

AD-A109 772

HYDROLOGIC ENGINEERING CENTER DAVIS CA
POTENTIAL FOR INCREASING THE OUTPUT OF EXISTING HYDROELECTRIC P--ETC(U)
JUN 81 O W DAVIS, J J BUCKLEY
HEC-TP-78

F/G 10/2

NL

UNCLASSIFIED

1-1
a 0000



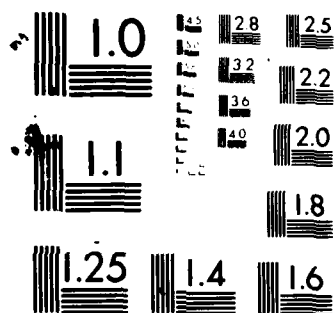
END

DATE

FILED

2 82

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Technical Paper No. 78

JUNE 1981

AD A109772

LEVEL

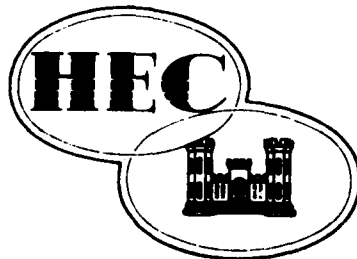
13

POTENTIAL FOR INCREASING THE OUTPUT
OF EXISTING HYDROELECTRIC PLANTS

by

Darryl W. Davis

John J. Buckley



DTIC
ELECTE
S JAN 20 1982 D

THE HYDROLOGIC^D
ENGINEERING CENTER

- research
- training
- application

U.S. Army Corps of Engineers
Water Resources Support Center

DTIC FILE COPY

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

01 19 82 018

Papers in this series have resulted from technical activities of The Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution within the Corps of Engineers.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Paper No. 78	2. GOVT ACCESSION NO. AD-A109772	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) POTENTIAL FOR INCREASING THE OUTPUT OF EXISTING HYDROELECTRIC PLANTS		5. TYPE OF REPORT & PERIOD COVERED
7. AUTHOR(s) Darryl W. Davis and John J. Buckley		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Corps of Engineers The Hydrologic Engineering Center 609 Second Street, Davis, CA 95616		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE June 1981
		13. NUMBER OF PAGES 10
		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Distribution of this publication is unlimited		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		Accession For NTIS GRA&I ☒ DTIC TAB ☐ Unannounced ☐ Justification
18. SUPPLEMENTARY NOTES Presented at Waterpower '81, an International Conference on Hydropower, June 22-24, 1981, Washington, D.C.		By Distribution/ Availability Dist Special A
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Hydropower, existing hydroelectric plants, renewable energy, uprating plants, efficiency increases.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The potential for increasing power output both through physical improvements in generating equipment and by changes in the manner that existing projects are operated were investigated and estimates of power increase prepared. The investigation was nationwide in scope, including Hawaii, Alaska, and Puerto Rico. All existing hydroelectric plants, regardless of ownership, were investigated for improvement in power output. The potential is identified by the type of improvement and is reported as aggregate regional values and national summaries.		

DD FORM 1473

JAN 73

EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

POTENTIAL FOR INCREASING THE OUTPUT OF EXISTING
HYDROELECTRIC PLANTS 1/

by
Darryl W. Davis* and John J. Buckley*

INTRODUCTION

The investigation reported herein (Hydrologic Engineering Center 1981) was undertaken to address the question of how much additional power might be generated at existing hydroelectric plants throughout the United States. The investigation was one of several special studies performed as part of the Corps of Engineers National Hydroelectric Power Study (NHS) (Institute for Water Resources 1979). The potential for increasing power output both through physical improvements in generating equipment and by changes in the manner that existing projects are operated were investigated and estimates of power increase prepared. The investigation was nationwide in scope, including Hawaii, Alaska, and Puerto Rico. All existing hydroelectric plants, regardless of ownership, were investigated for improvement in power output. The potential is identified by the type of improvement and is reported as aggregate regional values and national summaries.

The amount of power that can be generated at an existing hydroelectric power site is physically limited. The governing factors that determine this limit are: (1) the amount of flow volume that can pass through the powerhouse at a given time, (2) the "head" or elevation difference between the upstream and downstream water bodies acting at the time of power generation, and (3) the generation or "conversion" efficiency, i.e., the mechanical and electrical equipment efficiency in converting potential and kinetic energy of flowing water into electrical energy.

In order for there to be additional potential at an existing project, e.g., some "unused energy," an opportunity must exist for: (1) passing more of the annual volume through the powerhouse (there must be existing spill), (2) increasing the effective operating head (higher pool levels possible), or (3) technical opportunity to generate more efficiently from available head and flow. The option of increasing the storage capacity (raising the dam) was not considered in this study.

Short of this, all other measures that might be undertaken at a site that could effect the opportunities listed above and thereby increase energy output were considered. The primary measures for increasing energy output are: adding new generating units, rehabilitating or replacing existing units, modifying water handling facilities and, altering existing operating policies (reallocation of existing storage and/or change of annual and seasonal operation rule curves).

1/Presented at Waterpower '81, an International Conference on Hydropower, June 22-24, 1981, Washington, D.C.

*Chief, Planning Analysis Branch and Hydraulic Engineer, respectively, U.S. Army Corps of Engineers, The Hydrologic Engineering Center, 609 Second Street, Davis, California.

Excess flow or spill is by far the most important opportunity for increasing power output at an existing project. The measures available for capturing and routing additional flow volume through the powerhouse include: increasing the plant's generating capacity by adding additional generating units (expanding the powerhouse) or uprating existing units to higher generating capacity by rehabilitating, modifying or replacing turbines and/or generators; increasing the effective utilization of storage by reallocating additional storage to the power pool; and/or coordinating generation among a system of generating plants. For increasing the operating head, reallocation, or quasi-reallocation through modified rule curves and operating practices is necessary. Increasing the operating head may require that generating units be changed or modified to accommodate sustained operation at heads exceeding the design limits of the existing equipment. The measures available for increasing the conversion efficiency are those that can reduce the fluid energy loss in flow passage and energy loss in converting fluid energy (flow and head) to mechanical energy (turbine output) to electrical energy (generator output). The significant practical opportunity is improvement of the energy conversion efficiency of the hydraulic turbine since the energy conversion efficiency of electrical generators is quite high (about 95%) and modification of the water passage works of tunnels, penstocks, and draft tubes to reduce hydraulic energy loss would likely require significant and costly construction for minor increases. Table 1-1 summarizes the energy increase opportunities and candidate measures considered for capturing the potential.

Table 1-1.
MEASURES FOR INCREASING ENERGY
OUTPUT OF EXISTING HYDROPOWER PLANTS

<u>Measure</u>	:	<u>Spill</u> <u>Capture</u>	<u>Head</u> <u>Increase</u>	<u>Efficiency</u> <u>Increase</u>
Add New Units	:	X		
Replace Existing Units	:	X		X
Modify Existing Units	:	X		X
Modify Water Passage	:			X
Reallocate Reservoir Storage	:	X	X	
Improve System Operation	:	X	X	

The main source of information for this study was the data base developed for the National Hydropower Study. The data base, compiled by the District offices of the Corps of Engineers, contains storage space for over 600 data items relevant to each site. There is selected incomplete information stored for more than 15,000 sites with detailed information on 6,000 sites. Those sites with existing hydropower facilities (1,288) were extracted from the file and an additional data item entitled "Equipment Information" (supplied by the Federal Energy Regulatory Commission) was added and a new separate "study" file created. Relevant data items in this computer file are shown in Table 1-2.

Table 1-2. STUDY FILE - PLANT AND REGIONAL DATA

Item	Percentage* of Sites	Percentage of** Total Capacity
Installed capacity in kilowatts	100	100
Average annual energy	99	99
Turbine type	27	66
Age of installation	59	96
Rating of turbine	27	76
Rating of generator	28	76
Design head	28	76
Number of units	28	76
Weighted net power head	100	100
Average annual inflow	93	96
Flow duration data	78	86
Depth of the flood-control space, feet	14***	28
Regional dependable capacity		
benefit in \$/kW-yr	100	100
Regional average annual energy		
benefit in \$/MWh-yr	100	100

* 1,288 sites catalogued in data file.

** Total installed capacity of sites in file is 63,375 MW.

***Represents all existing sites that have flood control storage.

EXISTING HYDROPOWER FACILITIES

The total installed capacity of the existing 1,288 sites that were identified and catalogued into the study file is 63,375 megawatts (MW) and they generate 272,552 gigawatt hours (GWh) of electrical energy per year. Tables 2-2 and 2-1 summarize types and ownership of existing hydropower development. Figures 2-1, 2-2, and 2-3 summarize information on installation date, head, and installed capacity of existing plants. A sampling of the types of turbines representing 80% of the total installed capacity indicates that reaction turbines (Francis) are the predominate type--66%, followed by propeller--25% (Kaplan--17%, fixed blade--8%), then impulse (Pelton)--5%, and other--4%.

Table 2-2. TYPES OF EXISTING HYDROELECTRIC PLANTS

Plant Type	Number of Plants	Capacity kW	Average Annual Energy MWh
1. Run-of-River	431	8,632,900	38,311,800
2. Diversion	160	2,332,900	12,899,300
3. Reservoir	501	44,790,800	190,417,000
4. Reservoir with Diversion	190	7,604,000	30,848,500
5. Other	6	14,800	75,400
Totals	1,288	63,375,400	272,552,000

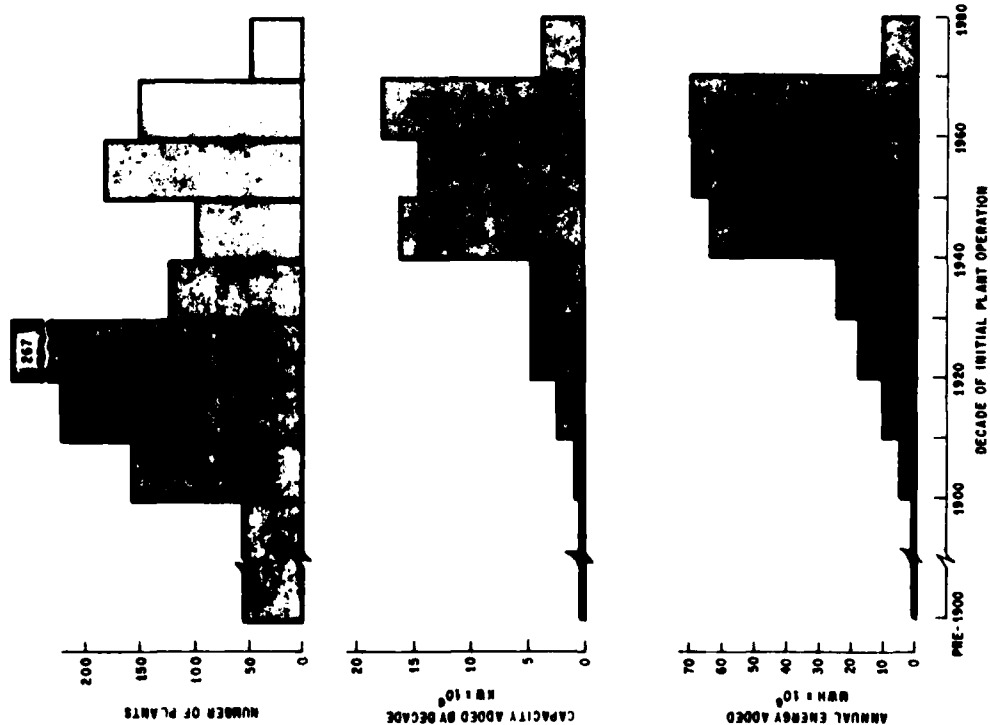


Figure 2-1. PLANT AGE VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

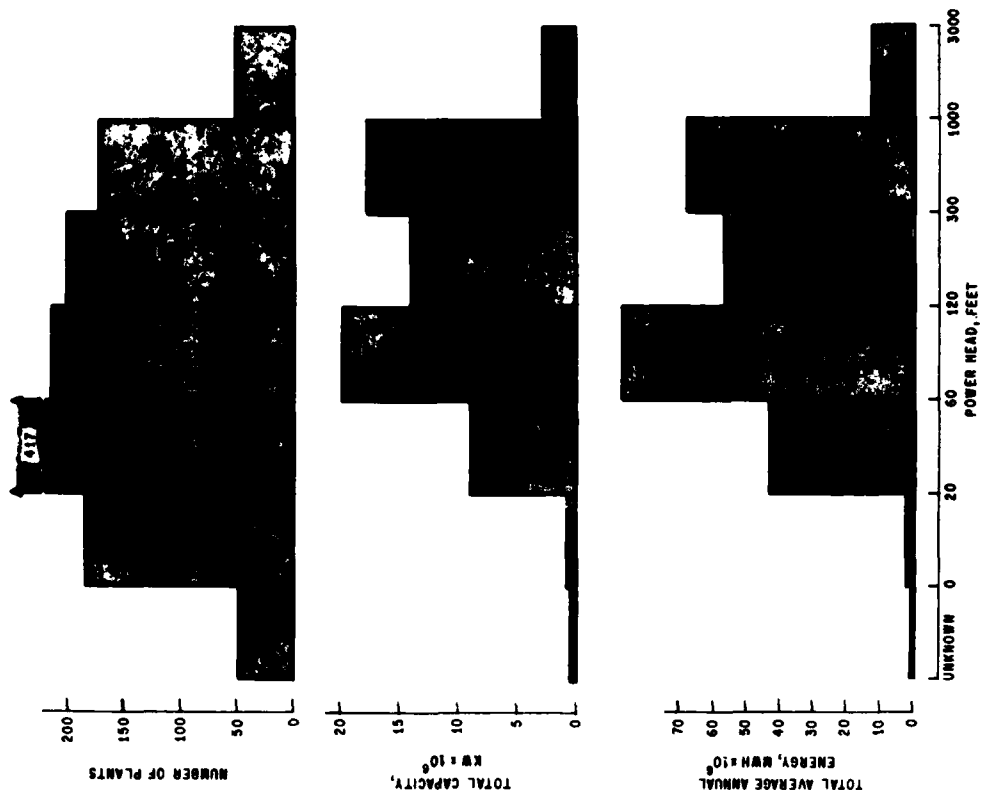


Figure 2-2. POWER HEAD VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

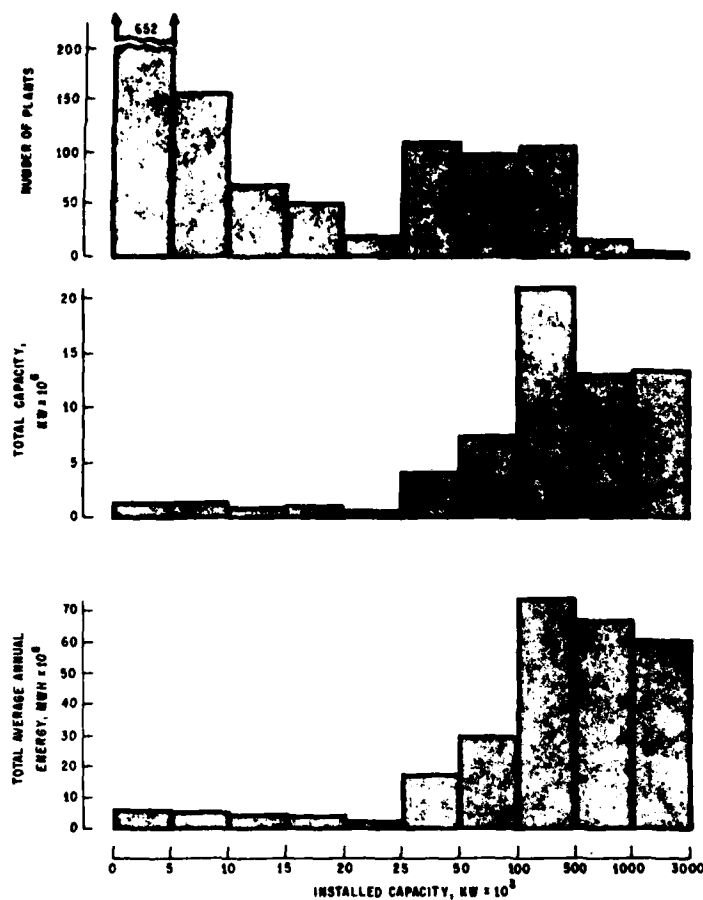


Figure 2-3.

INSTALLED CAPACITY VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

Table 2-1. OWNERSHIP OF EXISTING HYDROELECTRIC PLANTS *

Ownership Category	Number of Plants	Total Capacity kW	Total Average Annual Energy MWh
1. Corps	92	19,232,900	81,761,400
2. Other Federal	92	14,948,300	63,026,500
3. Non-Federal, Government	151	8,728,000	42,550,700
4. Investor Owned Utility	504	13,977,600	60,342,600
5. Cooperatively Owned Utility	57	2,330,100	8,353,500
6. Other Commercial or Industrial Firm	241	1,745,600	8,359,800
7. Private Citizen or Non-utility Cooperative	41	858,400	4,389,600
8. Unknown	110	1,554,500	3,767,900
Totals	1,288	63,375,400	272,552,000

* All information taken from study computer data file.

EQUIPMENT CHARACTERISTICS

Improvements due to research, materials, and design over the last 80 years have resulted in it being technically feasible to obtain substantial increases in capacity and to a lesser degree increases in efficiency from existing hydroelectrical equipment. When uprating an existing generating unit the amount of actual increase that can be obtained is limited by the specific design and manufacturing characteristics of the installed equipment. The year of manufacture or installation is used herein as an indicator of potential to assist in arriving at the capacity and/or efficiency gain possible.

Indications are that the generator is generally capable of being uprated to obtain a greater percentage capacity gain than can be developed from the turbine for an equivalent year of manufacturer. The turbine has been found in general to be the critical factor in determining the maximum output that can be developed. Figures 3-1, 3-2, 3-3 and 3-4 are examples of technical data compiled and used in this study for analyzing uprating potential. The reader is cautioned that these data were compiled to perform a nationally scoped study and should not therefore be used to make major decisions on a site specific basis. Also it must be emphasized that while these increases shown are within the capability of the machines, additional flow and/or head (beyond existing) must be developed through project changes before increased power output can result.

A major consideration in determining whether to uprate units of an existing hydroelectric powerplant is the question of the outage. Outage is the time the generating unit would be out of service undergoing replacement or modification. Opportunities for uprating appear to lend themselves more to powerplants with multiple units where outages can be scheduled to coincide with seasonal system power demand swings which would provide "windows" where a unit or units could be taken out of service without adversely affecting a system generating capability. This outage period can vary considerably depending on the uprating to be done. If only the turbine runner is replaced with minor structural adjustments, the outage time could be as low as two months. If more major changes are required, this time could be six to twelve months.

INCREASED OUTPUT FROM PHYSICAL MODIFICATIONS

Figure 4-2 is a schematic of the evaluation process that was adopted for this portion of the study. The existing 1,288 plants were separated into one of thirty-two categories based on whether or not the reservoir had flood control storage, whether or not there was spill occurring at the site, the ratio of potential head to existing, and the age of the plant. The following measures were designated as action categories that were studied to enhance the energy output at existing plants.

- Addition of new units for capacity increase
- Replacement of older units for capacity increase
- Uprating of older units for capacity increase
- Replacement of older units for efficiency increase
- Modification of older units for efficiency increase

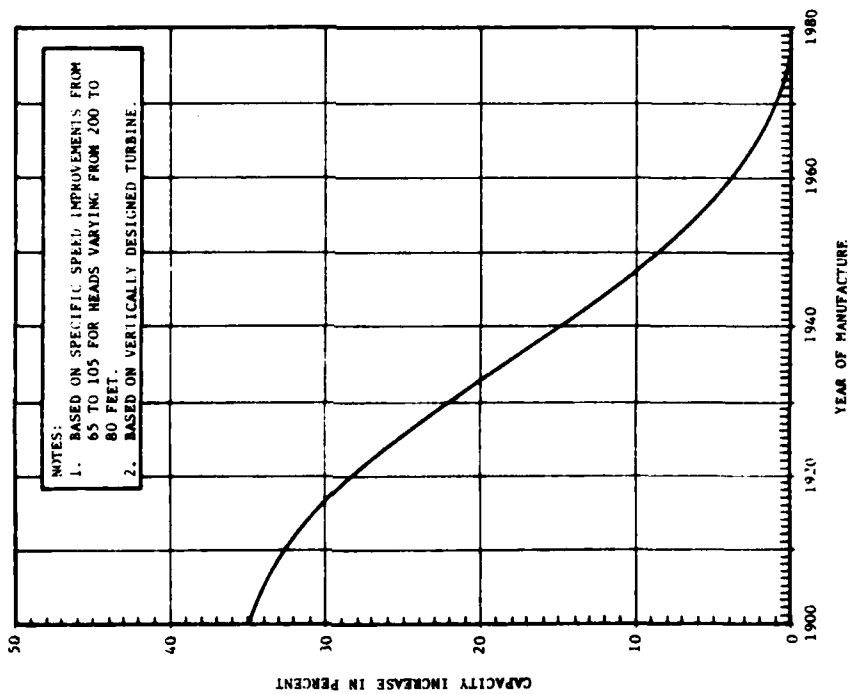


Figure 3-1.

POTENTIAL FOR CAPACITY
INCREASE - FRANCIS TURBINE

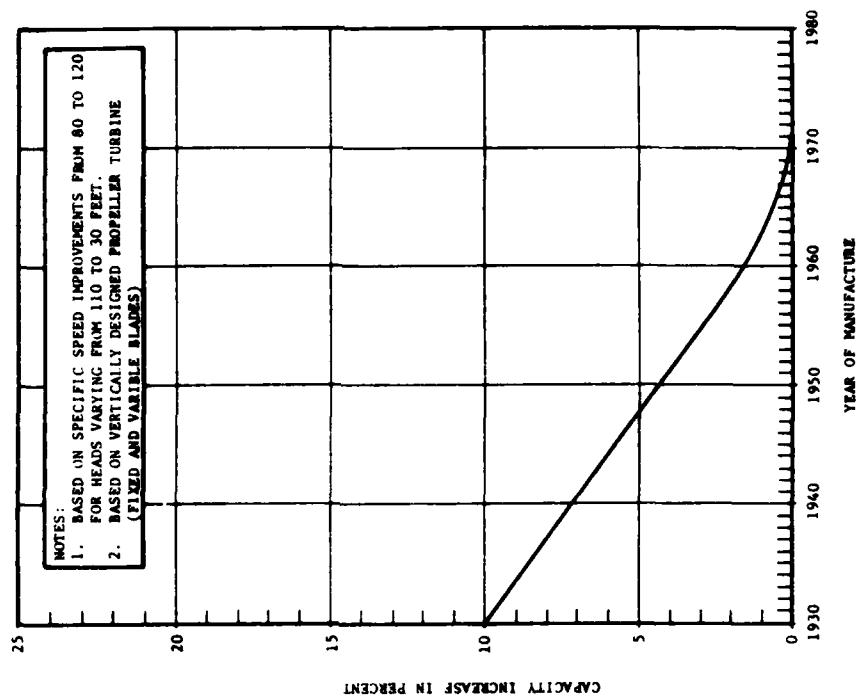


Figure 3-2.

POTENTIAL FOR CAPACITY
INCREASE - PROPELLER TURBINE

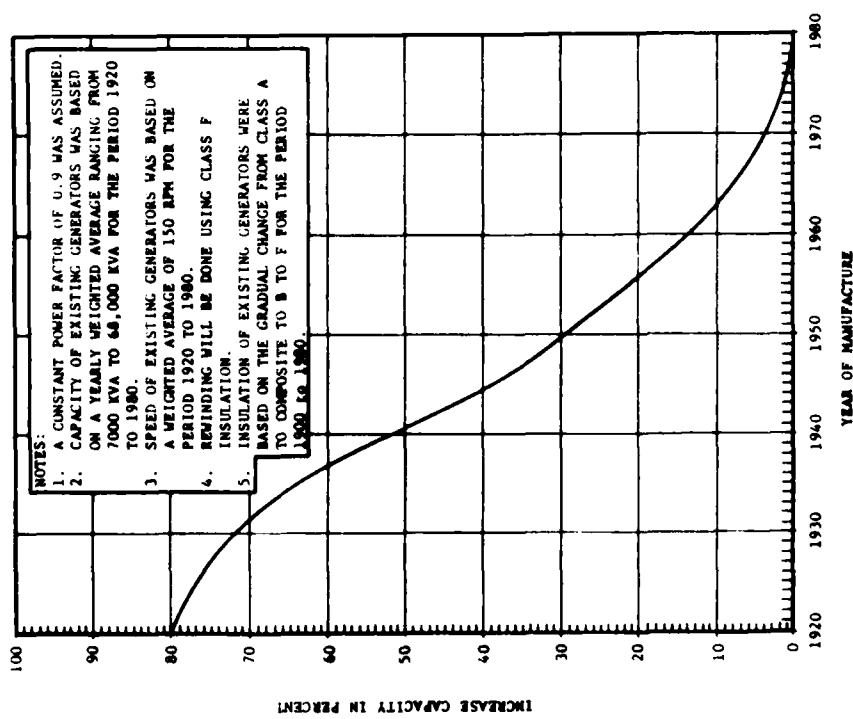


Figure 3-3.

POTENTIAL FOR CAPACITY INCREASE
- REWINDING OF STATOR

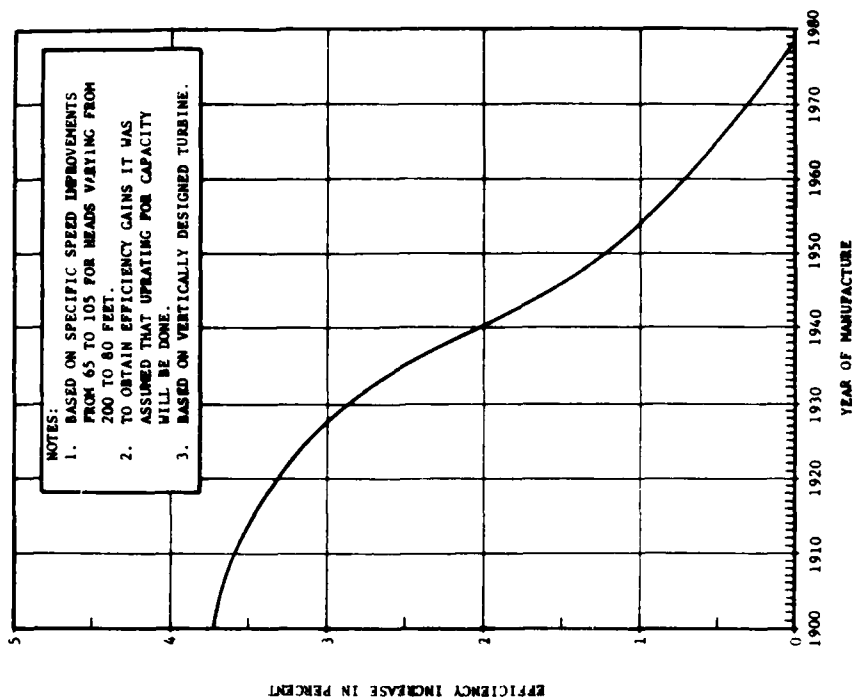


Figure 3-4.

POTENTIAL FOR EFFICIENCY INCREASE
- FRANCIS TURBINE

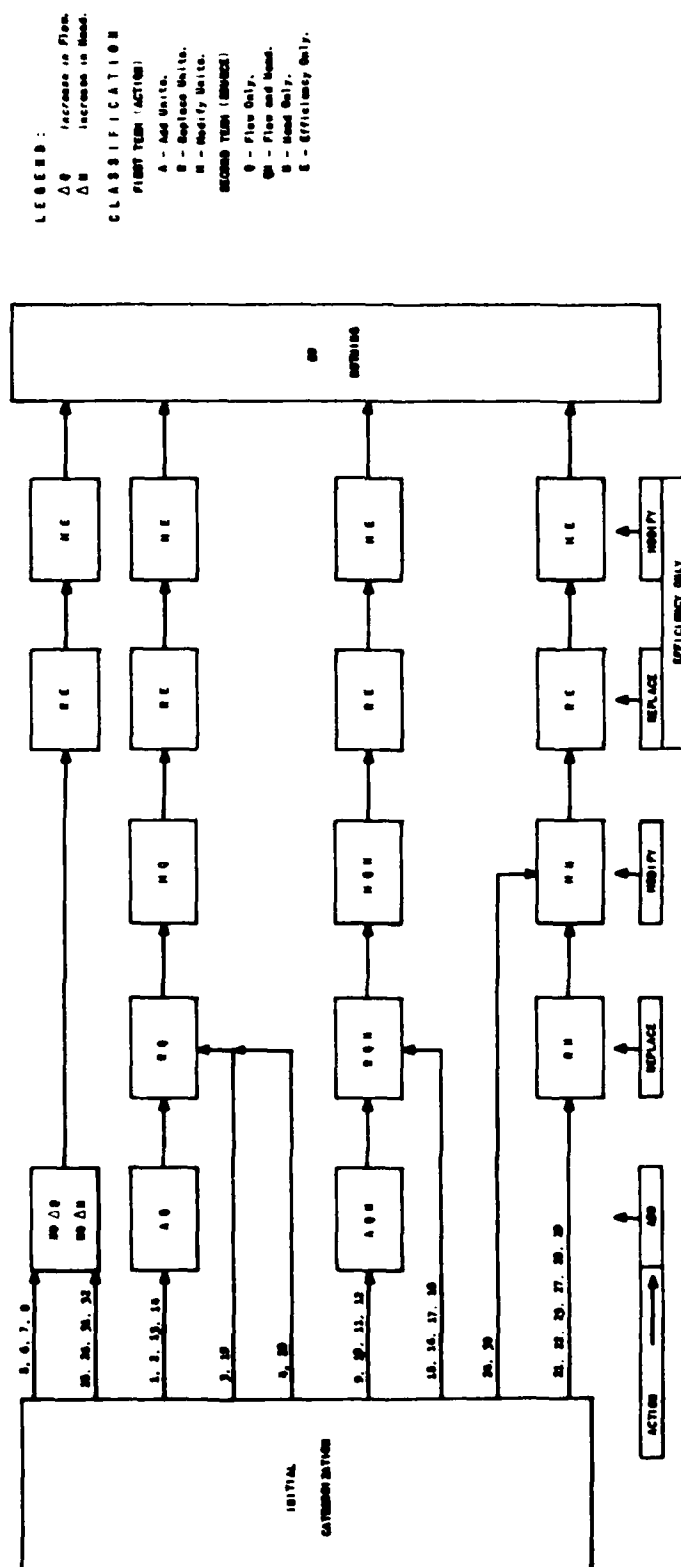


Figure 4-2. SCHEMATIC - EVALUATION PROCESS

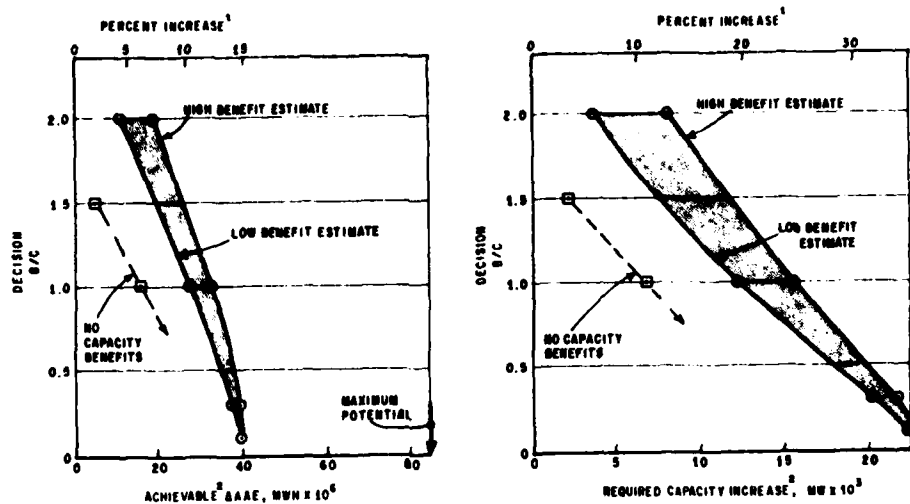
The total gross physical potential increase in energy and corresponding increase in capacity was estimated for each site and appropriate action categories. An indicator of benefit was estimated for the improvement by application of the Federal Energy Regulatory Commission (FERC) regional power values developed for the NHS study. Costs were estimated based on technical data compiled for this study. The test for "achievability" of the energy increase consisted of comparing the calculated benefit to cost (B/C) ratio for each action category to a specified decision B/C ratio. The decision B/C ratio was the decision device used to study the sensitivity of results to a range of acceptable economic criteria. The energy increase of each site that ended up in an action category with a B/C value equal to or greater than the specified decision B/C ratio was considered "achievable".

As an illustration of the evaluation process, consider those sites (Figure 4-2) that were initially classified as "add" categories 9, 10, 11, or 12. All of these sites have potential due to additional flow and head above existing conditions. First the costs and benefits at each site are evaluated for the add (AQH) conditions to see if the calculated B/C ratio is equal to or greater than the specified decision B/C value. If the site does meet this condition the developed information is stored in the AQH category. If the site does not meet the decision B/C ratio at the initially calculated capacity and energy increase, the site is completely re-evaluated at 75 percent of that capacity increase. If required, two more trials are made at 50 percent and 25 percent of the initial value before going on to the next potential action category - RQH. The processing of each site either meets the decision B/C ratio or ends up in the "do nothing" category. Therefore, before sites in categories 9, 10, 11 or 12 are considered "do nothing" sites they could conceivably be tested for achievability for up to twenty different conditions - four conditions for each of the five action categories.

Figures 4-5 and 4-6 present the results of the analysis on an aggregate national scale. Note the maximum physical potential is estimated at slightly over 80 million MWh with a more realistic estimate of physical potential of 40 million MWh. For a decision B/C ratio of 1.0, the achievable energy increase is about 11% (mid range of band) requiring about a 22% capacity increase to accomplish the energy output. Sensitivity results of benefit estimates (HIGH = capacity increase valued as dependable, LOW = capacity increase valued as intermittent), decision B/C ratio (uncertainty in costs and power values), and project life and discount rate (private sector criteria) are shown to provide a complete picture of the potential.

Table 4-4 is a summary computer printout of the computations for the HIGH benefit estimate and decision B/C ratio of 1.0. Note that essentially all the increase is found to be from adding new units (expanding the existing powerhouse). The Northwest accounts for about half of the increase estimated, the Northeast for about 30% of the increase and the Southeast about 10% of the increase.

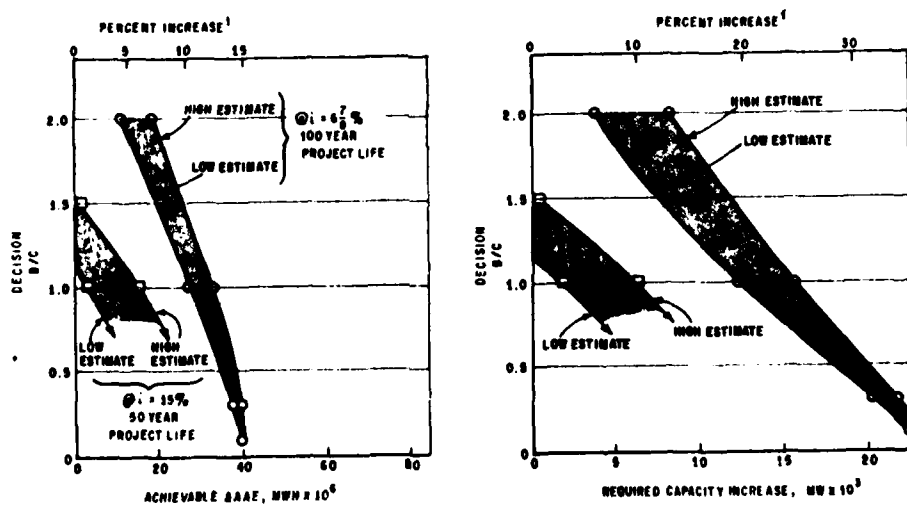
An analysis was performed with the add category removed from the evaluation process to provide some insight into the potential energy increase from the options of only rehabilitating existing plants. The potential increase achievable dropped to 1.4% (from 11%) nationwide.



- 1 Based on existing installed capacity and average annual energy
2 Costs and benefits are based on 1978 price levels and 6 7/8% interest

Figure 4-5.

ACHIEVABILITY ANALYSES - SENSITIVITY RESULTS



- 1 Based on existing installed capacity and average annual energy

Figure 4-6.

ACHIEVABILITY ANALYSES - SENSITIVITY RESULTS - INTEREST RATE AND PROJECT LIFE

**Table 4-4. SUMMARY
ACHIEVABILITY EVALUATION OF EXISTING HYDROELECTRIC
PLANTS, HIGH BENEFIT ESTIMATE, DECISION B/C = 1.0.**

ACTIVITY	NUMBER OF PLANTS	INSTALLED CAPACITY MW	CAPACITY INCREASE MW	AVERAGE ANNUAL ENERGY MILLION KWH	AVERAGE ANNUAL ENERGY INCREASE MILLION KWH	INVESTMENT COSTS MILLION DOLLARS	AVERAGE ANNUAL COSTS MILLION DOLLARS	AVERAGE ANNUAL BENEFITS MILLION DOLLARS
ADD UNITS								
AU	253	9423.0	14491.5	52,200	30,420	12502.7	945.12	1031.41
ADM	15	714.1	901.5	4,045	1,971	766.2	50.52	104.07
ADD SUBTOTAL	268	10137.1	15392.9	56,245	32,391	13268.9	1003.64	1736.07
REPLACE UNITS								
RD	0	0.	0.	0.	0.	0.	0.	0.
RDM	0	0.	0.	0.	0.	0.	0.	0.
RE	4	355.6	10.3	1,930	.019	13.0	1.10	1.79
REPLACE SUBTOTAL	4	355.6	10.3	1,930	.019	13.0	1.10	1.79
MODIFY UNITS								
MD	10	707.2	70.6	3,549	.002	69.2	7.93	9.28
MDM	1	870.5	111.1	1,714	.130	111.1	8.90	12.53
ME	1	22.5	3.2	.002	.002	.0	.00	.14
ME	15	1605.6	87.1	5,702	.056	67.3	5.40	7.43
MODIFY SUBTOTAL	27	2809.7	252.1	11,052	.200	270.5	22.40	29.39
A.U.M. SUBTOTAL	299	13802.3	15695.3	69,312	32,600	13421.1	1027.14	1767.25
DD MODIFICATIONS								
UM	909	44575.1	0.	203,240	0.	0.	0.	0.
TOTALS	1208	63375.0	15695.3	272,552	32,600	13421.1	1027.14	1767.25

INCREASED OUTPUT FROM OPERATIONAL CHANGES

Operational changes to existing plants that could potentially increase the energy output are possible. By reallocating a portion of the flood control storage to power storage there is the potential to increase the energy output by capturing and routing additional flow through the powerhouse and by increasing the head available for power generation by keeping the pool level higher. The additional energy increase may be possible without necessarily increasing the plants installed capacity. The loss to the existing project would be reduced flood control protection. It is unlikely that a significant reduction in flood control storage would be found to be acceptable. However, in some cases only a small portion of the flood control space may be needed to capture and control a significant amount of reservoir inflow volume.

Altering the reservoir operation policies is another potential way to increase energy output. Typically, there is a set of operating rules by which a reservoir is operated. The thesis is that there may be opportunities to increase power output such as reducing flood control releases during and following flood events to allow more volume to be passed through the plant; allowing seasonal power pool elevations to remain at higher elevations for longer periods of time; and minimizing all releases that do not go through the plant. In effect this might amount to a quasi-storage reallocation in that some of the goals of reallocation might be achieved without formally modifying the designated storage zones.

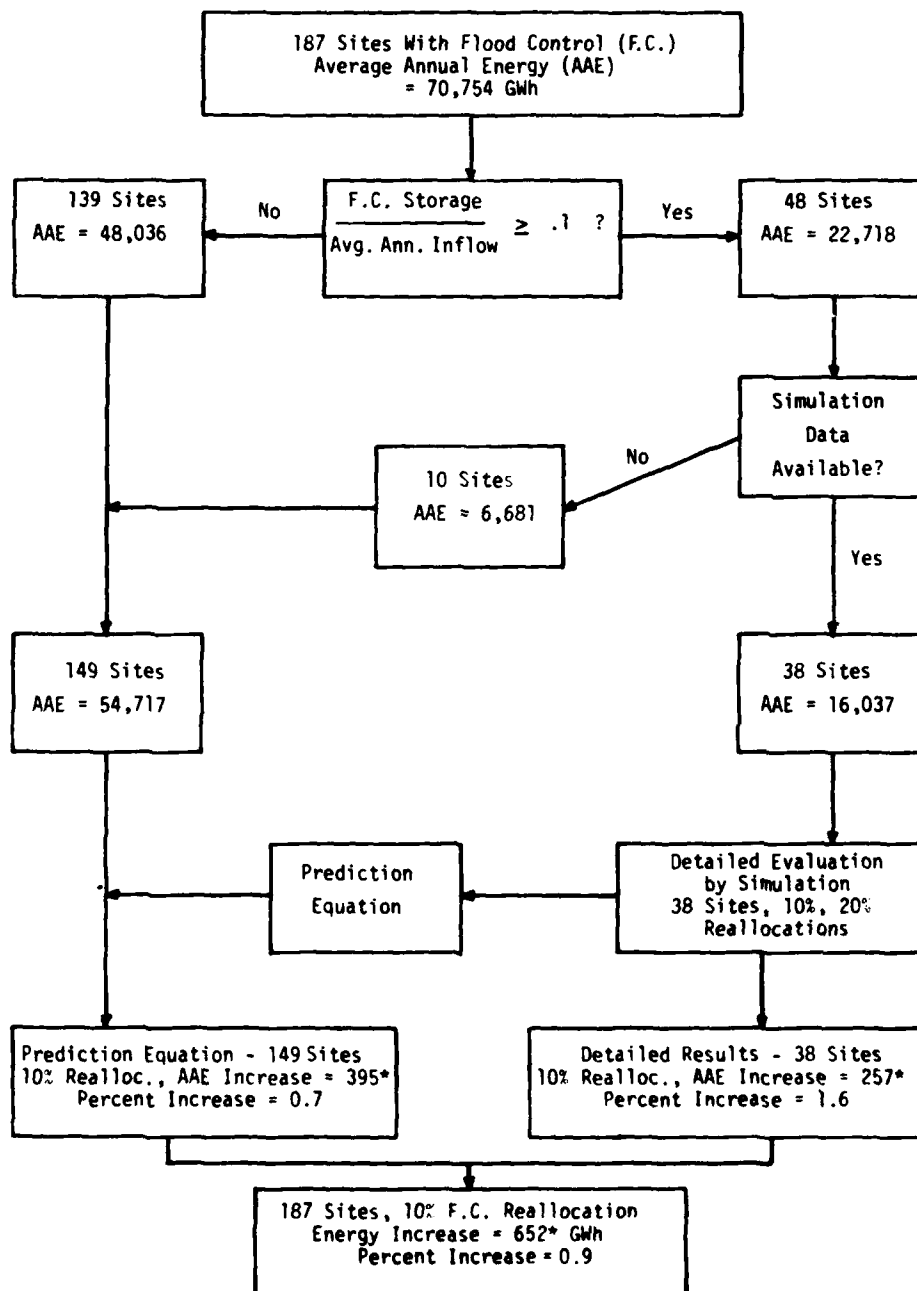
Storage in a multiple-purpose reservoir is usually allocated into flood control space, conservation storage (including hydropower), and inactive or dead storage. Flood control operation requires reservation of storage space in the event a flood might occur thus potentially releasing water that might have been later used for power generation. The hydropower reallocation question for all practical purposes reduces to allocating portions of existing flood control space to hydropower storage. The potential contribution to increased energy output of allocating from one conservation purpose to another is insignificant in comparison. The candidate projects for reallocation of flood control storage are therefore those existing hydropower projects that also have flood control storage. A total of 187 projects were found that met the criteria. Forty-eight (48) of these projects have flood control storage equivalent to 10% of the annual flow volume.

The reallocation analysis was accomplished by performing detailed sequential, hydropower analysis on 38 of the 48 project previously identified, developing a prediction equation from the results obtained, and applying the prediction equation to the remaining sites. Computer simulations were made based on existing storage allocations, then repeated for reallocation of 10% and 20% of flood control storage to power storage. Figure 5-1 is a schematic of the analysis flow and includes the results for the 10% flood control storage reallocation option.

The estimated increase in energy output for reallocation only (installed capacity remains at existing) is 10% reallocation - 652 GWh (.9% increase for all reallocation sites) and 20% reallocation - 1,225 GWh (1.7% increase for all reallocation sites). If the installed capacity is increased commensurate with the increased dependable capacity made possible by the increased power storage and decreased plant factor, an additional 1.7% increase in average annual energy for a 10% reallocation may be possible. The major factor in increased energy output was found to be increased head (pool levels). The contribution due to capturing additional spill was negligible. By adding to the power storage through reallocation, projects are able to meet increased power demands during critical low flow periods. The percentage increase in firm annual energy (conversion of non-firm energy to firm energy) was approximately 3 times the increase in average annual energy.

The likely acceptable reallocation project development would require formulation and implementation of mitigation measures to offset the loss in flood control performance by the reservoir. The benefits from increased power production would have to be greater than the cost of the mitigation measures needed to assure the same (or nearly so) flood control performance for reallocation to be economically justified.

Analysis of the potential for increased output by operational (rule curve) changes indicated that the potential was minor and in fact is included within the estimates made for reallocation analysis. Project operators appear to be diligent in operating their projects to extract the greatest amount of energy that is practical and reasonable.



* Installed capacity maintained at existing values.

**Figure 5-1. ESTIMATE OF POTENTIAL ENERGY INCREASE
FROM STORAGE REALLOCATION**

SUMMARY OF FINDINGS

The hydroelectric power generation system of the United States is comprised of 1,288 individual plants, totaling about 3,000 individual generating units, with installed capacity (exclusive of pumped storage) of 63,375 megawatts (MW), generating 272,552 gigawatt hours of electrical energy per year. The data documenting characteristics of the 1,288 plants have been catalogued into a computer file for use in the evaluation of the potential for increasing output from existing plants. There is modest potential for increasing energy output from these plants (11%) with virtually all the increase due to capturing existing spill through enlargement of the existing powerplant. Equipment uprating and improvements would likely contribute no more than 1.4% increase over existing output. Potential for increased energy output from operational improvements and storage reallocation is possible at sites with existing flood storage and is optimistically estimated to average 2% for the sites with flood control storage (a national increase of about 0.6%). While the total national potential for increasing energy output at existing plants is modest, the opportunities are real and in specific instances could be significant and important on a local scale. The existing hydropower generation system on the whole is making quite efficient use of the energy resources available at the existing sites.

Specifically, the investigation has found:

- The upper physical limit estimate of potential increase in energy output at existing hydropower sites is approximately 86,000 (GWh). A more realistic value for physical potential developed through detailed study in this investigation is a maximum practical limit of about 40,000 GWh (15% increase over existing) indicating that current utilization of potential energy at these sites is 87 percent on a nationwide basis. Based on present day cost and power benefit values as decision criteria, the potential energy increase that is achievable is estimated to be about 30,000 GWh or an 11 percent increase.
- 1,288 sites have been identified and catalogued into the basic data files of the national hydropower study. This data base provides an adequate basis for a national study of potential energy increases at existing sites.
- Existing federal plants (14 percent of total) contain a little over 50 percent of total installed capacity.
- There is flood control storage at about 15 percent of existing sites with a total installed capacity of 17,774 MW (28 percent of the national total).
- There are 431 (33 percent of total) sites with capacity of 8,633 MW (14 percent of national total) that are classified as run-of-the-river locations.
- Approximately 80 percent of the total existing capacity has been added since 1940.

- Two-thirds of existing plants were constructed prior to 1940 and contain only about 20 percent of the existing capacity.
- Approximately 75 percent of existing plants are less than 25 MW installed capacity yet these plants account for only 7 percent of the total installed capacity.
- There can be significant increases of up to 35 percent in turbine output capacity due to modifications to older turbines, if additional head and/or flow are available.
- Improvements in insulating material over the past 50 years allows significant generator capacity increases through uprating.

For summary purposes the values used in the following items are taken from analyses based on costs and benefits in present day values and a decision threshold benefit to cost ratio of 1.0.

- The major source of potential increase in energy at existing plants is the flow that is currently bypassing the existing powerplant and not being captured for power generation. Specific measures of adding additional units, replacing or modifying units to achieve higher output, or storage reallocation would be required to capture portions of the presently passed flows (spill). Utilization of this spillage through addition of units accounts for more than 94 percent of the estimated achievable potential energy output increase at existing sites.
- The increase in energy due to head increases, even using all of the flood control space, accounts for less than 6 percent of the total potential energy increase at existing sites.
- The achievable average annual energy based on the capacity and energy power values used herein and the federal interest rate of 6-7/8% is about 30,000 GWh or an 11 percent increase in energy above existing hydropower output. Development of this additional energy would require adding about 14,000 MW of capacity, an increase of 22 percent over existing capacity.
- If power benefit credit for dependable capacity is omitted from the evaluation (because not all additional capacity could be reasonably expected to be dependable), the achievable annual energy increase drops to about 18,000 GWh or a 6 percent increase over existing output.
- If the interest rate for the implementation decision criteria is raised to 15 percent from the 6-7/8 percent utilized in this study and the project evaluation period is decreased from 100 years to 50 years and the value of power is held constant, the achievable annual energy increase drops to about 10,000 GWh or a 4 percent increase over existing output.

- If adding units were not being considered as an alternative, (e.g., only existing unit uprates and improvements are considered) the potential increase in annual energy due to replacement of and/or modifications to existing units would be about 3,750 GWh or an energy increase of 1.4 percent over existing.
- The loss in energy (and thus revenue) from removing a unit from service to uprate through modification is presently seldom economically justified. Uprates through improvements are more attractive for implementation when the plant must be taken out of service for some other compelling reason.
- The Western Systems Coordinating Council (WSCC), Northeast Power Coordinating Council (NPCC), and Southeastern Electric Reliability Council (SERC) regions contain 88 percent of the estimated achievable annual energy increase.
- The potential energy development due to reallocation of flood control storage in existing power reservoirs - will likely contribute less than a one percent increase in hydroelectric energy output on a national basis. The conversion of non-firm energy to firm energy made significant - up to 3 times the increase that was estimated for annual energy. Substantial gains in average annual energy can be obtained at those projects where the reservoir power operation can be based on zero firm energy due to the higher heads resulting from the decreased reservoir drawdown.
- It would require about 60 million barrels of fuel oil annually, to produce the equivalent amount of electrical energy (30,000 GWh) that has been found in this investigation to be achievable.

ACKNOWLEDGEMENTS

The investigation reported herein was performed by The Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers, as a service to The Institute for Water Resources (IWR), U.S. Army Corps of Engineers, managers of the National Hydropower Study. Mr. Michael Walsh was the IWR contact for the study. Mr. Darryl W. Davis was the principal-in-charge and Mr. John J. Buckley was the study manager. HEC staff that performed significant tasks for the study were Messrs. Vernon R. Bonner, Dale R. Burnett, Robert C. Luethy, Gary M. Franc, and Brian V. Smith. Mr. Bill S. Eichert, Director of the HEC, provided guidance and participated in the technical performance of the reallocation analysis. Parsons, Brinkerhoff, Quade and Douglas, Inc. (PBQ&D) prepared technical data on equipment uprate potential and cost while under contract to HEC. Principals for PBQ&D were Messrs. Clarence E. Korhonen and Richard L. Hearth.

REFERENCES

- Hydrologic Engineering Center, "Potential for Increasing the Output of Existing Hydroelectric Plants" (Draft). January 8, 1981.
U.S. Army Corps of Engineers, Davis, CA.
- Institute for Water Resources, "Plan of Study - National Hydropower Study." January 1979. U.S. Army Corps of Engineers,
Fort Belvoir, VA.

TECHNICAL PAPERS

Technical papers are written by the staff of the HEC, sometimes in collaboration with persons from other organizations, for presentation at various conferences, meetings, seminars and other professional gatherings.

Price
\$2.00 each

- # 1 Use of Interrelated Records to Simulate Streamflow, Leo R. Beard, December 1964, 22 pages.
- # 2 Optimization Techniques for Hydrologic Engineering, Leo R. Beard, April 1966, 26 pages.
- # 3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs, Leo R. Beard, August 1965, 21 pages.
- # 4 Functional Evaluation of a Water Resources System, Leo R. Beard, January 1967, 32 pages.
- # 5 Streamflow Synthesis for Ungaged Rivers, Leo R. Beard, October 1967, 27 pages.
- # 6 Simulation of Daily Streamflow, Leo R. Beard, April 1968, 19 pages.
- # 7 Pilot Study for Storage Requirements for Low Flow Augmentation, A. J. Fredrich, April 1968, 30 pages.
- # 8 Worth of Streamflow Data for Project Design - A Pilot Study, D. R. Dawdy, H. E. Kubik, L. R. Beard, and E. R. Close, April 1968, 20 pages.
- # 9 Economic Evaluation of Reservoir System Accomplishments, Leo R. Beard, May 1968, 22 pages.
- #10 Hydrologic Simulation in Water-Yield Analysis, Leo R. Beard, 1964, 22 pages.
- #11 Survey of Programs for Water Surface Profiles, Bill S. Eichert, August 1968, 39 pages.
- #12 Hypothetical Flood Computation for a Stream System, Leo R. Beard, April 1968, 26 pages.

TECHNICAL PAPERS (Continued)

Price
\$2.00 each

- #13 Maximum Utilization of Scarce Data in Hydrologic Design,
Leo R. Beard and A. J. Fredrich, March 1969, 20 pages.
- #14 Techniques for Evaluating Long-Term Reservoir Yields,
A. J. Fredrich, February 1969, 36 pages.
- #15 Hydrostatistics - Principles of Application, Leo R. Beard,
July 1969, 18 pages.
- #16 A Hydrologic Water Resource System Modeling Techniques,
L. G. Hulman and D. K. Erickson, 1969, 42 pages.
- #17 Hydrologic Engineering Techniques for Regional Water
Resources Planning, Augustine J. Fredrich and Edward F.
Hawkins, October 1969, 30 pages.
- #18 Estimating Monthly Streamflows Within a Region, Leo R.
Beard, Augustine J. Fredrich, Edward F. Hawkins, January
1970, 23 pages.
- #19 Suspended Sediment Discharge in Streams, Charles E. Abraham,
April 1969, 24 pages.
- #20 Computer Determination of Flow Through Bridges, Bill S.
Eichert and John Peters, July 1970, 32 pages.
- #21 An Approach to Reservoir Temperature Analysis, L. R. Beard
and R. G. Willey, April 1970, 31 pages.
- #22 A Finite Difference Method for Analyzing Liquid Flow in
Variably Saturated Porous Media, Richard L. Cooley,
April 1970, 46 pages.
- #23 Uses of Simulation in River Basin Planning, William K.
Johnson and E. T. McGee, August 1970, 30 pages.
- #24 Hydroelectric Power Analysis in Reservoir Systems, Augustine
J. Fredrich, August 1970, 19 pages.
- #25 Status of Water Resource Systems Analysis, Leo R. Beard,
January 1971, 14 pages.
- #26 System Relationships for Panama Canal Water Supply,
Lewis G. Hulman, April 1971, 18 pages.
*This publication is not available to countries outside of
the U.S.*

TECHNICAL PAPERS (Continued)

Price
\$2.00 each

- #27 Systems Analysis of the Panama Canal Water Supply, David C. Lewis and Leo R. Beard, April 1971, 14 pages.
 This publication is not available to countries outside of the U.S.
- #28 Digital Simulation of an Existing Water Resources System, Augustine J. Fredrich, October 1971, 32 pages.
- #29 Computer Applications in Continuing Education, Augustine J. Fredrich, Bill S. Eichert, and Darryl W. Davis, January 1972, 24 pages.
- #30 Drought Severity and Water Supply Dependability, Leo R. Beard and Harold E. Kubik, January 1972, 22 pages.
- #31 Development of System Operation Rules for an Existing System by Simulation, C. Pat Davis and Augustine J. Fredrich, August 1971, 21 pages.
- #32 Alternative Approaches to Water Resource System Simulation, Leo R. Beard, Arden Weiss, and T. Al Austin, May 1972, 13 pages.
- #33 System Simulation for Integrated Use of Hydroelectric and Thermal Power Generation, Augustine J. Fredrich and Leo R. Beard, October 1972, 23 pages.
- #34 Optimizing Flood Control Allocation for a Multipurpose Reservoir, Fred K. Duren and Leo R. Beard, August 1972, 17 pages.
- #35 Computer Models for Rainfall-Runoff and River Hydraulic Analysis, Darryl W. Davis, March 1973, 50 pages.
- #36 Evaluation of Drought Effects at Lake Atitlan, Arlen D. Feldman, September 1972, 17 pages.
 This publication is not available to countries outside of the U.S.
- #37 Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes, Arlen D. Feldman, April 1973, 24 pages.
- #38 Water Quality Evaluation of Aquatic Systems, R. G. Willey, April 1975, 26 pages.
- #39 A Method for Analyzing Effects of Dam Failures in Design Studies, William A. Thomas, August 1972, 31 pages.

TECHNICAL PAPERS (Continued)

Price
\$2.00 each

- #40 Storm Drainage and Urban Region Flood Control Planning,
Darryl Davis, October 1974, 44 pages.
- #41 HEC-5C, A Simulation Model for System Formulation and
Evaluation, Bill S. Eichert, March 1974, 31 pages.
- #42 Optimal Sizing of Urban Flood Control Systems, Darryl
Davis, March 1974, 22 pages.
- #43 Hydrologic and Economic Simulation of Flood Control Aspects
of Water Resources Systems, Bill S. Eichert, August
1975, 13 pages.
- #44 Sizing Flood Control Reservoir Systems by Systems Analysis,
Bill S. Eichert and Darryl Davis, March 1976, 38 pages.
- #45 Techniques for Real-Time Operation of Flood Control Reservoirs
in the Merrimack River Basin, Bill S. Eichert, John C.
Peters and Arthur F. Pabst, November 1975, 48 pages.
- #46 Spatial Data Analysis of Nonstructural Measures, Robert P.
Webb and Michael W. Burnham, August 1976, 24 pages.
- #47 Comprehensive Flood Plain Studies Using Spatial Data Manage-
ment Techniques, Darryl W. Davis, October 1976, 23 pages.
- #48 Direct Runoff Hydrograph Parameters Versus Urbanization,
David L. Gundlach, September 1976, 10 pages.
- #49 Experience of HEC in Disseminating Information on Hydrological
Models, Bill S. Eichert, June 1977, 12 pages. (*Superseded by TP#56*)
- #50 Effects of Dam Removal: An Approach to Sedimentation,
David T. Williams, October 1977, 39 pages.
- #51 Design of Flood Control Improvements by Systems Analysis:
A Case Study, Howard O. Reese, Arnold V. Robbins, John
R. Jordan, and Harold V. Doyal, October 1971, 27 pages.
- #52 Potential Use of Digital Computer Ground Water Models,
David L. Gundlach, April 1978, 40 pages.
- #53 Development of Generalized Free Surface Flow Models Using
Finite Element Techniques, D. Michael Gee and Robert C.
MacArthur, July 1978, 23 pages.
- #54 Adjustment of Peak Discharge Rates for Urbanization,
David L. Gundlach, September 1978, 11 pages.

TECHNICAL PAPERS (Continued)

Price
\$2.00 each

- #55 The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers, R. Pat Webb and Darryl W. Davis, July 1978, 30 pages.
- #56 Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models, Bill S. Eichert, November 1978, 19 pages.
- #57 Flood Damage Assessments Using Spatial Data Management Techniques, Darryl W. Davis and R. Pat Webb, May 1978, 30 pages.
- #58 A Model for Evaluating Runoff-Quality in Metropolitan Master Planning, L. A. Roesner, H. M. Nichandros, R. P. Shubinski, A. D. Feldman, J. W. Abbott, and A. O. Friedland, April 1972, 85 pages.
- #59 Testing of Several Runoff Models on an Urban Watershed, Jess Abbott, October 1978, 56 pages.
- #60 Operational Simulation of a Reservoir System with Pumped Storage, George F. McMahon, Vern Bonner and Bill S. Eichert, February 1979, 35 pages.
- #61 Technical Factors in Small Hydropower Planning, Darryl W. Davis, February 1979, 38 pages.
- #62 Flood Hydrograph and Peak Flow Frequency Analysis, Arlen D. Feldman, March 1979, 25 pages.
- #63 HEC Contribution to Reservoir System Operation, Bill S. Eichert and Vernon R. Bonner, August 1979, 32 pages.
- #64 Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study, Steven F. Dalv and John Peters, July 1979, 19 pages.
- #65 Feasibility Analysis in Small Hydropower Planning, Darryl W. Davis and Brian W. Smith, August 1979, 24 pages.
- #66 Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems, Bill S. Eichert, October 1979, 14 pages.
- #67 Hydrologic Land Use Classification Using LANDSAT, Robert J. Cermak, Arlen D. Feldman, and R. Pat Webb, October 1979, 30 pages.

TECHNICAL PAPERS (Continued)

Price
\$2.00 each

- #68 Interactive Nonstructural Flood-Control Planning, David T. Ford, June 1980, 18 pages.
- #69 Critical Water Surface by Minimum Specific Energy Using the Parabolic Method, Bill S. Eichert, 1969, 14 pages.
- #70 Corps of Engineers' Experience with Automatic Calibration of a Precipitation-Runoff Model, David T. Ford, Edward C. Morris, and Arlen D. Feldman, May 1980, 18 pages.
- #71 Determination of Land Use from Satellite Imagery for Input to Hydrologic Models, R. Pat Webb, Robert Cermak, and Arlen Feldman, April 1980, 24 pages.
- #72 Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality, Robert C. MacArthur and William R. Norton, May 1980, 12 pages.
- #73 Flood Mitigation Planning Using HEC-SAM, Darryl W. Davis, June 1980, 23 pages.
- #74 Hydrographs by Single Linear Reservoir Model, John T. Pederson, John C. Peters, Otto J. Helweg, May 1980, 17 pages.
- #75 HEC Activities in Reservoir Analysis, Vern R. Bonner, June 1980, 16 pages.
- #76 Institutional Support of Water Resource Models, John C. Peters, May 1980, 23 pages.
- #77 Investigation of Soil Conservation Service Urban Hydrology Techniques, Duke G. Altman, William H. Espey, Jr. and Arlen D. Feldman, December 1980, 20 pages.
- #78 Potential for Increasing the Output of Existing Hydroelectric Plants, Darryl W. Davis and John J. Buckley, June 1981, 20 pages.
- #79 Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U.S. Hydropower Reservoirs, Bill S. Eichert and Vernon R. Bonner, June 1981, 18 pages.
- #80 Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects, Gary M. Franc, June 1981, 18 pages.

**DAT
FILM**