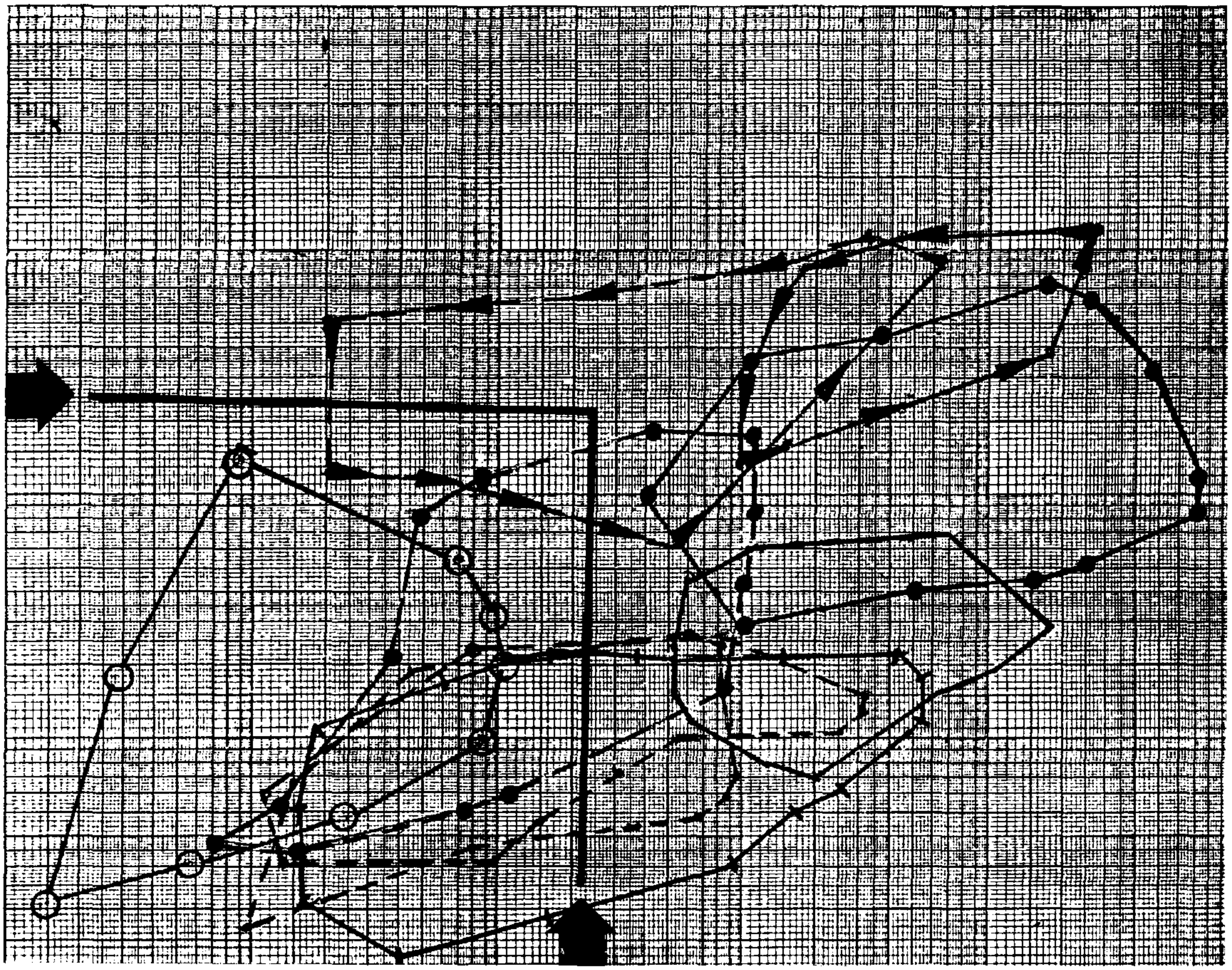
Monograph

A NEW METHODOLOGY FOR SELECTION OF HYDRAULIC TURBINES

By

C.S. Kojo Kpordze



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PREFACE

"A New Methodology for Selection of Hydraulic Turbines" was prepared from the results of dissertation research completed by the author in 1986 at the University of Idaho, at Moscow, Idaho, U.S.A.

This monograph utilizing information from the earlier study, presents an overview of the key steps in planning and feasibility studies for hydropower projects and emphasizes a new methodology using experience curves for selection of hydraulic turbines. Information is provided for selection of conventional, low-head and small-scale versions of the conventional turbines. These turbine types are the most commonly selected units for installation in hydropower developments all over the world. An example problem is presented to demonstrate the use of the methodology and experience curves.

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CHAPTER 1

INTRODUCTION

1. General

Hydroelectric power generation furnishes only a small percentage of the energy demands in most developed countries (about 4% of the total energy supplied in the United States) (Warnick, 1984). However, hydropower still is a very attractive source of energy because it is one of the oldest, most reliable, flexible and the leading renewable source of energy in the world with energy conversion efficiency of 80 to 90 percent. Hydropower units can be placed on-line rapidly and can respond quickly to changes in loading. Hydropower therefore is normally used for meeting all kinds of electrical load types, namely, for peaking, intermediate load and baseload operation. However, in the absence of adverse environmental and economic impacts the best and the most effective use of hydropower is for peaking operations (Kpordze, 1986) (U.S. Army Corps, 1985). Hydropower planning, design and development has attracted a lot of interest, study and discussion over the past three decades because of the above mentioned advantages of hydropower compared with other sources of energy.

Fundamental to a successful planning and feasibility study for a hydropower project is the full realization that a water resource is limited in quantity and its development has an environmental and a social impact. Therefore, proper development of a water resource must comply with environmental and social constraints as well as physical, engineering and economic requirements. The constraints must be given due consideration in all the steps of planning and feasibility studies based on the relative importance of each constraint to the site under consideration. The primary objectives in planning and feasibility studies for hydropower projects are to answer three basic questions as stated below:

(a) How much power is needed and what is the schedule for delivering the power? (Load study and scheduling of additional power)

(b) How much power can economically be developed at a proposed site? (Energy studies - power potential and capacity determination)

(c) How can the power produced be used to satisfy a local power demand or marketability plan? (Marketability plan).

A good reference which discussed the above questions is "Engineering and Design Hydropower", (U.S. Army Corps, 1985). The three questions are interdependent in the sense that the results of the solution to the first question become the input data for the second question and the results of the second study are necessary to evaluate marketability. This interdependence is shown in a flow-chart in Figure 1.1 which is a way of organizing hydropower planning studies.

A number of investigations and decisions have to be made to answer the three "HOW" questions for hydropower development. Possible required investigations to answer each question are listed below:

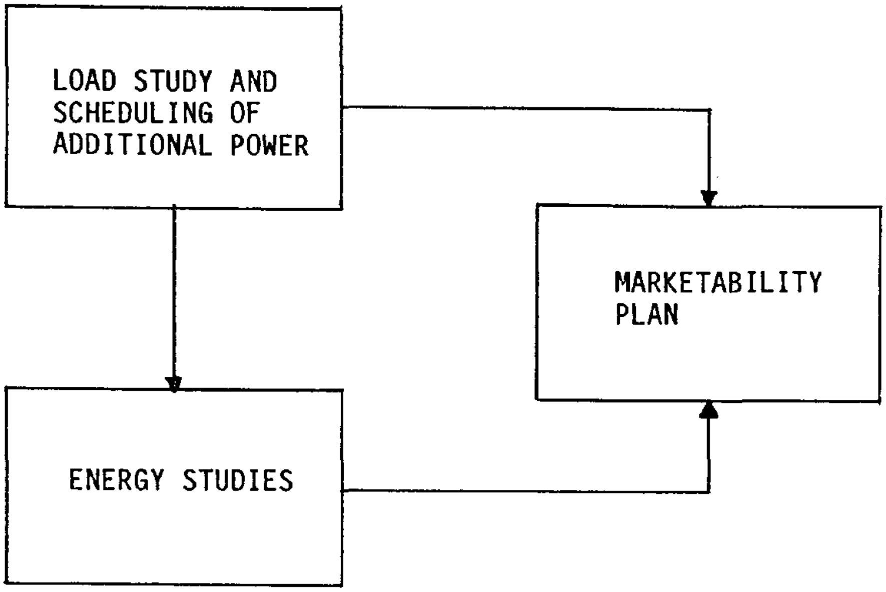

Figure 1.1 Hydropower planning flow chart.

2. Load Study and Scheduling of Additional Power
   - (a) Analyses of existing load and load pattern.
   - (b) Forecast of future load and load pattern.
   - (c) Study of present power resources.
   - (d) Forecast of future power resources.
   - (e) Identification of type and amount of load deficit and scheduling of additional power.
3. Energy Studies - (power potential and capacity determination)
   - (a) Determination of the magnitude and seasonal variation of the flow and head available at the site for power generation.
   - (b) Study of the physical limitations at the site.

(c) Development of reservoir characteristics and related data for the site.

(d) Investigation of possible power plant arrangements and energy potential at the site.

(e) Environmental and operational studies to establish permissible ranges of project discharges and factors which may limit operation for power.

(f) Selection of the type of project(s) which should be considered for the site.

(g) Capacity or scoping studies.

(h) Selection of generating equipment.

(i) Detailed estimation of expected energy output.

(j) Economic analysis.

4. Marketability Plan

Marketability study is based on the data from items 3-i and 3-j, detailed estimation of expected energy output and economic analysis.

For a detailed discussion on the above types of study, reference should be made to the references (U.S. Army Corps, 1985), (Warnick, 1984).

5. Turbine Selection

The major equipment item in a hydropower plant is the turbine-generator system. The remainder of the plant equipment is to control, protect, and provide services to the main generating unit (Tudor, 1980). Turbine selection, the main topic of this monograph, comes under item 3-h which deals with selection of generating equipment. The turbine selection process is a key factor in energy studies, hydropower planning and feasibility studies. Turbine selection is normally explained in terms of concepts and terminology used in the hydropower industry. Hydropower concepts and terminology essential to understanding the turbine selection process are defined in the Appendix A1.

The type of power generating equipment selected for a particular hydropower project depends on specific kinds of data and information available for the site. The required data for hydropower planning and feasibility studies are discussed in Chapter Two.

CHAPTER 2

DATA AND INFORMATION REQUIREMENTS

1. Introduction

In order to conduct hydropower planning investigations, some specific types of data and information are required. The three types of data required for hydropower feasibility studies are: load-resource data, project site data, and environmental and operational requirements. The collection of the three types of data are usually coordinated because of their interdependence. Furthermore, data collection also is coordinated with the type of project and the methods used for analyzing the data. The data requirements and analyses are discussed in the succeeding sections.

2. Load-resource Study

The purposes of load-resource studies are to identify the need for power, schedule for additional power and to determine the different ways in which power from the proposed plant could be used in the local power system.

The required steps for load-resource study as stated by the U.S. Army Corps of Engineers (1985), are:

(a) Collection and analysis of load data on existing power systems in terms of daily, weekly and seasonal load shapes and forecasting future load growth patterns. (Use either trend analysis, end-use analysis or econometric methods).

(b) Collection of data for and study of existing and planned power resources. Comparison of resources with current load and forecasted future load patterns to determine power deficits and the type, amount and the timing of additional power.

(c) Identification of the different ways in which the proposed plant could be used in the local power system.

3. Project Site Data and Information

Hydropower site data and information are required to estimate the optimum power potential of the site and plan for the ultimate development of the full economic potential of the proposed site.

The basic data required are topographic, hydrologic and hydraulic data.

(a) Topographic data

Topographic maps of adequate scale are necessary for estimating the gross head on the turbine and selecting the best plant layout. Topographic maps also are used for planning penstock routes, diversion structure location, reservoir surface area and for preparing reservoir capacity curves which are used in selection of the required reservoir volume (Tudor, 1980).

(b) Hydrologic data

The fundamental assumption for collection and use of hydrologic data in hydropower studies is that future streamflows and channel characteristics can be predicted from a set of historic streamflow record and information on channel characteristics. In order to undertake hydrologic studies, available mean daily and monthly streamflow records must be acquired. Necessary adjustments and extensions to the records may be performed to obtain long-term streamflow records which would represent the flows available for power generation. Generally, a set of thirty to fifty years of historical streamflow data is considered to be the minimum necessary to assure statistical reliability. It also is important that the length of record span periods of extreme events, that is, past floods and droughts (Tudor, 1980).

At some hydropower sites, streamflow records do not exist or are inadequate. In such cases extrapolations, correlations with nearby stream gaging or precipitation stations and basin rainfall-runoff models or stochastic streamflow generation procedures should be used to generate flow data for use in hydropower studies. The method that should be used for synthesis of flow data depends on the size and type of project and the plant design load.

The adopted average monthly streamflow records are used to study reservoir volume characteristics, if any, potential power output and to determine additional reservoir capacity requirements. Peak streamflow data are used to develop flood volume and frequency curves for planning and design of spillways and outlet releases.

4. Environmental and Operational Studies

The usual environmental and operational data requirements include any existing physical, geological, topographical data, archaeological investigations of the area, minimum streamflow requirements, migratory fish and wildlife resources of the project area and current water rights status which could affect hydropower development. The data are analyzed to determine the need for additional geologic exploration and topographic site conditions which could affect the project construction and operation. The effect the project would have on fish and wildlife resources of the area also is investigated. An assessment is made to determine which factors and constraints could limit power production. Environmental, physical, non-power and operational constraints are analyzed to establish permissible ranges of project discharges produceable by power operations. A plan is developed to resolve all problem areas without unnecessarily limiting the site's power potential. During the economic analysis phase of the project, an annual cost is estimated for the measures taken to comply with environmental constraints and to change physical constraints which adversely affect project construction and operation. A good reference to the environmental studies that need to be done is the publication "Engineering and Design Hydropower", Engineering Manual EM 1110-2-1701, by the United States Army Corps of Engineers (1985). The data collected are analyzed and used for the energy studies phase of hydropower planning which is discussed in the next chapter.

CHAPTER 3
ENERGY STUDIES

1. Introduction

Energy studies consist of two types of analyses which are normally done concurrently, namely, energy potential studies and capacity or scoping studies. The two types of analyses are discussed below.

2. Energy Potential Studies

The energy potential of a hydropower site is estimated in two steps. The first step consists of using environmental, physical and non-power operating constraints to establish permissible ranges of project discharges and the corresponding net hydraulic heads resulting from power operations. In the second step, the water power equation and either the flow-duration curve method or sequential streamflow routing method are used to estimate the power output over a specified period of time. The flow-duration curve method is used only for run-of-river types of development while the sequential streamflow routing method is used for all other types of development. An average overall efficiency, for example, 85 per cent, expected over the operating range is used in the water power equation to calculate energy output. The water power equation and the flow-duration curve and the sequential streamflow routing methods are discussed in Appendix A1. The energy potential studies are followed by capacity studies.

3. Capacity Studies

Capacity studies for a proposed hydropower development consist of reservoir potential evaluation for the site, power plant capacity selection and selection of generating equipment with suitable capacity to match the capacity of the site. The three components of capacity studies are discussed below.

(a) Reservoir potential evaluation

Maximum reservoir volume selection is based on reservoir management and optimization studies. The factors which are considered during potential reservoir volume evaluation for a hydropower project include topographic and geologic data, streamflow magnitude and its seasonal variation, local power system requirements and marketability considerations, environmental factors, physical and non-power operating constraints. The studies involve using average monthly or annual flow data and physical considerations of the site to determine the maximum reservoir volume for the site. Economic considerations are utilized to identify the optimum reservoir volume. The reservoir volume available for power generation is specified and reservoir operation rule curves are then developed to comply with the environmental and site constraints. Reservoir potential studies are followed by the selection of power plant installed capacity.

(b) Plant installed capacity selection.

Power plant installed capacity establishes an upper limit on the amount of energy that can be generated during a period. The maximum power that a hydropower plant is designed to deliver is selected on the basis of environmental, physical and non-power operating constraints and the operating characteristics of the generating equipment. The major equipment item in a hydro plant is the turbine-generator system. Therefore, the installed capacity selection for a hydro plant is usually coordinated with the maximum capacity selection of the turbine-generator system.

Installed capacity and turbine-generator capacity selection for a hydro plant is an iterative process. Normally the capacity selection process is initiated by using experience curves and tables to get general information on appropriate plant capacity, turbine type and expected operating ranges for the turbine-generator system. The initial values obtained from tables and experience curves provide input data for more detailed studies and economic analysis of the plant to identify the proper plant capacity and configuration and the best turbine-generator type, number of units, sizes and operating characteristics.

The procedure for selecting the proper hydropower plant installed capacity for a given project configuration may be divided into three steps which are discussed below.

Step 1

In the first step, the hydrologic data and site information are combined with environmental and operating constraints to develop operational rule curves and operating limits. The permissible type of development is selected based on the rule curves and operating constraints. The load-resources data are correlated with type of development, project site data and operational rule curves to identify the different ways in which the plant's power output could be effectively used in the local power system to satisfy present and future loads.

Step 2

The objectives of the second step in the selection of plant capacity are to identify the proper installed capacities suitable for meeting the local load, select the most economical generating equipments and specify the operating characteristics which will limit the computation of the power output to that which can actually be produced by the selected installation.

The second step consists of a number of procedures which are listed below. Each of the procedures may need to be iteratively executed until the desired values are obtained.

(i) Select, in a systematic manner, a range of plant sizes which satisfy the project constraints and local power system requirements.

For new projects it may be necessary to consider as variables alternative project configurations such as dam heights, reservoir capacities, project layouts and operating plans. For each project configuration, a range of plant sizes should be considered. Thus, the number of variables and computations increase very rapidly. Therefore, a systematic approach is normally used to screen out only the range of alternatives which have the greatest energy potential. A frequently used procedure is to assume a common plant sizing parameter for evaluating all the project configurations. The selected parameter should be one which results in optimum energy production at the site. The parameters normally used in the case of storage and run-of-river projects are a typical plant factor and a specified point on the flow-duration curve respectively (U.S. Army Corps, 1985).

(ii) Estimate the installed capacity for each plant size selected, by substituting into the water power equation the permissible hydraulic capacity of the plant and the corresponding net head and an assumed overall efficiency. It should be noted that for storage and pondage type projects, the sequential streamflow routing method will be used. The flow-duration curve method will be employed for run-of-river projects.

(iii) Use experience curves and tables to select turbine type, number, sizes and turbine characteristics to match the plant sizes selected in (ii). The turbine characteristics normally specified are turbine runner diameter, speed and operating characteristics. The required operating characteristics are maximum and minimum single unit turbine discharge and corresponding heads and average overall efficiency for the turbine operating range.

(iv) Estimate the average annual energy output for all the selected plant sizes with the operating constraints fully imposed. If the operating ranges of turbine types being considered overlap, energy estimates should be made for all types of turbines that could be used in the given head and flow ranges.

(v) Repeat the procedures (i) through (iv) as many times as necessary to identify three or more turbine units whose characteristics and operating ranges are such that they produce the largest amounts of annual energy.

(vi) Select a generator with suitable rated capacity to match the rated power output of each of the turbines selected. The generators must be rated at a specified power factor (usually 0.95 for large synchronous generators, rated power greater than 5 MW), (U.S. Army Corps, 1985).

(vii) Recompute average annual energy output of the plant and impose the limits of the generator capacity, turbine characteristics and the project operating constraints. If power output of any alternative does not meet the magnitude and variation of the design load, that alternative is removed from further consideration.

(viii) Estimate the dependable capacity for each alternative selected in (vii).

Step 3

The objective in the third stage of plant sizing is to apply net benefit analysis to the alternatives selected in Step 2 in order to identify the best plant size and power generating equipment whose operating characteristics match those of the plant. The procedure consists of computing capacity and energy benefits for each alternative and net benefit analysis is used to rank the alternatives. The best plant size is selected on the basis of the plant size which produces the highest net benefits. Once the best plant capacity has been identified, detailed studies of plant layout and generating equipment is conducted. A good reference to installed capactiy and hydropower generating equipment selection is the publication "Engineering and Design Hydropower" by the United States Army Corps of Engineers (1985).

CHAPTER 4

TURBINE SELECTION

1. Introduction

Turbine selection involves matching of turbine operating characteristics with hydropower site parameters such that optimum power is produced. In order to discuss turbine selection meaningfully, it will be helpful to first define hydropower site parameters and turbine characteristics and relationships involved in turbine selection. The salient site parameters and turbine characteristics are defined below.

Theoretically, the output energy, E, of a hydroelectric power plant can be expressed in a functional form as follows:

$$E = F(Q, H_g, TW, D, N, H_s, P_{max}) \qquad (4.1)$$

where

E = the energy generation in kilowatt-hours, (KWH)

H_g = gross head, (m)

Q = plant discharge, (m^3/sec)

TW = tailwater elevation, (m), or constraints at the turbine outlet

D = diameter of runner, (m)

N = generator speed, (rpm)

H_s = turbine setting elevation above or below tailwater, (m)

P_{max} = maximum output expected or desired at plant, (KW).

The first three parameters in Equation (4.1) relate to the project site and the rest are turbine characteristics. The project site parameters are time dependent while the turbine characteristics are basically deterministic although they vary with changes in head and flow. Thus there are seven parameters that can be varied to obtain the maximum annual energy.

Proper turbine selection for a hydropower development includes the matching of turbine characteristics with the three hydropower site parameters mentioned above. That is, properly sized equipment and operational characteristics should be selected for the power plant so that with the seasonally varying flows and the corresponding changes in net head, tailwater level and turbine characteristics, the optimal energy will be produced annually over the life of the project (Kpordze, 1986). Turbine characteristics which influence turbine selection are discussed below.

2. Turbine Characteristics

There are a number of characteristics which have effects on the ability of hydraulic turbines to produce power. The governing characteristics are operating head, flow, efficiency, runner size and runner speed. A variety of types of hydraulic turbines are available, each type of turbine is designed to operate within specified head and flow ranges. The limitations imposed by these characteristics establish the ranges of efficient operation of the turbine. Operation of the turbine beyond the specified head and flow ranges may lead to loss of efficiency, rough operation, occurrence of cavitation, power surges and vibration. The normal head, flow and power ranges of application of the conventional turbines, low-head units and small-scale versions of the conventional turbines are shown in Figure 4.1 and Tables 4-1 through 4-4.

Other factors which influence the hydropower plant's energy production are the installed capacity and number of turbines. These factors are discussed in the next section.

3. Capacity and Number of Units

In order to operate a power system efficiently, each power plant in

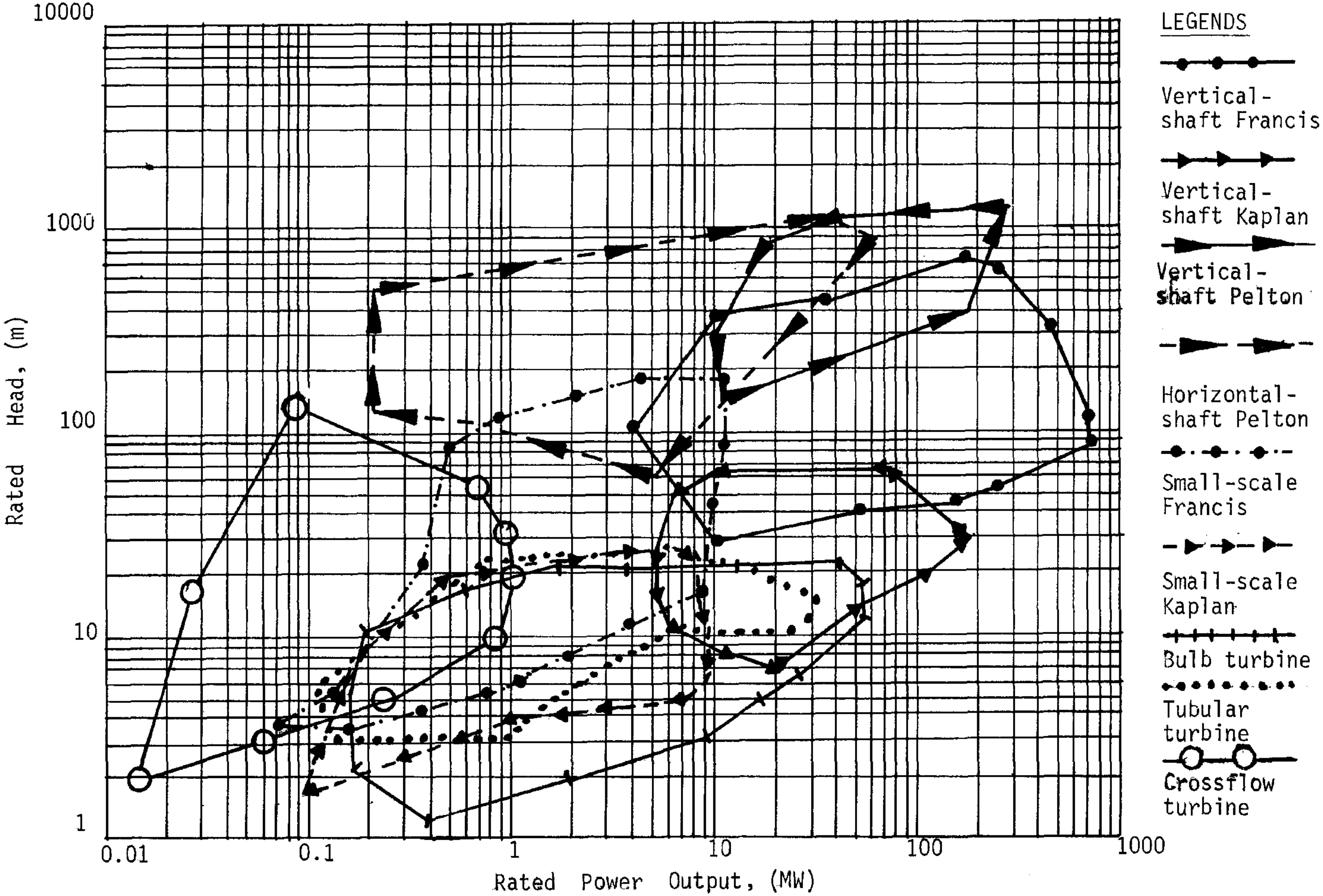

Figure 4.1 Head and power ranges for hydraulic turbines

Table 4-1 Discharge and head ranges for different types of turbines

Turbine Type	Ratio of Minimum Discharge to Rated Discharge	Ratio of Minimum Load to Design Load	Ratio of Minimum Head to Maximum Head
Francis	0.40	0.24	0.50
Vertical shaft Kaplan	0.40	0.20	0.40
Pelton (adjustable nozzles)	0.20	0.20**	0.80

*Table was taken from (U.S. Army Corps, 1985), (Kpordze, 1986)
**Information based on minimum efficiency of 80%

Table 4-2 Ranges of use of hydraulic turbines**

Type of Turbine	Head range (m)	Flow range (m^3/sec.)	Power range (MW)
Vertical-shaft Francis	30 - 734	8 - 781	4 - 740
Vertical-shaft Kaplan	6.6 - 72	34.5 - 618	5.2 - 180
Vertical-shaft Pelton	136 - 1230	2.5 - 52	10.2 - 269
Horizontal-shaft Pelton	62 - 1150	0.1 - 27	0.20 - 64.0
Small-scale Francis	4 - 186	0.8 - 25	0.07 - 11.4
Small-scale Kaplan	2 - 27	2.7 - 170	0.10 - 9.9
Bulb turbine	1.3 - 23	2.5 - 530	0.15 - 55
Tubular turbine	3 - 27	6.0 - 290	0.14 - 31.5
Cross-flow turbine	2 - 147	0.1 - 12	0.01 - 1.1

*Table was taken from (Kpordze, 1986)
**The ranges of use are based on the data collected for this study

Table 4-3 Speed and size ranges of use of hydraulic turbines***

Type of Turbine	Turbine Speed (rpm)	Runner Size (m)	Specific Speed Range
Vertical-shaft Francis	33.3 - 1500	1.08 - 9.56	66 - 302
Vertical-shaft Kaplan	65.5 - 514.3	2.25 - 9.50	283 - 943
Vertical-shaft Pelton	200 - 750	1.10 - 3.63	23** - 56**
Horizontal-shaft Pelton	120 - 1200	1.03 - 2.32	9** - 41**
Small-Scale Francis	139 - 1440	0.45 - 1.96	73 - 332
Small-scale Kaplan	68.2 - 765	0.71 - 5.60	415 - 849
Bulb turbine	62.5 - 800	0.63 - 7.70	142 - 1155
Tubular turbine	60 - 765	0.75 - 13.0	402 - 804
Cross-flow turbine	83 - 1200	0.2 - 1.25	21 - 255

*Table was taken from (Kpordze, 1986)
**Total specific speed of turbine
***The ranges of use are based on the data collected for (Kpordze, 1986)

Table 4-4 Efficiency range for hydraulic turbines**

Type of Turbine	Minimum Efficiency in (%)	Mean Efficiency	Maximum Efficiency in (%)	Standard Deviation (s) in %
Vertical-shaft Francis	77	92	98	3
Vertical-shaft Kaplan	83	92	98	2
Vertial-shaft Pelton	87	89	91	1
Horizontal-shaft Pelton	77	87	92	3
Small-scale Francis	78	85	90	3
Small-scale Kaplan	82	87	93	3
Bulb	72	89	97	5
Tubular	75	89	93	3
Cross flow	55	81	83	5

*Table was taken from (Kpordze, 1986)
**The ranges of use are based on the data collected for (Kpordze, 1986)

the system must be designed and operated efficiently. Multiple units may be required in a hydro plant in order to meet large variations in load and flow. Multiple unit plants can be operated in a high-efficiency range by varying number of units in service or by sharing the load distribution among plants in the system. Normally, for a given plant size, it is most cost effective to select the number of units of the largest practical size that give the minimum first cost. However, selection of the best capacity and number of units for a hydropower plant often require consideration of many other factors. The general factors, suggested by U.S. Army Corps of Engineers (1985), that should be considered when selecting the capacity and number of units for a given power installation are listed below.

(a) maximum unit size minimizes capital costs and (except for very large units) operation and maintenance costs;

(b) an installation consisting of units of equal size is less costly than a mix of unit sizes, in terms of both capital costs and maintenance costs;

(c) a mix of unit sizes may be useful where a wide range of streamflow is experienced;

(d) a minimum of two units may be desirable so that generation can be maintained (and energy loss minimized) when one unit is out of service;

(e) the proper number and size of units should be selected to insure that the plant will operate at as high an efficiency point as much of the time as possible;

(f) the largest turbine component that can be transported to the site using available modes sometimes establishes maximum unit size;

(g) cavitation considerations establish the minimum discharge at which a given turbine can operate (see Table 4-1). If a single unit is installed, considerable energy may be spilled under low flow conditions;

(h) the amount of space available for the power plant may influence selection of size and number of units. This is particularly a problem when retrofitting existing dam structures;

(i) where a wide range of head exists, separate units (to operate under different head ranges) may be desirable. An alternative would be to use interchangeable turbine runners for different head ranges;

(j) poor foundation conditions may limit excavation depth, resulting in a larger number of smaller units;

(k) an even number of units sometimes permits more economical bus and auxiliary systems arrangements;

(l) in small power systems, large units may increase system forced outage requirements.

Some of these constraints are intended to minimize costs, and others are intended to maximize energy output or dependable capacity. Often it may be necessary to examine several combinations of numbers and sizes of units in order to determine the best choice for a given plant size (U.S. Army Corps, 1985). Additional factors usually considered when selecting unit size and speed are discussed below.

4. Unit Size and Speed Selection

The two turbine characteristics which need to be estimated during planning and feasibility studies are turbine runner size and speed. The two characteristics are inversely related; therefore, selection of a value for one of them establishes the value of the other characteristic.

Selection of these two characteristics are discussed below.

(a) Turbine runner speed selection

In hydropower planning, experience curves and rules of thumb are used to estimate runner speed. The rotational speed of the runner must be synchronous speed if the turbine is to be directly connected to the generator. A synchronous speed is one which obeys the relationships given below:

$$\text{Rotational speed, } N = \frac{120\ f}{Np} \tag{4.2}$$

where

N = rotational speed, (rpm)

f = electrical current frequency, hertz, (Hz)

Np = number of generator poles.

$$N = \frac{7200}{Np} \text{ (rpm) at 60 Hz}$$

$$N = \frac{6000}{Np} \text{ (rpm) at 50 Hz.}$$

A universal parameter normally used for rating hydraulic turbines is the specific speed, N_S. The specific speed which is defined as the speed of a unit producing unit output under a head of unity is expressed as,

$$N_s = \frac{NP^{0.5}}{H^{1.25}} \tag{4.3}$$

where

N_S = specific speed (units of rpm, KW, m)

N = rotational speed of turbine, (rpm)

P = rated power output, (KW)

H = net head, (m)

The rules of thumb and factors considered during the selection of the runner speed are listed below.

(i) Generally the highest speed practicable should be selected. The maximum speed is limited by the following factors: mechanical design, occurrence of cavitation, vibration, drop in peak efficiency or loss of overall efficiency.

(ii) Greater runner speed for reaction turbines requires the turbine to be placed lower with respect to the tailwater. The lower setting of the turbine generally increases the power output and excavation and construction costs. Thus the best speed is the one which yields the maximum net benefits when additional excavation and construction costs and power output resulting from lowering the turbine setting are considered.

(iii) Greater turbine speed decreases the head range under which the turbine will operate satisfactorily.

(iv) Low specific speeds are associated with high heads and high specific speeds are associated with low heads.

(v) If experience curves are used to estimate the runner speed, the synchronous speed nearest to the estimated speed is chosen subject to the following considerations.

A multiple of four poles is preferred, but standard generators are available in some multiples of two poles.

If the net head varies by less than ten percent, it is customary to choose the next greater synchronous speed. If the net head varies more than ten percent, the next lower synchronous speed should be selected to ensure that the operating head and efficiency ranges of the turbine are not exceeded.

A new methodology for selection of turbine speed and diameter is presented in the next chapter.

CHAPTER 5

A NEW METHODOLOGY FOR TURBINE SELECTION

1. Introduction

The purpose of this monograph is to provide a set of experience curves and a methodology which will guide hydropower planners, designers and developers logically and consistently through all phases of turbine selection during planning and feasibility studies for hydropower developments. In order to get a representative set of experience curves, data were collected from major turbine manufacturers all over the world.

2. Turbine Data Collection and Analyses

The data used in developing the experience curves and turbine selection procedure presented in this monograph were collected on non-proprietary turbine characteristics of rated head, discharge, rated power output, design speed and diameter of the runner. Information on about 400 conventional turbines (Francis, Kaplan and Pelton), 300 low-head turbines (bulb, tubular and cross-flow) and 170 small-scale versions of the conventional turbines manufactured and placed in service between 1965 and 1984 were supplied by the major hydraulic turbine manufacturers throughout the world.

An extensive investigation of the data was carried out to establish relationships between turbine characteristics and hydropower site parameters on the basis of hydropower theory. Regression analysis was used to develop empirical equations and experience curves for selection of turbine runner speed and size when rated head, rated discharge and rated power output are known. The merits of using experience curves in turbine selection are discussed below.

3. Experience Curves and their Uses

In planning and feasibility studies of hydroelectric projects, the normal practice is to base the estimates of hydropower equipment sizes and costs on previous experience, hydraulic characteristics of turbines and hydropower site parameters. The procedures for using this experience are presented through the use of experience curves. Experience curves are graphical plots of relationships between particular characteristics of turbine units which have been manufactured and placed in service and their corresponding hydropower site parameters. Experience curves permit a logical, consistent and rapid selection of the proper units, estimation of their major dimensions, costs and prediction of their performance characteristics. Experience curves provide visual comparison of the characteristics of selected units with the units in existing installations and the units proposed by turbine manufacturers for final design selection. Experience curves form the basis of a new methodology for turbine selection which is described below.

4. A New Methodology for Turbine Selection

For the purposes of preliminary sizing of the hydropower plant and as a basis for cost estimation, it is customary at feasibility-level studies to provide data on turbine speed and diameter. In his study of low-head turbines for the U.S. Bureau of Reclamation (Kpordze and Warnick, 1983) and study of the conventional turbines for his doctoral dissertation (Kpordze, 1986), the author developed direct relationships between runner speed and diameter and hydropower site parameters.

The regression equations and experience curves presented in this monograph were prepared from the author's research results. The regression models were derived from the basic unit constant terms normally used in hydropower theory. The unit constant terms are presented here for easy reference.

$$\text{Unit Speed} \qquad N_{11} = \frac{ND}{H^{0.5}} \tag{5.1}$$

$$\text{Unit Discharge} \qquad Q_{11} = \frac{Q}{D^2 \; H^{0.5}} \tag{5.2}$$

$$\text{Unit Power} \qquad P_{11} = \frac{P}{D^2 \; H^{1.5}} \tag{5.3}$$

Note the symbols have the same meanings as previously defined in Equations 4.1 and 4.3

The above unit constant terms were employed in the specification of the linear regression models for the regression analyses. By rearranging the expression for unit power, the turbine runner diameter, D, can be expressed as a function of the ratio of rated power output over rated head of the turbine, (P/H). Similarly by rearranging the unit speed equation, the rated runner speed can be expressed in terms of the ratio of the square root of turbine rated head to runner diameter, ($H^{0.5}$/D). The above two relations form the basis of the new methodology for turbine speed and size selection. The log-linear functional form specifications of the above relations are shown below.

$$D = a_1 (P/H)^{n_1} \tag{5.4}$$

$$N = a_2 \left(\frac{H^{0.5}}{D}\right)^{n_2} \tag{5.5}$$

where a_1, a_2, n_1 and n_2 are constants.

Regression analyses were used to estimate the parameters of the regression model. The resulting regression equations and experience curves for selection of conventional turbines, low-head units and the small-scale versions of the conventional turbines are shown in Tables 5-1 through 5-9 and Figures 5.1 through 5.9 at the end of this chapter. The experience curves shown in Figures 5.1 through 5.9 were developed by using the water power equation, Equation A.1, mean turbine efficiency, e, from Table 4-4, and regression equations of the models shown in Equations 5.4 and 5.5. In order to make preliminary estimates of turbine runner diameter and rated speed, either the regression relations or the experience curves and Tables 4-2 through 4-4 may be used. An example problem is presented below to illustrate the selection of turbine runner diameter and rated speed.

5. Example Problem

For a given hydropower site, the following parameters are known.

Rated head, $H = 76.2$ m

Rated flow, $Q = 282$ m^3/sec.

(a) Using the given rated head of 76.2 m and discharge of 282 m^3/sec, in Figure 4.1 and Table 4-2, turbine type can be determined. In this case, the head of 76.2 meters with discharge of 282 m^3/sec is out of range of both Kaplan and Pelton turbines. The only turbine type which can be used is Francis. Therefore, the analysis has been done only for a Francis turbine. However, if the head and flow ranges are such that more than one type of turbine could be adopted, then the analysis should be done for all the applicable turbine types. In such a case economic analysis will be the basis for selecting the best turbine type. The following steps will be followed in the rest of the analysis.

(b) Select an average efficiency for all the turbine types adoptable for the given head and flow ranges from Table 4-4 and compute rated power output using the water power equation, Equation A.1. Average efficiency, e, for the Francis turbine is 92%, from Table 4-4.

Power, $P = \rho gHQe = (9.806)(76.2)(282)(0.92) = 193{,}858$ KW

(c) Use regression relation from Table 5-1 to estimate runner diameter.

$$D = 0.168\ (P/H)^{0.447} = 0.168(193{,}858/76.2)^{0.447}$$
$$= \underline{5.60\ \mathrm{m}}$$

(d) Compute a trial turbine speed, N^1, using the appropriate relation from Table 5-1.

$$N^1 = 80.387\ (H^{0.5}/D)^{0.828}$$
$$= 80.387\ ((76.2)^{0.5}/5.6)^{0.828} = \underline{116.10\ \mathrm{rpm}}$$

(e) Compute synchronous speed. For the speed to meet generator requirement of synchronous speed, Equation 4.2 must apply.

$$N = \frac{120\ f}{Np}$$

where

N = turbine rotational speed, (rpm)

Np = number of generator poles.
Np must be an even multiple of two or preferably four poles for large machines. For 60 Hertz frequency, avoid the selection of 54 or 108 poles (USBR, 1976).

f = electrical frequency = 60 Hertz for USA and 50 Hertz for some other countries of the world.

In the case of 60 Hertz frequency plants,

$Np = (120)(60)/N^1 = (120)(60)/(116.10) = 62$ poles.

There are two possible choices for Np to be an even multiple of four poles; Np equals either 60 or 64. A choice of a 60 pole-generator results in a higher speed runner than a choice of a 64 pole-generator. It is customary to choose the greater synchronous speed if the net head varies by less than ten percent and to choose the lower synchronous speed if the opposite occurs (USBR, 1976). This rule of thumb is used to ensure that the operating head and efficiency ranges of the turbine are not exceeded. The greater speed is selected for this example.

Synchronous speed, N = 7200/60 = <u>120 rpm</u>.

(f) Recompute runner diameter using step (d),

$$N = 80.387\,(H^{0.5}/D)^{0.828}$$

$$D = H^{0.5}/(N/80.387)^{1/0.828}$$

$$= (76.2)^{0.5}/(120/80.387)^{1/0.828} = 5.38 \text{ m}$$

(g) Summary of turbine characteristics

Power, P = 193,858 KW

Diameter, D = 5.38 m

Speed, N = 120 rpm

In order to demonstrate the use of Figures 5.1 through 5.9, Figure 5.1, which is the experience curve for selection of Francis turbines, was used to select a suitable turbine unit for the hydropower site given in Example 1. The intersection of the dashed lines drawn through 76.2 m and 282 m^3/sec on Figure 5.1 show the point corresponding to the characteristics of the turbine unit which best match the given hydropower site parameters. The desired characteristics are:

Power, P = 192 MW

Diameter, D = 5.63 m

Speed, N = 116.7 rpm.

For the turbine speed to match generator requirements, the selected turbine speed should be synchronous speed. Therefore the synchronous speed of 120 rpm which is the closest to the point of interest on Figure 5.1 should be adopted. The recommended turbine characteristics are summarized below.

Summary of turbine characteristics estimated from Figure 5.1

Power, P = 192 MW
Diameter, D = 5.63 m
Speed, N = 120 rpm.

For purposes of feasibility studies, the characteristics of the turbine selected using Figure 5.1 are close to those of the unit selected using the regression equations. It should be noted that although the turbine unit used in Example 1 to demonstrate the new turbine selection procedure was a large unit, the procedure is the same for smaller units.

Experience curves represent a balance of all the conditions and constraints normally found at most hydropower sites. Therefore, the selection of speed and size of hydraulic turbines using the experience curves and regression equations presented in this monograph represent the best estimates made for average conditions found at most hydropower sites.

TABLE 5-1

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for Francis turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.168\ (P/H)^{0.447}$	0.968	0.051	1965-1984	96
D	$D = 4.332\ (Q/N)^{0.291}$	0.960	0.054	1965-1984	96
D	$D = 1.556\ (H^{0.5}/Q)^{-0.368}$	0.925	0.070	1965-1984	96
N	$N = 80.387\ (H^{0.5}/D)^{0.828}$	0.964	0.055	1965-1984	100
N	$N = 89.461\ (H^{3/2}/Q)^{0.319}$	0.946	0.066	1965-1984	110
(P/H)	$(P/H) = 1444.782\ (Q/N)^{0.653}$	0.992	0.047	1965-1984	110

TABLE 5-2

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for Kaplan turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.175\ (P/H)^{0.452}$	0.978	0.019	1965-1984	46
D	$D = 4.552\ (Q/N)^{0.292}$	0.982	0.017	1965-1984	46
D	$D = 1.366\ (H^{0.5}/Q)^{-0.353}$	0.908	0.038	1965-1984	43
N	$N = 142.049\ (H^{0.5}/D)^{0.773}$	0.958	0.038	1965-1984	44
N	$N = 160.390\ (H^{3/2}/Q)^{0.296}$	0.912	0.063	1965-1984	44
(P/H)	$(P/H) = 1353.376\ (Q/N)^{0.632}$	0.966	0.049	1965-1984	47

TABLE 5-3

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for Pelton turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.594\ (P/H)^{0.288}$	0.689	0.072	1965-1984	35
D	$D = 5.049\ (Q/N)^{0.222}$	0.724	0.068	1965-1984	35
D	$D = 2.702\ (H^{0.5}/Q)^{-0.257}$	0.602	0.081	1965-1984	35
N	$N = 39.206\ (H^{0.5}/D)^{1.008}$	0.992	0.034	1965-1984	32
N	$N = 64.089\ (H^{3/2}/Q)^{0.272}$	0.819	0.059	1965-1984	35
(P/H)	$(P/H) = 1523.266\ (Q/N)^{0.744}$	0.976	0.057	1965-1984	35

TABLE 5-4

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for small-scale horizontal Pelton turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.315\ (P/H)^{0.483}$	0.797	0.047	1965-1983	9
D	$D = 13.001\ (Q/N)^{0.408}$	0.496	0.074	1965-1983	9
D	$D = 2.239\ (H^{0.5}/Q)^{-0.196}$	0.059	0.102	1965-1983	9
N	$N = 32.549\ (H^{0.5}/D)^{1.079}$	0.980	0.012	1965-1983	9
N	$N = 111.263\ (H^{3/2}/Q)^{0.214}$	0.697	0.069	1965-1983	31
(P/H)	$(P/H) = 2343.666\ (Q/N)^{0.855}$	0.958	0.098	1965-1983	31

TABLE 5-5

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for small-scale Francis turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.160\ (P/H)^{0.471}$	0.872	0.070	1966-1984	11
D	$D = 4.047\ (Q/N)^{0.332}$	0.990	0.012	1966-1984	9
D	$D = 0.921\ (H^{0.5}/Q)^{-0.430}$	0.994	0.037	1966-1984	10
N	$N = 110.133\ (H^{0.5}/D)^{0.809}$	0.955	0.048	1966-1984	10
N	$N = 143.455\ (H^{3/2}/Q)^{0.314}$	0.930	0.085	1966-1984	22
(P/H)	$(P/H) = 629.525\ (Q/N)^{0.628}$	0.877	0.171	1966-1984	22

TABLE 5-6

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for small-scale Kaplan turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.157\ (P/H)^{0.489}$	0.990	0.036	1965-1981	17
D	$D = 4.24\ (Q/N)^{0.320}$	0.992	0.031	1965-1981	17
D	$D = 0.823\ (H^{0.5}/Q)^{-0.449}$	0.980	0.051	1965-1981	17
N	$N = 156.662\ (H^{0.5}/D)^{0.922}$	0.990	0.039	1965-1981	17
N	$N = 209.843\ (H^{3/2}/Q)^{0.418}$	0.976	0.062	1965-1981	22
(P/H)	$(P/H) = 841.525\ (Q/N)^{0.652}$	0.972	0.123	1965-1981	22

TABLE 5-7

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for Bulb turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.183\ (P/H)^{0.446}$	0.980	0.049	1966-1984*	150
D	$D = 4.181\ (Q/N)^{0.318}$	0.990	0.024	1966-1984*	206
D	$D = 0.772\ (H^{0.5}/Q)^{-0.452}$	0.972	0.041	1966-1984*	124
N	$N = 163.897\ (H^{0.5}/D)^{0.874}$	0.925	0.063	1966-1984*	145
N	$N = 218.563\ (H^{3/2}/Q)^{0.376}$	0.876	0.083	1966-1984*	140
(P/H)	$(P/H) = 1088.478\ (Q/N)^{0.704}$	0.956	0.112	1966-1984*	140

*year of commissioning

TABLE 5-8

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameters for Tubular turbines

Dependent Parameter	Regression Equation	Corrected R^2 Coefficient	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.143\ (P/H)^{0.512}$	0.941	0.035	1957-1984*	45
D	$D = 4.511\ (Q/N)^{0.339}$	0.987	0.022	1957-1984*	37
D	$D = 0.793\ (H^{0.5}/Q)^{-0.485}$	0.955	0.04	1957-1984*	37
N	$N = 156.193\ (H^{0.5}/D)^{0.890}$	0.951	0.05	1957-1984*	41
N	$N = 197.825\ (H^{3/2}/Q)^{0.395}$	0.882	0.071	1957-1984*	38
(P/H)	$(P/H) = 874.477\ (Q/N)^{0.657}$	0.947	0.080	1957-1984*	38

*year of commissioning

TABLE 5-9

Regression information and equations relating turbine characteristics to various turbine constants and hydropower site parameter for Cross-flow turbines

Dependent Parameter	Regression Equation	Corrected R^2 Statistic	Log Standard Deviation (s_1)	Sample Period	Number of Units (n)
D	$D = 0.329\ (P/H)^{0.275}$	0.903	0.062	1966-1983	30
D	$D = 1.730\ (Q/N)^{0.191}$	0.828	0.083	1966-1983	30
D	$D = 0.814\ (H^{0.5}/Q)^{-0.222}$	0.764	0.096	1966-1983	30
N	$N = 38.451\ (H^{0.5}/D)^{1.032}$	0.990	0.050	1966-1983	27
N	$N = 74.927\ (H^{3/2}/Q)^{0.331}$	0.972	0.064	1966-1983	27
(P/H)	$(P/H) = 341.218\ (Q/N)^{0.641}$	0.945	0.150	1966-1983	30

Efficiency, e = 92%

Power, P = $(9.81)(0.92)QH$

Diameter, D = $0.168\ (P/H)^{0.447}$

Speed, N = $80.387\ (H^{0.5}/D)^{0.828}$

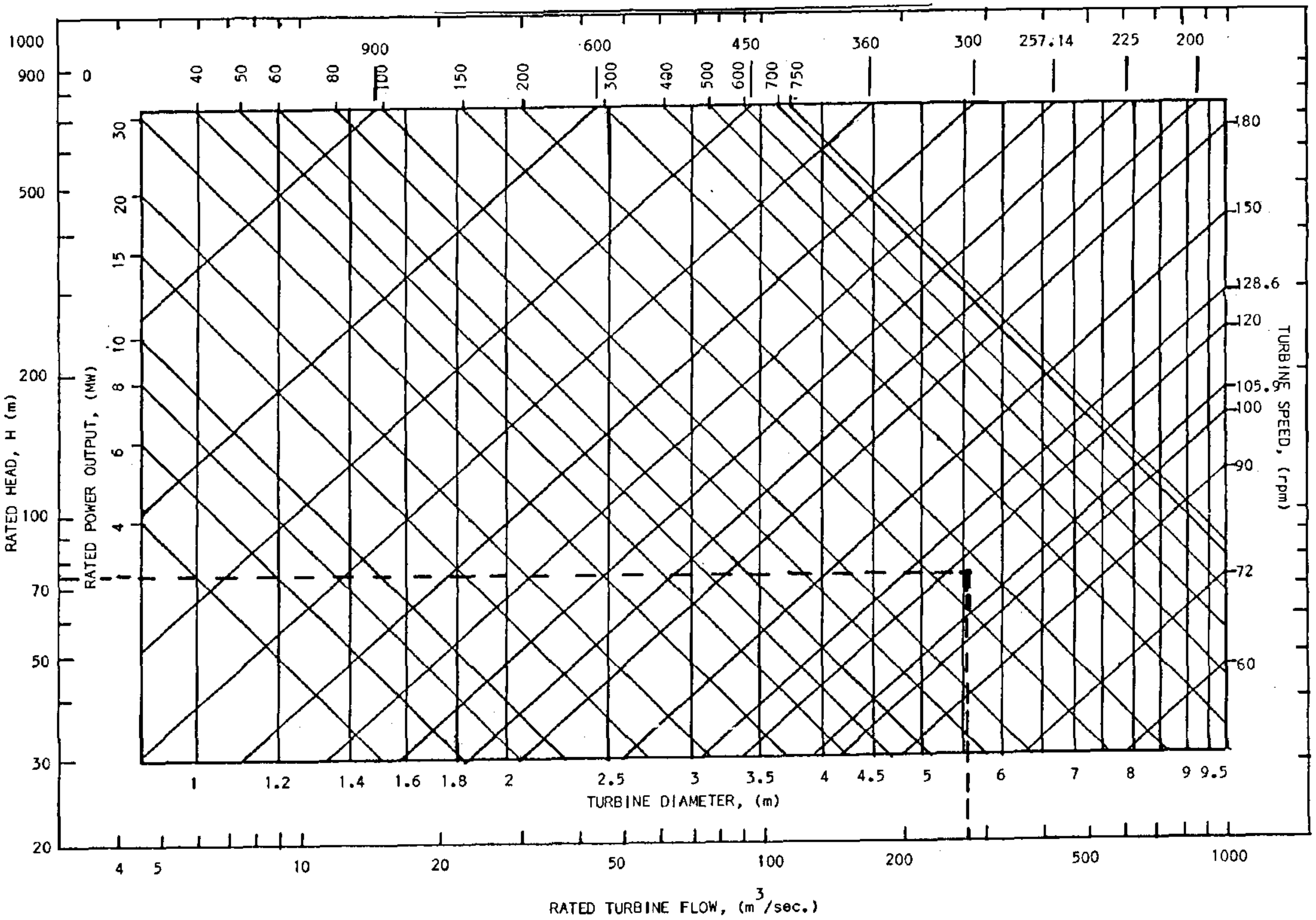

Figure 5.1 Nomograph for estimating turbine size and speed for Francis turbines

Efficiency, e = 92%

Power, P = $(9.81)(0.92)QH$

Diameter, D = $0.175\ (P/H)^{0.452}$

Speed, N = $142.049\ (H^{0.5}/D)^{0.773}$

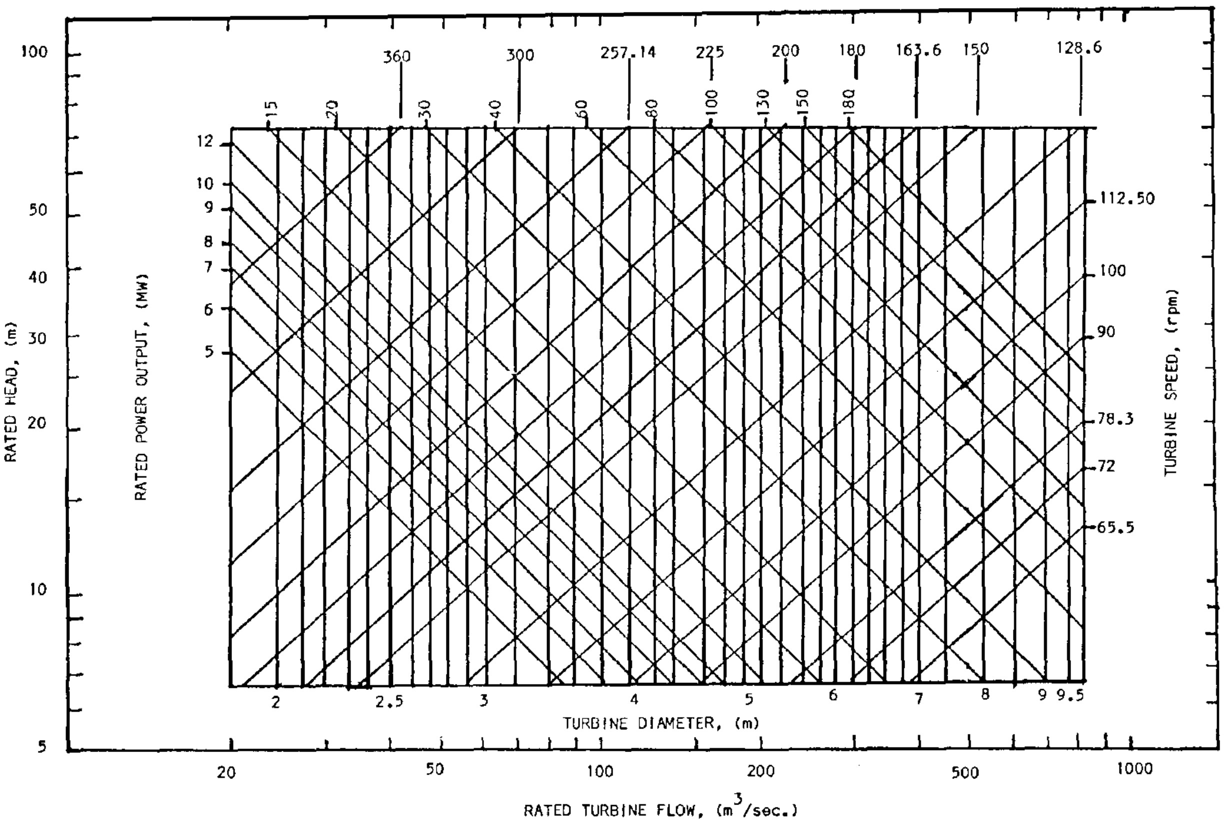

Figure 5.2 Nomograph for estimating turbine size and speed for Kaplan turbines

Efficiency, e = 89%
Power, P = $(9.81)(0.89)QH$
Diameter, D = $0.594\ (P/H)^{0.288}$
Speed, N = $39.206\ (H^{0.5}/D)^{1.008}$

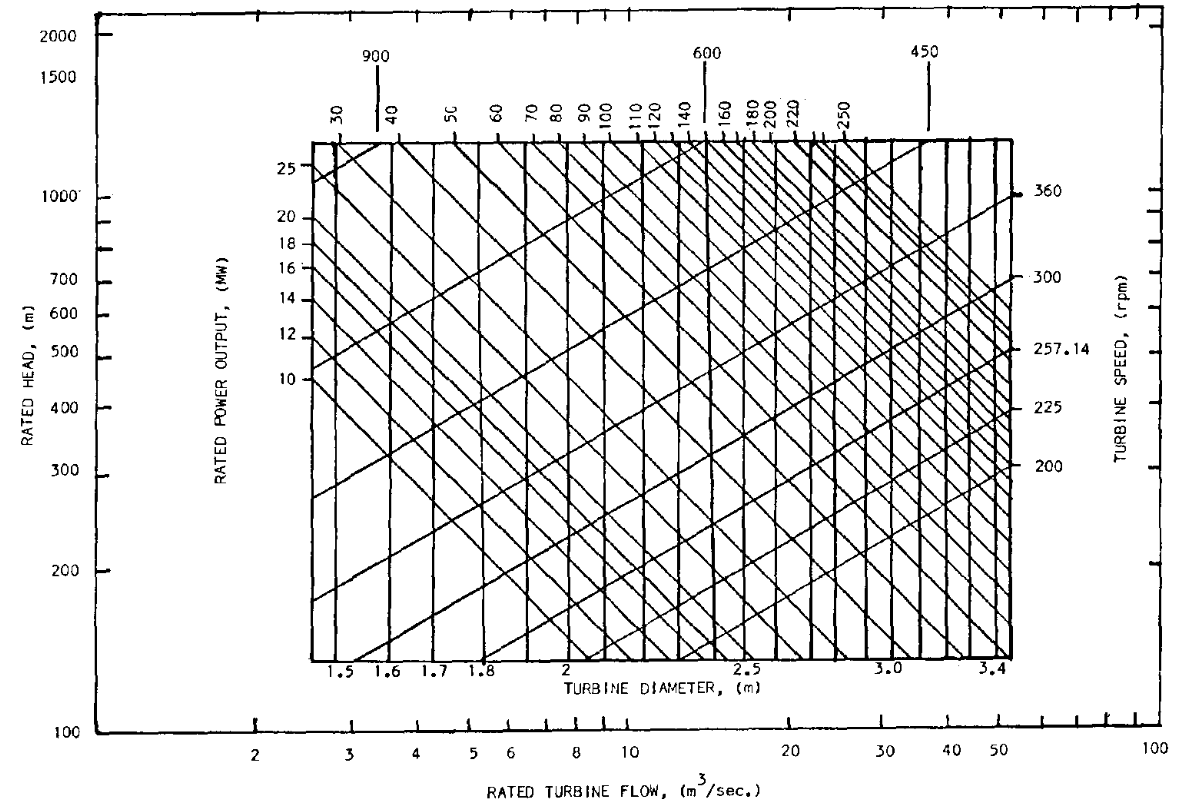

Figure 5.3 Nomograph for estimating turbine size and speed for Pelton turbines

Efficiency, e = 87%
Power P = (9.81)(0.87)QH
Diameter, D = $0.315\ (P/H)^{0.483}$
Speed, N = $32.549\ (H^{0.5}/D)^{1.079}$

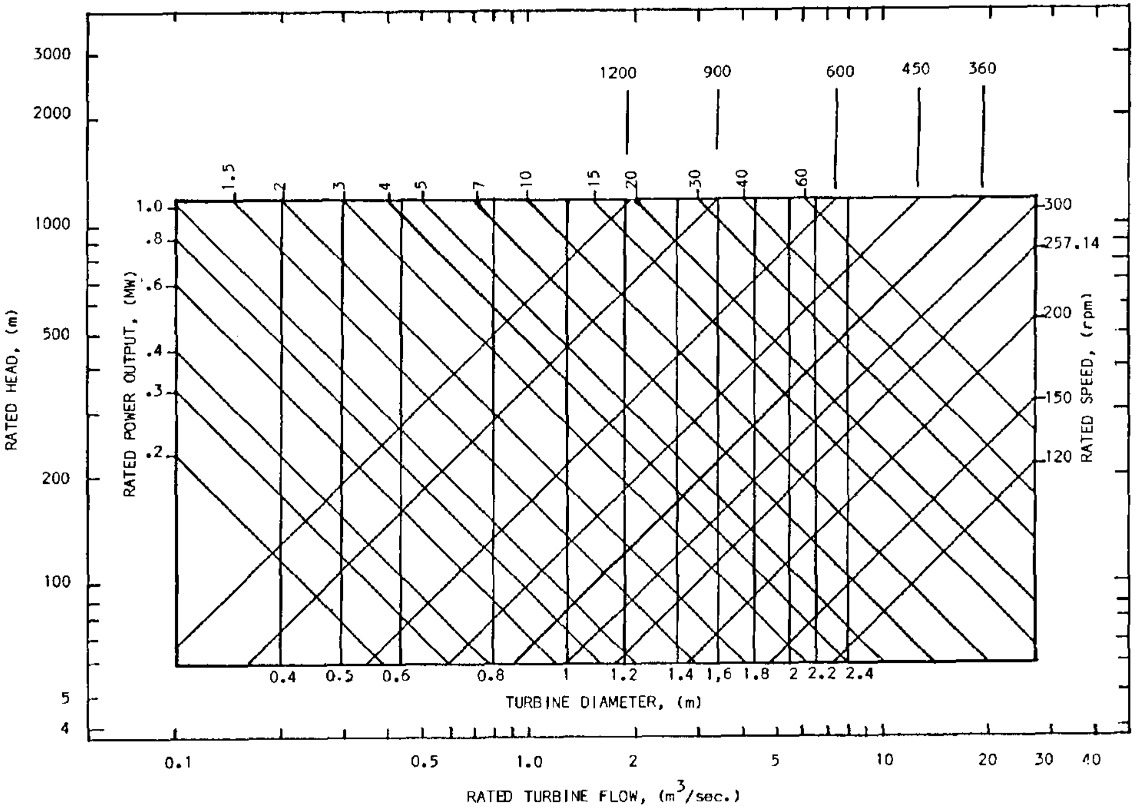

Figure 5.4 Nomograph for estimating turbine size and speed for small-scale horizontal Pelton turbines

Efficiency, e = 85%

Power, P = $(9.81)(0.85)QH$

Diameter, D = $0.160\ (P/H)^{0.471}$

Speed, N = $110.133\ (H^{0.5}/D)^{0.809}$

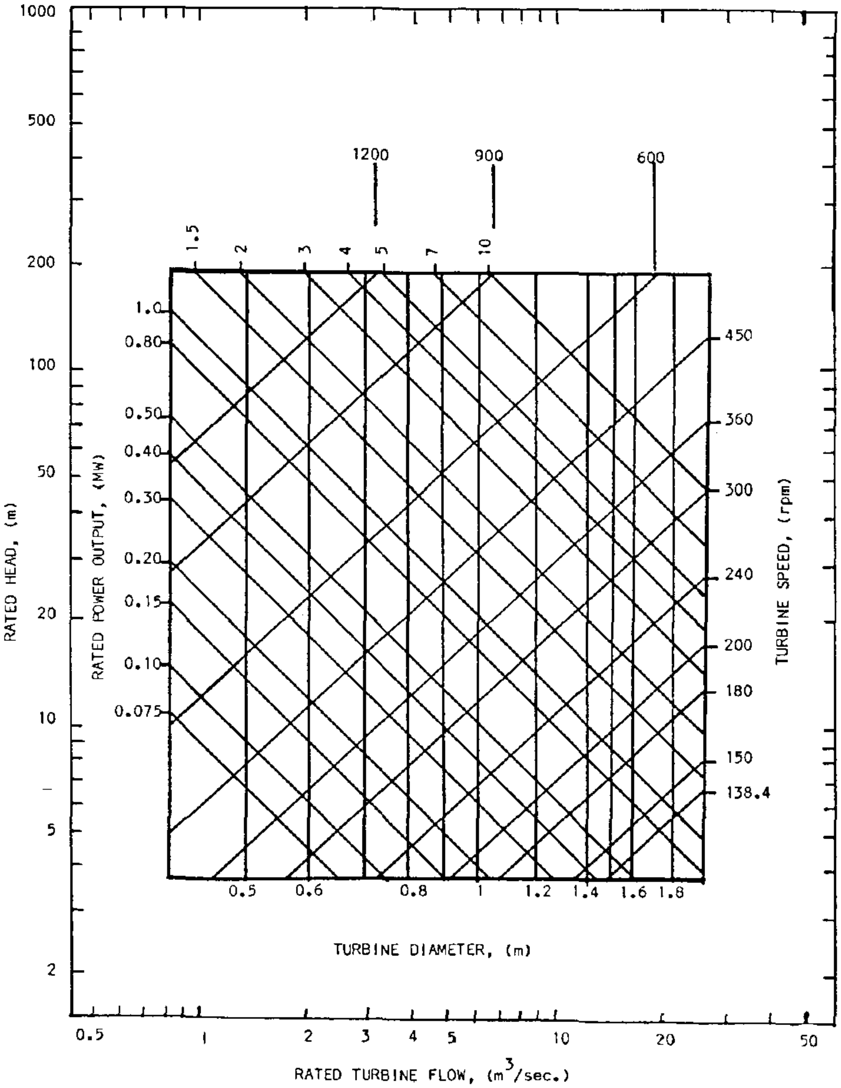

Figure 5.5 Nomograph for estimating turbine size and speed for small-scale Francis turbines

Efficiency, e = 87%

Power, P = $(9.81)(0.87)QH$

Diameter, D = $0.157\ (P/H)^{0.489}$

Speed, N = $156.662\ (H^{0.5}/D)^{0.922}$

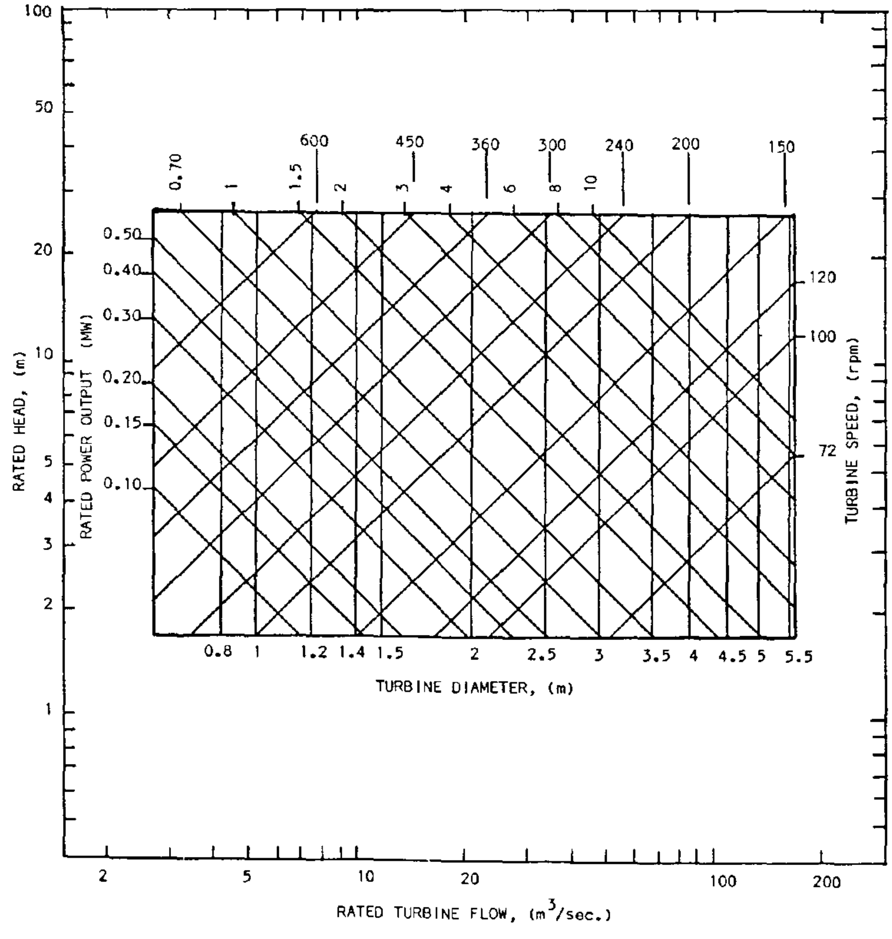

Figure 5.6 Nomograph for estimating turbine size and speed for small-scale Kaplan turbines

Efficiency, e = 89%
Power, P = (9.81)(0.89)QH
Diameter, D = $0.183\ (P/H)^{0.446}$
Speed, N = $163.897\ (H^{0.5}/D)^{0.874}$

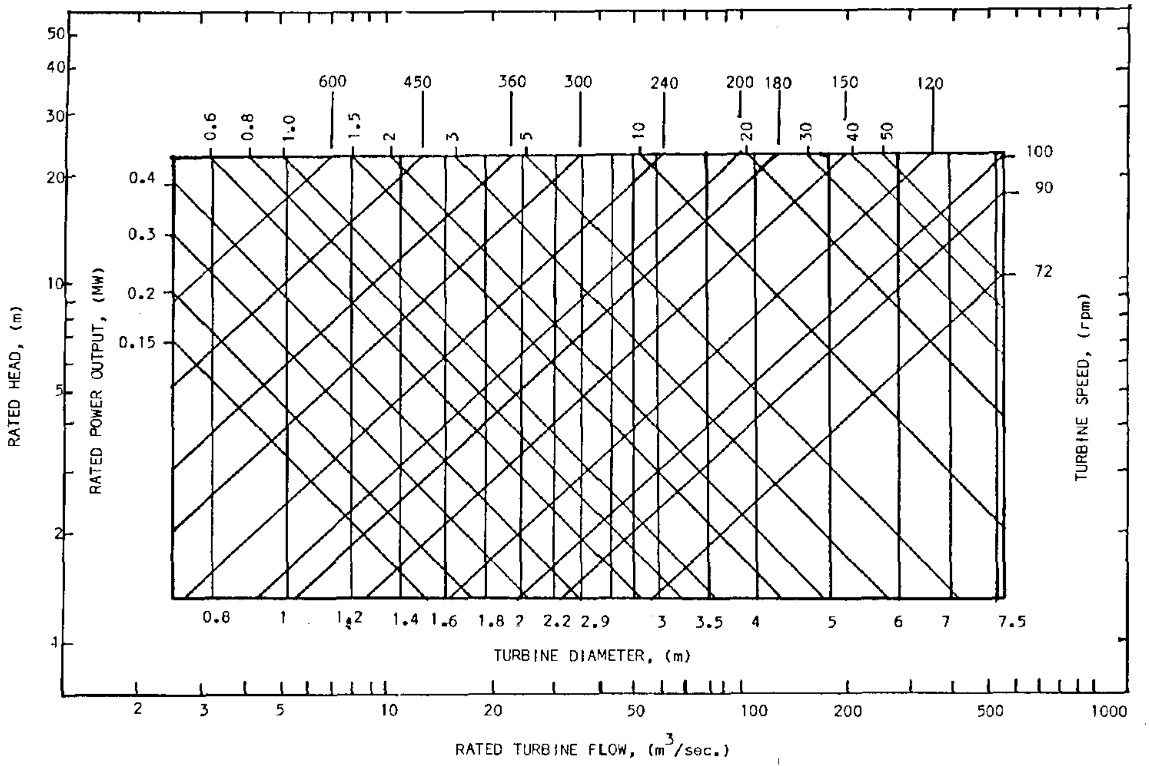

Figure 5.7 Nomograph for estimating turbine size and speed for bulb turbines

Efficiency, e = 89%

Power, P = $(9.81)(0.89)QH$

Diameter, D = $0.143\,(P/H)^{0.512}$

Speed, N = $156.193\,(H^{0.5}/D)^{0.890}$

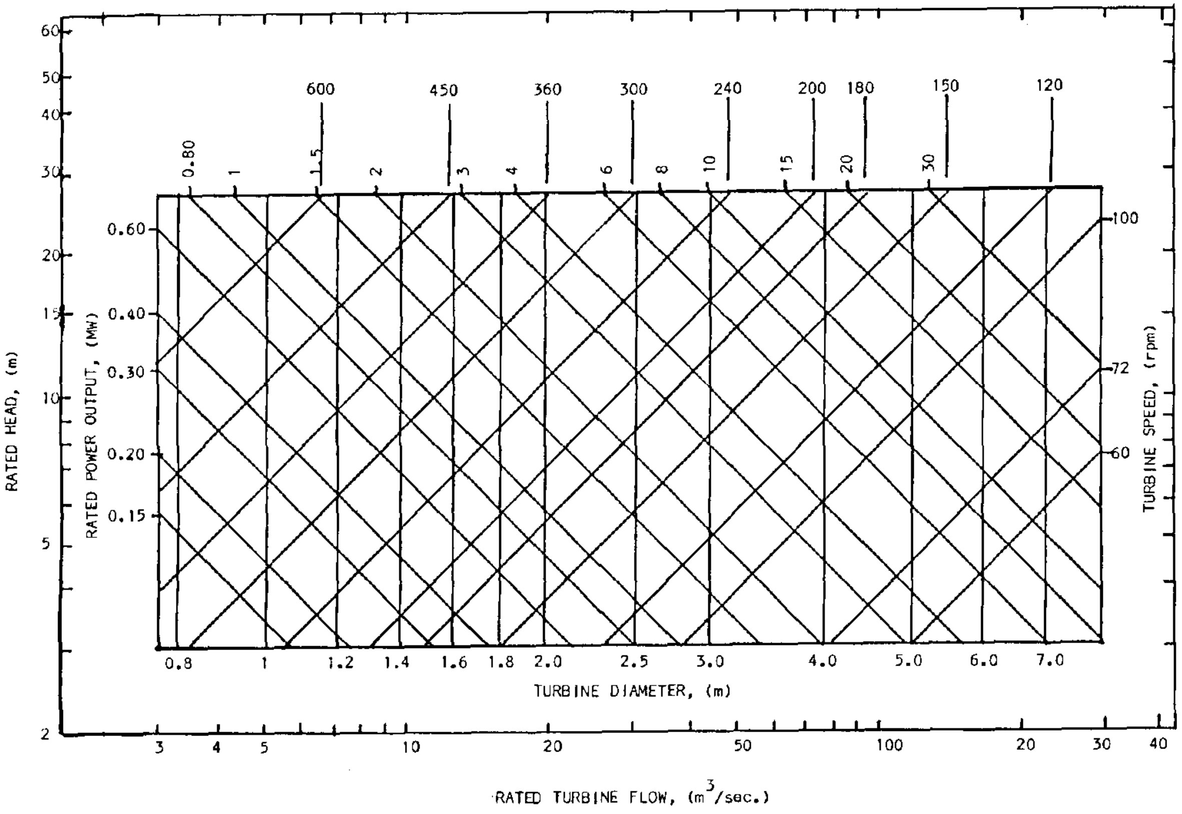

Figure 5.8 Nomograph for estimating turbine size and speed for tubular turbines

Efficiency, e = 81%
Power, P = $(9.81)(0.81)QH$
Diameter, D = $0.329\,(P/H)^{0.275}$
Speed, N = $38.451\,(H^{0.5}/D)^{1.032}$

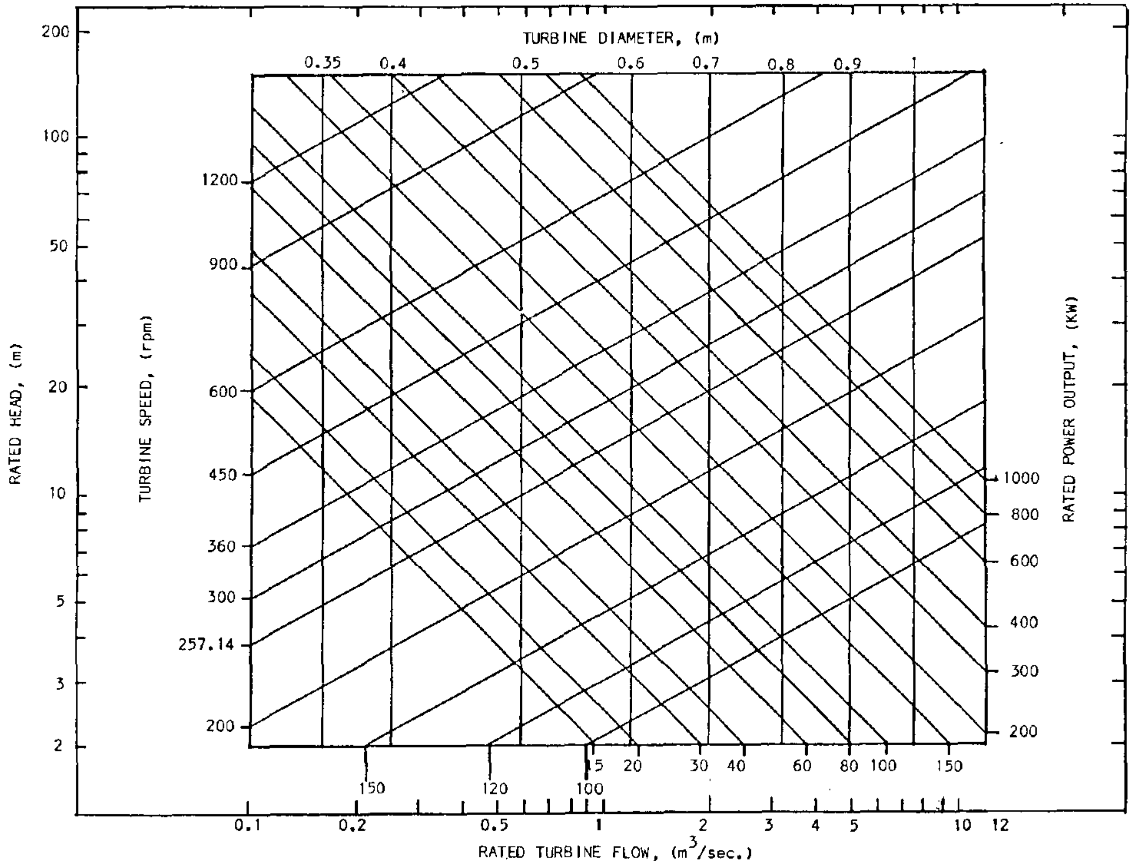

Figure 5.9 Nomograph for estimating turbine size and speed for cross-flow turbines

CONCLUSIONS

A simplified procedure based on experience curves has been presented in this nomograph for selection of diameter and speed of conventional, low-head and small-scale versions of the conventional turbines. The procedure utilizes regression equations relating turbine characteristics to the fundamental parameters of a hydropower site of rated power, rated head and discharge to estimate the turbine diameter and speed at a specified turbine setting. The two empirical equations used in the estimation process are in the following forms:

1. Turbine diameter, D, versus the ratio of rated power output, P, divided by the rated head, H, yielding D versus (P/H).
2. Turbine speed, N, versus the ratio of the square root of rated head, H, divided by the turbine diameter, D, yielding N versus $(H^{0.5}/D)$.

The above regression relations were developed so that units can be easily sized for cost estimates. The cost of the civil works and electrical and mechanical equipment form a sizable percentage of the total project cost. This percentage, however, decreases with increase in project size. The turbine diameter and speed are the parameters which determine the dimensions of the civil works portion of the project and the sizes of the remainder of the power generating equipment. The estimation of turbine size and speed during the early part of project planning and feasibility studies is therefore essential. The empirical equations and nomographs developed to be used with the methodology are presented in Tables 5-1 through 5-9 and Figures 5.1 through 5.9.

The new method has advantages over the USBR (1976) and the existing methodologies of turbine selection. The advantages are stated below. The new method is based on the fundamental definitions of turbine constants. The method relates the turbine characteristics directly to the parameters of a hydropower site which are usually available early during the planning and feasibility studies of a hydropower development. The USBR method and existing methods, however, use the turbine specific speed as the fundamental parameter to which all the turbine characteristics and hydropower site parameters are related. The specific speed is normally not known until its value is specified during final turbine selection by the turbine manufacturer. The USBR experience curves were based on the model test of eleven turbine units that have been manufactured between 1951 and 1972. Therefore the USBR experience curves need to be upgraded now and also upgraded in the future when required. The new experience curves presented in this monograph are based on the characteristics of a large number of more modern turbine units. The new method relates turbine characteristics directly to simple ratios of one hydropower site parameter to the other or to a turbine characteristic. The direct relations between the turbine characteristics and hydropower site parameters are easy to use. The new experience curves do not have to be updated unless there is a change in the definition of the unit constant terms on which they are based.

In order to select the proper turbine units for a given hydropower site, optimization procedures are normally used. The new nomographs in Figures 5.1 through 5.9 allow for direct variation of speed and diameter to meet the requirements of site and comply with the empirical equations that support the methodology. The new procedure is therefore easily adaptable to computer models using sensitivity type analyses to obtain optimal design parameters.

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LETTER SYMBOLS AND QUANTITIES

D = Design turbine diameter

dt = Differential of time

E = Energy generation

e = Turbine-generator total efficiency

f = Electrical current frequency

F = Function notation

ft-lb = Foot-pounds

g = Acceleration due to gravity

H = Rated hydraulic head

H_g = Gross head

H_{max} = Maximum head

H_{min} = Minimum head

H_s = Turbine setting elevation above or below tailwater

Hz = Hertz of A-C frequency

KW = Kilowatt power of generator

KWH = Kilowatt-hour of energy

m = Meter

MW = Megawatt power of energy

n = Number of turbine units

N = Turbine rotational speed

N_p = Number of generator poles

N^1 = Trial rotational speed

N_{11} = Unit speed

N_s = Specific speed

P = Power output at best efficiency

P_{max} = Maximum output power expected

P_{11} = Unit power

Q = Rated flow

Q_{11} = Unit discharge

R^2 = Corrected R^2 statistic

rpm = Revolutions per minute

S_1 = Logarithm of standard deviation

sec = Second

t = Time

TW = Tailwater elevation

ρ = Rho = Mass density of water

APPENDIX A1

A1. HYDROPOWER CONCEPTS AND TERMINOLOGY

1. Introduction

Turbine selection is an essential part of hydropower planning, therefore the concepts and terminology used in the hydropower industry are also used to describe the turbine selection process. The relevant terminology and concepts used for turbine selection are explained below.

2. Hydraulic Turbine

The hydraulic turbine is a machine which converts the potential, kinetic and pressure, (total), energy in a continuous water flow stream into mechanical energy. The mechanical energy produced by the turbine is used to drive a generator to produce electrical energy.

3. Basic Concepts and Terminology

The estimation of the hydroelectric power potential at a site is usually explained in terms of work, energy, power, and capacity. These terms are defined below:

(a) Work. Work is the transferred energy and is the product of force and distance moved in the direction of the force.

(b) Energy. Energy is the capacity to do work or time integral of power. It is measured in terms of the work it is capable of doing. Electric energy is usually measured in kilowatt-hours while mechanical energy is expressed in joules (or foot-pounds in the English system of units) (1kw-h = 2656000 ft-lb).

(c) Power. Power is work per unit time. It is the rate at which energy is being produced or used. It is usually expressed in terms of kilowatts or (horsepower).

1 kilowatt (kw) = 737.56 ft-lbs/second (English system of units)

= 1.341 horsepower

(d) Capacity. Capacity is the maximum power output or load for which a turbine-generator, station, or system is rated. It is usually measured in kilowatts (kw) or megawatts (MW).

(e) Installed (nameplate) capacity. Installed capacity is the total of the capacities as shown by the nameplates of similar kinds of apparatus such as generating units, turbines, synchronous condensers, transformers or other equipment in a station or system.

(f) Dependable capacity. Dependable capacity is the expected load-carrying ability of a power plant under adverse load and flow conditions.

(g) Load. Load is the amount of electricity delivered at a given point or demand for electricity.

(h) Resources. Resources are sources of electrical power for meeting present or future loads. A system's power resources could include both generating plants and imports from adjacent power systems.

(i) Discharge. Discharge is the volume rate of flow with respect to time in a stream channel or through a power plant.

(j) Rated Discharge. Rated discharge is the flow passing through the turbine when it is generating under rated head and producing rated power.

(k) Hydraulic Capacity. Hydraulic capacity is the maximum flow which a hydroelectric plant can utilize for energy production.

(l) Gross head (static head). Gross head is the difference of elevation between water surfaces of the forebay and tailrace under specified conditions.

(m) Net head. Net head is gross head minus all hydraulic losses except those chargeable to the turbine. Net head is the head available for doing work on the turbine.

(n) Design head. Design head is the head at which the turbine will operate to give the best overall efficiency under various operating conditions. This is the head which determines the basic dimensions of the turbine and therefore the power plant.

(o) Rated head. Rated head is the net head at which the full-gate output of the turbine produces the generator rated output in kilowatts or the net head at which a turbine at rated speed will deliver rated capacity at specified gate and efficiency.

(p) Maximum head (Hmax). Maximum head is the gross head resulting from the difference in elevations between the maximum forebay level without surcharge and the tailrace level without spillway discharge and with one unit operating at speed-no-load. (must not exceed 125% of design head)

(q) Minimum head (Hmin). Minimum head is the net head resulting from the difference in elevation between the minimum forebay level and the tailrace level minus losses with all turbines operating at full gate (must equal or exceed 65% of design head to avoid vibration and cavitation problems).

(r) Critical head. Critical head is the head at which the full-gate output of the turbine equals the nameplate generator capacity.

(s) Firm Energy. Firm energy is electrical energy which is intended to have assured availability to the consumers.

(t) Average annual energy. Average annual energy (AAE) is the product of average annual capacity and number of hours in a year, 8760 hours.

AAE = (Average capacity) (8760)

(u) Efficiency. Efficiency is the ratio of the energy developed from hydropower system to the total water energy received by the system under specified conditions. The efficiency of a turbine depends on the design, dimensions and the surface finish (roughness) of runner surfaces and water filled passages.

(v) Turbine performance. A measure of high performance of a hydraulic turbine is its ability to follow the design load variations closely and maintain high efficiencies over the design-load operating range. Turbine performance depends on the design of the unit, the design head on the turbine and the design of the associated water passages from the head water level through the tailrace.

(w) Types of Hydropower Development. Hydropower projects can be classified either on the basis of the amount of storage developed at the site or the mode of regulation of the natural flow of the river for power generation in order to follow the design load. The common types of conventional hydroelectric developments are defined below (U.S. Army Corps, 1985).

(x) Run-of-river development. A run-of-river development consists of a dam with a short penstock (supply pipe) which directs the water to the turbines, using the natural flow of the river with very little alteration to the terrain stream channel at the site and using little impoundment of the water. Power output at any time is strictly a function of the streamflow at the site (Warnick, 1984).

The term run-of-river may also be used to describe an operating mode where the project is designed to pass the natural flow for non-power purposes and no special regulation would be permitted for generation of power (U.S. Army Corps, 1985).

(y) Diversion and canal development. The second type of run-of-river development is one in which the water is diverted from the natural channel into a canal or a long penstock, thus changing the flow of the water in the stream for a considerable distance (Warnick, 1984).

(z1) Pondage project development. This refers to developments where either the project site topography or non-power uses of the river do not permit formation of sufficient storage for seasonal water regulation. Storage can be impounded only for shaping discharges to follow daily or weekly load patterns (U.S. Army Corps, 1985).

(z2) Storage Project Development. The term storage refers to long-term impoundment at the power plant or reservoirs upstream of the power plant with capacity for regulating seasonal discharges in order to more closely follow seasonal demand pattern.

4. Water Power Equation

The water power equation is the basic relation normally used for the estimation of energy potential at a hydropower site. Theoretically, water flowing from a higher to a lower elevation has a total energy in the form of potential, kinetic and pressure energy.

The power which a turbine-generator set can develop from water flowing from a higher to a lower elevation is a function of the quantity of water, the hydraulic net head on the turbine and the total efficiency of the turbine-generator set. This relationship is expressed by the water power equation. The power of a hydroelectric installation measured at the generator output is given by:

$$P = 9.806\ HQe,\ (KW) \qquad (A.1)$$

where

P = power produced, (KW)

H = net hydraulic head on the turbine, (m)

Q = Quantity of water flowing through the turbine, (m^3/sec.)

e = total efficiency (dimensionless)

9.806 = unit weight of water, (N/m^3)

Energy is defined as time integral of power. Therefore, the energy produced by a turbine-generator set is the integral of the water power equation and is given by:

$$E = 9.806 \int_{t=o}^{t=t_1} QHe \, dt \qquad (A.2)$$

The integration process is accomplished by using either the flow-duration curve or sequential streamflow routing method for computing energy (U.S. Army Corps, 1985). The two methods normally used in computing energy are discussed briefly below.

5. Flow-duration curve method

A flow-duration curve is the basis of this method. A flow-duration curve is a plot of flow versus the percent of time a particular flow value can be expected to be equalled or exceeded (Warnick, 1984). The area under the flow-duration curve represents the quantity of water available at the particular site being considered. Thus, when the head is known, the curve can be converted to a power-duration curve through the use of the water power equation. The flow-duration method is normally used to analyze run-of-river developments. For feasibility studies duration curves are normally prepared to describe the plant's energy output on a monthly or seasonal basis.

6. Sequential Streamflow Routing (SSR) Method

The sequential streamflow routing method entails computation of the potential energy generation sequentially, for discrete intervals of time in the period of analysis. The time interval used depends on the type of project being studied, record availability, load pattern, flow and/or head variations and the functions served by the project or system. A weekly or monthly interval is normally used.

The method uses the continuity equation to route streamflow through the project and thus accounts for the variation in reservoir elevation resulting from reservoir regulation. Sequential streamflow routing methods can be used to model almost any type of hydropower analysis including run-of-river operation, the effects of reservoir regulation for power as well as non-power objectives (Tudor, 1980).

For a more detailed description of the above two methods of estimating energy potential, reference should be made to publications by U.S. Army Corps (1985) and Warnick (1984).

APPENDIX A2

A2. TYPES OF HYDRAULIC TURBINES

1. Introduction

Hydropower technology has been a subject of research for over 150 years (Kpordze, 1982). This sustained research has led to the invention of different types of hydraulic turbines which can develop power from almost any combination of hydraulic head and water flow and plant operation. The two basic types of hydraulic turbines used for hydroelectric power generation are the impulse and reaction turbines.

2. Impulse Turbines

An impulse turbine is designed to convert the kinetic energy of a high velocity water jet impinging on its runners into mechanical energy. The commonly used impulse turbines in hydropower development are: Pelton, Turgo and crossflow or the Ossberger turbine.

3. Reaction Turbines

A reaction turbine is designed to produce mechanical energy when its runners are driven by both the kinetic energy of water and the difference in pressure between the inflow and outflow of its runners. The commonly used reaction turbines are Francis and propeller turbines.

Propeller turbines are operated by passing water through the turbine unit axially. This turbine type can be subdivided into four models or arrangements namely: convention vertical-shaft propeller units and three low-head propeller units consisting of bulb, tubular and rim-generator units (Kpordze, 1983). The Kaplan turbine is a special type of propeller unit with adjustable blades which are coordinated with the wicket gates to obtain the blade-gate relationship for most efficient operation. For a more detailed discussion of types of hydraulic turbines reference should be made to the publication by Warnick (1984).