - \exp[-(V/c)^k]; \quad k>0,\ V>0,\ c>1.0 \qquad (3.26)$$

where c = scale parameter

ΔV = wind speed interval

f(V) = cumulative distribution

k = shape factor

p(V) = probability density

For k greater than 1.0, p(V) becomes zero at zero wind speed, and Eqns. (3.25) and (3.26) cannot fit a wind speed frequency curve at zero wind speed because the frequency of calms is always greater than zero (Johnson [20]). However, Johnson [20] pointed out that this is not a serious problem because the output of a windmill would be zero below the cut-in wind speed.

3.3.3 Rayleigh Distribution

The PDF and the CDF are given by Eqns. (3.27) and (3.28) respectively.

$$p(V)\Delta V = (\pi/2)(V/\bar{V}^2) \exp[-(\pi/4)(V/\bar{V})^2]\Delta V \qquad (3.27)$$

$$f(V) = 1 - \exp[-(\pi/4)(V/\bar{V})^2] \qquad (3.28)$$

Cliff [8] derived a generalized wind characteristics using Rayleigh distribution and investigated their effect on wind turbine output. The percent down time and the percent time running at rated wind speed were included in the analyses.

3.3.4 Period of Wind Histogram

Because of the execution time and the availability of data and memory space, daily and monthly wind histograms were used in this thesis instead of the hourly histograms. With high-speed and large-memory mainframe computers, this may not present a problem, but memory limitations may be encountered with micro-computers. Yearly wind histograms do not provide any detail on the seasonal variations and they are mostly used to obtain an estimate of the yearly output of a windmill operating in a given wind regime.

Hourly or daily wind speed histograms can be transformed to give monthly histograms with a computer program. The storage model developed in this thesis does not handle this transformation because various methods and/or devices are available to handle and store wind speed data.

Klemes [25] and Kuiper [27] defined the average month as equal to 30.5 days. Because of computational reasons, all months of the year are assumed to be equal to 30 days.

3.4 VOLUME OF WATER PUMPED

By equating the average load torque due to pumping to the torque provided by the windmill, the wind speed can be calculated for each discharge. The discharge is assumed to be instantaneous. The volume is calculated from the product of the discharge and the time at each wind speed in the given wind regime ([49], vol. II, p. A61).

Four important characteristic wind speeds that should be considered when carrying out this piece-wise integration method, are given in [49], (vol I, p. 5) as follows:

1. The cut-in wind speed when the windmill begins to produce power.
2. The design wind speed when the windmill reaches its maximum efficiency.
3. The rated wind speed when the windmill produces its maximum power.
4. The furling (cut-out) wind speed when the windmill is shut off to prevent damage at high wind speed.

Below the cut-in and above the cut-out wind speeds, the output is zero.

Variable-speed windmills allow the output and the rotational speed to vary with the wind speed unlike constant-speed machines. The advantage of the variable-speed windmills is given in [12] as being more efficient at higher wind speed because it can maintain a favourable TSR throughout the entire range of wind speed, thus following Eqn. (3.12) much more closely than in the case with constant-speed machines.

3.5 STORAGE CALCULATIONS

The purpose of a storage reservoir as outlined by Rippl [45], is to equalize the fluctuations of supply and demand during an infinitely long period of time. Various methods of storage calculations have been investigated by different researchers ([21], [36] and [44]). The methods used in this thesis are Rippl's method and the behaviour analysis of McMahon and Mein.

3.5.1 Rippl or Mass Curve Method

According to Rippl [45], first the inflow to the reservoir and the outflow from the reservoir are estimated for successive equal periods of time (usually one month for streamflow analyses) and for the whole period of time to be considered. A mass curve can be constructed using the procedure given by McMahon and Mein [33]:

1. Plot the cumulative inflow versus time.
2. Superimpose on the mass curve the cumulative draft line for the reservoir such that it is tangential to each peak of the mass inflow curve.

3. Measure the largest intercept between the mass inflow curve and the cumulative draft line.

The major advantages are that the procedure is simple and it is easily understood. The storage calculated by this method is at a 100% reliability level.

3.5.2 Sequent Peak Procedure

The sequent peak procedure is a modified version of the mass curve technique. Loucks et al. [30] give the following algorithm:

1. Let S_t be the storage capacity required at the beginning of period t.
2. Let S_{t+1} be the storage capacity required at the beginning of period t+1.
3. Let D_t be the required constant release in period t.
4. Let Q_t be the inflow in period t.
5. By setting the initial storage, $S_o = 0.0$, the procedure involves calculating S_{t+1} using Eqn. (3.29) consecutively for up to twice the total length of record.
6. The maximum of all S_{t+1} is the required storage capacity for the specified releases, D_t.

$$S_{t+1}/\Delta t = D_t - Q_t + S_t/\Delta t \; ; \quad S_{t+1} \geq 0.0 \qquad (3.29)$$

where Δt = duration of a single time period

3.5.3 Behaviour or Simulation Analysis

Since the mass curve and the sequent peak procedures can not be used to compute the storage size for a given probability of failure, the simulation analysis is adopted. McMahon and Mein [33] give the steps in constructing a behaviour diagram as follows:

1. Arbitrarily choose a reservoir of capacity, C, and assume that it is initially full, that is, $S_o = C$.
2. Apply Eqn. (3.30) period by period for the whole record, D_t being assumed to be constant.
3. Compute the probability of failure using Eqn. (3.31) by dividing the total time, $\Sigma\Delta t_f$ for which the reservoir is empty by the total time, T.
4. If the probability of failure is unacceptable, choose a new value of C and repeat the steps.

$$S_{t+1}/\Delta t = S_t/\Delta t + Q_t - D_t \; ; \quad 0 \leq S_{t+1} \leq C \qquad (3.30)$$

$$\text{Prob} = \Sigma\Delta t_f/T \qquad (3.31)$$

$$\text{Rel} = 1 - \text{Prob} \qquad (3.32)$$

where Prob = probability

Rel = reliability

Instead of computing the probability of failure, Eqn. (3.32) is used to compute the reservoir reliability. Different levels of time-based reliability considered are 80.0, 85.0, 90.0, 95.0 and 100.0%. In caculating the storages, the reliabilities were determined to one percentage difference.

Daily, monthly or yearly time periods can be used for behaviour storage calculations. From the literature review, monthly time intervals are recommended for behaviour storage calculations ([21], [32], [33] and [45]) for river flows. According to ref. [21], the advantage of using the monthly behavioural storage is that it naturally takes into account the effects of monthly serial correlation and seasonality.

Chapter IV.

SIMULATON MODEL AND RESULTS

A computer program was written in FORTRAN IV and operated with the University of Ottawa's Amdahl 470/V8 VS/FORTRAN compiler, which is equipped with an IBM VM/SP-R3 operating system, using the Conversational Monitor System (CMS). In order to invoke FORTRAN, the LANGLVL(66) option was used. The flowchart and a complete listing of the computer program are given in appendices A and B respectively.

4.1 BASIC CONSIDERATION

In developing the storage model, the following points were considered.

1. The model should be simple, keeping in mind that it can be used by a maximum number of people.
2. The model is written so that it can be easily updated and modified. Different subroutines are included to handle different phases of the computations.
3. For convenience, the model is developed in such a way that once the required data are entered in the correct format, the computations proceed to the end without any interruption.

4. All input parameters are in SI units except the demand (m^3/day), and the time (hours) during which the wind speed blows at a particular wind speed interval.

In developing this model, the pump rod and inertia loads, and the wind directions were not considered; therefore, the model may tend to overestimate the windmill output. Lysen [31] has pointed out that in practice the windmill is subjected to both varying wind speeds and wind directions, resulting in lower outputs. He also noted that both the instantaneous wind speed and output are not well correlated because of the inertia of the system. Therefore, during a short increase in wind speed, the output is still low, but when the wind is already slowing down, the windmill has gained momentum and produces more output, even when the wind speed at that same moment is low. This creates a hysteresis region in the lower end of the pumping curve (van Meel and Oldenkamp [51]).

Wyatt and Hodgkin [53] incorporated the hysteresis region in their model by estimating the probability that the windmill will continue to run down to a minimum wind speed, but will require a higher wind speed to start. The hysteresis region is neglected in this research work in order to compensate for the overestimate of output.

4.2 METEOROLOGICAL DATA

Summary of hourly wind speed data were obtained from the Atmospheric Environment Service [1] for Ottawa International Airport, which is assigned the station number of 6106000. It is situated at latitude 45^0 19' and longitude 75^0 40'.

The daily record of hourly values yields 24 entries, representing the observations taken on the hours 0000-2300 for 32 years were put on a magnetic tape. The wind speeds were recorded in kilometres per hour as integers at a site elevation of 114 metres above sea level.

4.3 QUALITY OF DATA

The history of the station is not known regarding instrument changes and station relocation during any expansion and or upgrading of the airport for the duration that the wind speeds were recorded. However, the record was checked for missing and estimated values, but none were found to be missing or estimated. This therefore means that the station is equipped with continuous recording anemometers.

4.4 WIND SPEED AVERAGE VALUES

Computer programs were written to analyze the hourly wind speed data from the magnetic tape. Parameters required for the wind speed distributions were computed. All wind speed data were used in the computations. The average wind speed was caculated using Eqn. (4.1).

$$\bar{V} = \sum_{i=1}^{N} V_i / N \qquad (4.1)$$

where N = the total number of wind-speed observations
V_i = the wind speed at i-th period

Table 1 gives a brief summary of the statistics of the data for the 32-year record.

TABLE 1

Minimum, average and maximum wind speeds in m/s for Ottawa International Airport, 1953-1984

MINIMUM	AVERAGE	MAXIMUM
0.0	4.0	24.7

Observations were taken on the hours. The maximum wind speed was recorded at 0900 hours on July 27, 1954. The minimum of zero wind speed occurred more than once.

Month-to-month variations of average wind speeds are shown in Table 2 and plotted in Fig. 2. As it can be seen, the windy months are between the months of November and May inclusive.

TABLE 2

Monthly average wind speeds in m/s for Ottawa International Airport, 1953-1984

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4.42	4.42	4.58	4.66	4.03	3.63	3.27	3.15	3.54	3.83	4.20	4.29

4.5 THE CANADIAN CLIMATE

As shown in Table 2 and Fig. 2, the windmill will give a greater output between the months of November and May than between the months of June and October. However, between November and May the temperatures sometimes drops below the freezing-point, and the windmill may not be able to operate efficiently because of ice build-up on the blades. Also storage tank and pipe freezing due to insufficient insulation of the storage tank and pipes, may prevent the smooth flow of water.

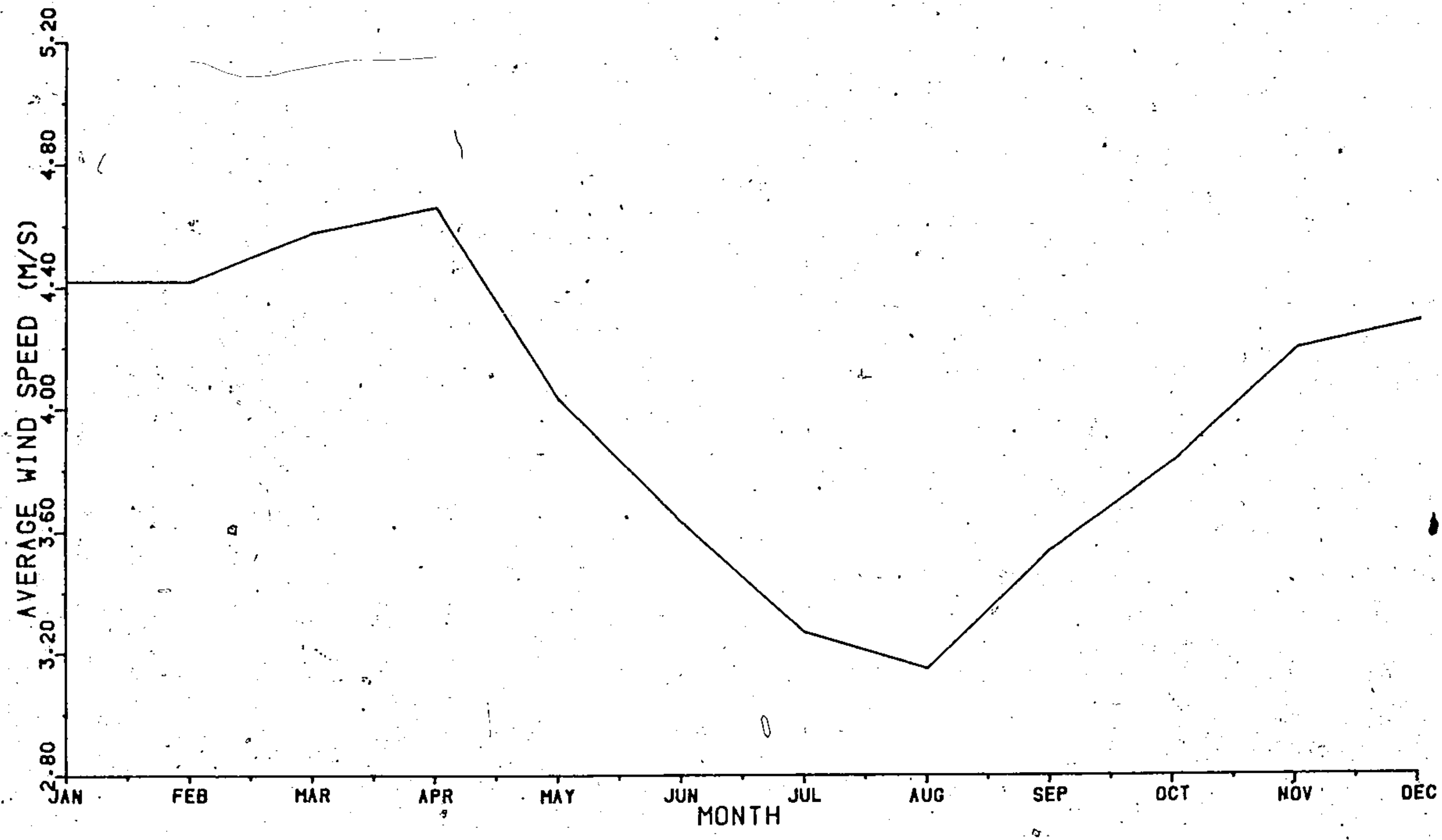


Figure 2: Monthly variations of average wind speeds for Ottawa International Airport , 1953-1984

4.6 COMPARISONS OF WIND SPEED DISTRIBUTIONS

In determining the Weibull parameters, Eqn. (4.3), (Eqn. (4.45) of [24]), was used to determine k after computing the average wind speed and the standard deviation from Eqns. (4.1) and (4.2) respectively. The value of c was then calculated using Eqn. (4.4), (Eqn. (2.38) of [20]). For values of k and c outside the given ranges, Eqns. (4.5) and (4.6), (Eqns. (4.26) and (4.27) of [24]) were used to solve for k and c.

$$\sigma = \sqrt{\left[\sum_{i=1}^{N}(V_i-\bar{V})^2/(N-1)\right]} \qquad (4.2)$$

$$k = (\sigma/\bar{V})^{-1.086}; \qquad 1 \le k \le 10 \qquad (4.3)$$

$$c = 1.12\ \bar{V}; \qquad 1.5 \le k \le 3 \qquad (4.4)$$

$$\bar{V}/c = \Gamma(1+1/k) \qquad (4.5)$$

$$(\sigma/\bar{V})^2 = [\Gamma(1+2/k)/\ \Gamma^2(1+1/k)]-1 \qquad (4.6)$$

where σ = standard deviation
Γ = gamma function

Table 3 and Fig. 3 show the monthly variations of the Weibull parameters for the 32 years of data. Lysen [31] stated that if monthly k and c values are required, then the use of identical months of subsequent years will give more reliable results.

TABLE 3

Monthly Weibull parameters for Ottawa International Airport, 1953-1984

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
k	1.84	1.87	1.85	2.0	1.89	1.85	1.84	1.74	1.82	1.83	1.83	1.79
c	4.95	4.94	5.14	5.2	4.51	4.06	3.79	3.53	3.97	4.29	4.70	4.81

Table 4 shows the percent of time the wind blows at the given wind speed ranges for the three different distributions considered in this thesis while Fig. 4 displays the same information graphically. Wind speed intervals of 1 m/s were used for all computations, and the intervals shown in Table 4 were chosen with the understanding that the upper boundary is exclusive.

The 32-year average values of k and c were computed to be 1.87 and 4.49 m/s respectively. These values were used in Eqn. (3.25) to define the Weibull distribution. The 32-year average wind speed of 4 m/s was used in Eqn. (3.27) for the Rayleigh distribution.

It can be seen in Fig. 4 that winds between 1 and 5 m/s are observed more often than winds outside this speed range. Graphically, it can not be determined if the Weibull or Rayleigh distribution closely approximate the actual distribution. In order to determine this, the root-mean-square

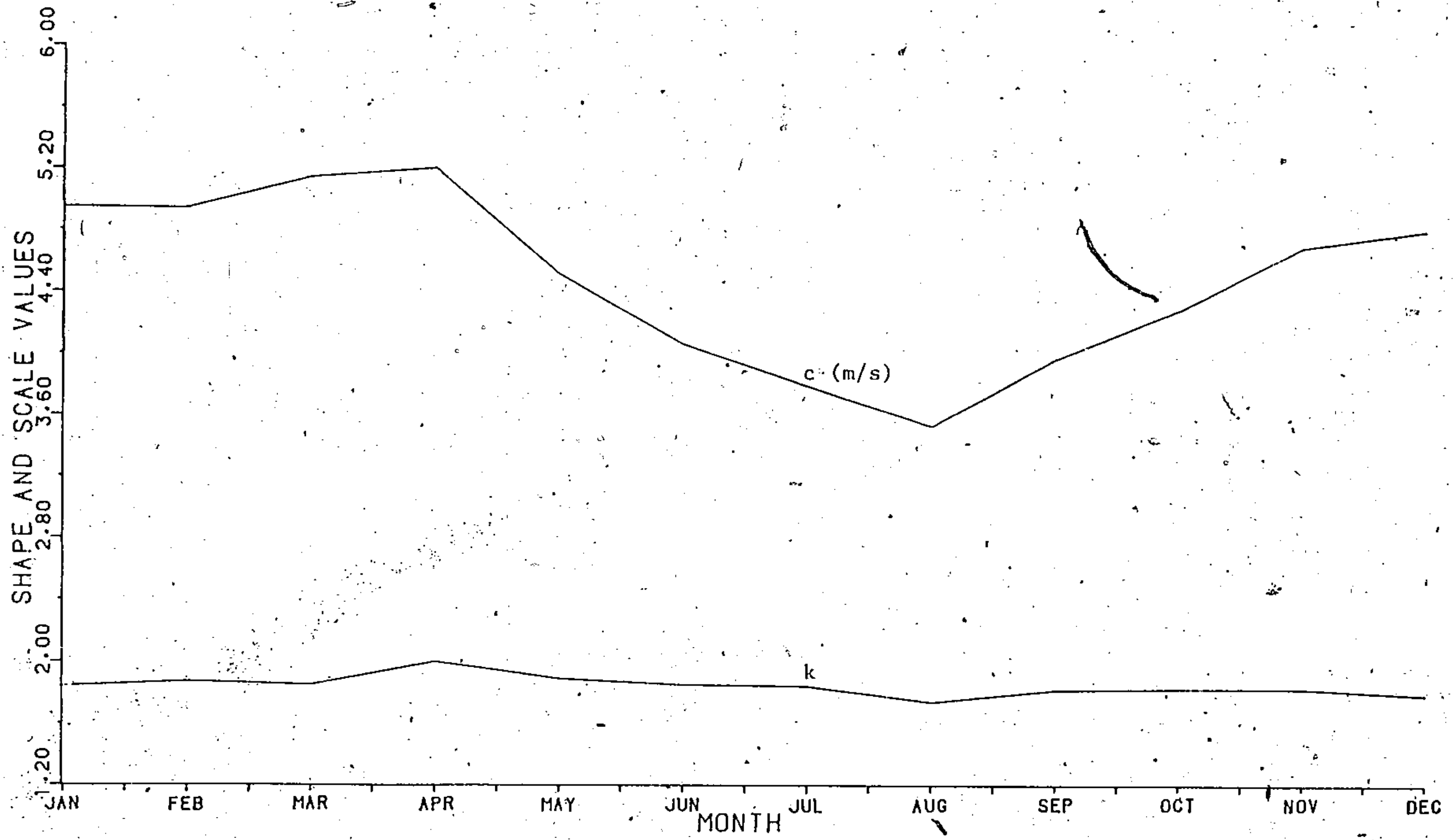


Figure 3: Monthly variations of Weibull parameters for Ottawa International Airport, 1953-1984

TABLE 4

Actual, Weibull and Rayleigh wind speed distributions for Ottawa International Airport, 1953-1984

Wind speed range (m/s)	Mid-point V (m/s)	Percent time: Actual p(V)	Actual f(V)	Weibull k=1.87 c=4.49 m/s p(V)	Weibull f(V)	Rayleigh $\bar{V}$=4 m/s p(V)	Rayleigh f(V)
0 - 1	0.5	7.74	7.74	6.07	6.07	4.85	4.85
1 - 2	1.5	14.45	22.19	14.11	20.18	13.19	18.04
2 - 3	2.5	14.98	37.17	17.91	38.09	18.06	36.10
3 - 4	3.5	20.05	57.22	17.90	55.99	18.83	54.93
4 - 5	4.5	9.95	67.17	15.29	71,28	16.35	71.28
5 - 6	5.5	12.31	79.48	11.52	82.80	12.23	83.51
6 - 7	6.5	8.52	88.00	7.80	90.60	8.02	91.53
7 - 8	7.5	4.91	92.91	4.78	95.38	4.65	96.18
8 - 9	8.5	4.24	97.15	2.68	98.06	2.41	98.59
9 -10	9.5	1.22	98.37	1.38	99.44	1.11	99.06
10-11	10.5	0.72	99.09	0.65	100.09	0.46	100.16
11-12	11.5	0.53	99.62	0.28	100.37	0.17	100.33
12-13	12.5	0.14	99.76	0.11	100.48	0.06	100.39
13-14	13.5	0.13	99.89	0.04	100.52	0.02	100.41
14-15	14.5	0.049	99.94	0.015	100.54	0.005	100.42
15-16	15.5	0.026	99.97	0.005	100.55	0.001	100.42

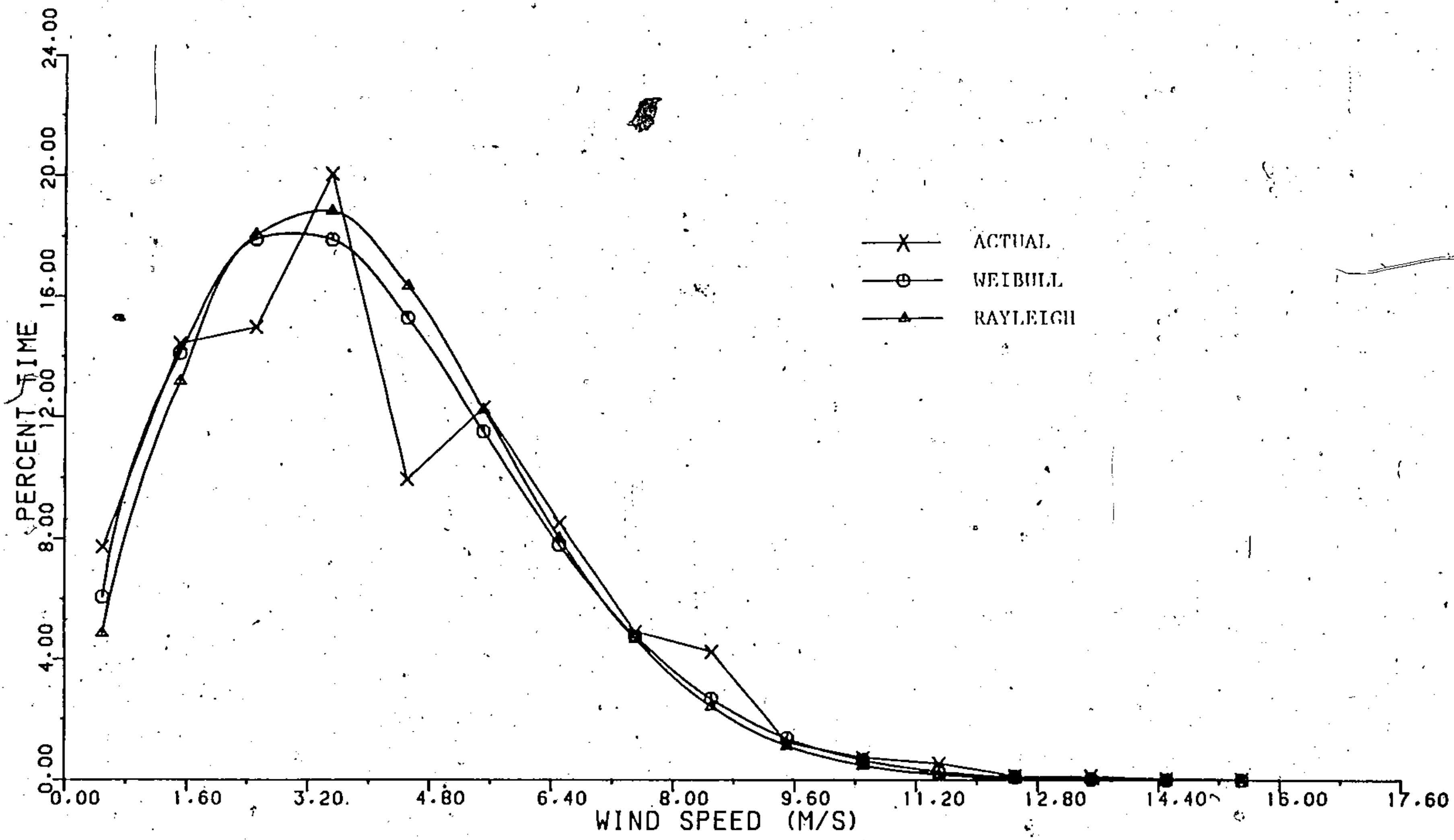


Figure 4: Actual, Weibull and Rayleigh wind speed distributions for Ottawa International Airport, 1953-1984

(rms) residual error, ϵ, (Eqn. (4.7)) suggested by Justus et al. [22], was used as a measure of goodness-of-fit of the distribution.

$$\epsilon^2 = \sum_{i=1}^{N}[f_o(V_i)-f_c(V_i)]^2 \qquad (4.7)$$

where $f_c(V_i)$ = calculated probability
$f_o(V_i)$ = observed probability

From Table 4, the rms residual errors were found to be 7.4% and 9.7% for the Weibull and Rayleigh distributions respectively. Therefore, the Weibull distribution fits the actual distribution better, that is, it produced smaller ϵ value.

For this wind regime, Weibull distribution should be used if the actual distribution is not known and the values of k and c are known. However, the Rayleigh distribution can be used if only the average wind speed is known.

4.7 MODEL TESTING

4.7.1 Wind Characteristics

The model developed in this thesis was tested using the meteorological data of Ottawa International Airport. It was assumed that the windmill is installed at this location and at the same elevation as the anemometer that was used to record the wind speeds. If this assumption is not true as regards to the windmill elevation, the height projection of wind speed distribution should be applied. This process is dealt with by Justus [24].

4.7.2 Well Characteristics

Due to lack of Q vs. s_w data for the site, Jacob's solution, Eqn. (2.1), was used to predict Q vs. s_w curve. The constants $B_1 = 78$ sec/m^3 and $C_1 = 2340$ sec^2/m^5 were taken from pp. 178-180 of Raghunath [43], and were assumed to represent the aquifer properties at the windmill location. If the Q vs. s_w characteristics were available from pumping tests, they would have been used directly without resorting to mathematical approximation.

4.7.3 Windmill and Pump Characteristics

A Dempster windmill [11] coupled to a reciprocating piston pump having the parameters given in Table 5 were used in the wind pump storage model. However, ref. [11] did not give the values of C_{pm} and the efficiencies of the pump. Values that were not given were taken from Park [38] and Wyatt and Hodgkin [53]. Lysen [31] gave estimates of the mechanical efficiency to be between 0.50 and 0.85.

TABLE 5

Windmill and pump characteristics

Windmill

Type: multibladed

Model: # 12

Diameter = 3.7 m

Gear ratio = 3:1

# of blades = 18

Cut-in speed = 2.2 m/s

Rated speed = 8.5 m/s

Cut-out speed = 22 m/s

C_{pm} = 0.30; ref. [38]

λ_d & λ_m = 1 & 2 respectively; ref. [53]

η_t = 0.90; ref. [53]

Pump

Type: piston

Diameter = 0.10 m

Stroke = 0.30 m

η_m & η_v = 0.60 & 0.90 respectively; ref. [53]

4.7.4 Other Parameters

The length of pipe used was 30 m with a diameter equal to that of the pump. Hazen-Williams coefficient of 100 was assumed. The static height of 25 m was used and the demand rates were calculated as a percentage of the average flow.

4.8 MODEL RESULTS

For comparison purposes, different computer runs were made for the three wind speed distributions, actual, Weibull and Rayleigh, at 100% reliability level, using the daily and monthly wind histograms. Behaviour and sensitivity analyses were done using the actual wind speed (daily) distributions.

4.8.1 Pumping and Power Curves

The pumping and power characteristics are independent of the type of wind speed distribution used. Figs. 5 and 6 show the pumping and power characteristics for the windmill chosen. Below the cut-in wind speed of 2.2 m/s and above the cut-out wind speed of 22 m/s, the output is zero. At the rated wind speed, the output remains constant until the cut-out speed is reached.

From Dempster [11] data sheet, the rated output is given as 8.1 m^3/h at 10 m head. This is equivalent to 9×10^{-4} m^3/s at 25 m head. Comparing this value to the value of 9.33×10^{-4} m^3/s given by the model (Fig. 5), an error of less than 4% is obtained.

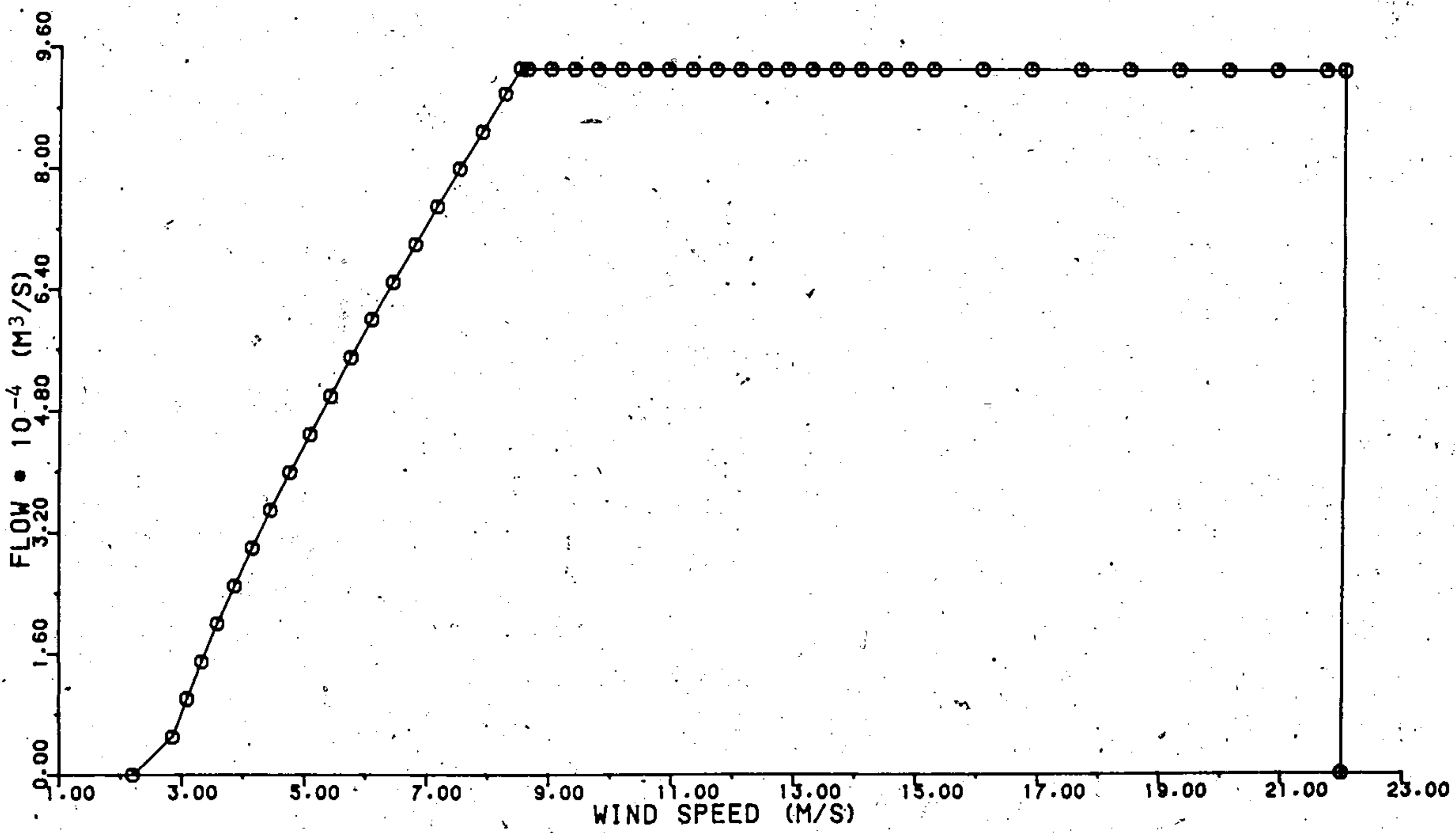


Figure 5: Instantaneous windmill output (flow) versus wind speed

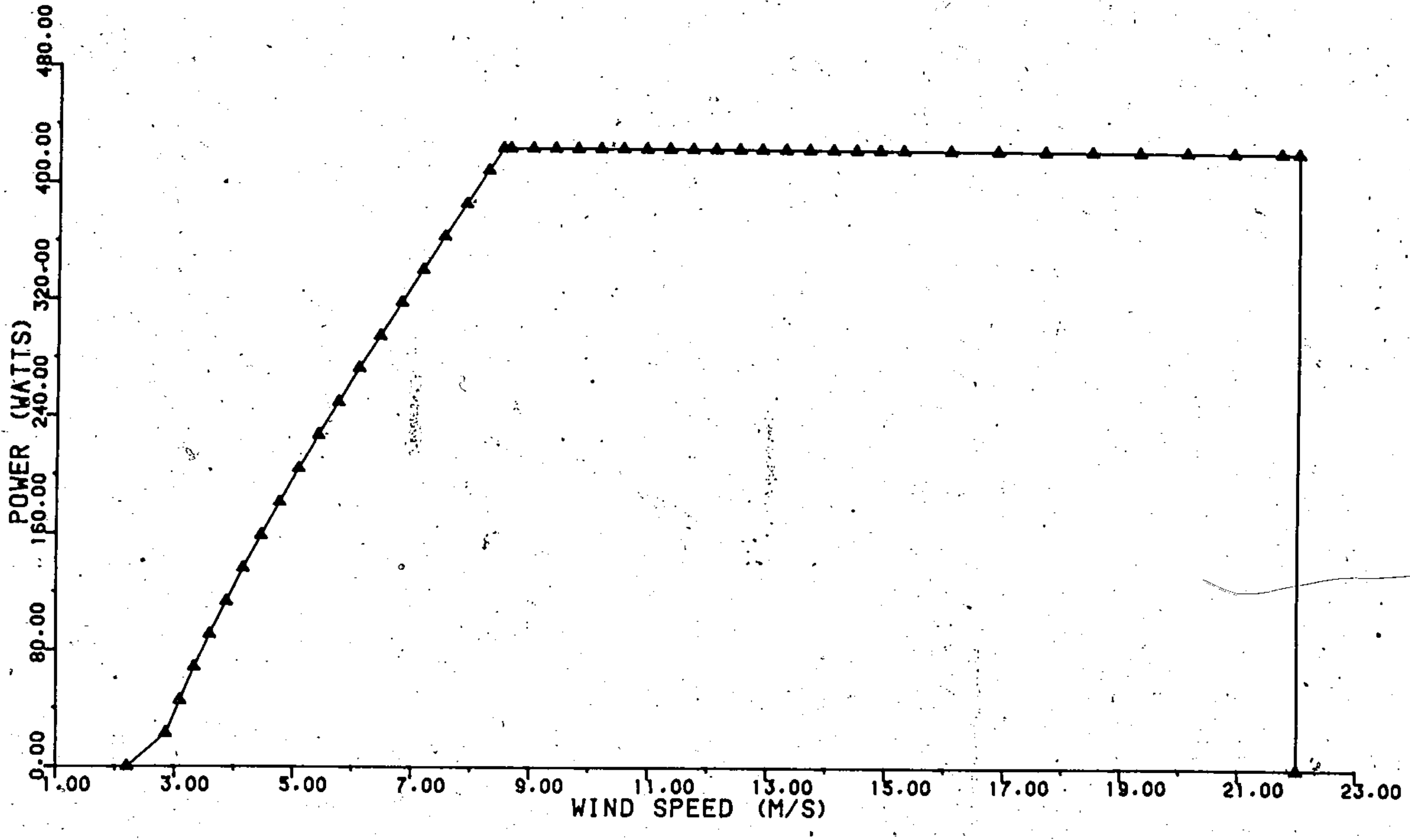


Figure 6: Instantaneous windmill power versus wind speed

4.8.2 Volume of Water Pumped

The total volume and the average flow, using the daily and monthly histograms derived from the 32 years (384 months) of data, for the three wind speed distributions (100% reliability level) are shown in Table 6. It can be seen that the output computed using the daily and monthly wind histograms are approximately the same for this wind regime. The maximum difference obtained was less than 3%.

TABLE 6

Model output for Ottawa International Airport, 1953-1984

	Wind speed distribution					
	Actual		Weibull		Rayleigh	
	(dly)	(mly)	(dly)	(mly)	(dly)	(mly)
Total vol. (m^3)	302805	302081	290680	284582	273055	281076
Mean flow (m^3/d)	25.90	25.85	25.23	24.70	23.70	24.40

dly = daily, mly = monthly

Using an average wind speed of 4 m/s, the discharge from Fig. 5 would be 2.74×10^{-4} m^3/s, that is, 23.67 m^3/d. This would give a difference of less than 3% when compared to the average flows obtained using the Rayleigh distribution. This close correspondence, using only the average wind speed for calculations, occurs only when the wind regime is fairly uniform in nature.

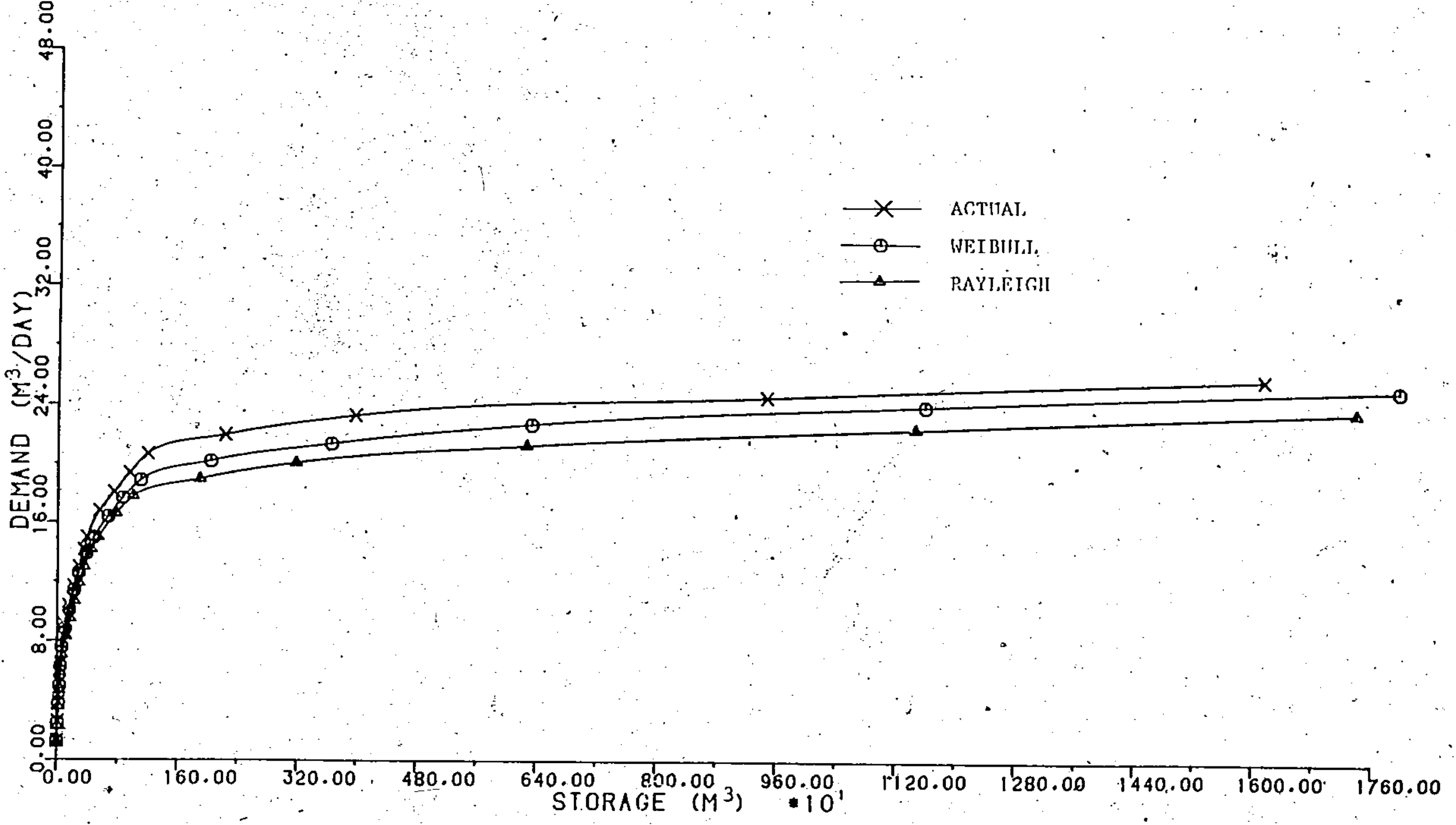


Figure 7: Storage-yield functions at 100% reliability for actual, Weibull and Rayleigh wind speed (daily) distributions

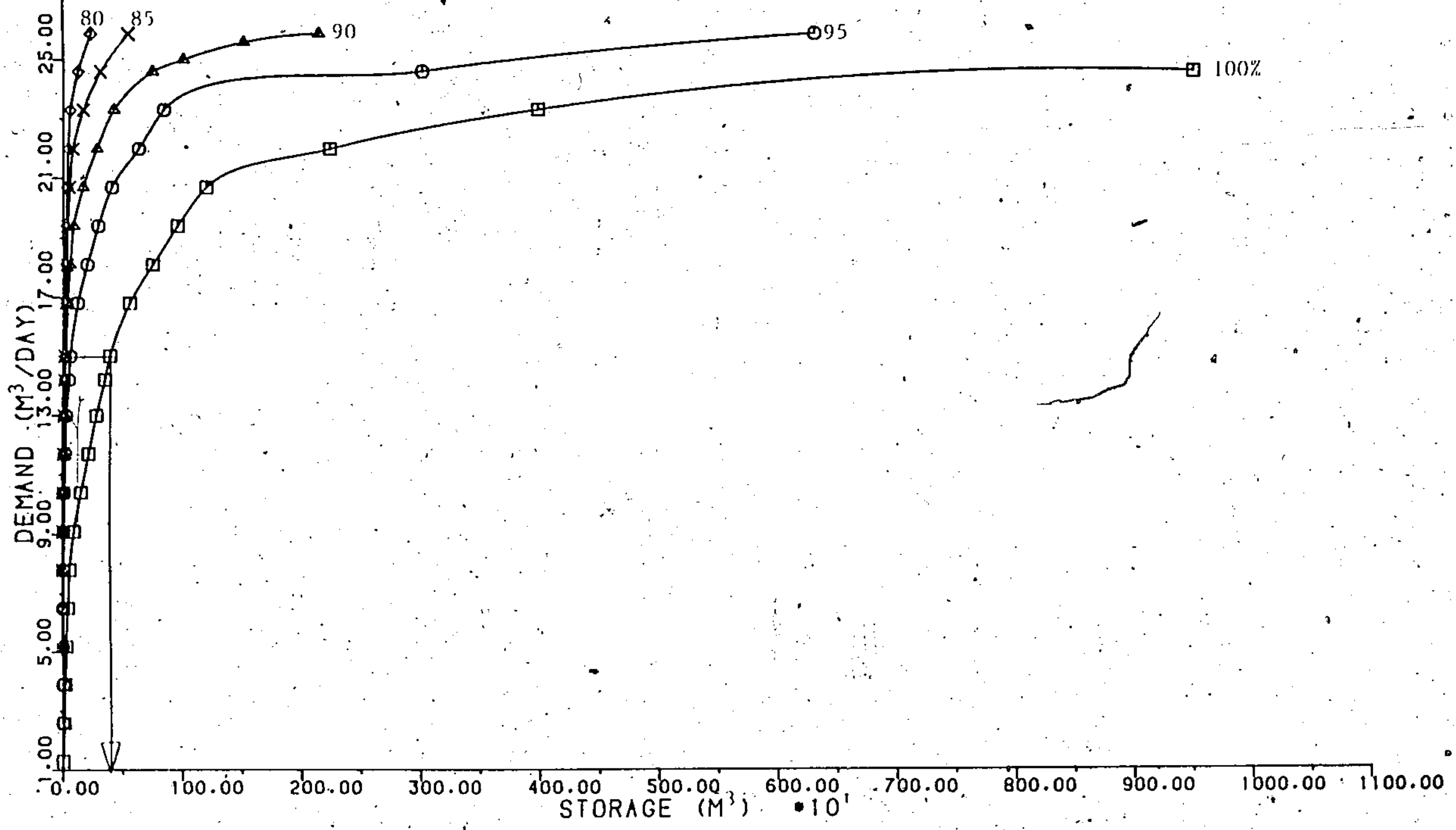


Figure 8: Storage-yield functions at different levels of time-based reliability for actual wind speed (daily) distributions

4.8.3 Storage-Yield Functions

Fig. 7 compares the storage-yield functions, calculated using the sequent peak method, at 100% reliability level for the three wind speed (daily) distributions. The storage capacity increases dramatically as the average flow is approached. Kuiper [27], who did his studies with reservoirs for large river systems, argued that this upper part of the curve loses some of its meaning because a full reservoir is required at the beginning of the period.

However, in wind pumping systems, the size of the reservoir required will not be as large as that required for huge river flows. In any case, this upper part of the curve confirms the fact that if demand becomes too large and exceeds supply, the demand cannot be met no matter how large the tank may be.

Behaviour analysis was applied to calculate the storage required for a given demand level for the five different reliability levels using the actual wind speed (daily) distribution. The results are shown in Fig. 8. The storage capacity required increases as the reliability level increases for a given demand level.

4.9 SENSITIVITY ANALYSES

In order to investigate the effects of some of the input parameters on the model output, sensitivity analysis was done using the actual wind speed (daily) distributions. Parameters altered were the maximum power coefficient, gear ratio, mechanical and volumetric efficiencies of the pump. The results are shown in Figs. 9, 10, 11 and 12, including the values of the parameters altered.

4.9.1 Discussion

-- Fig. 9 depicts the variations of the storages required for a given demand level for three values of C_{pm}. The effect of G_r, η_m and η_v on the storage-yield functions are shown in Figs. 10, 11 and 12.

A larger storage size is required as C_{pm} (Fig. 9), η_m (Fig. 11) and η_v (Fig. 12) decreases, implying that less water is pumped. A change in the gear ratio has a dramatic effect in the upper part of the curve (Fig. 10), because the storage decreases rapidly as the gear ratio decreases.

Multibladed windmills have low C_{pm} values, and the C_{pm} value used should not exceed that of the selected windmill; otherwise, the calculated values of the storages will be in error. Furthermore, the variations of C_p and C_q should follow the parabolic and linear relationships given by Eqns.

(3.15) and (3.16) respectively. However, the calculated storages are not very sensitive to changes in C_{pm} as evidenced by the closeness of the curves in Fig. 9 for this windmill operating in the given wind regime.

For a direct drive system, $G_r = \eta_t = 1.0$, and the storage size required decreases in the upper part of the curve. This theoretical result is obtained because the windmill chosen rotates faster than the operating speed of the piston pump. Under this condition, the pump will be running at the same speed as the windmill, thus more water is assumed to be pumped.

Higher values of η_m or η_v indicate that more water is pumped. Constant values of the pump's efficiencies were assumed in developing the storage model. However, this is not the case for all possible ranges of operation of the pump because efficiency of the pump changes as leakholes developed due to wear of the pump cylinder and piston. As the life of the pump increases, its efficiencies will be reduced.

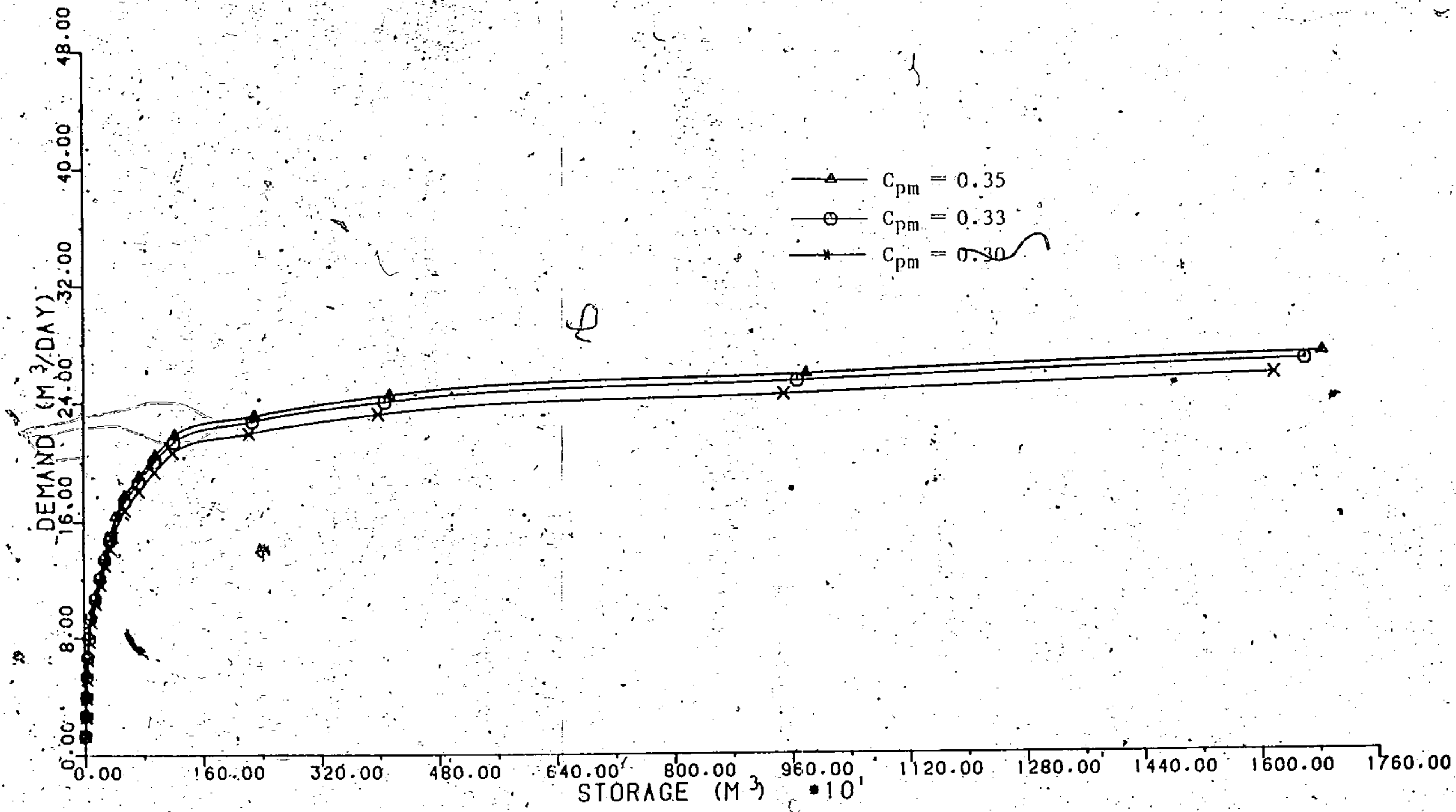


Figure 9: Sensitivity analysis on maximum power coefficient using actual wind speed (daily) distributions

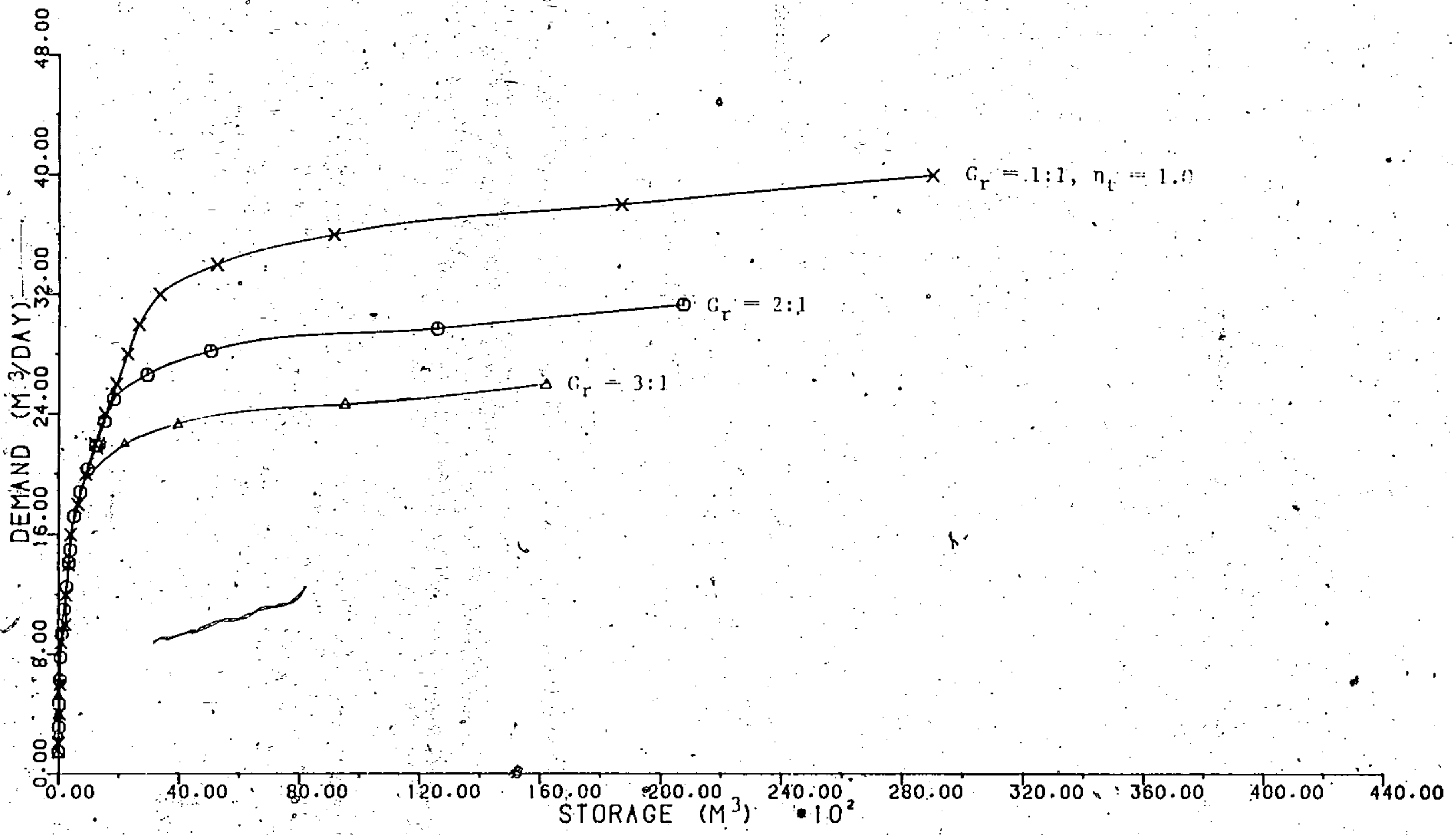


Figure 10: Sensitivity analysis on gear ratio using actual wind speed (daily) distributions

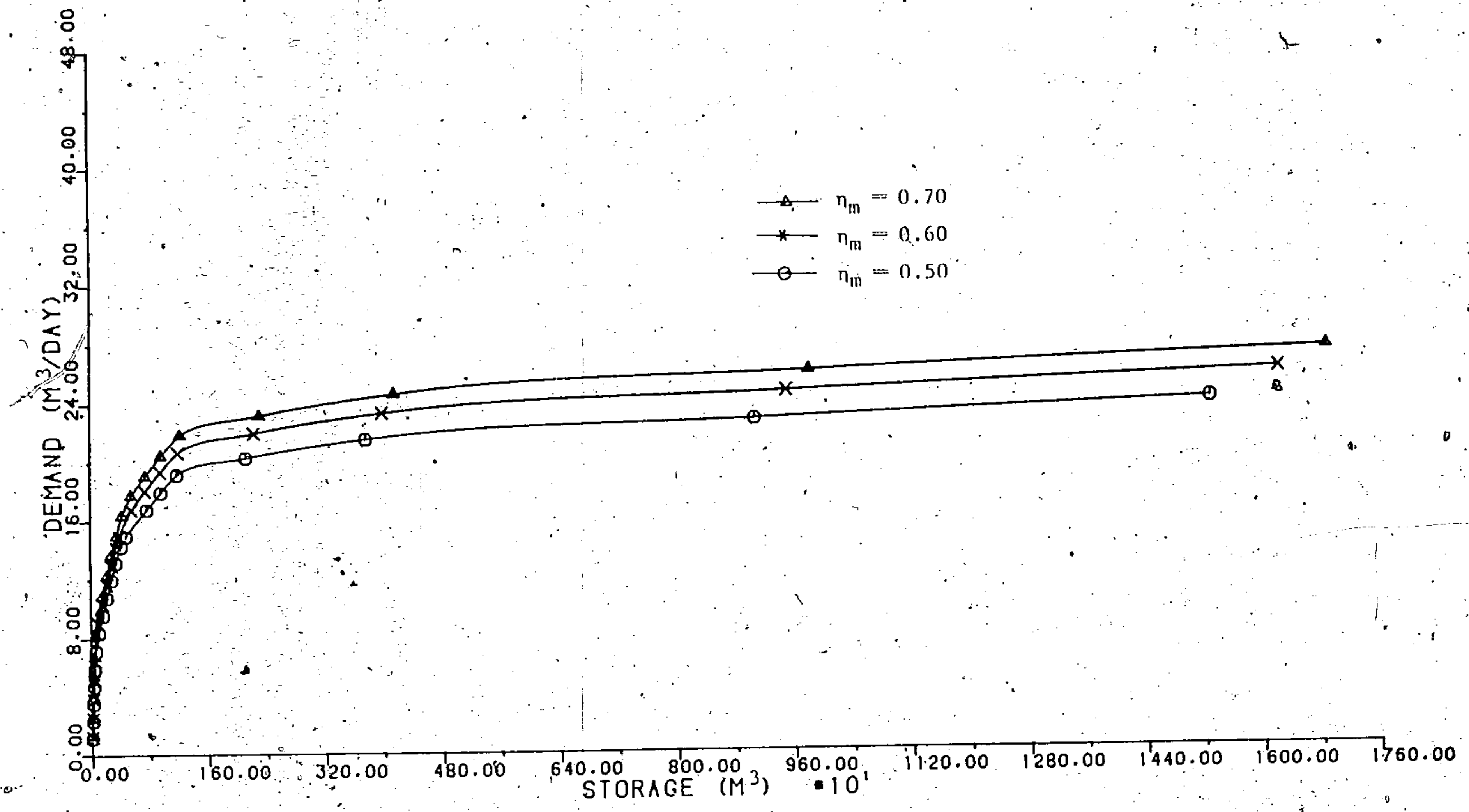


Figure 11: Sensitivity analysis on mechanical efficiency using actual wind speed (daily) distributions

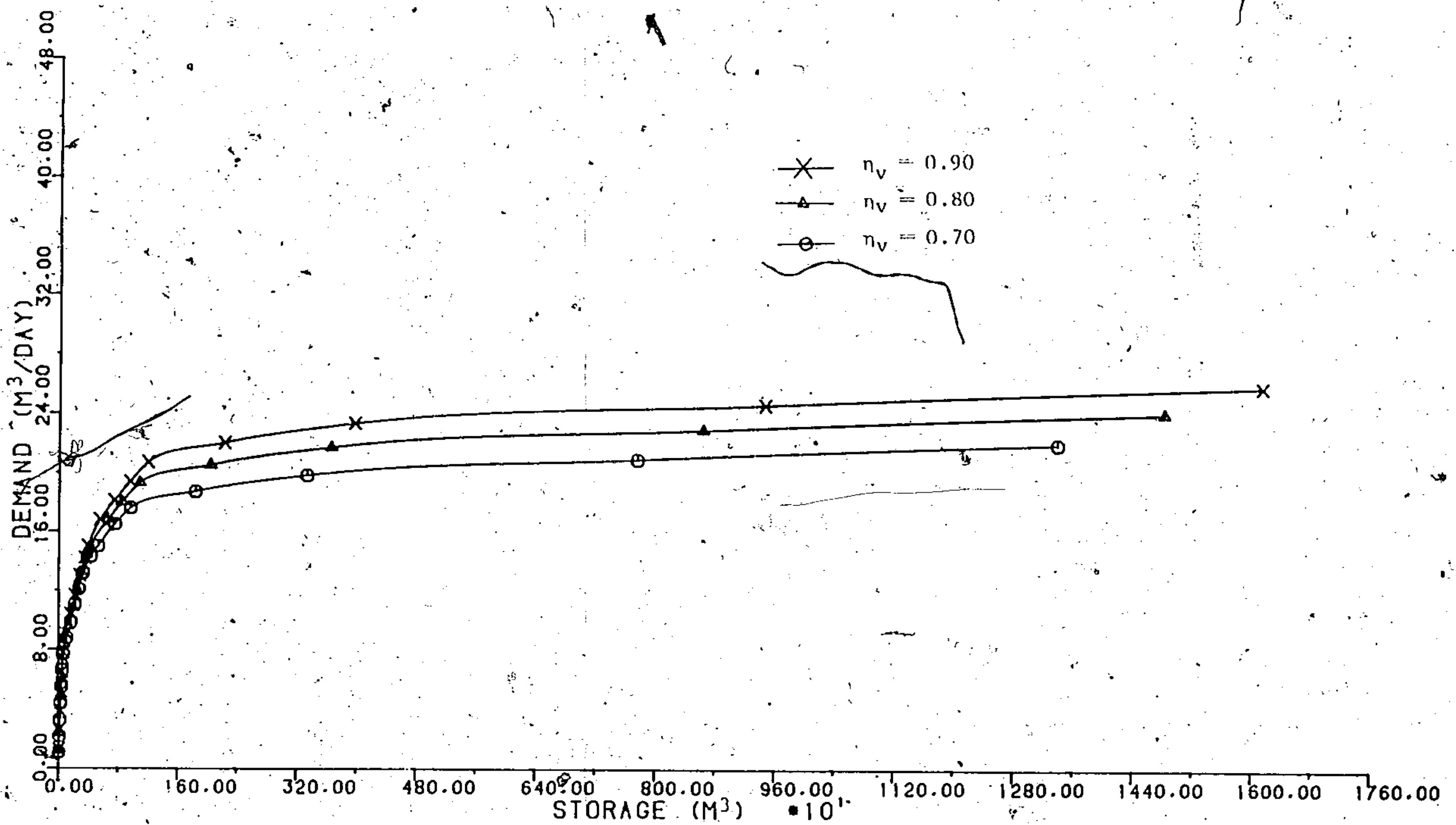


Figure 12: Sensitivity analysis on volumetric efficiency using actual wind speed (daily) distributions

Chapter V

DISCUSSIONS AND CONCLUSION

5.1 SUMMARY

A storage model has been developed which is only applicable for multibladed water pumping windmills having cut-in, rated and cut-out wind speeds. Only single windmill, pump and storage tank are considered.

Given the wind histograms, the windmill and pump characteristics, an optimum storage size can be determined for a given demand level. As an example, consider a community of 500 people. Using an average rate of water consumption of 30 litres/capita/day, that is, 15 m^3/day, the design value of the storage size from Fig. 8 would be 400 m^3 for a 100% reliability level.

Knowledge of the input parameters is highly desirable because an incorrect parameter may adversely underestimate or overestimate the windmill output resulting in incorrect storage calculations. The sensitivity analyses done in Chapter IV confirm this point. It was found that changes in C_{pm}, G_r, η_m and η_v affect the storage size, with increase in windmill and pump efficiencies allowing the use of a smaller reservoir for a given demand level.

5.2 CONCLUSION

The ultimate aim of this research work was to develop a model that will compute the volume of tank required using readily available data from meteorological stations and windmill and pump manufacturers. A computerized wind pump storage model was developed which has the following capabilities:

1. The model can be used to design the reservoir size for multibladed water pumping wind systems. By trying different windmill, pump cylinder and stroke combinations, an estimate of the water output can be found for a chosen static height and demand rate given the wind regime.
2. Rippl's method and the behaviour analysis of MacMahon and Mein [33] are used to calculate the storage-yield fuctions at five different reliability levels.
3. Various options are included:
   a) Head loss due to pipe friction can be calculated using Darcy-Weisbach or Hazen-Williams equation.
   b) Wind speed distribution (daily or monthly) can be either actual or derived distributions. For derived distributions, only Weibull and Rayleigh distributions are considered.
   c) Behaviour analysis can be specified or not. If it is not specified, only the storages at 100% reli-

ability level will be computed for different demand rates.

The model can be used to investigate the sensitivity of the input parameters on the storage size. By altering the value of a particular parameter, its effect can be determined. From the sensitivity analyses that were done in this research work, the storage size increases as C_{pm}, n_m, or n_v decreases and decreases as G_r, decreases.

5.3 FURTHER WORK

Other topics of interest have evolved as a result of this research work.

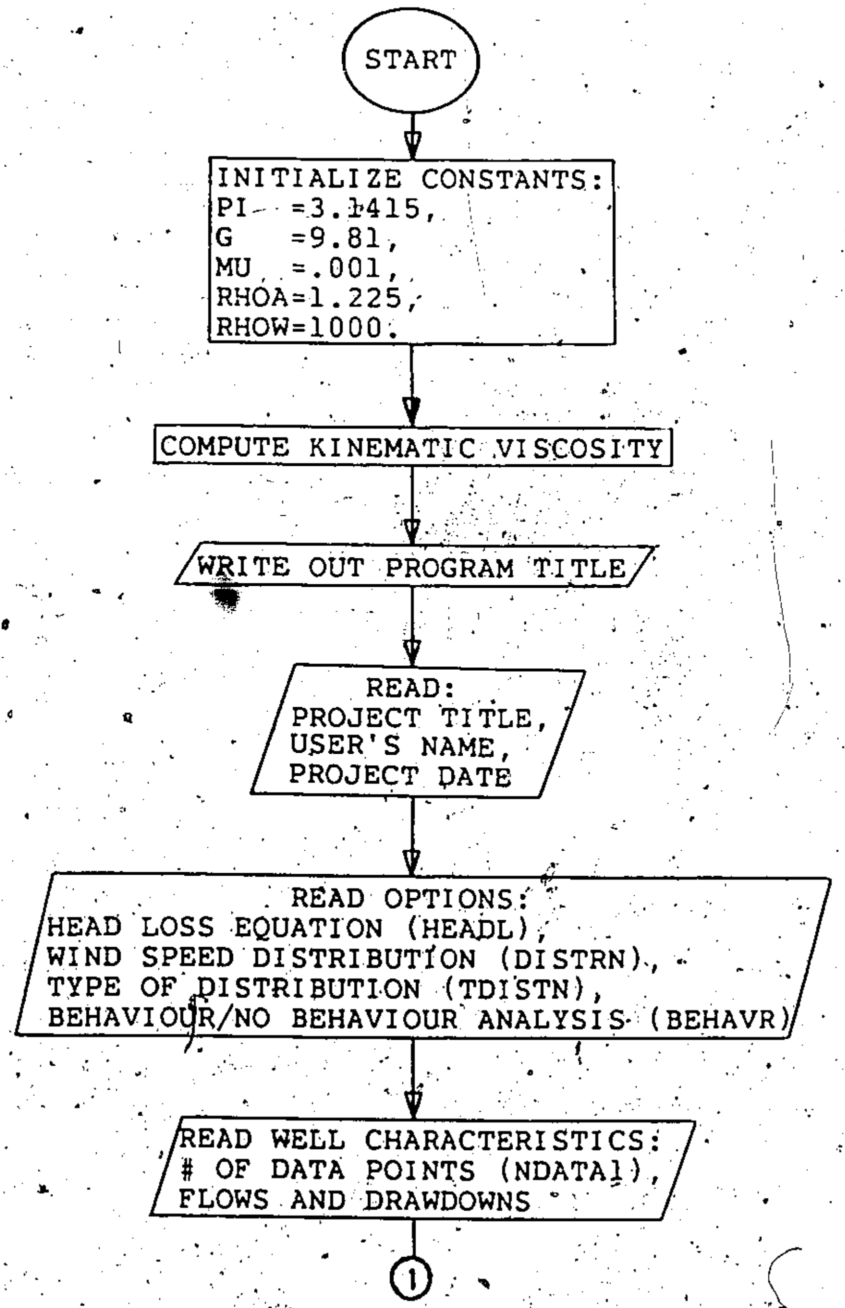
1. Windmill Characteristics
   - a) While this storage model is only applicable for multibladed windmills, the power coefficient models of other types of windmills could be incorporated into the model.
   - b) The steady-state equilibrium has been assumed. Dynamic equilibrium could be included, not only as an option, but also for comparison purposes.
2. Storage Model
   - a) Occurrence and volume-based dependabilities have not been compared with time-based dependability.
   - b) Constant demand rate has been used. Variable demand rate could be considered.

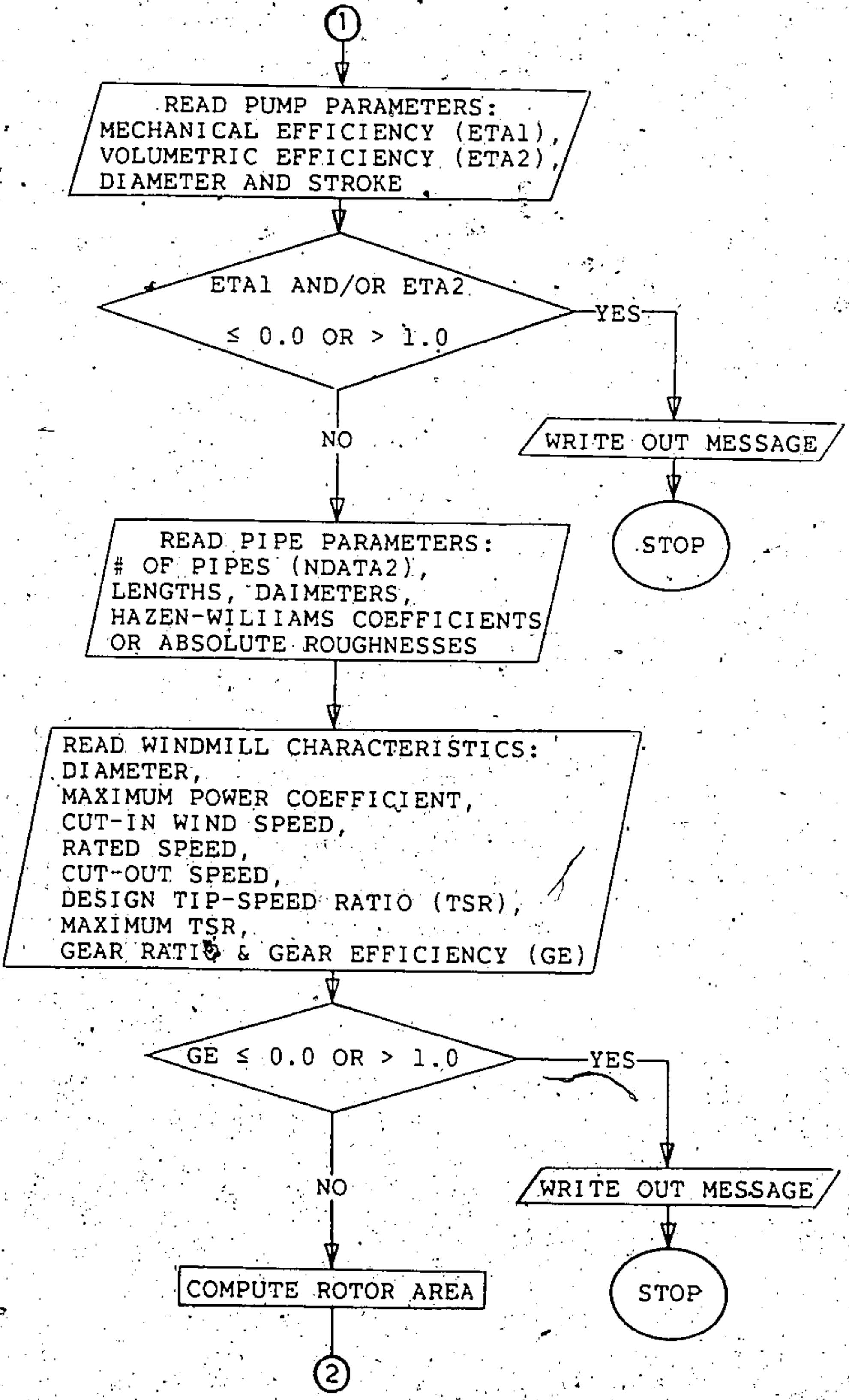
3. Multiple Components
   a) This storage model could be extended to accomodate multiple windmills, pumps and storage tanks.
4. Field Investigations
   a) Since this model was developed using the theoretical aspects of the windmills and pumps, field tests should be conducted with actual operating windmills in order to check the validity of these theoretical assumptions.

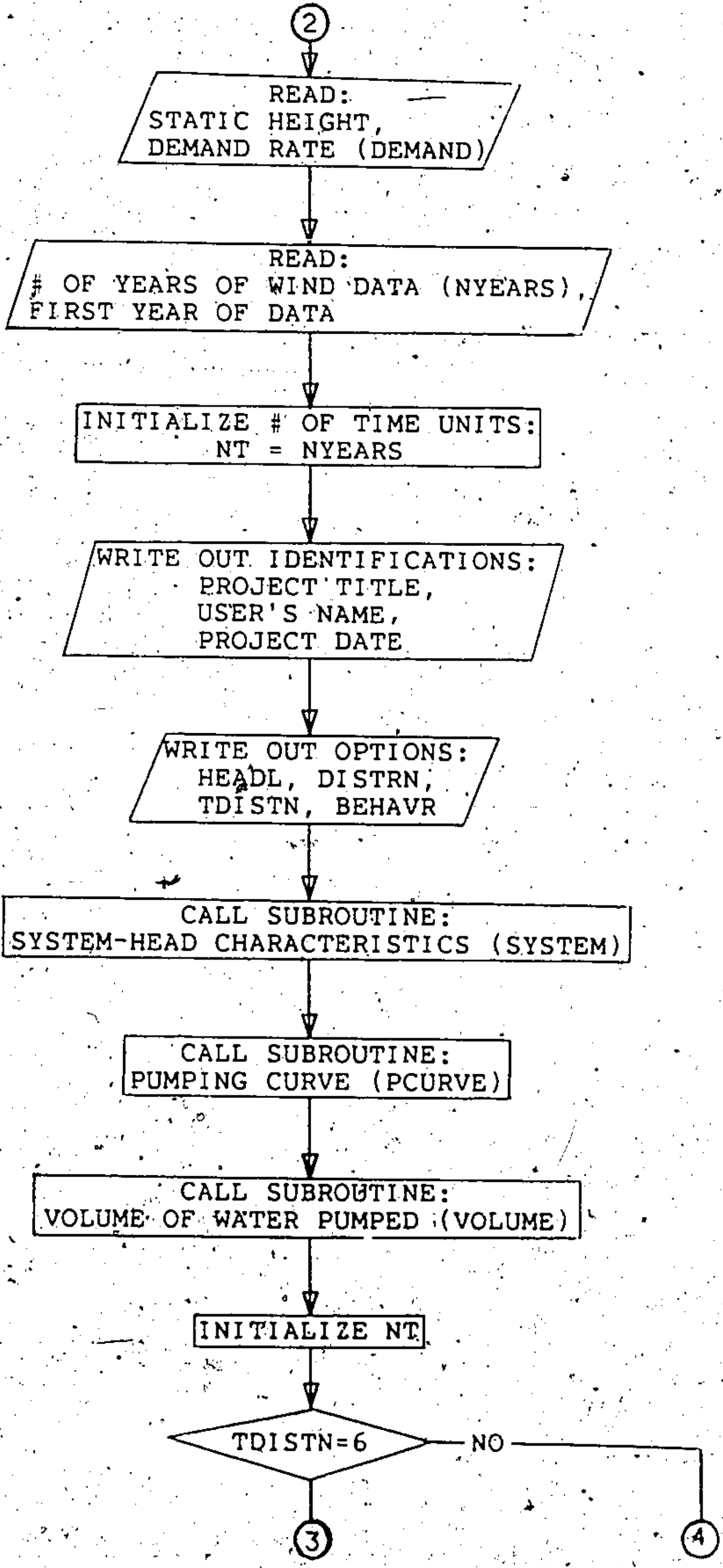
Appendix A

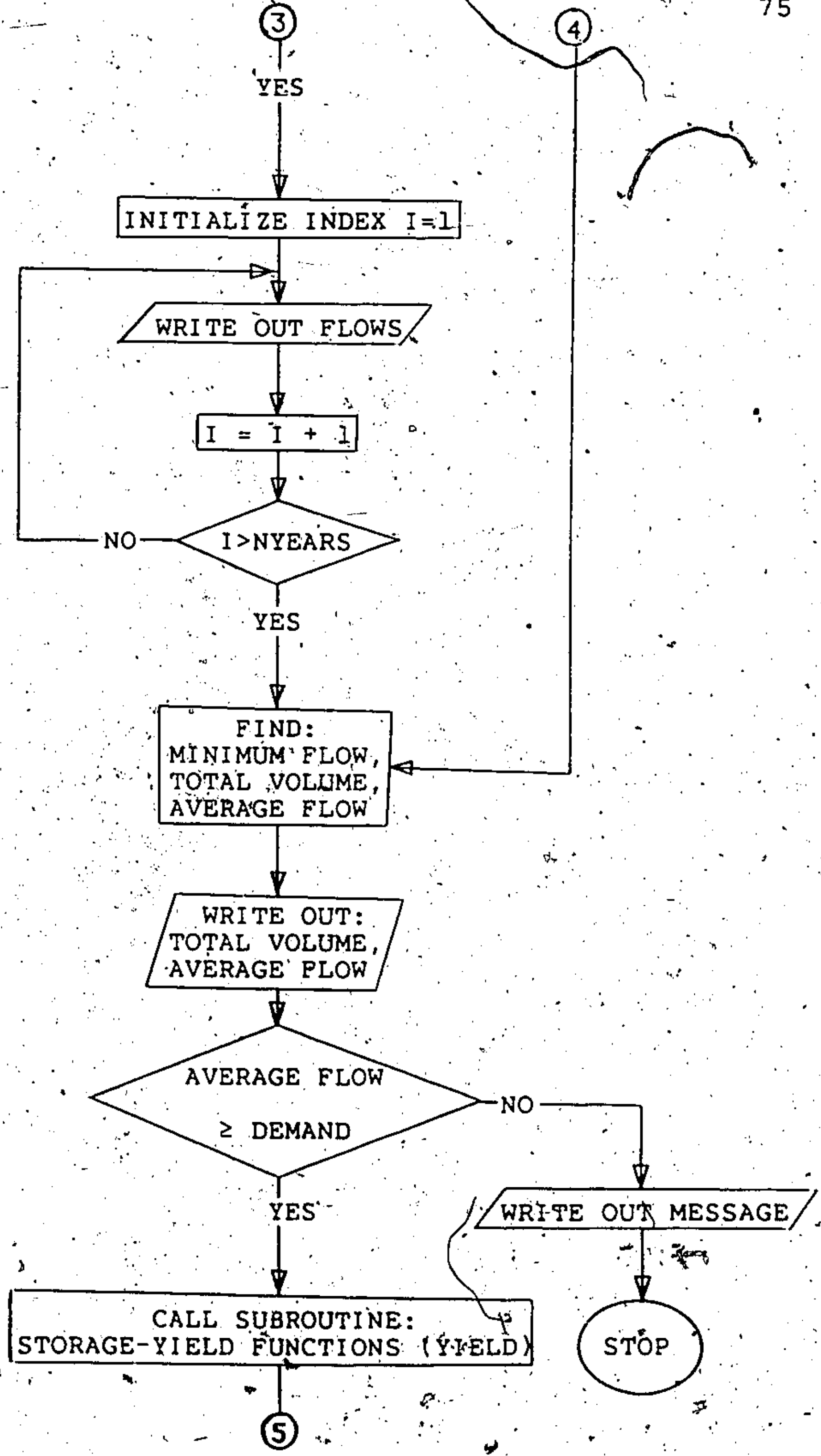
FLOWCHARTS

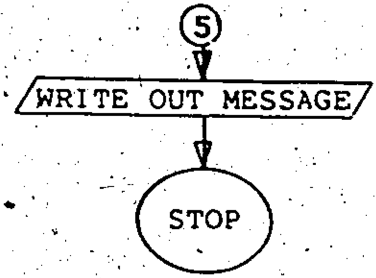
MAIN PROGRAM



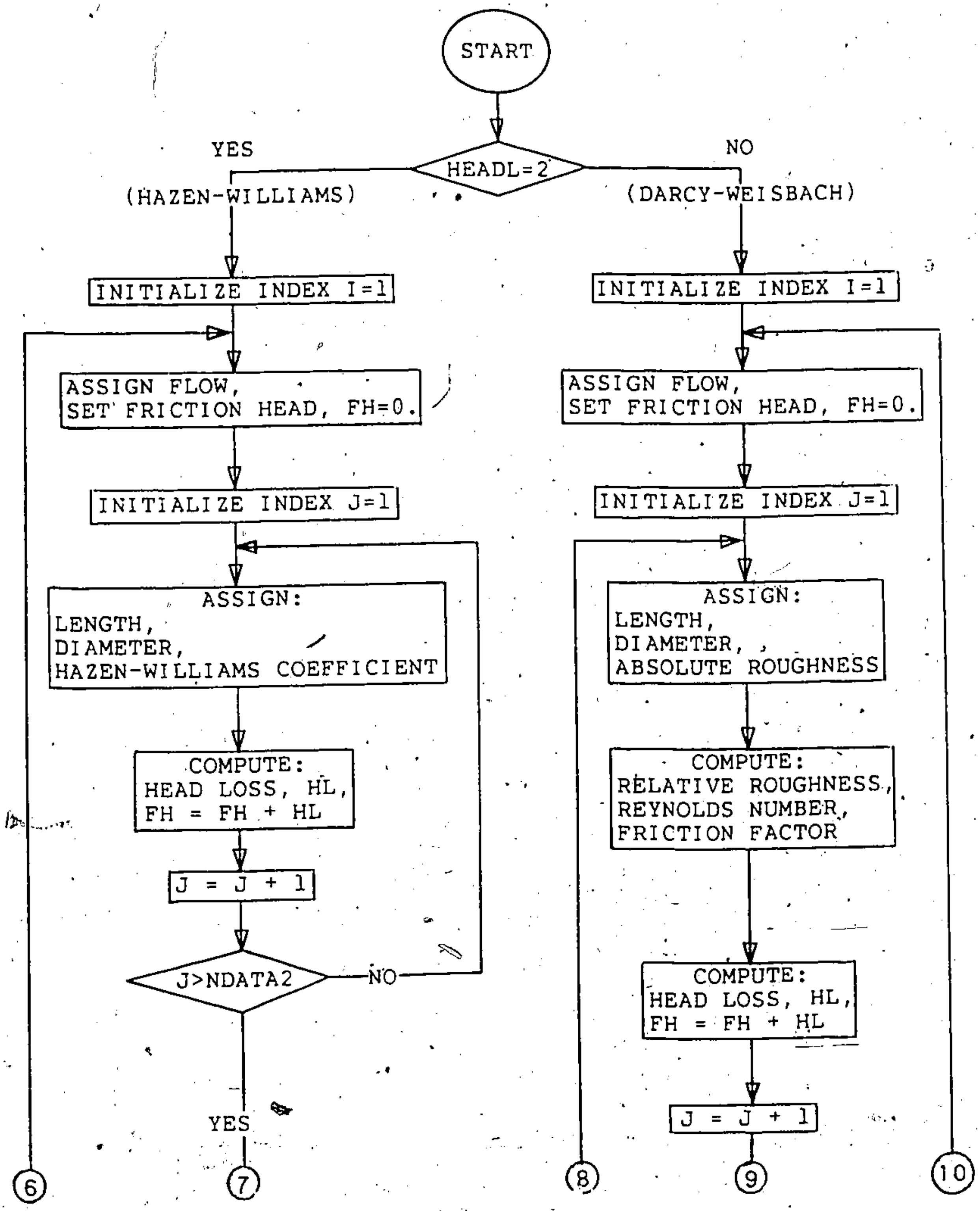

①
READ PUMP PARAMETERS:
MECHANICAL EFFICIENCY (ETA1),
VOLUMETRIC EFFICIENCY (ETA2),
DIAMETER AND STROKE
ETA1 AND/OR ETA2
≤ 0.0 OR > 1.0
YES
WRITE OUT MESSAGE
STOP
NO
READ PIPE PARAMETERS:
OF PIPES (NDATA2),
LENGTHS, DAIMETERS,
HAZEN-WILIIAMS COEFFICIENTS
OR ABSOLUTE ROUGHNESSES
READ WINDMILL CHARACTERISTICS:
DIAMETER,
MAXIMUM POWER COEFFICIENT,
CUT-IN WIND SPEED,
RATED SPEED,
CUT-OUT SPEED,
DESIGN TIP-SPEED RATIO (TSR),
MAXIMUM TSR,
GEAR RATIO & GEAR EFFICIENCY (GE)
GE ≤ 0.0 OR > 1.0
YES
WRITE OUT MESSAGE
STOP
NO
COMPUTE ROTOR AREA
②

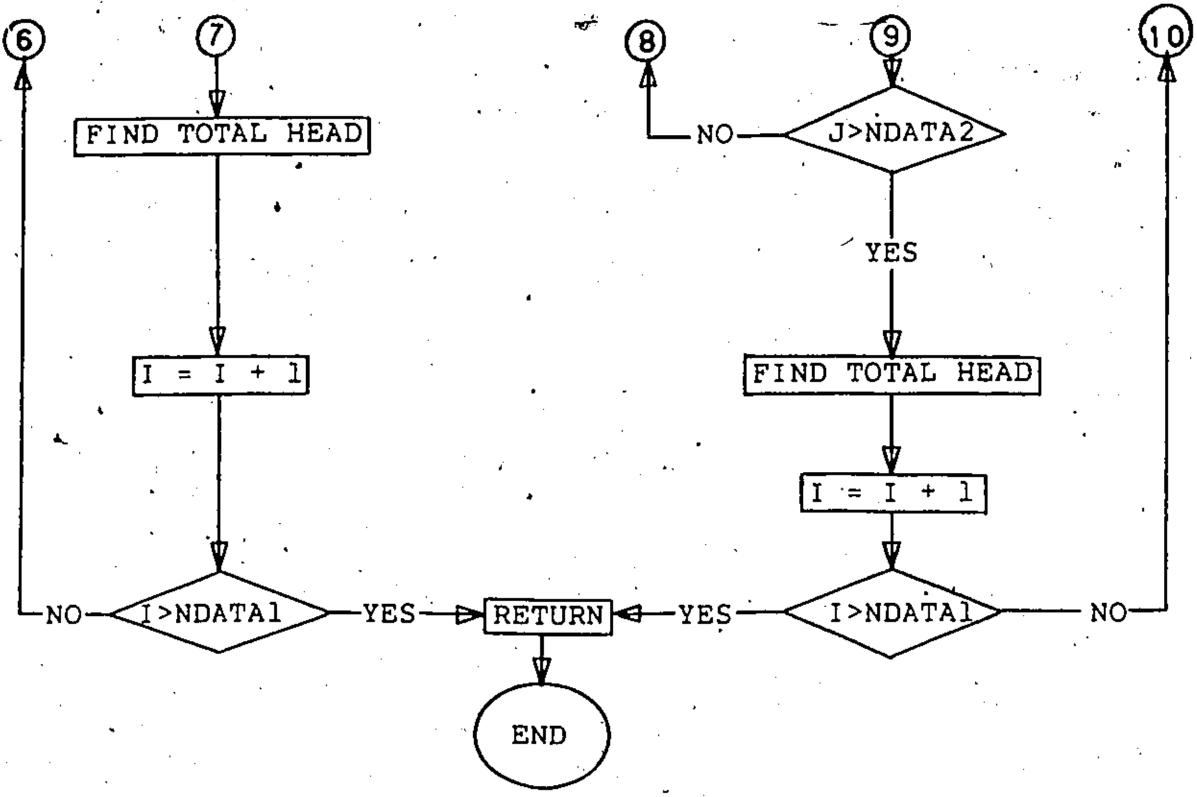

2
READ:
STATIC HEIGHT,
DEMAND RATE (DEMAND)
READ:
OF YEARS OF WIND DATA (NYEARS),
FIRST YEAR OF DATA
INITIALIZE # OF TIME UNITS:
NT = NYEARS
WRITE OUT IDENTIFICATIONS:
PROJECT TITLE,
USER'S NAME,
PROJECT DATE
WRITE OUT OPTIONS:
HEADL, DISTRN,
TDISTN, BEHAVR
CALL SUBROUTINE:
SYSTEM-HEAD CHARACTERISTICS (SYSTEM)
CALL SUBROUTINE:
PUMPING CURVE (PCURVE)
CALL SUBROUTINE:
VOLUME OF WATER PUMPED (VOLUME)
INITIALIZE NT
TDISTN=6
NO
3
4


3
YES
INITIALIZE INDEX I=1
WRITE OUT FLOWS
I = I + 1
I>NYEARS
NO
YES
4
FIND:
MINIMUM FLOW,
TOTAL VOLUME,
AVERAGE FLOW
WRITE OUT:
TOTAL VOLUME,
AVERAGE FLOW
AVERAGE FLOW
≥ DEMAND
NO
YES
WRITE OUT MESSAGE
STOP
CALL SUBROUTINE:
STORAGE-YIELD FUNCTIONS (YIELD)
5

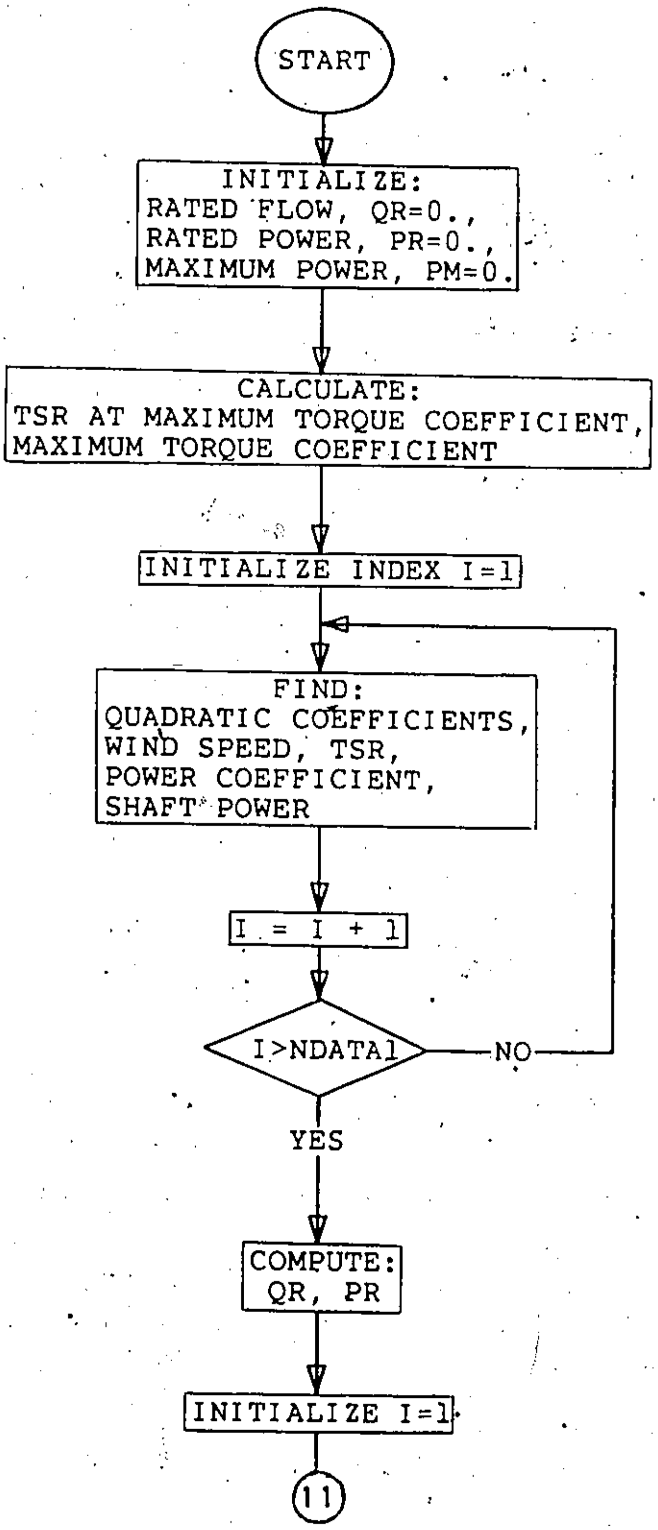

5
WRITE OUT MESSAGE
STOP

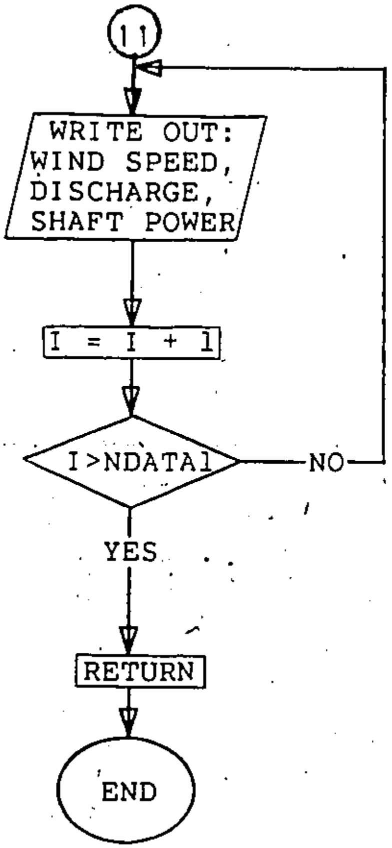
SUBROUTINE SYSTEM



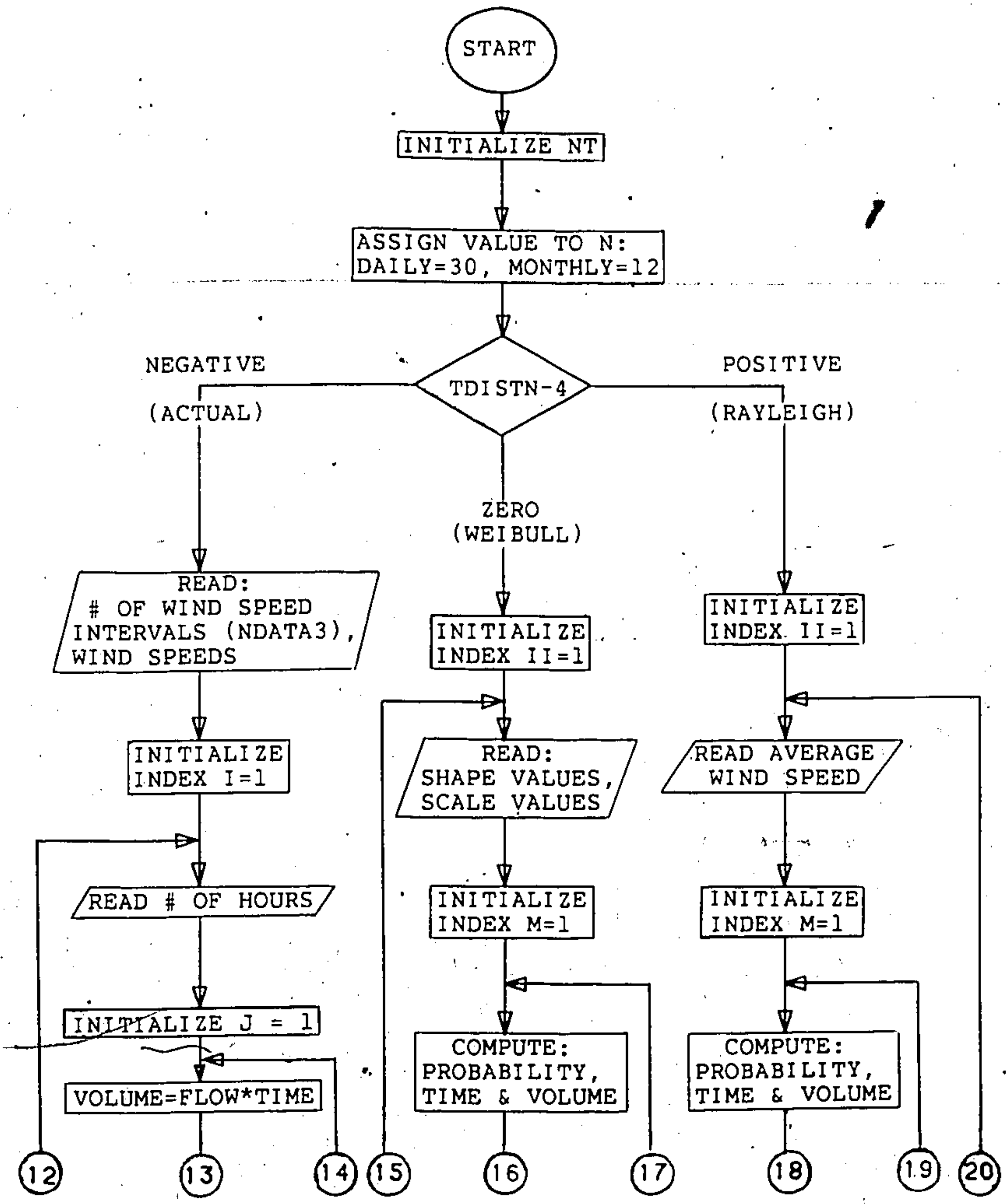

6
7
8
9
10
FIND TOTAL HEAD
I = I + 1
I>NDATA1
NO
YES
RETURN
END
J>NDATA2
NO
YES
FIND TOTAL HEAD
I = I + 1
I>NDATA1
YES
NO

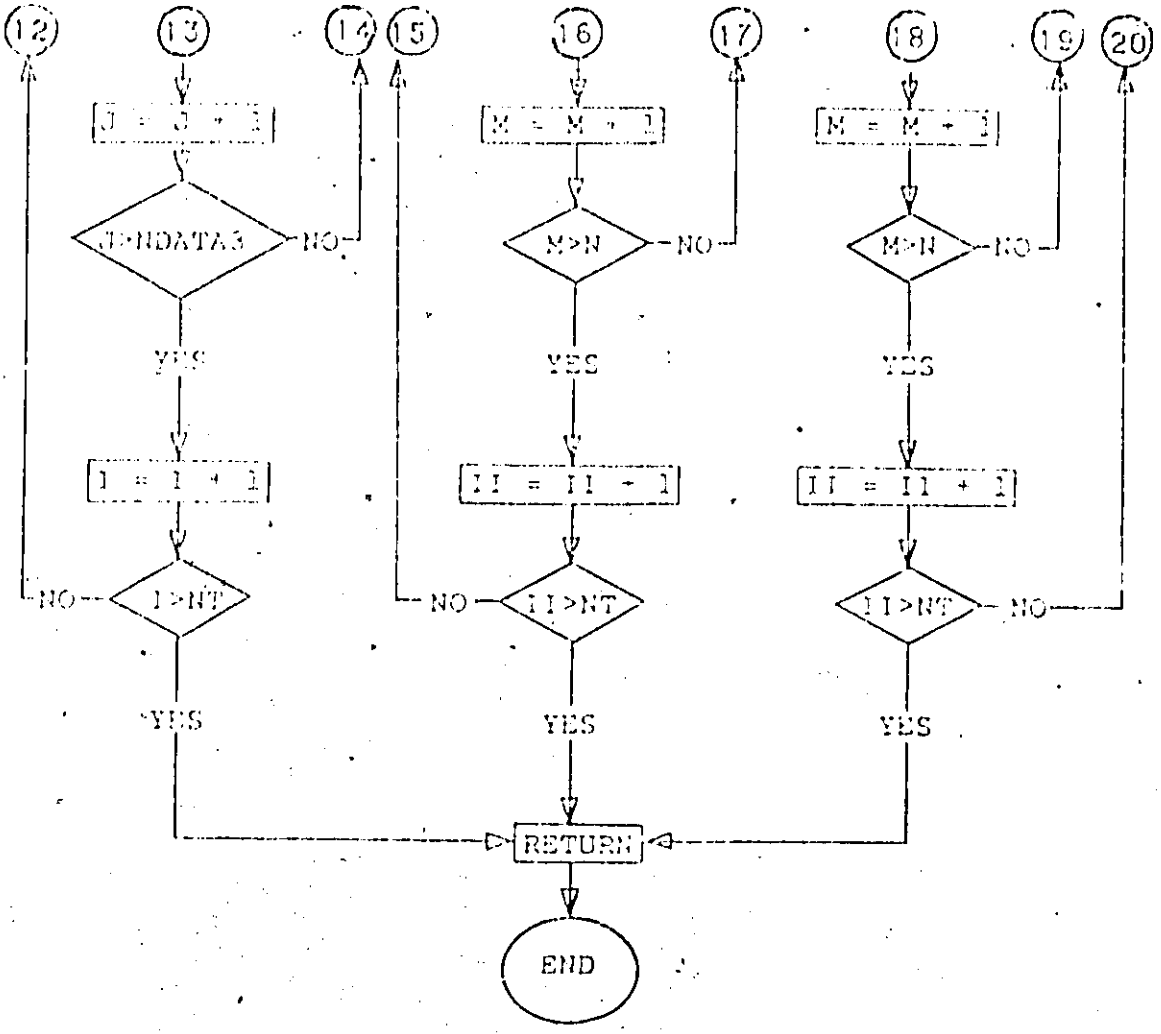
SUBROUTINE PCURVE



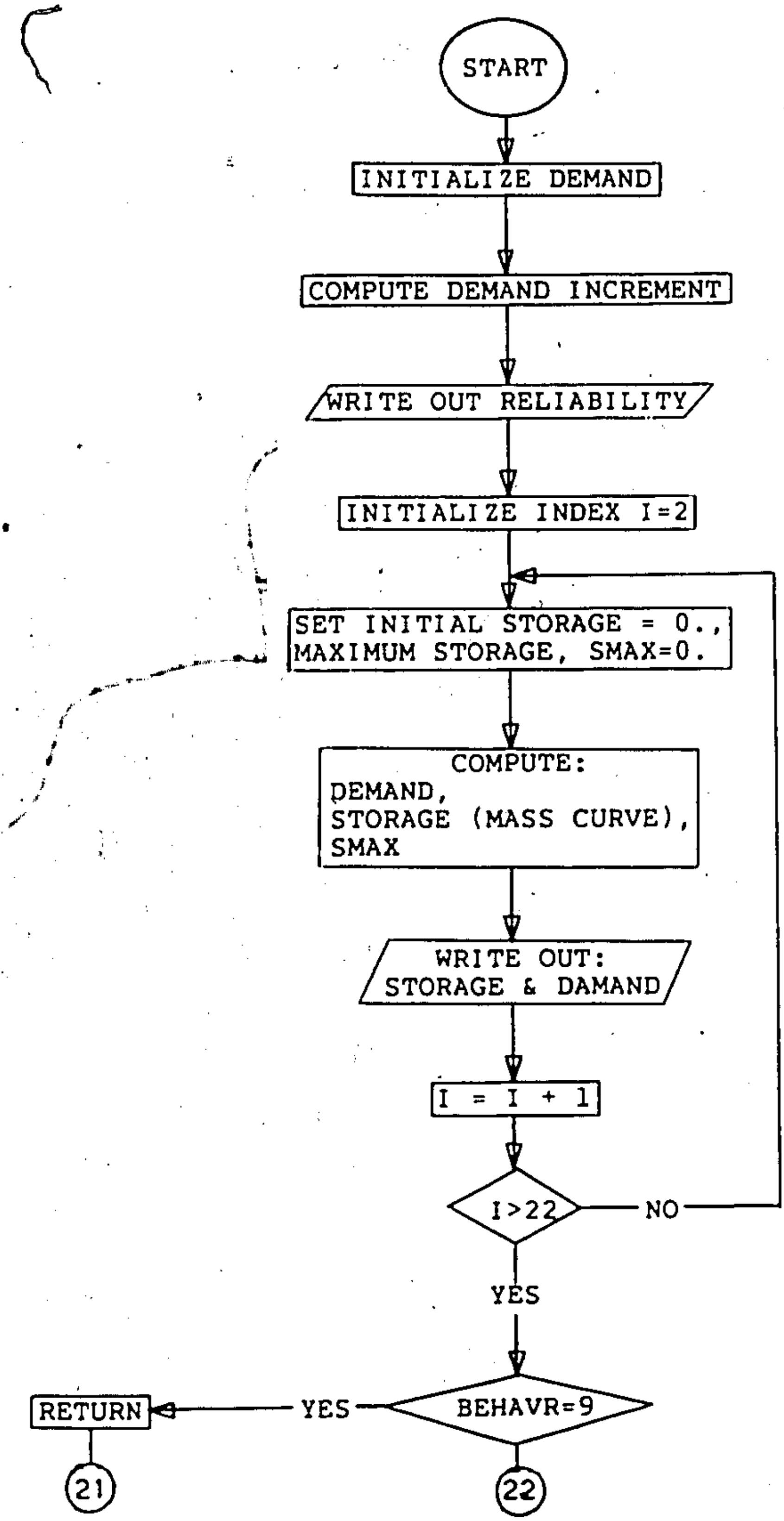

11
WRITE OUT: WIND SPEED, DISCHARGE, SHAFT POWER
I = I + 1
I>NDATA1
NO
YES
RETURN
END

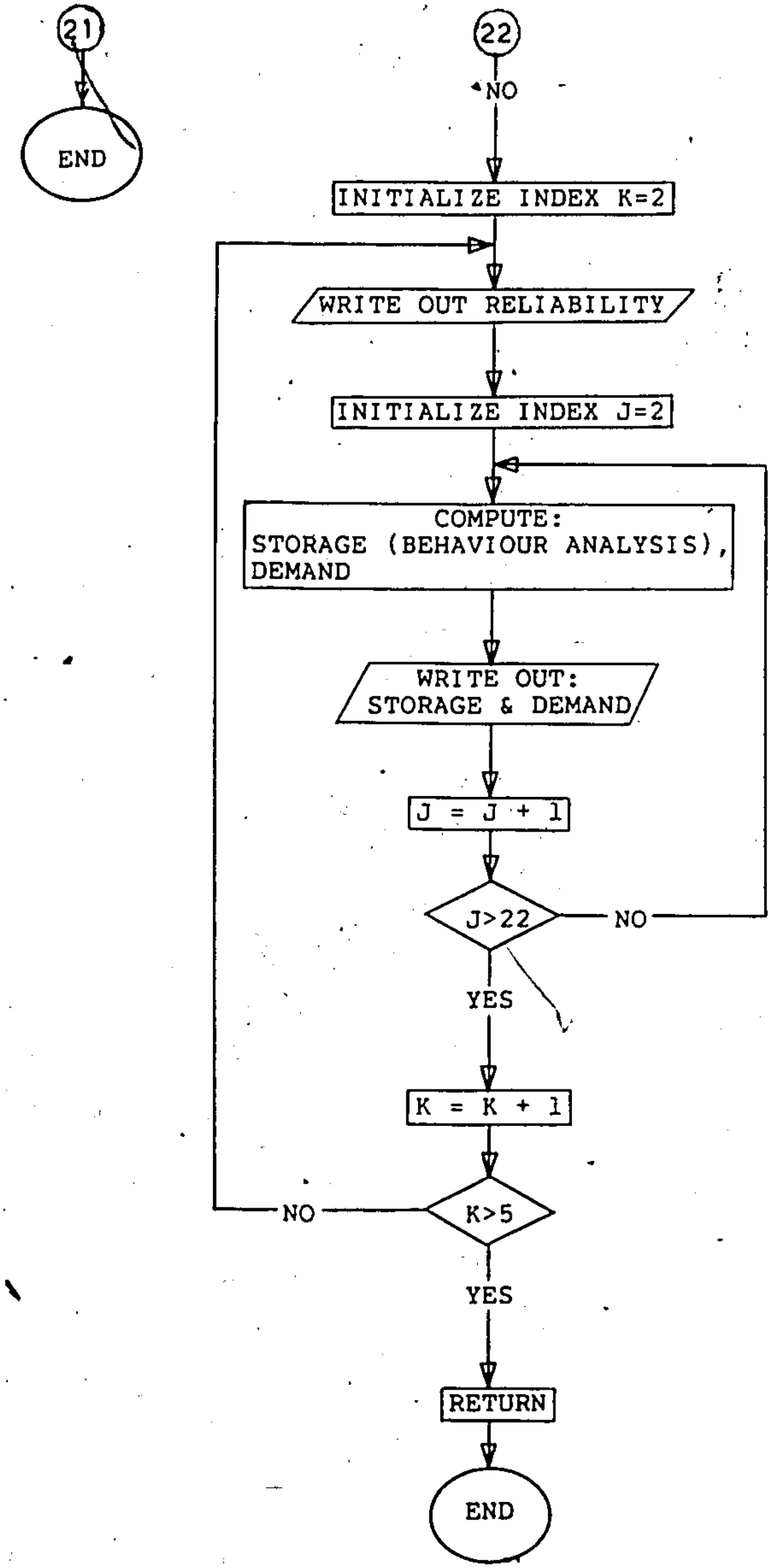
SUBROUTINE VOLUME




12
13
14
15
16
17
18
19
20
J = J + 1
J>NDATA3
NO
YES
I = I + 1
I>NT
NO
YES
M = M + 1
M>N
NO
YES
II = II + 1
II>NT
NO
YES
M = M + 1
M>N
NO
YES
II = II + 1
II>NT
NO
YES
RETURN
END

SUBROUTINE YIELD




21
END
22
NO
INITIALIZE INDEX K=2
WRITE OUT RELIABILITY
INITIALIZE INDEX J=2
COMPUTE:
STORAGE (BEHAVIOUR ANALYSIS),
DEMAND
WRITE OUT:
STORAGE & DEMAND
J = J + 1
J>22
NO
YES
K = K + 1
K>5
NO
YES
RETURN
END

Appendix B

COMPUTER PROGRAM

```
C     **********************************************************
C     *                      WINDPUMP                          *
C     **********************************************************
C     * STORAGE MODEL FOR MULTIBLADED WATER PUMPING WINDMILLS  *
C     * WITH RECIPROCATING  PISTON  PUMPS.  THE  STEADY-STATE  *
C     * EQUILIBRIUM HAS BEEN ASSUMED.                          *
C     **********************************************************
C
C                     VARIABLE LIBRARY
C
C           AREA      ROTOR AREA (M**2)
C           CPM       MAXIMUM (DESIGN) POWER COEFFICIENT
C           CUTIN     CUT-IN WIND SPEED (M/S)
C           CUTOUT    CUT-OUT WIND SPEED (M/S)
C           DATE      DATE OF PROJECT
C           DEMAND    RATE OF WATER USAGE (M**3/DAY)
C           DIAMET    ROTOR DIAMETER (M)
C           DISTRN    WIND SPEED DISTRIBUTION
C           ETA1      MECHANICAL EFFICIENCY OF PUMP
C           ETA2      VOLUMETRIC EFFICIENCY OF PUMP
C           FIRSTY    FIRST YEAR OF WIND DATA
C           G         GRAVITATIONAL ACCELERATION = 9.81 (M/S**2)
C           GE        GEAR EFFICIENCY
C           GR        GEAR RATIO
C           HEADL     HEAD LOSS EQUATION
C           HEIGHT    STATIC HEIGHT (M)
C           INFLOW    VOLUME OF WATER PUMPED PER DAY OR MONTH
C                     RESERVOIR INFLOW (M**3/DAY OR M**3/MONTH)
C           MU        VISCOSITY OF WATER = 0.001 (KG/M.S)
C           NAME      USER'S NAME
C           NDATA1    # OF PAIRS OF DATA FOR FLOW VS. DRAWDOWN
C           NDATA2    # OF PIPES
C           NDATA3    # OF WIND SPEED INTERVALS
C           NYEARS    # OF YEARS OF WIND DATA
C           PI        3.1415
C           PIPEC     PIPE ABSOLUTE ROUGHNESS OR
C                     HAZEN-WILLIAMS COEFFICIENT
C           PIPED     PIPE DIAMETER (M)
C           PIPEL     PIPE LENGTH (M)
C           POWER     SHAFT POWER (WATTS)
C           PROJET    TITLE OF PROJECT
C           PUMPD     PUMP DIAMETER (M)
C           RATEDV    RATED WIND SPEED (M/S)
C           RHOA      AIR DENSITY = 1.225 (KG/M**3)
```

```
C       RHOW     WATER DENSITY = 1000. (KG/M**3)
C       RL       RELIABILITY LEVEL
C       SCALE    WEIBULL SCALE FACTOR (M/S)
C       SHAPE    WEIBULL SHAPE FACTOR
C       SPEED    WIND SPEED (M/S)
C       STROKE   PUMP STROKE (M)
C       TDISTN   TYPE OF DISTRIBUTION (DAILY OR MONTHLY)
C       TIME     # OF HOURS
C       TSR      TIP-SPEED RATIO
C       TSRD     DESIGN TSR
C       TSRM     MAXIMUM TSR
C       WELLQ    WELL FLOW RATE (M**3/S)
C       WELLS    WELL DRAWDOWN (M)
```

```
C     ***************         MAIN  PROGRAM        ***************
C
C
      REAL WELLQ(50),WELLS(50),SPEED(30),INFLOW(36000),
     +MU,RL(5)/100.,95.,90.,85.,80./,SPD(50),NU
      DIMENSION PIPEL(5),PIPED(5),PIPEC(5),SHAPE(30),
     +SCALE(30),POWER(50),ST(22),DD(22)
      INTEGER HEADL,DISTRN,BEHAVR,A1/'PROJ'/,A2/'ECT:'/,
     +A3/'DATE'/,A4/'NAME'/,A5/':'/,PROJET(20),DATE(20),
     +NAME(20),TIME(20),FIRSTY,TDISTN
      COMMON /DAT/ NDATA1,NDATA2,HEIGHT
      COMMON /HQC/ CPM,TSRD,TSRM,STROKE,ETA1,ETA2
      COMMON /WML/ AREA,CUTIN,RATEDV,CUTOUT,DIAMET,GR,GE
      DATA PI,G,MU,RHOW,RHOA/ 3.1415,9.81,.001,1000.,1.225/
      NU=MU/RHOW
      WRITE(6,770)
  770 FORMAT(1X,'*********************************',
     +'*****************************************')
      WRITE(6,910)
  910 FORMAT(1X,'*',73X,'*'/1X,'* STORAGE MODEL FOR MULTI'
     +,'BLADED WATER PUMPING WINDMILLS WITH PISTON PUMPS *'
     +/1X,'*',73X,'*'/1X,'*',33X,'(1986)',
     +34X,'*'/1X,'*',73X,'*'/1X,'*',73X,'*'/1X,'*',13X,
     +'DEVELOPED BY U. D. ASSAM AND DR. E. J. SCHILLER',13X,
     +'*'/1X,'*',73X,'*'/1X,'*',21X,
     +'DEPARTMENT OF CIVIL ENGINEERING',21X,'*'/1X,'*',73X,
     +'*'/1X,'*',19X,'UNIVERSITY OF OTTAWA, OTTAWA, CANADA'
     +,18X,'*'/1X,'*',73X,'*')
      WRITE(6,770)
      WRITE(6,790)
  790 FORMAT(/////)
C
C        DATA INPUT
C
C        IDENTIFICATION
      READ(5,140)PROJET
      READ(5,140)NAME
      READ(5,140)DATE
  140 FORMAT(20A4)
C
C        SELECT OPTIONS
C
C        HEAD LOSS EQUATION
C        HEADL=01: DARCY-WEISBACH
C             =02: HAZEN-WILLIAMS
C        WIND SPEED DISTRIBUTION
C        DISTRN=03: ACTUAL
C              =04: WEIBULL
C              =05: RAYLEIGH
C        TDISTN=06: DAILY
C              =07: MONTHLY
```

```
C       BEHAVIOUR ANALYSIS
C       BEHAVR=08: YES
C             =09: NO
      READ(5,145)HEADL,DISTRN,TDISTN,BEHAVR
  145 FORMAT(4(I2,1X))
C       WELL CHARACTERISTICS
      READ(5,145)NDATA1
      READ(5,115)(WELLQ(I),WELLS(I),I=1,NDATA1)
  115 FORMAT(2(E9.3,1X))
C       PUMP CHARACTERISTICS
      READ(5,165)ETA1,ETA2,PUMPD,STROKE
  165 FORMAT(2(F4.2,1X),2(F6.4,1X))
      IF(ETA1.LE.0..OR.ETA1.GT.1.)GOTO 110
      IF(ETA2.LE.0..OR.ETA2.GT.1.)GOTO 110
C       PIPE PARAMETERS
      READ(5,145)NDATA2
      READ(5,185)(PIPEL(I),PIPED(I),PIPEC(I),I=1,NDATA2)
  185 FORMAT(F5.1,1X,F5.3,1X,E9.3)
C       WINDMILL CHARACTERISTICS
      READ(5,125)DIAMET,CPM,CUTIN,
     +RATEDV,CUTOUT,TSRD,TSRM,GR,GE
  125 FORMAT(12(F5.2,1X))
      IF(GE.LE.0..OR.GE.GT.1.)GOTO 110
      AREA=PI*DIAMET**2/4.
C       STATIC HEIGHT AND DEMAND RATE
      READ(5,115)HEIGHT,DEMAND
      IF(TDISTN.EQ.7)DEMAND=DEMAND*30.
C       NUMBER OF YEARS AND THE FIRST YEAR OF WIND DATA
      READ(5,760)NYEARS,FIRSTY
  760 FORMAT(I3,1X,I4)
      NT=NYEARS
C
C       WRITE OUT IDENTIFICATION
      WRITE(6,780)A1,A2,PROJET
      WRITE(6,780)A4,A5,NAME
      WRITE(6,780)A3,A5,DATE
  780 FORMAT(/16X,2A4,1X,20A4)
C       WRITE OUT OPTIONS
      WRITE(6,870)
  870 FORMAT(/////16X,'OPTIONS SPECIFIED')
      WRITE(6,880)
  880 FORMAT(//16X,'HEAD LOSS EQUATION:')
      IF(HEADL.EQ.1)WRITE(6,830)
      IF(HEADL.EQ.2)WRITE(6,860)
  830 FORMAT('+',36X,'DARCY-WEISBACH')
  860 FORMAT('+',36X,'HAZEN-WILLIAMS')
      WRITE(6,930)
  930 FORMAT(/16X,'WIND SPEED DISTRIBUTION:')
      IF(DISTRN.EQ.3)WRITE(6,950)
      IF(DISTRN.EQ.4)WRITE(6,970)
      IF(DISTRN.EQ.5)WRITE(6,990)
  950 FORMAT('+',41X,'ACTUAL')
  970 FORMAT('+',41X,'WEIBULL')
  990 FORMAT('+',41X,'RAYLEIGH')
```

```
      IF(TDISTN.EQ.6)WRITE(6,920)
      IF(TDISTN.EQ.7)WRITE(6,940)
  920 FORMAT(41X,'(DAILY)')
  940 FORMAT(41X,'(MONTHLY)')
      WRITE(6,180)
  180 FORMAT(//16X,'BEHAVIOUR ANALYSIS:')
      IF(BEHAVR.EQ.8)WRITE(6,310)
      IF(BEHAVR.EQ.9)WRITE(6,320)
  310 FORMAT('+',36X,'YES')
  320 FORMAT('+',36X,'NO')
C
C         SYSTEM-HEAD CHARACTERISTICS
      CALL SYSTEM(WELLQ,WELLS,PIPEL,PIPED,PIPEC,HEADL,
     +NU,G)
C         PUMPING CURVE
      CALL PCURVE(WELLQ,WELLS,SPD,PI,RHOW,G,PUMPD,LL,
     +POWER,QR,PR,RHOA)
C         VOLUME OF WATER PUMPED
      CALL VOLUME(WELLQ,SPD,SPEED,TIME,SHAPE,SCALE,INFLOW,
     +DISTRN,LL,NDATA3,PI,QR,PR,NT,TDISTN)
      NT=12*NYEARS
      IF(TDISTN.EQ.6)NT=360*NYEARS
      IF(TDISTN.EQ.6)GOTO 100
      WRITE(6,370)
  370 FORMAT('1',///15X,'VOLUME OF WATER PUMPED (M**3)')
      WRITE(6,890)
  890 FORMAT(//6X,'MONTH')
      WRITE(6,150)
  150 FORMAT('+',13X,'JAN',7X,'FEB',7X,'MAR',7X,'APR',7X,
     +'MAY',7X,'JUN',7X,'JUL',7X,'AUG',7X,'SEP',7X,'OCT',
     +7X,'NOV',7X,'DEC')
      WRITE(6,330)
  330 FORMAT(1X,'YEAR')
C         WRITE OUT FLOWS (MONTHLY DISTRIBUTIONS ONLY)
      K=FIRSTY
      N=1
      DO 360 I=1,NYEARS
       M=12*I
       WRITE(6,380)K
       WRITE(6,390)(INFLOW(J),J=N,M)
       N=M+1
  360 K=K+1
  380 FORMAT(/1X,I4)
  390 FORMAT('+',11X,12(E9.2,1X))
  100 TOTAL=INFLOW(1)
      QMIN=INFLOW(1)
C         FIND THE MINIMUM AND THE TOTAL FLOWS
      DO 340 I=2,NT
       TOTAL=TOTAL+INFLOW(I)
  340 IF(INFLOW(I).LT.QMIN)QMIN=INFLOW(I)
```

```
C        AVERAGE FLOW
      AVE=TOTAL/FLOAT(NT)
      WRITE(6,350)TOTAL,AVE
  350 FORMAT(///2X,'TOTAL VOLUME=',E14.7,1X,'M**3',';',5X,
     +'AVERAGE FLOW=',E14.7,1X,'M**3/DAY OR MONTH')
      IF(AVE.GE.DEMAND)GOTO 130
      WRITE(6,720)
  720 FORMAT(///2X,'AVERAGE FLOW IS LESS THAN DEMAND.',1X,
     +'A RESERVOIR OF ANY CAPACITY WILL NOT BE'/2X,
     +'ABLE TO MEET THIS DEMAND. TRY OTHER WINDMILL/',
     +'PUMP COMBINATIONS.')
      GOTO 900
C        STORAGE-YIELD FUNCTIONS
  130 CALL YIELD(INFLOW,ST,DD,RL,NT,DEMAND,AVE,QMIN,BEHAVR)
      GOTO 900
  110 WRITE(6,120)
  120 FORMAT(///2X,'PROGRAM TERMINATED. EFFICIENCY HAS',1X,
     +'BEEN FOUND LESS THAN OR EQUAL TO 0.0 OR GREATER',1X,
     +'THAN 1.0'//)
  900 WRITE(6,850)
  850 FORMAT(////4X,'***  THANK YOU FOR USING THE',1X,
     +'UNIVERSITY OF OTTAWA WINDPUMP STORAGE MODEL  ***'///)
      STOP
      END
```

```
C     ****************       SUBROUTINES      *****************
C
      SUBROUTINE SYSTEM(WELLQ,WELLS,PIPEL,PIPED,PIPEC,HEADL,
     +NU,G)
C
C       THE SYSTEM-HEAD CHARACTERISTICS IS OBTAINED BY
C       COMBINING THE SYSTEM-FRICTION CHARACTERISTICS,
C       THE STATIC HEIGHT AND THE DRAWDOWN DUE TO PUMPING
C
      INTEGER HEADL
      REAL WELLQ(50),WELLS(50),NU,L
      DIMENSION PIPEL(5),PIPED(5),PIPEC(5)
      COMMON /DAT/ NDATA1,NDATA2,HEIGHT
      IF(HEADL.EQ.2)GOTO 235
C       HEAD LOSS CALCULATION USING DARCY-WEISBACH EQUATION
      DO 230 I=1,NDATA1
       Q=WELLQ(I)
       FH=0.
       IF(Q.EQ.0.)GOTO 280
       X=.81*Q**2/G
        DO 240 J=1,NDATA2
         L=PIPEL(J)
         D=PIPED(J)
         E=PIPEC(J)
         IF(D.LE.0.)GOTO 240
C          RELATIVE ROUGHNESS
         RR=E/D
         Y=RR/3.7
C          REYNOLDS NUMBER
         RE=(1.273*Q)/(D*NU)
C          LAMINAR FLOW
         IF(RE.LE.2.E3)F=64./RE
         IF(RE.LE.2.E3)GOTO 270
         IF(E.NE.0.)GOTO 170
C          SMOOTH PIPE FLOW (BLASIUS EQUATION)
         IF(RE.LE.3000..OR.RE.GE.1.E5)GOTO 170
         F=.316/(RE)**.25
         GOTO 270
C          TURBULENT FLOW
 170     IF(RE.GT.2.E5)GOTO 250
C          ASSUME A TRIAL VALUE OF FRICTION FACTOR
         IF(RR.GT.8.E-3)F1=.051
         IF(RR.LE.8.E-3)F1=.022
 250     IF(RE.GT.2.E3.AND.RE.LE.2.E5)GOTO 260
         IF(RR.LE.4.E-4)F1=.011
         IF(RR.LE.8.E-3.AND.RR.GT.4.E-4)F1=.022
         IF(RR.GT.8.E-3)F1=.051
C          COLEBROOK-WHITE FUNCTION
 260     F=-2.*ALOG10(Y+2.51/(RE*SQRT(F1)))
         F=1./F**2
         IF(ABS(F-F1).LE..001)GOTO 270
         F1=F
         GOTO 260
```

```
C          DARCY-WEISBACH EQUATION
  270     HL=X*F*L/D**5
          FH=FH+HL
  240    CONTINUE
C           TOTAL HEAD
  280   WELLS(I)=WELLS(I)+FH+HEIGHT
  230 CONTINUE
      GOTO 295
C        HEAD LOSS CALCULATION USING HAZEN-WILLIAMS EQUATION
  235 DO 290 I=1,NDATA1
        Q=WELLQ(I)
        FH=0.
         DO 300 J=1,NDATA2
          L=PIPEL(J)
          D=PIPED(J)
          C=PIPEC(J)
          IF(C.LE.0..OR.D.LE.0.)GOTO 300
C          HAZEN-WILLIAMS EQUATION
          HL=(10.675*L*Q**1.852)/(D**4.87*C**1.852)
          FH=FH+HL
  300    CONTINUE
        WELLS(I)=WELLS(I)+FH+HEIGHT
  290 CONTINUE
  295 RETURN
      END
```

```
C     *******************************************************
C
      SUBROUTINE PCURVE(WELLQ,WELLS,SPD,PI,RHOW,G,PUMPD,LL,
     +POWER,QR,PR,RHOA)
C
C       THE PUMPING CURVE IS DERIVED BY EQUATING THE ROTOR
C       TORQUE TO THE AVERAGE WATER LOAD TORQUE. THIS IS
C       USED TO COMPUTE THE DISCHARGE AT EACH WIND SPEED
C
      REAL WELLQ(50),WELLS(50),POWER(50),SPD(50)
      COMMON /DAT/ NDATA1,NDATA2,HEIGHT
      COMMON /HQC/ CPM,TSRD,TSRM,STROKE,ETA1,ETA2
      COMMON /WML/ AREA,CUTIN,RATEDV,CUTOUT,DIAMET,GR,GE
      QR=0.
      PR=0.
      PM=0.
      TD=TSRD
      TM=TSRM
      TX=TM-TD
C       TSR AT MAXIMUM TORQUE COEFFICIENT
      TT=SQRT(TM*(2.*TD-TM))
C       MAXIMUM TORQUE COEFFICIENT
      CQM=-2.*CPM*(TT-TD)/TX**2
      D2=.5*RHOA*AREA
      D1=D2*GR*GE
      A1=2./(D1*DIAMET)
      A2=1./(PI*DIAMET*GR)
      A3=(ETA2*PI*STROKE*PUMPD**2)/4.
      A=A2*A3*TM
      DENOM=A+A
      C1=A*A1/CQM
      A4=PUMPD**2*RHOW*ETA2*G*STROKE/(8.*ETA1)
      DO 430 I=1.NDATA1
       V=0.
       POWER(I)=0.
       X=A4*WELLS(I)
       B=-WELLQ(I)
       C=-C1*X
       D4=B**2-4.*A*C
       IF(D4.LT.0.)GOTO 430
       LL=I
       D4=SQRT(D4)
       IF(B.NE.0.)GOTO 400
       GOTO 430
 400   V=(-B-D4)/DENOM
       V1=(-B+D4)/DENOM
       TSR=TM-(TM*A1*X)/(CQM*V**2)
C        POWER COEFFICIENT
       CP=CPM-CPM*((TSR-TD)/TX)**2
       POWER(I)=D2*V**3*CP
       IF(V.GT.0..AND.POWER(I).GT.PM)PM=POWER(I)
       IF(V.GT.0..AND.POWER(I).GT.PM)GOTO 430
       V=V1
       TSR=TM-(TM*A1*X)/(CQM*V**2)
```

```
        CP=CPM-CPM*((TSR-TD)/TX)**2
        POWER(I)=D2*V**3*CP
C          WIND SPEED
  430 SPD(I)=V
      J=0
      DO 450 I=1,LL
  450  IF(SPD(I).LT.RATEDV)J=I
      IF(J.EQ.0.OR.J.GE.LL)GOTO 440
C        FLOW AND POWER AT RATED WIND SPEED
C        (BY LINEAR INTERPOLATION)
      VV=SPD(J+1)-SPD(J)
      IF(VV.LE.0.)GOTO 440
      SL=(WELLQ(J+1)-WELLQ(J))/VV
      QR=WELLQ(J)+SL*(RATEDV-SPD(J))
      SL=(POWER(J+1)-POWER(J))/VV
      PR=POWER(J)+SL*(RATEDV-SPD(J))
  440 WRITE(6,515)
      WRITE(6,545)
  515 FORMAT('1',//19X,'PUMPING AND POWER CHARACTERISTICS')
  545 FORMAT(//12X,'SPEED (M/S)',7X,'FLOW (M**3/S)',6X,
     +'POWER (WATTS)')
      DO 470 I=1,LL
       V=SPD(I)
       IF(V.GT.CUTIN.AND.V.LT.CUTOUT)GOTO 480
       WELLQ(I)=0.
       POWER(I)=0.
  480  IF(V.LT.RATEDV.OR.V.GT.CUTOUT)GOTO 470
       WELLQ(I)=QR
       POWER(I)=PR
  470 WRITE(6,620)SPD(I),WELLQ(I),POWER(I)
  620 FORMAT(/10X,3(E14.7,5X))
      RETURN
      END
```

```
C     *****************************************************
C
      SUBROUTINE VOLUME(WELLQ,SPD,SPEED,TIME,SHAPE,SCALE,
     +INFLOW,DISTRN,LL,NDATA3,PI,QR,PR,NT,TDISTN)
C
C       THE PRODUCT OF THE DISCHARGE AND THE TIME AT EACH
C       WIND SPEED GIVES THE VOLUME OF WATER PUMPED
C
      INTEGER DISTRN,TDISTN,TIME(20)
      REAL WELLQ(50),SPD(50),SPEED(30),SHAPE(30),
     +SCALE(30),INFLOW(36000),K
      COMMON /WML/ AREA,CUTIN,RATEDV,CUTOUT,DIAMET,GR,GE
      IF(DISTRN.EQ.3.AND.TDISTN.EQ.6)NT=360*NT
      IF(DISTRN.EQ.3.AND.TDISTN.EQ.7)NT=12*NT
      IF(DISTRN.EQ.4.AND.TDISTN.EQ.6)NT=12*NT
      IF(DISTRN.EQ.5.AND.TDISTN.EQ.6)NT=12*NT
      N=30
      IF(TDISTN.EQ.7)N=12
      IF(DISTRN-4)500,540,570
C       VOLUME COMPUTATION USING ACTUAL WIND SPEED
C       DISTRIBUTION
  500 READ(5,960)NDATA3
      READ(5,210)(SPEED(J),J=1,NDATA3)
      DO 530 I=1,NT
       READ(5,200)(TIME(J),J=1,NDATA3)
       VOL=0.
        DO 520 J=1,NDATA3
         T=FLOAT(TIME(J))*3600.
         V=SPEED(J)
         IF(V.LE.CUTIN.OR.V.GE.CUTOUT)GOTO 520
         IF(V.LT.RATEDV.OR.V.GT.CUTOUT)GOTO 420
C         VOLUME OF WATER CORRESPONDING TO RATED WIND SPEED
         VL=QR*T
         GOTO 490
  420    J2=0
          DO 510 J1=1,LL
  510     IF(SPD(J1).LT.V)J2=J1
         IF(J2.EQ.0.OR.J2.GE.LL)GOTO 520
         VV=SPD(J2+1)-SPD(J2)
         IF(VV.LE.0.)GOTO 520
         SL=(WELLQ(J2+1)-WELLQ(J2))/VV
         Q=WELLQ(J2)+SL*(V-SPD(J2))
         VL=Q*T
  490    VOL=VOL+VL
  520   CONTINUE
  530  INFLOW(I)=VOL
      GOTO 600
  210 FORMAT(20(F4.1))
  200 FORMAT(20(I3,1X))
  960 FORMAT(I2)
```

```
C       VULUME COMPUTATION USING WEIBULL DISTRIBUTION
  540 I=0
      DO 560 II=1,NT
       IF(TDISTN.EQ.6)GOTO 410
       READ(5,980)(SHAPE(J),J=1,N)
       READ(5,980)(SCALE(J),J=1,N)
       GOTO 160
  410  READ(5,460)(SHAPE(J),J=1,N)
       READ(5,460)(SCALE(J),J=1,N)
  160   DO 100 M=1,N
         K=SHAPE(M)
         C=SCALE(M)
         VOL=0.
         IF(C.LE.0..OR.K.LE.0.)GOTO 555
          DO 550 J=2,LL
           V1=SPD(J-1)
           V2=SPD(J)
           V=(V1+V2)/2.
           VV=V2-V1
           IF(V.LE.0..OR.VV.LE.0.)GOTO 550
           IF(V.LE.CUTIN.OR.V.GE.CUTOUT)GOTO 550
           SL=(WELLQ(J)-WELLQ(J-1))/VV
           Q=WELLQ(J-1)+SL*(V-V1)
C            WEIBULL PROBABILITY DENSITY FUNCTION
           P=(K/C)*(V/C)**(K-1.)*EXP(-(V/C)**K)
           IF(P.LE.1.E-10)GOTO 555
           T=P*2.592E6*VV
           IF(TDISTN.EQ.6)T=P*8.64E4*VV
           VL=Q*T
           IF(V.GE.RATEDV.AND.V.LT.CUTOUT)VL=QR*T
           VOL=VOL+VL
  550     CONTINUE
  555    I=I+1
         INFLOW(I)=VOL
  100   CONTINUE
  560 CONTINUE
      GOTO 600
  460 FORMAT(15(F4.1,1X))
  980 FORMAT(12(F5.2,1X))
C       VOLUME COMPUTATION USING RAYLEIGH DISTRIBUTION
  570 X1=PI/2.
      I=0
      DO 590 II=1,NT
       IF(TDISTN.EQ.6)READ(5,460)(SPEED(J),J=1,N)
       IF(TDISTN.EQ.7)READ(5,980)(SPEED(J),J=1,N)
        DO 585 M=1,N
         VA=SPEED(M)
         VOL=0.
         IF(VA.LE.0.)GOTO 595
         X=X1/VA**2
          DO 580 J=2,LL
           V1=SPD(J-1)
           V2=SPD(J)
           V=(V1+V2)/2.
```

```
           VV=V2-V1
           IF(V.LE.0..OR.VV.LE.0.)GOTO 580
           IF(V.LE.CUTIN.OR.V.GE.CUTOUT)GOTO 580
           SL=(WELLQ(J)-WELLQ(J-1))/VV
           Q=WELLQ(J-1)+SL*(V-V1)
C            RAYLEIGH PROBABILITY DENSITY FUNCTION
           P=X*V*EXP(-X*V**2/2.)
           IF(P.LE.1.E-10)GOTO 595
           T=P*2.592E6*VV
           IF(TDISTN.EQ.6)T=P*8.64E4*VV
           VL=Q*T
           IF(V.GE.RATEDV.AND.V.LT.CUTOUT)VL=QR*T
           VOL=VOL+VL
  580     CONTINUE
  595    I=I+1
         INFLOW(I)=VOL
  585   CONTINUE
  590 CONTINUE
  600 RETURN
      END
```

```
C     **********************************************************
C
      SUBROUTINE YIELD(INFLOW,ST,DD,RL,NT,DEMAND,AVE,QMIN,
     +BEHAVR,TDISTN)
C
C       THE STORAGE-YIELD FUNCTIONS ARE CALCULATED USING THE
C       MASS CURVE AND THE BEHAVIOUR OR SIMULATION ANALYSES
C
      INTEGER BEHAVR,TDISTN
      REAL INFLOW(36000),ST(22),DD(22),RL(5)
C
      TN=FLOAT(NT)
      WRITE(6,800)
      WRITE(6,810)
      WRITE(6,630)RL(1)
  800 FORMAT('1',//19X,'STORAGE-YIELD FUNCTION')
  810 FORMAT(//2X,'RELIABILITY (%)',6X,'STORAGE (M**3)',6X,
     +'DEMAND (M**3/DAY OR MONTH)')
  630 FORMAT(/6X,F5.1)
      DE=DEMAND
      X=.05*(AVE-QMIN)
      ST(1)=0.
C       MASS CURVE TECHNIQUE (AFTER LOUCKS ET AL. [30])
      DO 670 I=2,22
       S=0.
       SMAX=0.
       D=QMIN+X*FLOAT(I-1)
       IF(D.GT.AVE)GOTO 670
       L=I
       IF(DE.GT.(D-X).AND.DE.LT.D)D=DE
        DO 650 K=1,2
        DO 650 J=1,NT
         S=D-INFLOW(J)+S
         IF(S.LE.0.)S=0.
         IF(S.GT.SMAX)SMAX=S
  650   CONTINUE
       ST(I)=SMAX
       DD(I)=D
       IF(I.NE.2)GOTO 640
       WRITE(6,820)SMAX,D
       GOTO 670
  640  WRITE(6,660)SMAX,D
  670 CONTINUE
  820 FORMAT('+',21X,2(E14.7,9X))
  660 FORMAT(/22X,2(E14.7,9X))
      IF(BEHAVR.EQ.9)GOTO 730
C       BISECTION TECHNIQUE
      DO 710 K=2,5
       U=0.
       WRITE(6,630)RL(K)
      DO 710 J=2,L
       M=0
       D=DD(J)
       Y=ST(J)-ST(J-1)
```

```
      E=Y/2.
      C=ST(J)-E
      S=ST(J)-E
      X=ST(J)-E
C        BEHAVIOUR ANALYSIS (AFTER MCMAHON & MEIN [33])
  680 T=0.
       DO 690 I=1,NT
        S=S+INFLOW(I)-D
        IF(S.GT.C)S=C
        IF(S.GT.0.)GOTO 690
        S=0.
        T=T+1.
  690  CONTINUE
C         TIME-BASED RELIABILITY
      R=(1.-T/TN)*100.
      IF(ABS(R-RL(K)).LE.1.)GOTO 700
      E=E/2.
      IF(E.LT..9)E=1.
      IF(X.LT.1.E-6)GOTO 710
      IF(R.LT.RL(K))GOTO 740
      C=X-E
      S=X-E
      X=X-E
      GOTO 750
  740 C=X+E
      S=X+E
      X=X+E
  750 M=M+1
      IF(C.LE.U.OR.C.GE.ST(J))GOTO 710
      IF(M.GT.9999)GOTO 710
      GOTO 680
  700 IF(J.NE.2)GOTO 705
      WRITE(6,820)C,D
      GOTO 715
  705 WRITE(6,660)C,D
  715 U=C
      ST(J)=C
  710 CONTINUE
  730 RETURN
      END
```

Appendix C

DATA FILE PREPARATION

All input data and parameters are in SI units except the demand rate (m^3/day) and the time (hours) during which the wind blows at a particular wind speed range. Efficiencies are expressed in decimals.

FIRST LINE - title of project (80 characters long)
NEXT LINE - user's name (80 characters long)
NEXT LINE - date of project (80 characters long)
  FORMAT(20A4)
NEXT LINE - options values
  FORMAT(4(I2,1X))
    First value - head loss equation
        01 = Darcy-Weisbach equation
        02 = Hazen-Williams equation
    Second value - wind speed distribution
        03 = actual wind speed distribution
        04 = Weibull distribution
        05 = Rayleigh distribution
    Third value - type of distribution
        06 = daily
        07 = monthly
    Fourth value - behaviour or no behaviour analysis
        08 = behaviour analysis

09 = no behaviour analysis

NEXT LINE - number of pairs of data points for well characteristics (1 ≤ NDATA1 ≤ 50)

FORMAT(I2)

NEXT LINES - discharge and the corresponding drawdown value
- each pair of data is placed on a separate line

FORMAT(2(E9.3,1X))

First value - discharge
Second value - drawdown

NEXT LINE - pump parameters

FORMAT(2(F4.2,1X),2(F6.4,1X))

First value - mechanical efficiency
Second value - volumetric efficiency
Third value - diameter
Fourth value - stroke

NEXT LINE - # of pipes (1 ≤ NDATA2 ≤ 5)

FORMAT(I2)

NEXT LINES - pipe parameters

FORMAT(F5.1,1X,F5.3,1X,E9.3)

First value - length
Second value - diameter
Third value - absolute roughness or Hazen-Williams coefficient

NEXT LINE - windmill parameters

FORMAT(9(F5.2,1X))

First value - diameter
Second value - maximum power coefficient

Third value - cut-in wind speed
Fourth value - rated wind speed
Fifth value - cut-out wind speed
Sixth value - design TSR
Seventh value - maximum TSR
Eigth value - gear ratio
Ninth value - gear efficiency

NEXT LINE - static height and demand rate
FORMAT(2(E9.3,1X))
First value - static height
Second value - demand rate (m^3/day)

NEXT LINE - # of years (1 ≤ NYEARS ≤ 100), and the first year of wind data
FORMAT(I3,1X,I4)
First value - # of years
Second value - first year

The rest of the data lines are arranged according to the wind speed distribution. Only one distribution can be used at a time.

Actual Distribution

NEXT LINE - # of wind speed intervals (1 ≤ NDATA3 ≤ 20)
FORMAT(I2)

NEXT LINE - wind speeds (arranged in increasing order)
FORMAT(20(F4.1))

NEXT LINES - # of hours corresponding to the wind speed
FORMAT(20(I3,1X))

Daily distribution

The first 30 lines are for the first month of the first year, starting with the first day of the month. The second 30 lines are for the second month, and so on.

Monthly distribution

The first 12 lines are for the first year, starting with the first month of the year.

The second 12 lines are for the second year, and so on.

Weibull Distribution

NEXT LINES - Shape and Scale values

Daily distribution

`FORMAT(15(F4.1,1X))`

The first two lines contain 30 daily values (15 on each line) of the shape factors for the first month of the first year, starting with the first day of the month.

The next two lines contain 30 daily values (15 on each line) of the scale factors for the first month of the first year, starting with the first day of the month, and so on.

monthly distribution

`FORMAT(12(F5.2,1X))`

The first line contains 12 monthly values of the shape factors for the first year, starting with the first month of the year.

The next line contains 12 monthly values of the scale factors for the first year, and so on.

Rayleigh Distribution

NEXT LINES - Average wind speeds

Daily distribution

FORMAT(15(F4.1,1X))

The first two lines contain 30 daily values (15 on each line) of the average wind speeds for the first month of the first year, starting with the first day of the month.

The next two lines contain 30 daily values for the next month, and so on.

monthly distribution

FORMAT(12(F5.2,1X))

The first line contains 12 monthly values of the average wind speeds for the first year, starting with the first month of the year.

The next line contains 12 monthly values of the average wind speeds for the second year, and so on.

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