HYDROLOGIC STUDIES

VOLUME III

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SECTION 1
INTRODUCTION AND OVERVIEW

Scope and Objectives

This volume presents techniques and examples of procedures and references on investigations leading to investments in small hydroelectric power additions to existing facilities. Many of the procedures discussed are equally applicable to larger power installations but generally this volume is restricted to those structures which presently make use of present reservoir release patterns and authorized project purposes. Small hydropower additions are intended to make a nonconsumptive use of water presently flowing past the site or released from the impoundment for other purposes, generally consumptive in nature. Even if storage is not available at the damsite for other purposes, the hydraulic head created by the structure can often be economically utilized to generate electrical energy.

The definition of "small" as adopted in this guide manual, refers to installed capacities less than 15 MW. References are made to various publications containing detailed procedures beyond the intent of this volume. More comprehensive discussions can be found in these references on the concepts addressed herein.

Two levels of study are assumed when discussing techniques of investigation procedures. A reconnaissance level of study is discussed first. More detailed studies are then covered, which are intended to serve as the basis for investment decisions and licensing application requirements.

This volume presents procedures for developing data concerning stream flow, evaporation, capacity vs. average annual energy, spillway design, dam safety from overtopping and statistical data concerning generation patterns and power availability.

Overall Strategy for Hydrologic Study

The general procedure is to establish how much water is available to divert through a turbine and the hydraulic head associated with this flow. Information is needed on the variability of the flow presently passing or released from the structure. These data may be readily available from the project owner-operator or may require estimation from such records as are available at nearby points. Estimates should first be made with reconnaissance level of detail and later, if a feasibility level of study is warranted, they can be refined and prepared in greater detail. Net power head can be estimated based on pool level and tailwater elevations which prevail at least 50 percent of the time. Estimates of hydraulic losses can be based on engineering judgment. If average annual energy estimates appear to have a value exceeding the cost of adding the power plant to the existing facility, the next step is to evaluate the spillway for structural and hydraulic adequency. This entails the estimation of a spillway design discharge and an evaluation of the hydraulic characteristics of the existing spillway. Any structural rehabilitation or improvement costs are included in a second economic evaluation while still in a reconnaissance level of study. All costs for the power plant, including rehabilitation and improvements, should be compared with the expected value of average annual energy. If the project revenue from power exceeds power costs by a wide margin, a more detailed analysis should be made of all of the same basic items but to a greater level of accuracy. Figure 1-1 presents a diagram outlining the various tasks necessary to reach a meaningful conclusion to hydrologic aspects associated with the investment decision process.

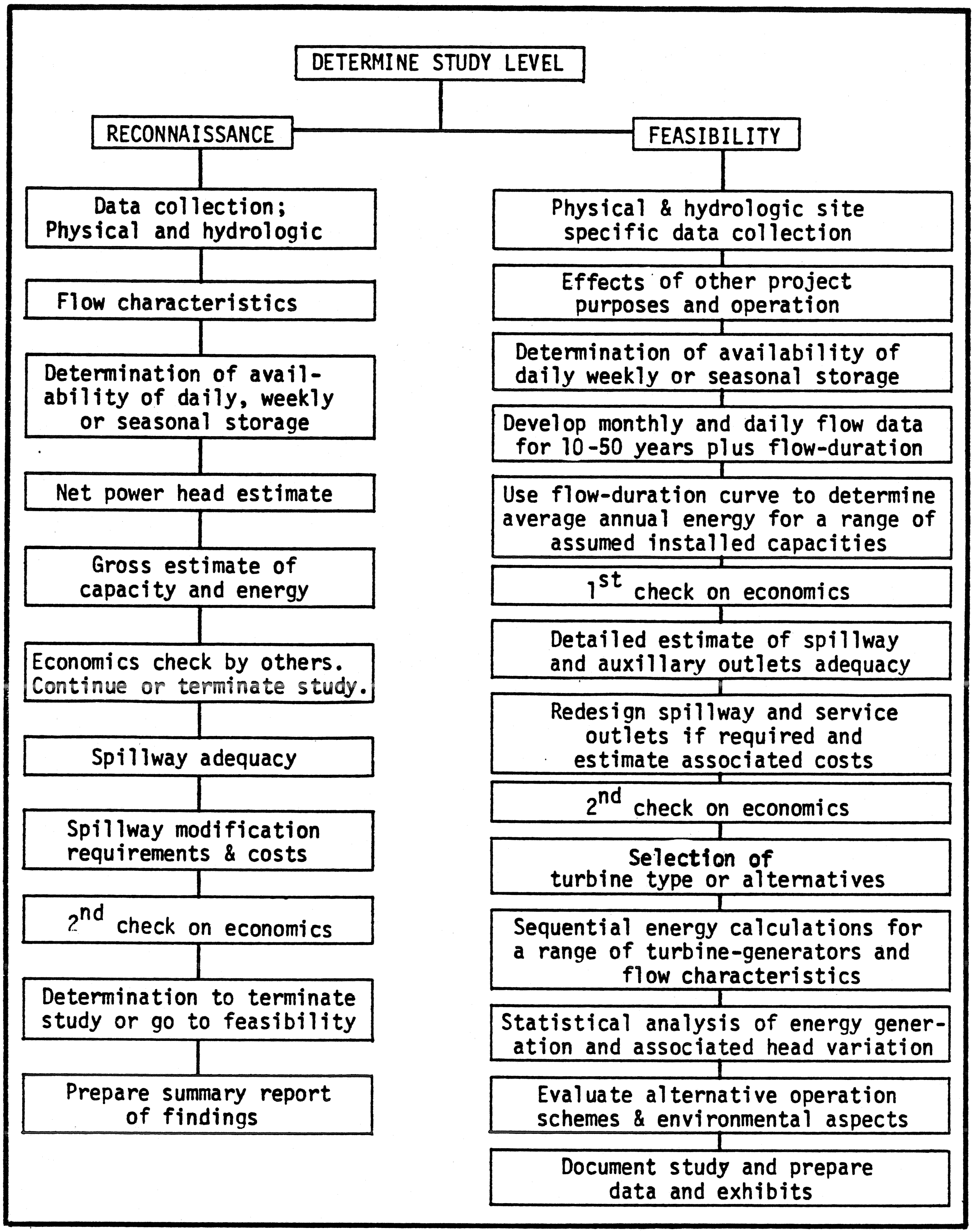


Figure 1-1. Hydrology and hydraulics study task outline for small hydropower additions to an existing facility.

SECTION 2
DATA NEEDS AND SOURCES

Level of Study

Although the basic data needs are not much different between the reconnaissance level of study and the feasibility level of study, the detail and accuracy of these estimates and the manpower expended to obtain them usually will be significantly different. For instance, all that may be needed in a reconnaissance level of investigation is an estimate of average annual flow, and average net power head. Some idea of the flow availability during low flow seasons and years is needed in order to estimate the likelihood of credit for dependable capacity. However, power benefits will typically be based on average annual energy generation since capacity will usually not meet the standard definition of "dependable".

Physical and Operational Data

Physical and operational data concerning the existing structure are fundamental to even a gross reconnaissance estimate of power potential and energy estimate. The following list indicates those items needed in the feasibility level of data collection with those minima data required for estimates at the reconnaissance level shown with an asterisk (*).

1. Maximum hydraulic height of dam.
2. Emergency spillway elevation, type and dimensions.
3. Maximum elevation at which water can be stored.
4. *Normal water surface elevation.
5. Maximum allowable drawdown or inactive pool elevation.
6. Outlet size, location and rating curve.
7. *Tailwater elevation at normal flow.
8. Surface area and storage versus elevation relationships.
9. Storage purposes, if applicable, and operation rules.

Terminology frequently applied to a dam and storage facility are shown schematically on Figure 2-1.

Hydrologic Data

Basic information and data are needed about the drainage area and run off characteristics of the watershed and any major water usage or diversions upstream of the dam. Usually these data are available in the files of the owner-agent or reports by State or Federal water resources agencies. Recorded pool elevations and releases should be compiled and adjusted to flow at the site under expected future conditions in order to make reliable estimates of hydopower potential. If no records have been kept, a search must be made for stream gages in the surrounding region for which comparisons and adjustments can be made to develop long term (10-50 years) daily and/or monthly flow data.

If daily flow data are readily available flow-duration data can be constructed from which to make average annual energy estimates. The accuracy of the capacity and energy estimates is dependent on the combined accuracy of estimating flow characteristics and corresponding head variability. The following list of hydrologic data required in feasibility level energy calculations shows those items needed for reconnaissance level studies marked with an asterisk (*).

1. Drainage area.
2. Daily and/or monthly flow data for an extensive period of time (10-50 years).
3. *Flow-duration curves.
4. *Tailwater elevation versus flow relationship.
5. Spillway and outlet rating curves.
6. Spillway design flood hydrograph.
7. *Project purposes, operation rules and storage available.
8. Evaporation rates.
9. *Seepage losses, fish ladder water requirements, diversions direct
from storage.
10. Pool elevation-duration data.
11. *Annual peak discharge data may be needed to assess the adequacy of the spillway capacity at some projects.
12. Minimum flow requirements downstream of the site.

Data Sources

The most logical source for both the physical and hydrological data is the operator-owner of the existing facility. The U.S. Corps of Engineers have been given the responsibility to prepare Phase I safety inspection and evaluation reports on high hazard non-Federal dams. These reports are a primary source of both reconnaissance and feasibility level data. State Division of Dams permit and inspection agencies files are a primary data source in many states.

The majority of continuous flow data are published by the U.S. Geological Survey (USGS). Mean daily flow data are published annually by state and five year summary reports are published by major river basin grouping. Data published by States and by the USGS are usually available in the State libraries, University libraries or libraries of Federal agencies such as the U.S. Army Corps of Engineers, Bureau of Reclamation, or Soil Conservation Service. District and Sub-District offices of the Geological Survey can obtain computer

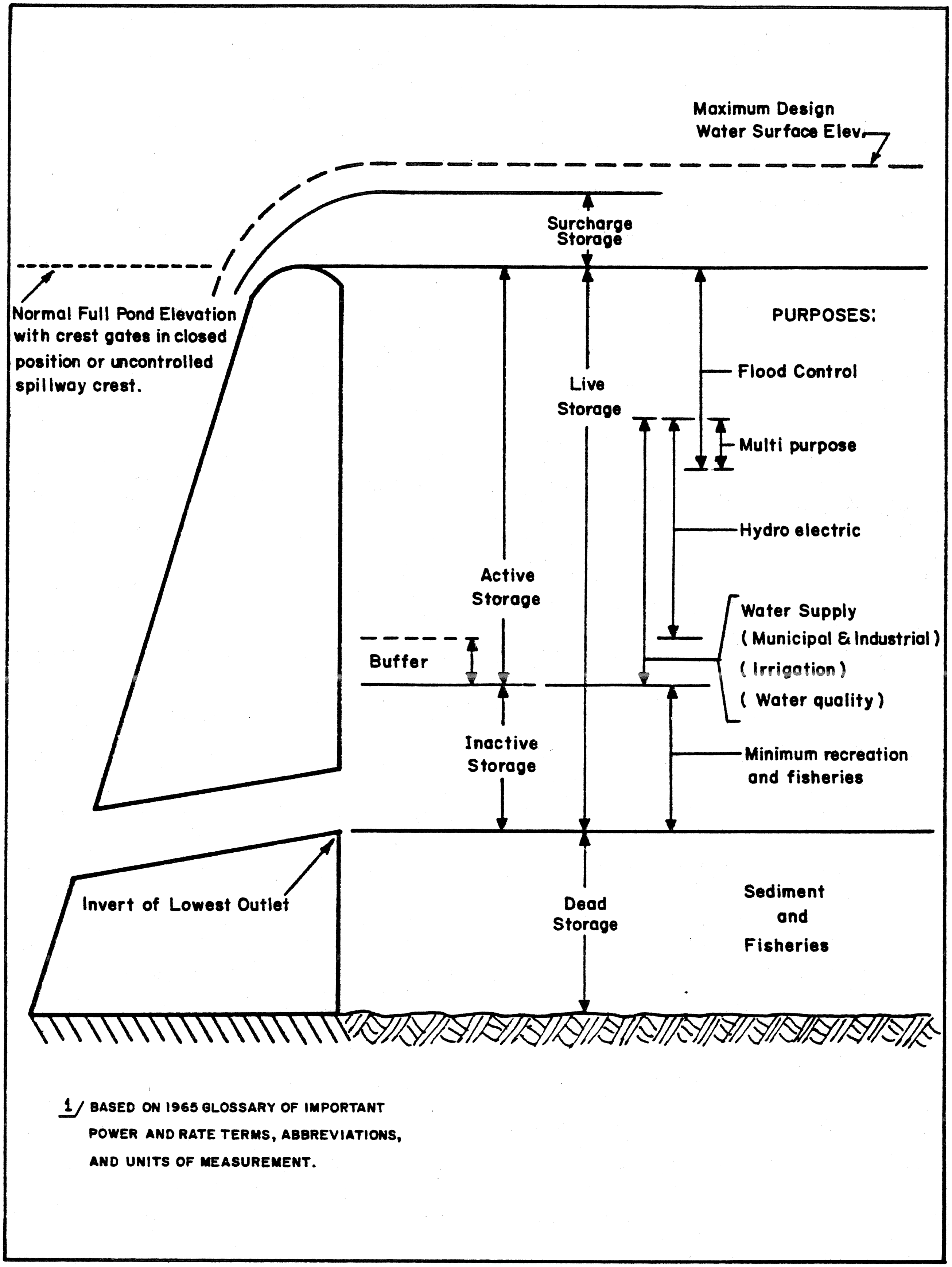


Figure 2-1. Illustration of reservoir terms.

listings from their National Water Data Storage and Retrieval System (WATSORE). Both daily values and annual peak discharges are available along with several statistical analysis capabilities. Frequently, utility companies, irrigation districts, water companies, and other water using organizations collect similar surface runoff data which may be published separately from the Geological Survey publications or may be unpublished but available if one is willing to spend the necessary effort to compile the data in a usable form.

Streamflow Correlation Studies

If streamflow data are not available at the project site, the nearest site of similar size and hydrologic characteristics should be evaluated as a source of data that can be proportioned by drainage area ratio. It would be preferable to have observed data as near as possible downstream of the project site in order to require a minimum of adjustment for runoff between the project site and the gage. This situation can also circumvent the necessity of adjusting for evaporation and diversion from the project. If comparison must be made strictly by site similarities or from a nearby upstream gage, adjustments must be made for any significant evaporation losses, diversions, seepage losses and fish ladder flow requirements. Sophisticated regional studies and correlation procedures are generally not warranted during reconnaissance studies and probably only infrequently even during feasibility studies. In a situation where a large investment cost and where installed capacities approach the upper boundary of this manual may be involved, it may be worthwhile to utilize a stochastic procedure for estimating long term flow sequences to evaluate extreme droughts. This would be particularly applicable if dependable capacity were an issue. Detailed discussion of correlation procedures and examples are contained in Hydrologic Data Management, Vol. 2, Corps of Engineers IHD 1972 and in most textbooks on hydrology and statistics.

Introduction. Stochastic procedures are only justified at the feasibility level of investigation and only then in those cases where dependable capacity is a significant issue and where project benefits warrant the extra study expenditure. The term "simulation" is applied to the mathematical or physical modeling of a phenomenon or process. In this section, it is used to denote only the mathematical modeling of a stochastic process. A stochastic process is one in which there is a chance component in each successive event and ordinarily some degree of correlation between successive events. Modeling of a stochastic process involves the use of the "Monte Carlo" method of adding a random (chance) component to a correlated component in order to construct each new event. The correlated component can be related, not only to preceding events of the series, but also to concurrent and preceding events of a series of related phenomena. Work in stochastic hydrology has related primarily to annual and monthly streamflows, but the results often apply to other hydrologic quantities such as precipitation and temperatures. A computer program, HEC-4 Monthly Streamflow Simulation, number 723-X6-L2340, that can be used for this purpose is available from The Hydrologic Engineering Center, Corps of Engineers, Davis, California.

Data Fill-In. Ordinarily, periods of recorded data at different locations do not cover the same time span, and therefore, it is necessary to estimate missing values in order to obtain a complete set of data for analysis. In estimating the missing values, it is important to preserve all statistical characteristics of the data, including frequency and correlation characteristics. To preserve these characteristics, it is necessary to estimate each individual value on the basis of multiple correlation with the preceding value at that location and with the concurrent or preceding values in all other locations. There are many mathematical problems involved in this process, and the details involved are discussed in the computer program description for HEC-4, 1971.

Reliability. While the simulation of stochastic processes may be able to add some dependability in hydrologic design, the techniques have not yet developed to the stage that they are completely dependable. All mathematical models involve some simplification of the physical phenomena represented. In most applications, simplifying assumptions do not cause serious discrepancies. It is important at this state of the art, however, to examine carefully the results of hydrologic simulation to assure that they are reasonable in each case.

Flow-Duration Curve

After monthly flow estimates have been completed, these can be analyzed to find critically low flow periods where several months or perhaps several years of daily flow data should be estimated. These data will be used to make more precise evaluations of electrical generation during average years and critical drought periods. If daily flow data are available, or can be developed with a reasonable degree of reliability, this should be done in order to compute a flow-duration curve for the complete period of record.

A duration curve of the observed, or estimated, flow characteristics at the site should be based on daily data. Adjustments for errors in estimates based on monthly curves can be made but results would likely be less reliable than those obtained from daily data. A duration curve is developed by grouping all the daily flow values into groups or classes within set ranges of discharge. Enough classes should be specified to reasonably define the curve (usually 10 to 30 classes). Starting at the highest discharge class, the number of days when the lowest range limit was exceeded is accumulated for successive classes and expressed as a percent of the total number of recorded days. An example of this procedure is illustrated in Table 2-1. A curve is then plotted with the lower range limit of each class as the ordinate and the precent of total events as the abcissa as shown in Figure 2-2.

Flow-duration curves developed from monthly data generally become increasingly less reliable if power storage is relatively small or nonexistent. Average discharge estimates made from flow-duration curves developed from monthly data will overestimate the average flow through a given turbine capacity by as much as 15 to 50 percent, depending on the day-to-day variability of flow. Figure 2-2 illustrates this possible source of error. Use of flow-duration curve will be discussed in Section 3.

Evaporation Data

Loss of water by evaporation can be a significant quantity in the arid western United States if there is a large surface area associated with the project storage. Generally this refinement is ignored at the reconnaissance stage of investigation. Gross evaporation for the reservoir area may be obtained from "Class A" pan records in the locality. These data are published by the Environmental Data Services of NOAA by States each month. Evaporation data obtained from Class A pans are too high and a coefficient averaging about 0.70 is commonly used to reduce them to equivalent evaporation values from a reservoir surface. Estimates can also be made by theoretical formulae but the availability of wind velocities and vapor pressure data required for the formula are less likely to be available than evaporation data. A good source of evaporation data or estimates is Federal, State, municipal, and private water agencies which collect these data at their existing projects.

Often the same monthly evaporation is used for each year of analysis, but if added refinement appears warranted, a greater evaporation rate can be used during drought years. Estimates of *net*evaporation at about 130 locations throughout the United States are contained in Exhibit I taken from EM 1110-2-1701 (U.S. Army Corps of Engineers, 1952). Average annual values in the sited reference range from 96 inches at Yuma, Arizona, to a minus 20 inches at Mobile, Alabama.

If energy calculations are based on flow data representing observed reservoir releases, canal flow or similar type data, no adjustment need be made to lake evaporation since it is already imbedded in the data.

Losses and Efficiencies

Losses. There are several reasons why all of the energy of flowing or stored water cannot be converted to useable electrical energy. Besides evaporation losses, there are seepage losses to groundwater, through the dam, and around gate seats, leakage losses through idle turbines, station use for sanitary and drinking purposes, cooling water use for generator bearings, and water use by navigation locks and fish ladders.

For existing structures, many of the possible sources of loss can be evaluated by observation or measurements. Large earth dams may exhibit losses as great as 5 to 10 cfs. Leakage losses through power plants vary, depending on the number, type, and size of turbine units and percent of time not operating. Estimates can be obtained from similar operating plants or from turbine manufacturers.

Efficiencies. Efficiencies of generators are dependent on design peculiarities but generally they can be expected to average about 97 percent within the operating range of the connected turbine. Turbine efficiencies depend on blade angle and design as well as draft tube design and placement. Best efficiencies generally occur at about 0.8 gate opening, at design head. Turbine efficiencies drop off as the net head falls below the rated head. Eighty-nine percent is frequently assumed for an average turbine efficiency in preliminary studies. If a speed increasing gear set is used to increase the rotational speed of the generator over that of the turbine, another 2 percent in efficiency is usually lost. The various turbine designs and efficiency characteristics are discussed in Volume V "Electromechanical Equipment".

TABLE 2-1
FLOW DURATION CURVE COMPUTATION

07144200 LITTLE ARKANSAS RIVER AT VALLEY CENTER, KS

LOCATION.--Lat 37°49'56", long 97°23'16", river gage is in NE¼NW¼SW¼ sec.36, T.25 S., R.1 W., Sedgwick County, Hydrologic Unit 11030012, at downstream side of highway bridge, 0.5 mi west of Valley Center, and 17.5 mi upstream from mouth. Little Arkansas River Floodway gage is in NE¼NE¼NE¼ sec.34, T.25 S., R.1 W., at downstream side of highway bridge, 1.2 mi northwest of river gage.

DRAINAGE AREA.--1,327 mi², of which about 77 mi² is probably noncontributing.

PERIOD OF RECORD.--June 1922 to September 1976.

REMARKS.--Natural flow of stream affected by diversions and ground-water withdrawal for irrigation and municipal supply. Since May 1957, part of high-water flow bypasses river gage through floodway channel for which separate records are computed; figures representing combined discharge are given herein.

AVERAGE DISCHARGE.--54 years, 273 ft³/s, 197,800 acre-ft/yr.

Source: U.S. Geological Survey, Reston, VA.

DURATION TABLE OF DAILY VALUES FOR YEAR ENDING SEPTEMBER 30

DISCHARGE, IN CUBIC FEET PER SECOND
MEAN
L ARKANSAS R AT VALLEY CENTER, KS

NUMBER OF DAYS IN CLASS

CLASS / YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1923										1	13	68	124	49	26	10	20	9	5	4	3	6	4	3	3	1	4	1	6	1	3	1			
1924												5	34	33	55	114	60	20	8	10	8	3	6	2	1	2		2	2	1					
1925											79	54	105	103	12	6	4	1		1															
1926										49	95	156	32	7	3	6	5	6	1	3	1	1													
1927													28	151	49	26	25	17	8	6	7	5	10	10	7	3	5	3		4	1				
1928													9	62	156	28	32	20	11	7	8	10	5	3	6	6	1	1	1						
1929													21	67	118	46	33	20	10	7	7	5	4	5	3	6	2	4	4	2	1				
1930											2	24	45	102	100	49	17	4	6	3	5	2	1		1	3	1								
1931									3	29	36	45	175	60	8	5		1	1	1	1														
1932										6	38	41	51	117	38	25	12	8	4	3	4	5	6	2	4	1	1								
1933								27	40	21	4	98	111	16	6	9	6	3	4	3	1	6	1	1	5	3									
1934								2	24	99	65	122	27	10	4	3	5	3	1																
1935									7	6	64	153	45	18	5	5	11	9	6	7	3	4	2	2	1	4	3	6	2	2					
1936								18	21	41	31	171	54	14	5	3	3	1	2				2												
1937											66	105	57	39	19	16	8	10	4	5	7	7	6	4	6	4	2								
1938											2	169	38	26	29	19	14	10	4	8	6	6	3	11	6	6	4	2	1		1				
1939												16	152	96	26	15	15	13	5	4	5	1	3	3	3	3	3	2							
1940											12	131	96	38	21	17	16	14	3	2	4	3	2	2	3	1	1								
1941											14	37	99	100	26	23	17	8	9	4	7	3	1	4	3	2	2	3	1	1	1				
1942															62	77	69	35	27	16	9	15	7	13	9	7	7	10	2						
1943													24	24	63	76	76	26	14	17	11	10	7	4	5		4	1	3						
1944													30	80	59	34	29	31	18	10	7	11	8	5	10	2	8	4	6	4	7	2		1	
1945														26	16	63	96	52	22	15	11	11	12	10	7	6	6	2	2	2	1	3	1		1
1946												41	41	39	99	73	34	13	5	9	4	1		2	2		1		1						
1947												24	72	78	47	26	27	17	12	14	8	4	8	1	6	10	3	5	1	1		1			
1948												16	61	61	46	36	28	14	12	18	9	10	9	7	7	3	3	9	8	5	4				
1949														7	65	61	54	31	21	18	15	19	15	10	9	11	10	17	2						
1950													9	179	67	21	15	10	2	6	7	8	6	9	3	9	5	3		4	2				
1951													4	18	137	23	14	13	21	17	16	15	14	12	10	11	6	7	7	8	3	4	4	1	
1952												6	54	39	9	23	109	47	27	17	11	6	9	1	3	3	2								
1953										6	29	47	116	113	20	11	10	2	4	4	1	2													
1954									28	58	42	132	57	19	9	5	7	2	1	1			3		1										
1955						10	30	31	8	99	98	41	21	3	6	3	5	1	1	1	1	1	1			1	1	2							
1956				1	30	23	10	18	26	42	120	57	12	4	5	3	3	3	1	1	1		1	2		1	2								
1957		3		5	7	6	3	35	73	38	1	1	38	20	8	20	17	14	10	10	13	6	6	5	7	2	1	2	2	6	4	1		1	
1958												10	123	28	11	19	55	28	13	17	8	7	5	3	4	8	9	8	6	2		1			
1959											6	34	12	77	110	42	29	16	14	4	3	4	4	1	3	2	1	3							
1960													1	64	48	43	39	47	23	17	13	15	8	6	11	9	4	5	3	6	2	2			
1961														12	110	85	48	38	20	15	10	18	3	4	4	6	1	1	2	2	1	1			
1962													6	25	56	89	61	32	21	18	10	3	8	7	8	3	6	1	4	1	2	2		2	
1963										2	9	26	48	68	130	33	16	7	4	4	6	3	1	5	1	1	1								
1964										8	10	39	138	72	25	17	14	10	8	5	4	4	2	2	2	5	1								
1965											23	12	10	107	52	29	28	15	8	10	16	9	4	5	4	7	5	6	8	4	1	1	1		
1966											29	30	40	66	122	36	17	8	3	6	2	2	1		2	1									
1967										14	84	121	14	12	11	11	8	10	9	9	10	10	6	4	10	3	9	5	2	3					
1968										4	17	25	51	107	76	28	15	13	7	4	3	2	1	1	6	2		2	1	1					
1969											4	4	23	30	76	41	46	26	23	14	14	12	6	9	10	6	7	4	5	3	1	1			
1970										7	27	18	30	133	49	27	25	13	5	4	5	2	4	1	5	1	5	2	1	1					

SUMMARY FOR 1923-1970

CLASS	VALUE	TOTAL	ACCUM	PERCT	CLASS	VALUE	TOTAL	ACCUM	PERCT	CLASS	VALUE	TOTAL	ACCUM	PERCT
0	0.00	0	19724	100.0	12	30.0	2552	15490	78.5	24	1100	240	1033	5.2
1	1.00	3	19724	100.0	13	41.0	2986	12938	65.6	25	1500	197	793	4.0
2	1.50	0	19721	100.0	14	56.0	2582	9952	50.5	26	2100	170	596	3.0
3	2.00	6	19721	100.0	15	75.0	1710	7370	37.4	27	2800	156	426	2.1
4	2.70	37	19715	100.0	16	100.0	1537	5660	28.7	28	3800	98	270	1.3
5	3.70	39	19678	99.8	17	140.0	913	4123	20.9	29	5100	78	172	.8
6	5.00	43	19639	99.6	18	190.0	556	3210	16.3	30	6900	46	94	.4
7	6.70	131	19596	99.4	19	250.0	458	2654	13.5	31	9400	30	48	.2
8	9.10	230	19465	98.7	20	340.0	372	2196	11.1	32	13000	11	18	
9	12.00	530	19235	97.5	21	460.0	319	1824	9.2	33	17000	5	7	
10	17.00	1037	18705	94.8	22	620.0	258	1505	7.6	34	23000	2	2	
11	22.00	2178	17668	89.6	23	840.0	214	1247	6.3					

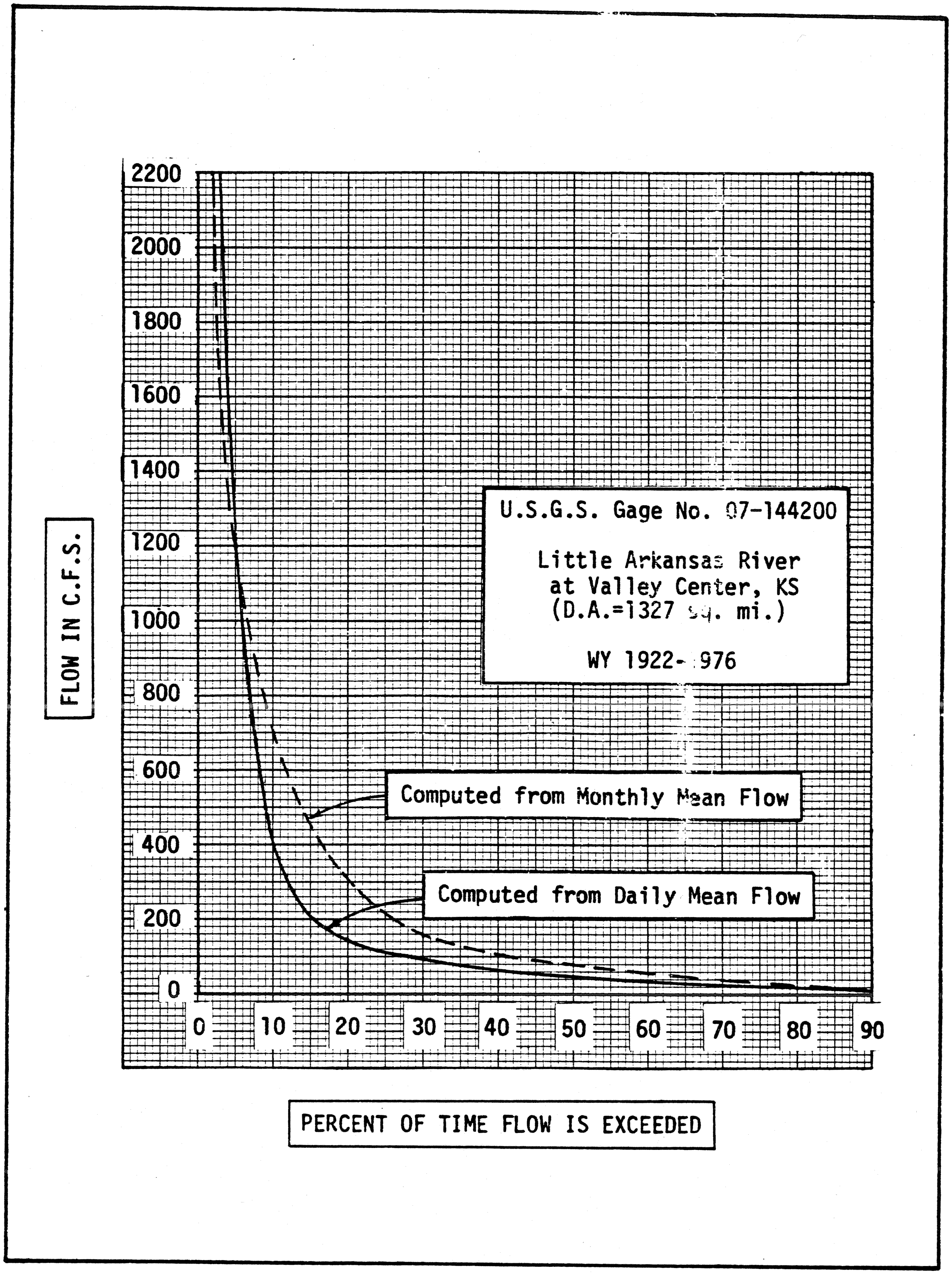


Figure 2-2. Flow duration curves.

SECTION 3
CAPACITY AND ENERGY CALCULATIONS

Energy-Flow-Head Relationship

The fundamental procedure for generating electrical energy from flowing water between different elevations is to convert kinetic energy to electrical energy by means of a prime mover (turbine, et al.) connected to a generator which is in-turn connected to an electrical load. The energy, in foot pounds, is measured by the weight of the water in pounds (equal to 62.4 lbs/ft^3) times the quantity of water (Q) in cubic feet (ft^3) multiplied by the elevation difference (head) in feet (H) through which the water drops. Mechanical power is the rate of this energy transformation or work done in a specified time. The usual unit of power is horsepower (550 foot-pounds per second) and is equal to 62.4 times Q in c.f.s. times H divided by 550.

$$\text{Mechanical power (hp)} = (62.4 \times Q \times H) / 550 = (Q \times H) / 8.81 \quad (3\text{-}1)$$

This is the theoretical power at 100 percent efficiency. The actual power developed on the turbine shaft is adjusted by multiplying by the turbine efficiency (E_t). The kilowatt output of the generator is determined by multiplying by the conversion factor from horsepower to kilowatts (.746 hp/kW) and by the generator efficiency E_g thus

$$\text{Electrical power (kW)} = (Q \times H \times E_t \times E_g) / 11.8$$

A major effort of the hydrologic investigations deals with estimating the long term values and sequential variability of the flow and developing operational criteria which will lead to a determination of the corresponding change in head (H). Existing project purposes must generally be met while providing the additional hydro—power benefits.

Reconnaissance Sizing Procedures

Reconnaissance Estimates. Simplified methods using estimates for the variables in the power equation presented are typically used to make estimates of capacity and energy at potential power sites in order to determine the desirability of expending more time and funds to refine these preliminary estimates. Also, these approximate methods are used to "screen" large numbers of potential sites to a more select group of most likely candidates for development. Screening based on factors other than capacity and energy is also a necessary study step, but this section is limited to capacity and energy aspects.

Duration Curve Analysis. A duration curve of the observed, or estimated, flow characteristics at the site should be based on daily data. A typical curve for a stream with low base flow is shown in Figure 3-1. The area under the curve represents the average flow. The average daily observed runoff at this site for the period June 1922 to September 1976 was 273 cfs. If a run-of-river site evaluation were to be made for a dam with an estimated net power head of 30 feet at an assumed plant efficiency of 86 percent we could use the power formula to estimate the site capability:

$$\begin{aligned}\text{Site capability} &= (Q \times H \times E) / 11.8 \\ &= (273 \times 30 \times .86) / 11.8 \\ &= 597 \text{ kW}\end{aligned}$$

If the plant could generate continuously at this rate it would produce 5.2 $\times$ 10^6 kWh of energy in a years time. However, it is apparent from inspection of Figure 3-1 that a flow rate of 273 cfs is available about 13 percent of the time and with no storage available to capture water during these periods of above average flow, 87 percent of the time the generator would be operating at less than name plate capacity.

Assume that regional studies have developed a guidance rule that turbines should be designed for a flow that will be exceeded at least 15 percent of the time. From the flow-duration curve, a flow of 200 cfs is shown to be exceeded 15 percent of the time. This would establish a preliminary turbine-generator selection of

$$(200 \times 30 \times .86) / 11.8 = 437 \text{ kW}.$$

The allowable operating range of the turbine is determined by the type of turbine and its characteristics as discussed in Volume V. If the selected turbine can only be operated within a flow range of 30 to 110 percent of the design flow, the lower limit of operation would be about 60 cfs (.30 $\times$ 200). The flow duration curve indicates the flow of the river is less than 60 cfs about 58 percent of the time. Also, it is likely that at extremely high flows the tailwater will rise so high that the net power head will become too small for the powerplant to function. If this should occur when discharges exceed 3,000 cfs, an additional two percent of the time or about seven days a year on the average would be unsuitable for power production. Therefore, about 60 percent (58 + 2) of the time the plant would be inoperable, unless there is available storage to regulate flows to more favorable discharge rates. The energy potential from the site would now be restricted to the area shown cross hatched on the flow-duration curve (Figure 3-1). The cross-hatched area under the curve is equivalent to 54.5 cfs flowing 100 percent of the time. Converting this flow

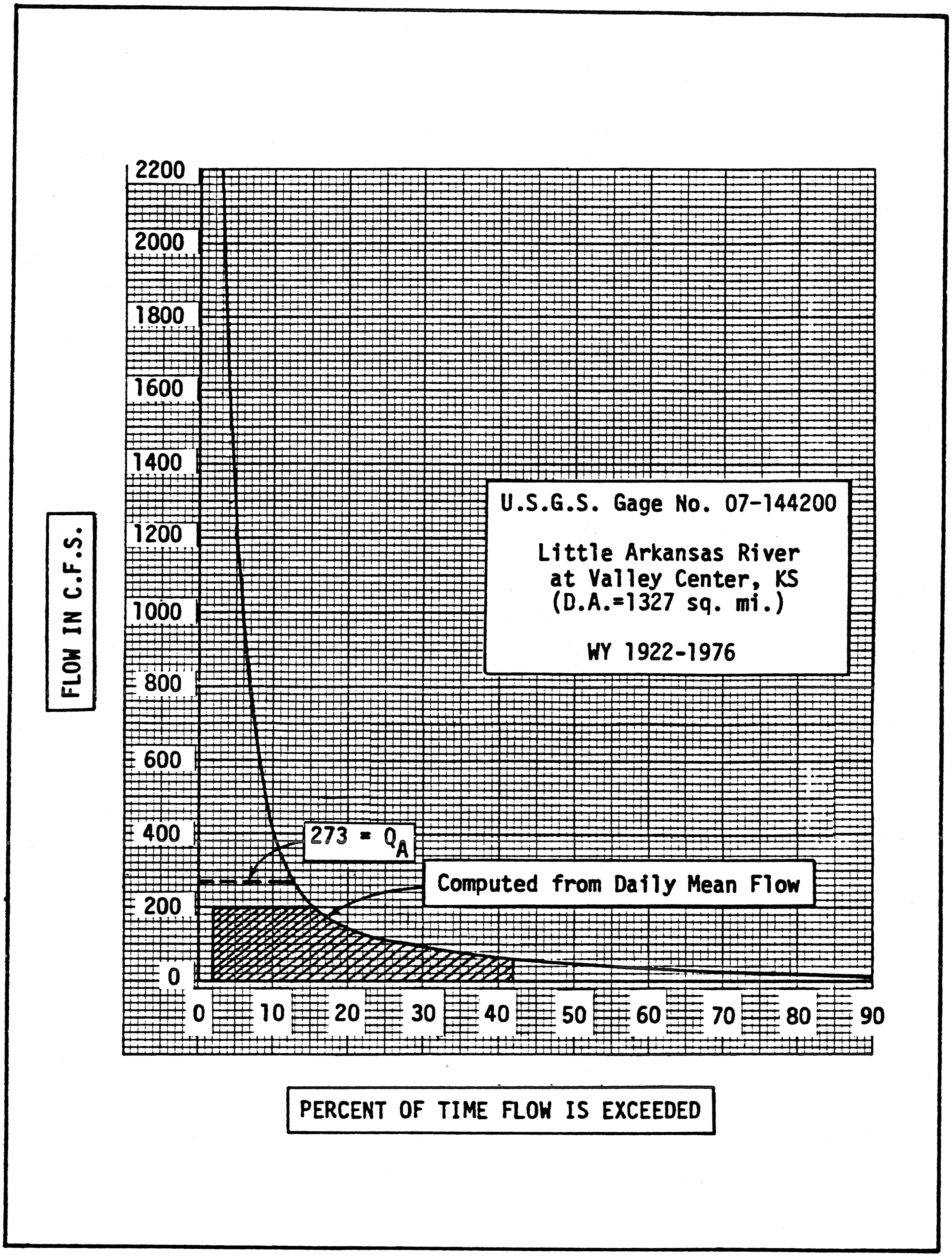


Figure. 3-1. Flow duration curve.

to average annual energy we get

Average annual energy
$= (54.5 \times 30 \times .86 \times 8760) / 11.8$
$= 1.044 \times 10^6$ kWh.

An average annual capacity factor or plant factor of 27 percent $(1.044 \times 10^6 / (437 \times 8760))$. Installation of two units of 218 kW each would allow generation until the flow fell below 30 cfs and would result in approximately 200,000 kWh per year more energy and 23 percent more time when at least one unit of the plant could operate. However, the value of this additional energy may not justify the added expense of 2 units, instead of one unit twice the size.

A similar procedure could be used to work through reconnaissance estimates of several assumed plant sizes. With appropriate cost and energy value curves, rough economic analysis could be completed. If some pondage (storage) were available to store low flow and release it during a shorter period each day, electrical energy could be generated from the stored flow. For example, a continuous flow of 60 cfs accumulates to about 85 acre feet in 17 hours time. So, with that amount of pondage, water could be stored for 17 hours and used to generate at capacity during the other 7 hours each day. As the inflow dropped to 30 cfs storage would be required for a longer period of time or generation would be at less than nameplate capacity, or some combination of the two. There could be water quality, environmental, recreational, and other reasons why a store-release pattern of flow would be undesirable. If greater amounts of storage were available in this hypothetical problem, surplus flow could be stored during times when flow exceeds 200 cfs and released during periods of flow deficiencies, depending on water rights, project purposes, and other operating constraints.

The above analysis is based on a run-of-river situation where net power head is likely to be nearly constant. If existing project purposes are such that this is not true, a reconnaissance estimate would use an estimate of average net power head. If the project were evaluated to be economically favorable at this point, more detailed energy evaluations would be conducted using a sequential monthly or daily analysis.

Sequential Period of Record Routing

The most reliable estimates of energy yield from a given set of inflow and storage data can be obtained from sequential analysis. The time interval chosen for sequential analysis should be consistent with the accuracy desired. In the case of power estimates during feasibility studies the maximum time interval used should not exceed one month. Feasibility estimates of firm energy should be based on daily or weekly time intervals during critical periods using all available information on project purposes, diversions, seasonal storage levels, losses, tailwater rating, and plant efficiency data. If "dependable capacity" is not a consideration, a monthly analysis for the entire period of record will usually suffice.

Importance of Load Pattern. If dependable capacity is a serious consideration, the seasonal load pattern is an important variable in determining firm power and firm energy estimates. This is true because the project must be capable of delivering its credited firm power during the most critical drought period and coincident load pattern. The importance of whether the load pattern (curve) is synchronized with the seasonal flow pattern can be seen in Figure 3-2. This example is taken from a water supply demand but is illustrative of the increased storage or decreased yield which comes from flow versus demand patterns. A project that has either the water demand or energy demand schedule "out-of-sync" with the inflow pattern will require a greater amount of storage from which to draw the needed demand. Generally, increasing storage is not an alternative in small hydropower additions. If existing project purposes require release patterns which are near enough to the energy demand, or useable on the load, some dependable capacity can be credited to the project.

Typically load patterns fluctuate throughout the day and are lower on Saturdays and Sundays. Figure 3-3 shows an hourly load curve for a typical week of a large electric utility system. The peak demands on a system vary from week to week and from month to month throughout the year. The system related to Figure 3-3 has its highest demand in August and its average annual demand is about 60 percent of its annual peak (annual load factor = 60%) and monthly load factors range from 65 to 75 percent.

Figure 3-3 shows the role played by hydroelectric energy sources in meeting peak power demands each day. Run-of-river plants could be used to assist in meeting base load requirements. It is apparent that if a hydroplant only generates during the hours of high demand each day, reservoir storage (or pondage) must be available to store water during the remainder of the day or water will pass thru the project without producing power. Energy generated to meet peak demands has greater value as it would replace more expensive fuel consuming sources as discussed in Volume II of this guide manual. However, when used to replace nonrenewable energy sources, hydropower has considerable value, regardless of its position in the load curve.

Seasonality of Storage Allocation. Multipurpose projects usually allocate the total available storage to the various purposes proportional to some cost and benefit relationship or to achieve prescribed objectives. Often these objectives have conflicting demands on storage, such as when flood control storage must be evacuated as soon as possible after an occurrence of surplus inflow, whereas a power purpose would prefer to hold it until it could be evacuated through the turbines. If the season when major floods occur is a different season than when the highest demand for energy occurs, some of the flood control space can be seasonally assigned to power and

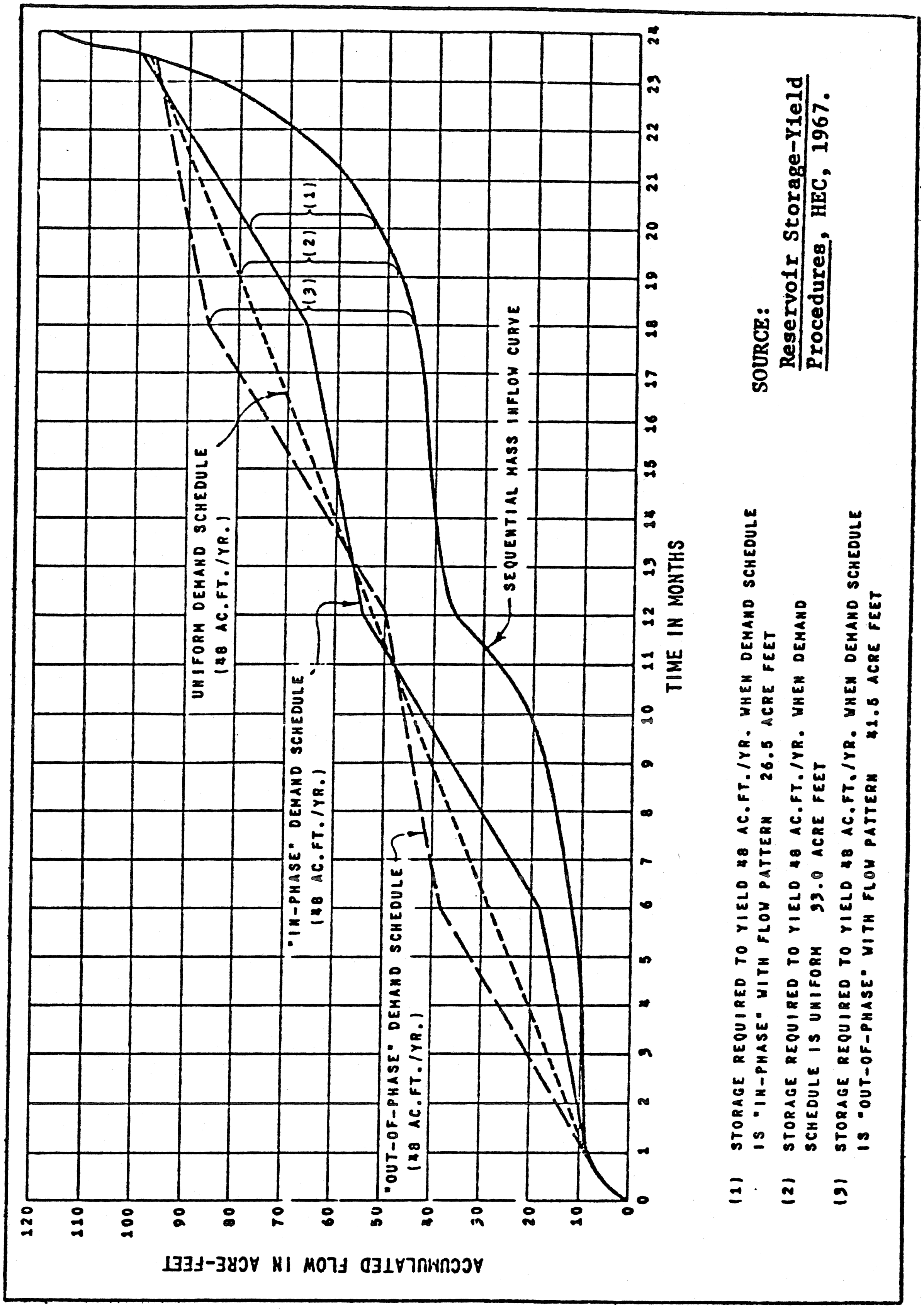


Figure 3-2. Effect of demand sequence on storage requirement.

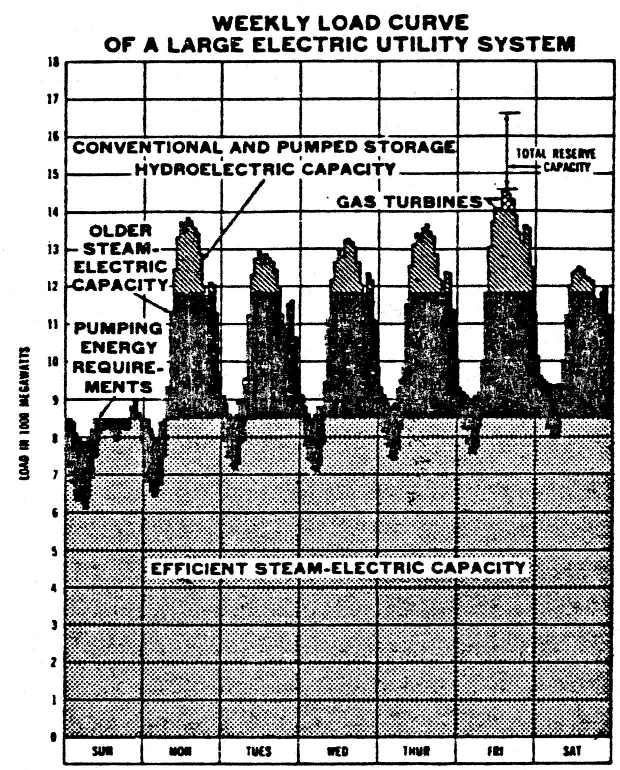
thus obtain a multiple-use of common storage space. The depth of such studies is generally beyond the scope of the small hydropower investigation.

Head Limitations. Each turbine type and design has its own efficiency characteristics as discussed and illustrated in detail in Volume V. Even reconnaissance estimates of power potential at a site should account for efficiency characteristics and an operating range limitation consistent with the turbine type likely to be installed. Operating head ranges of 60 to 120 percent of the design or rated head are typical of the limitations which must be kept in mind when determining the amount of active storage which can be used for energy generation. When performing sequential routings during feasibility studies it is common practice to incorporate the efficiency characteristics of the turbine-generator system into the computations rather than using a uniform efficiency at all head values.

Computational Aids. It is almost a practice of the past to do sequential routing by hand computations and "spread-sheet" accounting, but there are several computational aids that provide valuable tools for checking computer output and assisting in making better estimates than can be otherwise made. These include curves or tables of storage-elevation-area, tailwater rating, storage-efficiency curves and storage-evaporation-month of year tables. A typical format of an elevation-area-storage table is illustrated in Table 3-1 and several formats for hydropower sequential analysis are shown in Table 3-2. Several of these can be combined to develop the kW/cfs nomograph shown in Table 3-3 and Figure 3-4 which is almost a necessity for sequential routing by desk top calculator.

Computer Programs

With the increasing availability of computer service firms and reasonably priced but powerful mini com-



Source: FCC P-35 Hydroelectric Power Evaluations, Federal Power Commission (FERC) 1968

Figure 3-3. Weekly load curve of a large electric utility system.

TABLE 3-1.
EXAMPLE OF ELEVATION-AREA-STORAGE TABLE

ROLLINS RESERVOIR NR CULFAX, CA (11421800) AREA AND CAPACITY TABLE (CONIC)

ELEV FEET	CAP AREA .0	CAP AREA .1	CAP AREA .2	CAP AREA .3	CAP AREA .4	CAP AREA .5	CAP AREA .6	CAP AREA .7	CAP AREA .8	CAP AREA .9
2060.0	11027	11051	11075	11100	11124	11148	11173	11197	11222	11246
	242	242	243	243	243	244	244	245	245	245
2061.0	11271	11295	11320	11345	11369	11394	11419	11444	11468	11493
	246	246	246	247	247	248	248	248	249	249
2062.0	11518	11543	11568	11593	11618	11643	11669	11694	11719	11744
	249	250	250	250	251	251	252	252	252	253
2063.0	11769	11795	11820	11846	11871	11897	11922	11948	11973	11999
	253	253	254	254	255	255	255	256	256	256
2064.0	12024	12050	12076	12102	12128	12153	12179	12205	12231	12257
	257	257	258	258	258	259	259	260	260	260
2065.0	12283	12309	12335	12362	12388	12414	12440	12467	12493	12519
	261	261	261	262	262	263	263	263	264	264
2066.0	12546	12572	12599	12625	12652	12678	12705	12732	12759	12785
	264	265	265	266	266	266	267	267	268	268
2067.0	12812	12839	12866	12893	12920	12947	12974	13001	13028	13055
	268	269	269	269	270	270	271	271	271	272
2068.0	13082	13110	13137	13164	13192	13219	13246	13274	13301	13329
	272	273	273	273	274	274	275	275	275	276
2069.0	13357	13384	13412	13440	13467	13495	13523	13551	13579	13607
	276	276	277	277	278	278	278	279	279	280

CAP = STORAGE CAPACITY IN ACRE-FEET
AREA = LAKE SURFACE AREA IN IN ACRES

TABLE 3-2.
TYPICAL FORMAT FOR HYDROPOWER SEQUENTIAL ANALYSIS

PROJECT NAME ____________ Computed by ____________

Date ____________

FIXED DATA:

Installed Capacity ____________	Representative Gage ____________
Overload Factor ____________	Data Sources ____________
Effeciency ____________	Spillway (Elev/Stor) ____________
Penstock Loss ____________	Top of Power Pool (Elev/Stor) ____________
Tailwater Elev. ____________	Bottom of Power Pool (Elev/Stor) ____________

Yr.	Mo.	Inflow (cfs)	End of Mo. Storage (Ac. Ft.)	End of Mo. Elevation (Ft.)	Net Power Head. (Ft.)	Released Water — cfs — Irr.	W.Q.	Fish	Spill	Flow Through Turbine	Unit Power (KW/cfs)	Power (KW)	Energy (KWh)	Energy Potential Wasted (KWh)
														(Spill, Fish ladder, leakage, etc)
			On a simple analysis, columns marked (*) may be unnecessary											
		*	*			*	*	*						*

A more complex accounting of variables might require adding the following column headings:

Area (Ac.)	Evap. (Ac. Ft.)	Pool Index Level	Tail-Water Elev. (Ft.)	Plant Effic. (%)	Diversion From Pool (cfs)	Total Flow Past Project (cfs)	Required Power (KW)	Power Shortage (KW)	Release Case (Index No.)	**Remarks**

Legend:

- Irr. = Irrigation requirement
- W.Q. = Water quality
- Fish = Fish ladder requirements
- Eff. = Efficiency of generator and turbine

puters, it is almost easier to make a monthly sequential analysis than to plot a duration curve and make reconnaissance estimates. The results are more accurate and costs are comparable. Basic input requirements of well documented computer programs can be expanded and upgraded to the level of precision required in later feasibility estimates.

Utility computer programs, which can develop detailed tabular data of elevation-storage-area relations and tailwater and spillway rating curves, are readily available from State and Federal water resources agencies at minimal handling charges. One such source available to both public and private sectors is the U.S. Army Corps of Engineers, Hydrologic Engineering Center. Abstracts of several such applicable programs are contained in Exhibit II. A comparison of several computer models developed by the Corps of Engineers is contained in Table 3-4. An example of user specified output format using HEC-5C for a run-of-river project, where outflow is dependent on criteria other than power demand, is illustrated in Table 3-5.

TABLE 3-3
SAMPLE KW/CFS NOMOGRAPH COMPUTATION PROCEDURE

Pool Elevation (ft, m.s.l.)	Storage(1) (wsf/1000)	Net Head (2) (ft)	Efficiency(3) (%)	kW/cfs(4)
1131	145.2	203.5	83.2	14.34
1128	136.0	199.5	84.0	14.19
1124	127.3	195.5	84.6	14.01
1120	119.0	191.5	85.1	13.80
1116	111.0	187.5	85.5	13.58
1112	103.5	183.5	85.9	13.35
1108	96.3	179.5	86.1	13.09
1104	89.5	175.5	86.3	12.83
1100	83.0	171.5	86.1	12.51
1096	76.9	167.5	85.9	12.19

Based on constant average tailwater at elevation 927.8 ft, m.s.l. with assumed constant penstock losses of 0.7 ft.

(1) The use of storage in week-second-feet (wsf) for this example is based upon the selection of a week as the routing interval and week-second-feet as the flow units.

(2) Net head = pool elevation - penstock losses - average tailwater (Both penstock loss and average tailwater may be varied with pool elevation if relationship known).

(3) Overall station efficiency (may be assumed constant at all pool elevations).

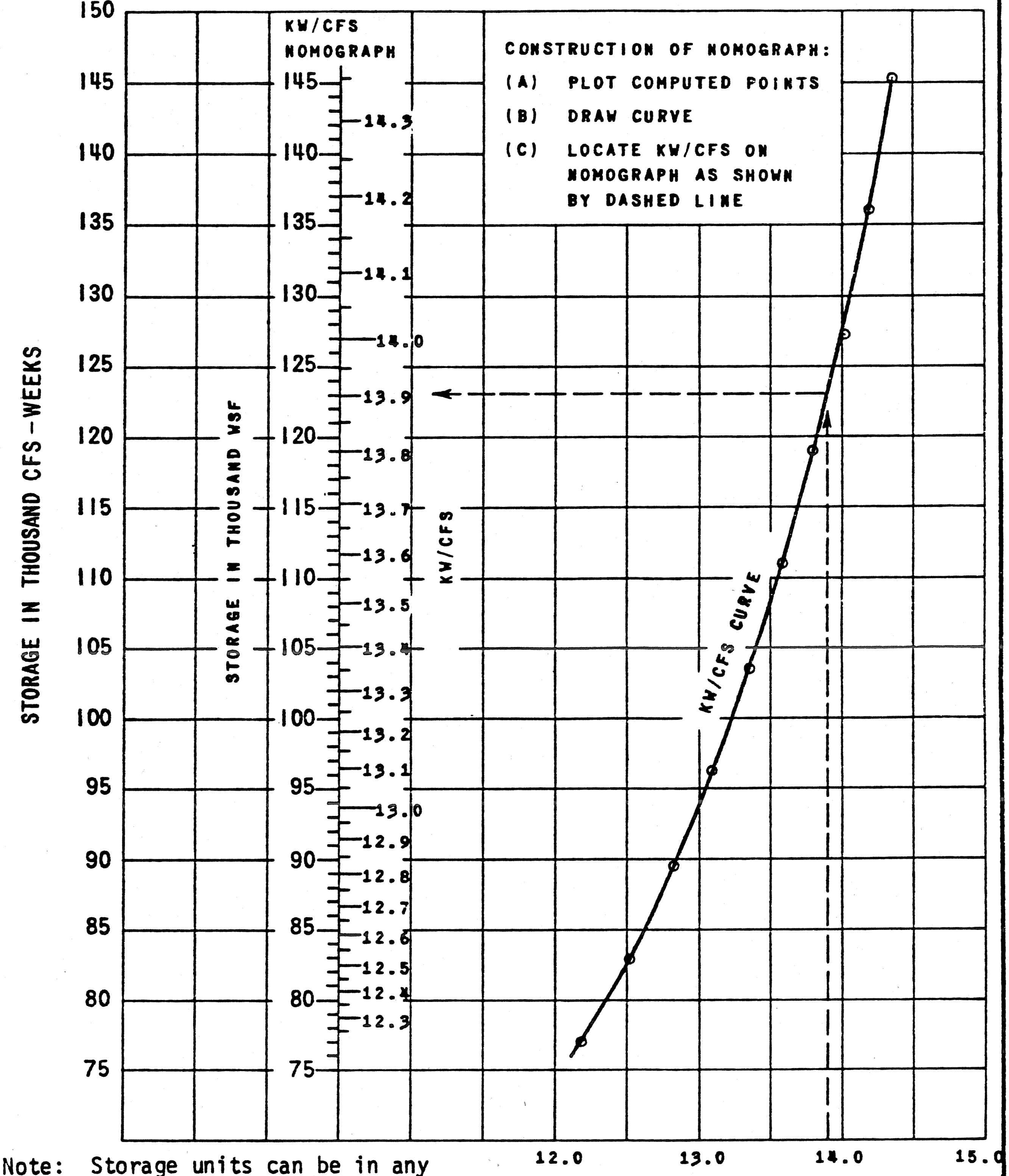
(4) kW/cfs = Head × Eff × .08474

(Source: U.S. Army Corps of Engineers, HEC, 1967, **Methods Systemization Manual, Reservoir Storage-Yield Procedures**.)

TABLE 3-4
COMPARISONS OF HYDROLOGIC MODEL CAPABILITIES IN HYDROPOWER STUDIES

		HEC-5C	HEC-3	SWD SUPER	HYSSR	NPD HYSIS(1)	HLDPA(2)
a.	Routing Intervals	Any	Monthly	Daily	Monthly or 2 weeks	1-4	Hourly
b.	Routing Methods	6	No	Puls	No	SSARR	SSAAR
c.	System Power Operation	Yes	Yes	Yes	Yes	Yes	Yes (also thermal)
d.	Yield Maximization	Yes	Yes	No	No	No	No
e.	Peaking Capability	Yes	Yes	Yes	Yes	Yes	Yes
f.	Evaporation	Yes	Yes	Yes	Yes	SSARR	SSARR
g.	Power Benefits	Yes	Yes	Yes	No	No	No
h.	Flood Control	Yes	No	Yes	No	Limited	No
i.	Pumped Storage	Yes	No	No	No	No	Yes

(1) Basically a model used in operation
(2) Model used primarily for planning
SWD Southwestern Division, Corps of Engineers
NPD North Pacific Division, Corps of Engineers
SSARR The NPD Stream Simulation and Reservoir Routing Model (storage routing and loss procedures)



Note: Storage units can be in any convenient units (acre-feet, cfs-months, cfs-days . . .) depending on flow units and time interval.

Source: Reservoir Storage-Yield Procedures, HEC, 1967.

Figure 3-4. KW/CFS nomograph.

TABLE 3-5.
EXAMPLE OF USER SPECIFIED FORMAT USING HEC-5C

```
ROLLINS RES. BEAR RIVER CA    EXISTING PROJECT                  APR 1979
SEQUENTIAL ROUTING MONTHLY       TAILWATER=1958.3    INST CAP=13000KW
USING GENERATOR-TURBINE DATA FROM TUDOR ENGR INC.         SP. CREST=2171.
```

PER	DY	MO	YR	DW	ROLLINS INFLOW	ROLLINS OUTFLOW	ROLLINS EOP STOR	ROLLINS LEVEL	ROLLINS EL/STAGE	ROLLINS ENERGY G	ROLLINS PEAK CAP
1	0	10	64	1	253.20	253.20	66000.00	3.00	2171.00	2950.52	13433.77
2	0	11	64	1	371.50	371.50	66000.00	3.00	2171.00	4189.42	13433.77
3	0	12	64	1	1079.70	1161.00	61000.98	2.92	2167.90	9646.08	12965.16
4	0	1	65	1	1803.90	1825.00	59703.58	2.89	2163.94	9354.12	12572.75
5	0	2	65	1	836.50	1292.00	34406.02	2.47	2145.00	7335.05	10915.26
6	0	3	65	1	767.50	356.00	59708.54	2.89	2145.01	3767.06	10915.57
7	0	4	65	1	1114.00	993.00	66908.64	3.12	2167.66	9317.69	12941.24
8	0	5	65	1	689.00	698.00	66355.24	3.05	2171.75	8144.67	13557.24
9	0	6	65	1	644.30	651.00	65956.56	3.00	2171.19	7343.64	13464.23
10	0	7	65	1	600.00	600.00	65956.56	3.00	2170.95	6990.71	13425.26
11	0	8	65	1	88.00	307.60	52453.69	2.77	2162.43	3499.93	12429.76
12	0	9	65	1	74.50	282.90	40052.84	2.56	2143.76	2877.55	10815.35
13	0	10	65	1	75.40	216.90	31352.22	2.41	2125.59	2056.43	9244.86
14	0	11	65	1	602.60	400.90	43354.38	2.62	2128.72	3747.26	9555.77
15	0	12	65	1	855.70	481.60	66357.23	3.05	2156.48	5370.32	11867.63
16	0	1	66	1	816.00	816.00	66357.23	3.05	2171.43	9516.16	13503.57
17	0	2	66	1	536.80	544.00	65957.35	3.00	2171.19	5727.68	13464.50
18	0	3	66	1	804.10	796.00	66455.41	3.06	2171.25	9279.89	13474.09
19	0	4	66	1	970.00	970.00	66455.41	3.06	2171.54	9736.38	13522.75
20	0	5	66	1	574.10	592.00	65354.77	2.99	2170.86	6896.28	13415.22
21	0	6	66	1	269.10	354.80	60255.19	2.90	2167.04	3956.38	12878.47
22	0	7	66	1	336.00	336.00	60255.19	2.90	2163.81	3836.89	12560.64
23	0	8	66	1	470.50	460.70	60857.78	2.91	2164.21	5266.28	12598.20
24	0	9	66	1	377.80	443.30	56960.20	2.85	2162.05	4876.22	12392.84
25	0	10	66	1	559.60	548.20	57661.17	2.86	2159.94	6195.71	12193.62
26	0	11	66	1	672.20	526.00	66360.80	3.05	2166.05	5848.70	12779.50

ANNUAL SUMMARY

YEAR	ROLLINS INFLOW AVG	ROLLINS OUTFLOW AVG	ROLLINS EOP STOR AVG	ROLLINS EOP STOR MAX	ROLLINS EOP STOR MIN	ROLLINS ENERGY G SUM
65	693.51	732.60	58708.55	66908.64	34406.02	75416.85
66	557.34	534.35	59164.36	66455.41	31352.22	70266.18
67	952.45	939.68	65587.58	67461.44	57661.17	107102.27
68	593.60	615.04	59030.10	66473.86	43972.04	79389.27
69	1061.10	1049.38	65549.70	66974.69	59681.16	101431.36
70	914.84	927.67	63076.32	66883.65	50789.33	97081.72
71	943.17	938.28	65398.70	67090.33	54790.25	110582.39
72	662.85	658.03	61944.92	66795.38	50494.58	86002.91
73	895.17	909.00	64870.94	66886.23	49089.27	104235.32
74	1151.38	1164.67	62902.29	67393.01	39597.83	109467.31
75	752.41	742.28	56770.26	66696.01	37495.52	68739.43
76	406.62	437.47	46595.30	66695.22	23092.53	52871.07
77	111.98	135.91	8939.48	13385.28	4959.57	7735.30
SUM =	9696.41	9784.35	738538.51	816099.55	537381.51	1090321.50
MAX =	1151.38	1164.67	65587.58	67461.44	59681.16	110582.39
MIN =	111.98	135.91	8939.48	13385.28	4959.57	7735.30
MPER=	74.00	74.00	67.00	67.00	69.00	71.00
AVG =	745.88	752.64	56810.65	62776.89	41337.04	83870.69