Small scale hydropower design optimization and analysis of hydrologic sensitivity
by David Alan Peterson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
A method by which the hydraulic design of small scale hydropower facilities can be economically optimized and tested for sensitivity to hydrologic prediction has been developed. The method is based on computer modeling of the annual operation of various hydraulic designs for a given flow-duration curve. The optimum design is chosen on the basis of economic rate of return. Economic sensitivity of the optimum design to inaccuracies in hydrologic prediction is analyzed by altering the predicted flow-duration curve by varying degrees and monitoring the project's rate of return.

Three hypothetical project sites representing high, medium, and low head types of development were analyzed using the design method. A flow-duration curve prediction procedure, developed specifically for the geographic region containing the three sites, served as the source of flow data.

The results of the three sensitivity analyses provided both illustration of the method and a basis by which conclusions regarding choice of design from a hydrologic sensitivity and risk mitigation standpoint could be drawn.

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APPROVAL

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David Alan Peterson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Nov 18 1983
Date

Alfred R. Cunningham
Chairperson, Graduate Committee

Approved for the Major Department

Nov. 18, 1983
Date

Fred F. Videon
Head, Major Department

Approved for the College of Graduate Studies

11-28-83
Date

Michael Malone
Graduate Dean

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Date Nov. 18, 1983

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ABSTRACT

A method by which the hydraulic design of small scale hydropower facilities can be economically optimized and tested for sensitivity to hydrologic prediction has been developed. The method is based on computer modeling of the annual operation of various hydraulic designs for a given flow-duration curve. The optimum design is chosen on the basis of economic rate of return. Economic sensitivity of the optimum design to inaccuracies in hydrologic prediction is analyzed by altering the predicted flow-duration curve by varying degrees and monitoring the project's rate of return.

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CHAPTER 1

INTRODUCTION

With the passage of the Public Utility Regulatory Policies Act (PURPA) in 1978, potential small hydropower developers began a race to secure permits on the developable streams of the United States that has been deemed by some to be the Gold Rush of the 80's. Until the passing of this act, small scale hydropower (less than 5MW) was seldom considered an economical manner of power production in this country, lending itself useful only in cases of extreme isolation. PURPA, however, stipulated that power companies were required to purchase renewable energy at a price consistent with the price necessary to recover the cost of building new power plants (avoided cost). In addition, the Federal Government provided for an 11 percent tax credit on qualifying alternative energy projects, to be credited in addition to the standard 10 percent investment tax credit. In response to these financial incentives, a new industry has been introduced which is centered around commercial power generation by the private sector.

This type of power generation brings with it some unique problems in terms of engineering analysis and design. In contrast to traditional power developments of past decades, small scale projects are being proposed for locations representing diverse and often highly variable physical and hydrologic conditions - a situation often compounded by a chronic lack of climatic, streamflow and soil test data. In addition, small scale projects are heavily impacted by a variety of state and federal requirements (highly variable from state to state) for permitting and licensing. Negotiation of a power sales agreement with the local utility company likewise adds uncertainty to the ultimate success of proposed projects. These and other factors require that small scale hydroelectric projects be analyzed and designed with a high degree of sensitivity to site specific conditions.

Design

At present there are no design standards for small hydropower facilities, nor is engineering review required for licensing by the Federal Energy Regulatory Commission (F.E.R.C.) Thus any review of project design that occurs is accomplished by the various state and Federal agencies involved in the permitting process. Such agencies include the Montana Department of Fish, Wildlife and Parks, Army Corps of Engineers, Forest Service, Montana Department of Natural Resources and Conservation, and the power company with which the plant will do business. Aside from staying within the guidelines and constraints set by these governing agencies and others,[2] the design process is rather arbitrary.

A good comprehensive summary of design and construction procedures is given by Ott[9] for all of the major components of a small hydropower plant. Specific details on small dams can be found in Design of Small Dams.[14] Valuable input to the design of the powerhouse and pipeline can be obtained from equipment manufacturers. In addition to these sources of information on design, several demonstration projects funded by the Department of Energy (D.O.E.) include blueprints and associated data that can be helpful in selecting a design for a future project.

Design Optimization

Review of the literature associated with design reveals a large void concerning the concept of design optimization. Several sources deal with optimization of design for large hydropower plants at regulated dams with accurate, long-term flow records,[1,4,6] but none adequately discuss the case of a small run-of-the-river power plant proposed at a previously ungaged, unregulated site. In addition to the problems posed by

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2 Superscripts refer to references listed in the "References Cited" section of this report.

inadequate flow records, very little information is currently available concerning such things as guidelines for location of diversion and powerhouse structures and sizing of project components to provide an optimum design. Optimum design, in this case, refers to that particular combination of project components which results in the maximum economic rate of return to the developer.

Design Sensitivity

The major problem associated with engineering analysis and design of installations of this type is prediction of a valid flow regime for the site. Annual hydrographs and flow-duration curves represent the foundation for virtually all major design decisions. Because of this, it is very important to assess the degree of economic sensitivity for various types of small hydro projects to variations in the predicted flow regime used in project design.

Statement of Objectives

It is the purpose of this thesis to develop a method by which the hydraulic design of small hydropower facilities can be economically optimized and then tested for sensitivity to variations in hydrologic prediction. Specifically, this method should provide a means by which the pertinent project components(i.e. intake, pipeline(s), turbine, tailrace) can be chosen so as to provide the optimal economic rate of return for the project. Also, three site examples will be analyzed for sensitivity to inaccuracies of flow-duration curve prediction as a means of illustrating the procedures outlined.

The method and concepts discussed in the following chapters will provide a developer with the most economical design among the alternatives considered for the site in question and give an indication as to the degree of risk associated with implementation of the design.

CHAPTER 2

PROJECT LAYOUT

In general, three main types of hydroelectric installations exist: low head, medium head, and high head. In its most general usage, the term head refers to the gross head of a facility, that is, the difference in elevation between the water surfaces at the intake and tailrace. The breakpoint between low and medium head is usually defined as 20 m (66 ft.).[9] No such clear breakpoint exists between medium and high head sites, but most sources refer to a breakpoint in the vicinity of 122 m (400 ft.).[9] All three types of projects share the same basic set of components: an intake structure, a conveyance system for efficient delivery of water to the turbine, and a turbine-generator unit for removal of the fluid energy. The form that these three basic components take for each type of plant is discussed below.

Low Head

The two main types of low head facilities are canal drop structures and existing small dams. In the case of a canal drop, the intake is formed by damming the upper canal and

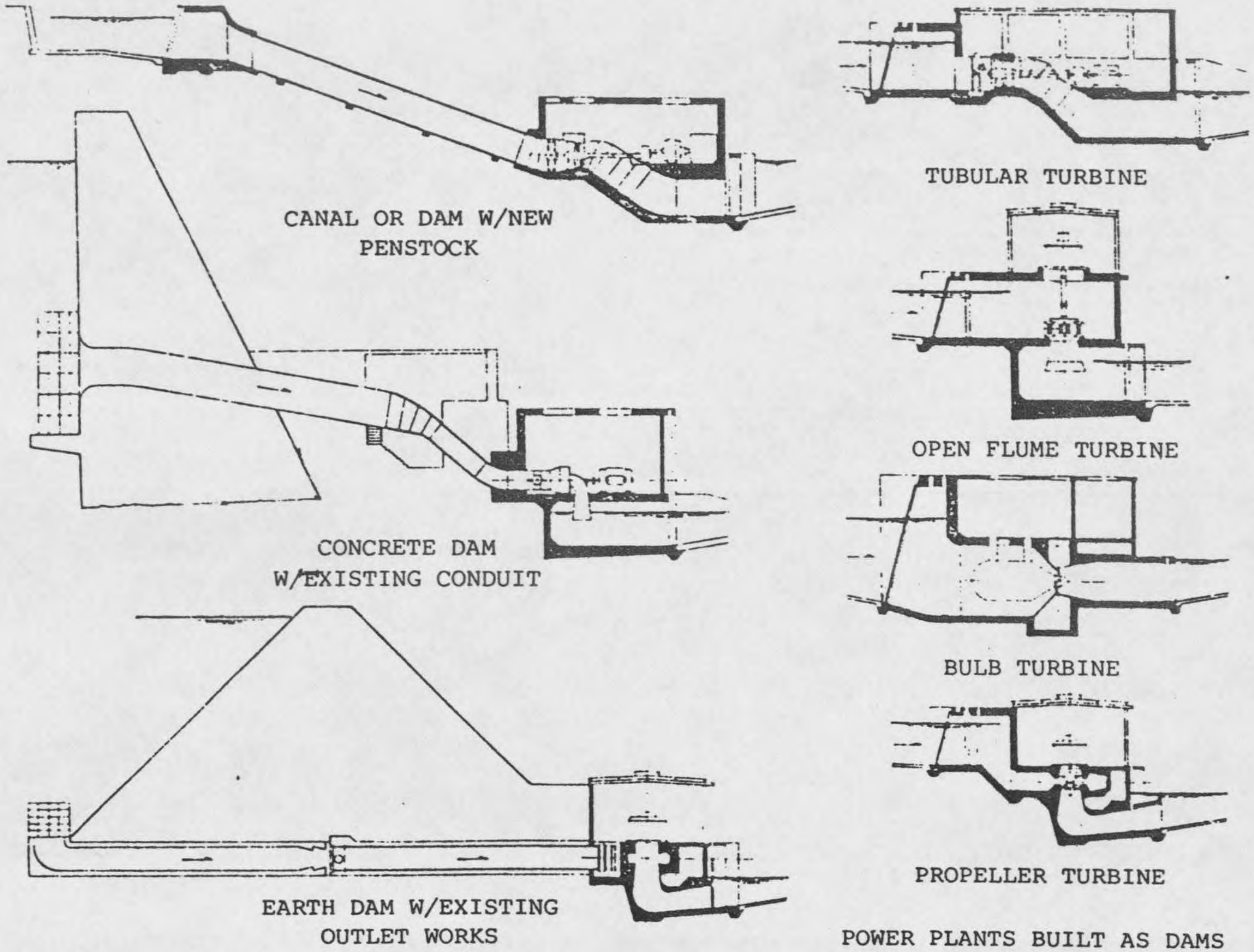

FIGURE 1. TYPICAL LOW-HEAD LAYOUTS [13]
(PERMISSION TO REPRODUCE)

diverting water into a pressure conduit, which carries the water downslope a short distance to a powerhouse, then discharges it either into a canal or natural stream (Figure 1). The unique aspects of such a facility center around the frequent lack of environmental constraints such as maintenance of fish habitat, allowance for spring floods, and streambed protection laws. In the case of an existing dam with a low level outlet works intact, a powerhouse can be attached to the outlet works either at the dam or a short distance downstream with minor modifications (Figure 1). An analysis of the safety of the dam and outlet works is required before this type of construction can begin, however, and any weaknesses will have to be rectified before construction can proceed. Such repairs can be costly and often times render the project uneconomical. A third type of low head plant is the open flume type in which a small dam is built to serve as a power plant (Figure 1). This type of plant is best under very low heads where the extent of the required dam structure is small.

Medium and High Head

There is very little difference in the layout of medium and high head small hydropower facilities, so they will be grouped together here. The intake structure of this type of facility is typically a small diversion into a canal or low pressure pipeline. The low pressure conduit or canal carries the water with a minimum of headloss along a contour to a surge tank. The high pressure penstock carries the water from the surge tank to the powerhouse, and must withstand both static and waterhammer pressures.

The design of the intake structure must take into consideration fish protection both at the intake and below the overflow structure, flood protection, debris protection, and sediment passage. The low pressure conduit or canal must be designed to minimize risk from avalanche, landslide, freeze, sedimentation, linear expansion, and vandalism. The surge tank is located as near to the powerhouse as possible to minimize water hammer transients caused by sudden changes in turbine gate opening. It must be built with its top at least equal in elevation to the water surface at the diversion and its bottom low enough in elevation to maintain submergence of both inlet and outlet during high flow. Any overflow during a surge must be correctly channeled to the main stream. Special consideration in high pressure penstock design must be given to transfer of forces from the penstock to the ground through thrust blocks or burial. In cases of a relatively short distance from diversion to powerhouse, it may be acceptable to run the high pressure pipeline directly from the diversion to the powerhouse without a surge tank. This arrangement is highly susceptible to damage from high surges and unstable transients due to changes in valve setting.

The powerhouse represents the major difference between high and medium head installations for the purposes of this paper. Medium head plants utilize reaction turbines which operate on a pressure difference across the blades, and high head plants use impulse turbines which operate on a change in momentum of a free jet of water. All other aspects of high and medium head sites are the same.

CHAPTER 3

HYDROLOGIC SIMULATION

At the heart of the problem of designing a small hydropower plant at an ungaged location is the lack of information describing the magnitude and time variation of streamflows. Even if stream gaging commences at the conception of a project, data requirements necessary for preliminary design, feasibility analysis, and permitting dictate a need for generation of synthetic flow data. The form that synthetic flow data assumes depends on the availability of methodologies and preference of the engineer performing the study. The two most useful means for expressing flow data for run-of-the-river hydropower installations are the annual hydrograph and the flow-duration curve.

Annual hydrograph synthesis usually involves correlation of the daily streamflows at the site in question with daily streamflows at a nearby gaged basin using either a ratio of drainage areas or area weighted average annual precipitation volumes. The long term "typical" annual hydrograph can be formed by multiplying the daily flows by the ratio of the long term mean annual flow to the mean annual flow of the year used at the gaged site. One major problem with this method is its short term nature. The year used to generate the annual hydrograph may exhibit non-typical characteristics, such as low spring runoff and high baseflow, or abnormally high spring floods and low baseflow. Long-term simulation under these conditions could possibly yield inaccurate results.

Flow-duration (F-D) curve prediction at the site in question is generally accomplished by a correlation procedure similar to that used to produce a synthetic annual hydrograph, but with F-D curve ordinates substituted for daily flows. Since the gaged flow-duration curves are formed using all historical data, long term variation can be accounted for. In addition, the ease of usage of the finished product for design and economic simulation is attractive to hydropower analysts. For these reasons, the F-D curve was chosen for usage in this thesis.

Methodologies for synthesizing flow-duration curves at ungaged locations have been developed for different geographic regions by various authors.[3,5]

The flow-duration curve prediction procedure for ungaged mountainous and high plains streams in Montana[3] was used to synthesize flow-duration curves for all three sites investigatged in this thesis. The procedure is summarized as follows:

1. Obtain the weighted mean annual basin precipitation by weighting annual precipitation isohyetal values by their areas of influence.

2. Estimate the average annual runoff from the mean annual precipitation obtained in step 1 using Figure 2 and convert average annual runoff to average annual streamflow using the equation:

   $Q_{AA} = (A)(\text{Runoff})(.0737)$ Where: Q_{AA} = Average Annual Flow (cfs)

   A = Drainage Area (sq. mi.)

   Runoff = Average Annual Runoff (in/yr.)

   .0737 = Units Conversion Factor

3. Compute the 10% exceedence flow using the equation:

   $Q_{10} = (Q_{AA})(3.056)$ Where: Q_{AA} = Average Annual Flow (cfs)

   Q_{10} = 10% Exceedence Flow (cfs)

   3.056 = Emperical coefficient based on existing streamflow records.

4. Select a dimensionless flow-duration curve from within the band of Figure 3. The band was formed by the union of the dimensionless F-D curves of selected U.S. Geological Survey (U.S.G.S.) stream gages in Montana. The selected gages were devoid of large springs, diversions, and regulation in their drainage basins. The vertical position of the curve within the band is selected from judgement of the magnitude of the baseflow end of the F-D curve relative to the gages used to form the band. For example, a small, narrow, steep, rocky drainage basin with fast time of concentration and low groundwater storage would most likely plot near the bottom curve (low position), and a large, wide, flat basin with deep soil and a slow concentration time would most likely plot near the top curve (high position).

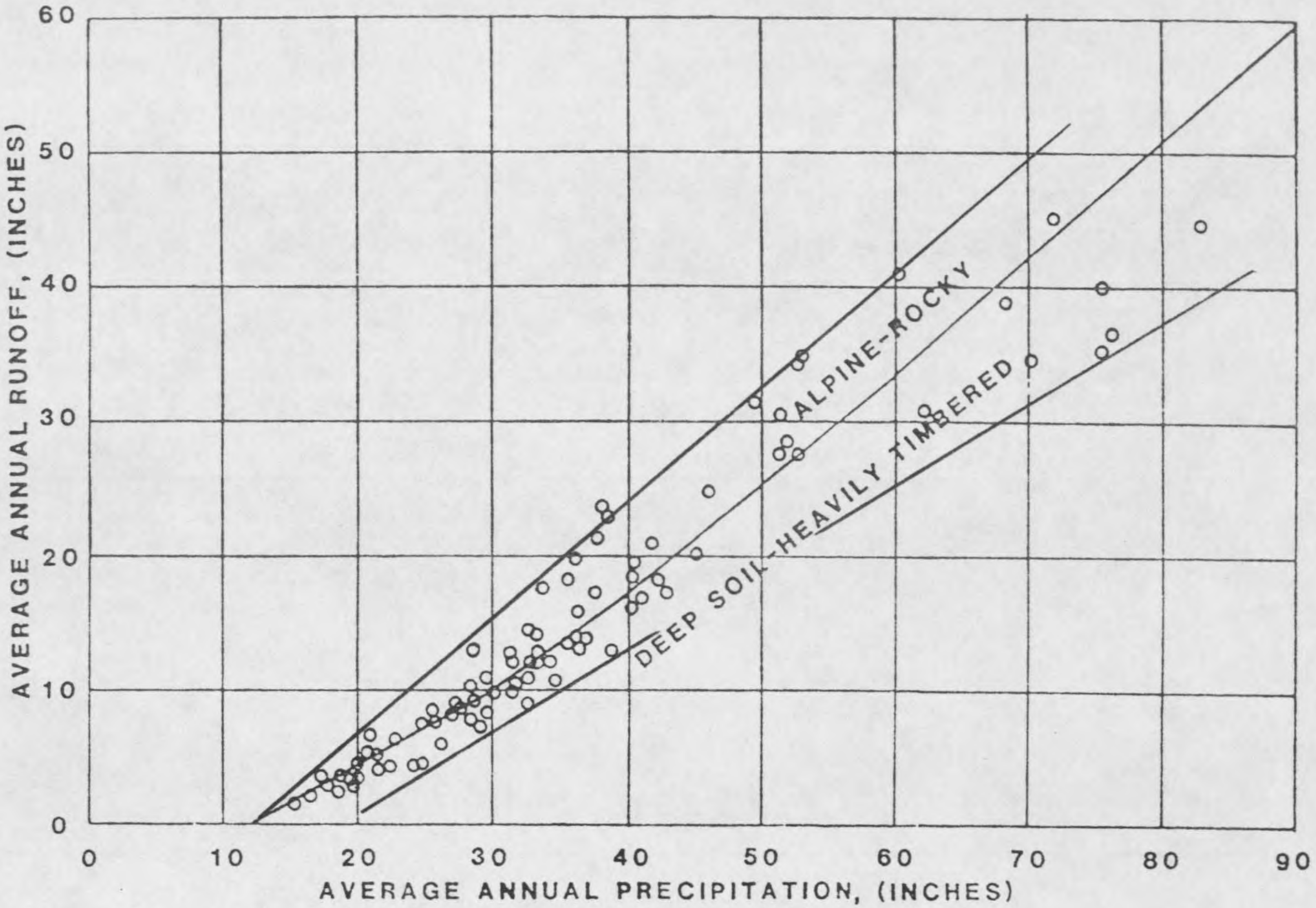

FIGURE 2. PRECIPITATION VS. RUNOFF[2]
(PERMISSION TO REPRODUCE)

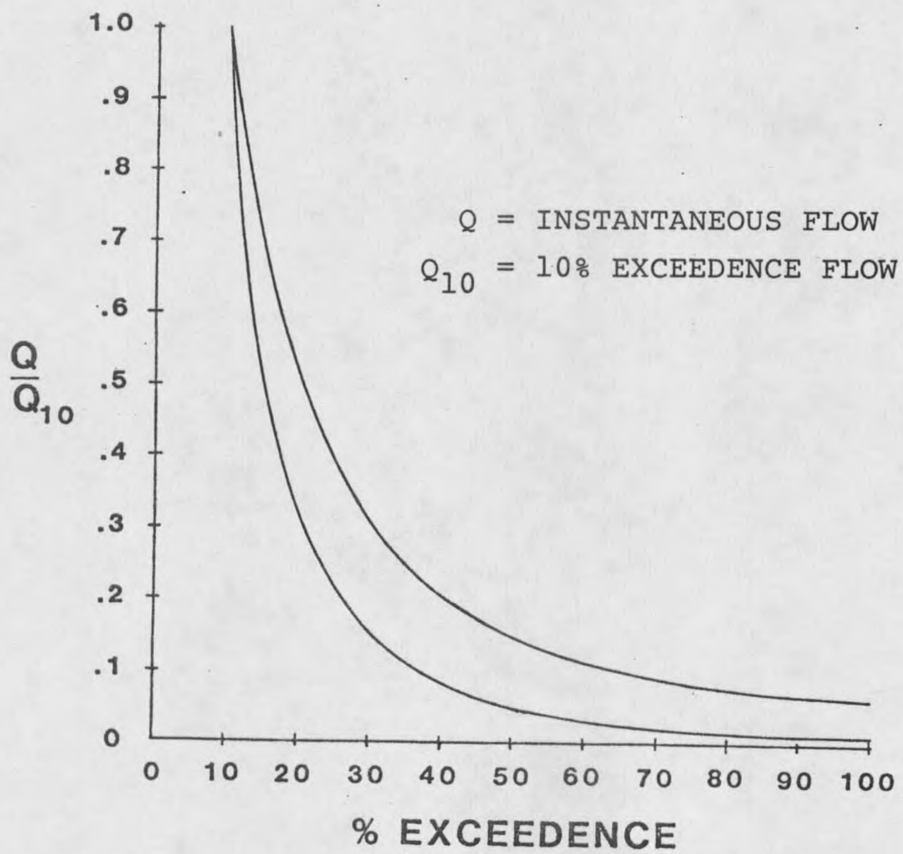

FIGURE 3. DIMENSIONLESS FLOW-DURATION CURVE BAND - MONTANA STREAMS (PERMISSION TO REPRODUCE)[3]

The curve synthesized for the area in question contains a degree of uncertainty because of the difficulty in assessing the hydrologic similarity between the basins used in the prediction. Any flow measurements at the site, when incorporated into the predicted F-D curve, will decrease the amount of risk associated with the synthesized F-D curve. Since long term flow records will probably not be obtained prior to final design of the project, some risk of inaccurate flow forecasts will still be present. It is necessary to identify the sources of uncertainty in the prediction procedure and to assess the consequences of inaccurate flow-duration curve prediction.

CHAPTER 4

HYDRAULICS

Small scale hydropower facility design utilizes the concepts of both open channel and closed conduit flow. The open channel flow concepts apply at the intake and outlet sections of the power plant. In addition, open channel principles apply to the diversion canal when used instead of a low pressure conduit. Closed conduit analysis applies to the penstock, draft tube and turbine. At the intake structure, the water surface elevation is dependent on the combined spillway flow and power plant diversion. In high and medium head systems where a small diversion structure forms the intake, operation of the turbine valving mechanism is such that the water surface elevation in the impoundment is held constant. This provides accurate minimum flow over a weir or other measuring device for maintenance of minimum fish requirements. At flows greater than the turbine maximum, the headwater elevation rises in accordance with the spillway rating curve. The low head system operates in much the same manner except in situations where storage exists and releases do not follow the reservoir inflow pattern.

In these cases the upstream elevation may fall far below the spillway crest. At the outlet of all types of plants, the tailwater elevation varies with the total streamflow, so the total gross head available at any given time depends on the hydraulic design and the stream flow. In cases of high and medium head design, the variation in gross head may be insignificant and hence neglected in hydraulic computations, simplifying computations greatly. The effects of headwater and tailwater elevation changes must be accounted for in the final design of the intake structure and powerhouse so that flood damage, turbine cavitation, and inadequate submergence of the intake are avoided.

The closed conduit portion of the power plant is analyzed using the energy equation written between the two free water surfaces:

$$\Delta z = h_e + V_2^2/(2g) + \Sigma h_{LP} + \Sigma h_{LM}$$

Where: Δz = Gross Head(ft)

h_e = Effective Head Removed by Turbine

V_2 = Draft Tube Exit Velocity (f/s)

g = Gravitational Acceleration (f/s/s)

h_{LP} = Pipe Friction Losses (ft)

h_{LM} = Minor Losses (ft)

It should be noted that effective head (h_e), is defined as the gross head minus the sum of all head losses in the system, excluding those in the turbine manufacturer's definition of efficiency. For steady state conditions, the hydraulic grade line exhibits a configuration as illustrated by Figure 4. The efficiency of the turbine is a measure of how well the effective head is removed. The efficiency varies with the flow rate due to the changing incidence angles of the streamlines to the guide vanes, valves, and turbine blades in a reaction turbine, and the variable jet velocity in an impulse turbine. In addition, varying efficiency is the result of variable head losses through the turbine manufacturer-supplied parts and the variable rotational speed when attached to an induction generator. The head losses accredited to turbine efficiency are all those between the upstream connection to turbine-supplied machinery and either a point just inside the draft tube as specified by the International Electrotechnical Commission (I.E.C.) Code or the equivalent still water surface after exit from the draft tube as specified by the American Society of Mechanical Engineers (A.S.M.E.) Code.[10] Turbines classified by the I.E.C. Code, therefore, will have higher efficiencies than those classified by the A.S.M.E. Code. The efficiency curves for different types of turbines are unique, but vary only slightly among manufacturers. For purposes of preliminary design and analysis, general efficiency curves based on proportions of design flow (at which peak efficiency occurs) can be used (Figure 5).