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APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES.(U)
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APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES

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6 APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES.

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FOREWORD

This training document was written to assist users of computer program HEC-5, Simulation of Flood Control and Conservation Systems, in hydropower applications. This document supplements the program Users Manual, which is the basic documentation for the program. The chapters on hydropower application describe the data requirements, program operation, and program output for the HEC-5 hydropower routines. The Users Manual provides the input specifications.

ACKNOWLEDGEMENTS

The HEC-5 program has developed over the last seven years principally through the efforts of Bill S. Eichert, Director of the Hydrologic Engineering Center. Mr. Eichert has written most of the program, including the system power routine and the routine used to optimize firm energy which has had major use in the National Hydropower Survey of 1979-80. Mr. Gary Franc has made significant contributions to the hydropower, pumped storage and system power routines. For the past few years, the author has been the "Engineer-in-Charge" of the HEC-5 program, providing program maintenance and support in addition to program improvements.

The author wishes to acknowledge the contributions of Mr. Eichert for writing sections on Firm Energy Optimization and Strategies for Using the HEC-5 Program for Power Studies, as well as for his review and comments. Review and comments have also been provided by Messrs. Dale Burnett, Gary Franc and Richard Hayes.

APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES

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APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES

INTRODUCTION

Purpose and Scope

This training document is intended to assist engineers in the application of the computer program HEC-5, Simulation of Flood Control and Conservation Systems, to hydropower problems. While the general capabilities of the program are described, the emphasis is on hydropower simulation. The data requirements, program operation, and types of output available are described for all of the available hydropower routines. Strategies for using the program and program availability are also presented. Detailed instruction on the use of the program can be obtained from the users manual (reference 1).

Program Purpose

The HEC-5 program was developed primarily for planning studies to determine the hydrologic and economic consequences of existing and proposed reservoirs in a system. The program was initially (1973) designed for flood control operation studies; however, extensive capability to simulate hydropower operation and other conservation purposes has been added to provide project and system simulation capabilities for most project purposes. (Earlier program versions were labeled HEC-5C to identify the conservation capability.) The program is useful in simulating the operation of a single reservoir or system of reservoirs operating for the typical "at site" and "system" demands, within specified constraints. Sizing reservoir storage, determining reservoir yield (or firm energy) or evaluating operation schemes are typical ways the program is used. The program was designed so that preparation of input to the model is an easy task. For simple jobs, little input is required, yet complex simulations can be accomplished by supplying more data.

Program Documentation

The primary documentation for HEC-5 is the users manual. The June 1979 manual describes the program capabilities, input requirements and output. To use the program, one would need a users manual, as this document does not give details on many program features or on input formats. The manual is available through the Hydrologic Engineering Center, 609 Second Street, Davis, California 95616 (FTS 448-3292).

Application of the program to flood control planning and operation problems is described in Technical Papers 41, 43, 44, and 45 (see reference list). "The Analysis of Structural and Nonstructural Flood Control Measures Using Computer Program HEC-5C" demonstrates the use of the program's flood damage evaluation capability. Application of the model to a three-reservoir power system with pumped storage is described in Technical Paper 60 (reference 7). These publications can also be obtained from the Hydrologic Engineering Center.

PROGRAM CAPABILITIES AND LIMITATIONS

The June 1979 version of HEC-5 is the basis for this description. The full capabilities described are based on the program as used on the HEC maintained files (Lawrence Berkeley CDC 7600 and Boeing CYBER 175). The library version of the program, distributed to others, is scaled down to fit the "typical" large computer. Though it has the same general capabilities, the library version may not be able to simulate as many reservoirs, power plants, etc., as described here.*

Reservoir System Description

Generally, any reservoir system configuration can be used as long as the dimension limits are not exceeded. In many cases, those limits can be readily changed to meet a particular job requirement. The dimension limits for the HEC maintained files* are as follows:

55 Control Points (including reservoirs)

35 Reservoirs

11 Diversions

9 Power Plants

2 Power Systems

Unlimited time periods, although the program processes a fixed number of periods per cycle.

*Library version is set with 15 Control Points, 10 Reservoirs, and 5 Power Plants.

The conceptual model of a reservoir system is a branching network with a reservoir at the start of every branch. The reservoirs and nonreservoir control points are linked to each other by routing criteria. The whole system cascades downstream and converges to a final control point. Reservoirs and control points are the only locations where flows, constraints, and demands are evaluated by the program. Diversions may be used to route flows to other locations in or out of the basin.

Reservoir Description

Each reservoir is described by the cumulative storage for each target level (see reservoir operation paragraph), and a starting storage. A rating table of storage vs. maximum outlet capacity defines the upper limit for reservoir releases. The reservoir operates for its demands and the demands at specified downstream locations. Additional data on reservoir areas, elevation, diversions, and minimum flows can be given as a function of reservoir storage. Each reservoir is also considered a control point and requires control point description. The required control point description includes a maximum channel capacity, an identifying name and number, and the routing criteria that links it with the next location.

Reservoir Purposes

The program can simulate reservoir operation for most of the typical operating purposes. Conservation operation can be specified by minimum flow requirements at the reservoir and at downstream control points. Flows can be diverted from a reservoir or control point and all or a portion of the diverted flow can return to the system at some other downstream location. Hydropower requirements are defined by energy demands for which the program determines the necessary release. All of these requirements can be varied monthly and the minimum flow and energy requirements can be specified for each period of the simulation.

There is no explicit recreation purpose; however, recreation use may be the basis for minimum flow requirements. Also, the minimum pool level (inactive) may be specified to maintain a full recreation pool during the recreation season.

The flood control operation is based on the specified channel capacity at each control point. Those reservoirs with flood control storage will be operated to maintain flows within those channel capacities at each downstream control point for which the reservoirs are operated.

The priority among purposes in the program can be changed, to some extent, by input specification. When flooding occurs at a downstream location, the program's default operation is flood protection. However, the program user may specify that power releases and/or minimum flow releases be made during flood events.

Reservoir Operation

The reservoir operation is primarily defined by the allocation of reservoir storage. The program has provision for four basic storage zones: (1) Inactive, (2) Conservation, (3) Flood Control, and (4) Surcharge. There is also provision for subdividing the conservation storage into two zones with a buffer level.

In the inactive pool, no releases are made. The only loss of water would come from evaporation, if defined.

In the conservation pool, the goal is to release the minimum amount of water necessary to meet specified requirements. If the buffer level is being used, then two levels of minimum flows are usually defined, desired and required flow. Above the buffer pool level, the reservoir operates to meet all conservation demands, which includes the higher minimum flow (desired flow). When water in storage drops below the buffer level, some conservation purposes may not be met (i.e., hydropower and reservoir diversions) and the lower minimum flow (required flow) would be met. Whether reservoir diversions or hydropower operates in the buffer pool can be specified by the program user. The normal priority is to just provide for minimum required flows.

The program tries to keep the flood control storage empty, if possible. The ideal state for a reservoir would be a full conservation pool and an empty flood control pool. The only reason for storing in the flood control pool would be to maintain flows within channel capacity at specified downstream control points. The program also has provision to limit the rate of change on reservoir outflow to provide for a reasonable transition for increasing and decreasing reservoir releases. The maximum outlet capacity would be another constraint on reservoir flood releases. The program also has two options for making emergency flood control releases when it is apparent that the flood control storage will be exceeded.

Above the top of flood control pool lies the surcharge storage. In this zone, the reservoir is operating uncontrolled and only the outlet capacity vs. storage relationship and the reservoir inflow determine the reservoir outflow. The program would spill the inflow up to the outlet capacity. Inflow above the outlet capacity would be stored to the point of continuity balance. The storage-outflow relationship can be used to model an induced surcharge envelope curve.

Many of the operation decisions are based on reservoir requirements; however, when there is a choice among several reservoirs, the program uses index levels to determine priorities. If two or more reservoirs are operating for a common control point, the program will try to balance the index levels among the projects when making the release determination. The balancing would only occur (for conservation operation) when the sum of the releases for individual project requirements is less than the target flow at the downstream location. Exhibit 3 of the Users Manual describes how index levels can be used to set priorities among projects.

Balancing index levels can also be used with tandem reservoirs. If the upstream reservoir is operating for a downstream reservoir, the program will attempt to keep the two reservoirs balanced (at the same index level). As the lower reservoir makes releases, the upper reservoir will make a release so that the two will draw down together. If the upper reservoir should only operate for specified demands, and not operate for the lower reservoir, the two tandem reservoirs can be operated independently by not indicating the upper reservoir operates for the lower one.

The basis for a reservoir release determined by the program is shown in the output variable Case. The variable is printed for every time period at every reservoir in the Normal Sequential Output and it can be requested in the User Designed Output. The following list shows the reasons for a reservoir release and the Case value. The list also represents the demands and operational constraints the program considers in reservoir operation.

Basis for Reservoir Releases	Case
a. Can be based on maximum reservoir release (channel capacity at the reservoir	.01
b. Can be based on rate of change of release for flood control releases	.02
c. Can be based on not exceeding the top-of-conservation pool	.03
d. Can be based on not exceeding top-of-flood control pool (including prerelease options)	.04

<u>Basis for Reservoir Releases</u> (cont)	<u>Case</u>
(1) Prerelease up to channel capacity if top-of-flood pool will be exceeded	
(2) Prerelease, which may be greater than the channel capacity, to just fill flood pool	
e. Can be based on keeping tandem reservoirs in balance using target levels	.05
f. Can be based on maximum outlet capacity for given pool elevation (surcharge routing)	.06
g. Can be based on not drawing reservoir empty (below inactive pool level)	.07
h. Can be based on minimum <u>required</u> flow	.08
i. Can be based on releases to draw reservation down to top-of-buffer pool	.09
j. Can be based on power demand	.10
k. Can be based on minimum flow until fullest reservoir can release (scheduling option)	.11
l. Can be based on system power requirements	.12
m. Can be based on release given on QA card	.99
n. Can be based on minimum <u>desired</u> flow	.00
o. Can be based on filling downstream channel at location X and time period Y for flood control or conservation operation	X.Y

Time Interval and Duration

The program is capable of operating on a time interval as small as one hour and as large as one month. For conservation purposes, many of the input parameters can vary by the month (e.g., evaporation, flow requirements, storage allocation) and therefore a monthly time interval is often used to set up the reservoir model. Even though the reservoir model is developed on a monthly basis, the actual simulation can be on a smaller time interval. The program's date routine keeps track of time and provides for the monthly changing data. Only the flow data input to the model need be in the smaller time interval. Therefore, a model with monthly varying data can be developed and then used with flow data for any time interval (e.g., one hour, one day, or one month).

When flood flows are a concern, short interval routing is necessary to simulate the rapidly changing conditions. The program has the capability to change between two different time intervals during a simulation. Therefore, monthly conservation routing could be used until a flood starts, at which time the model could shift to a shorter time interval. Then, after the flood sequence, the time interval could return to monthly. As before, the flow data input to the model would provide for the time interval used in the model.

The duration for simulation studies is often the period of record. The program has provision for continuous simulation even though only a finite number of flow periods can be stored in core memory. When the number of periods simulated exceeds the dimension limit, the program will automatically subdivide the data into sets of "floods" that can be processed. The subdivision of flow data by the program is transparent to the user, and the input and output are continuous.

There is a provision in the program to "window in" on a portion of the flow data. For instance, if a long period of flow data was input to the model, it would be fairly expensive to run repeatedly through the data for testing or evaluating a proposal. By isolating a critical period, the cost of analysis could be reduced by the percent reduction in flow data processed. Then, once the decisions were made, the entire flow data set could be processed.

Operation Parameters

There are several operation parameters that play a role in the program's simulation of the reservoir operation. The priorities between competing purposes can be specified by input data as previously discussed in the Reservoir Purposes Section. The index level was discussed in the Reservoir Operation Section. This section presents what might be called control parameters.

For short-interval simulation (i.e., hourly or daily) with routing effects, there is a time delay between the time a reservoir makes a release and when it arrives downstream. Under those conditions, the program needs to look several periods into the future (foresight) to determine the effect of reservoir releases. There should be a a practical limit on the foresight (such as 24 hours), because in the real world we cannot accurately forecast flows too far into the future. In simulation, we can and should limit foresight in the model to provide a realistic operation.

In a similar vein, the future flows in the real world are not known with the surety of the given flow data in the model. Therefore, it is unrealistic to simulate reservoir releases using the observed flows as forecasted inflows. In the program, a contingency factor can be used to temporarily adjust control point flow data when making a release determination. That way, the releases will be more conservative than those computed using exactly known flow data. A contingency factor of 1.2 is frequently used, thus providing for a 20 percent "error" in uncontrolled local flow forecasts.

Another constraint to reservoir operation for flood control is the rate at which reservoir releases can be increased or decreased (rate of change). For short-interval routings, the rate of change parameter prevents the reservoir releases from being changed too rapidly. The rate of change per time period can be expressed as a ratio of the reservoir's channel capacity or in absolute discharge units. There is also provision for having a different rate of change for increasing and decreasing releases as well as different values for each reservoir.

Data Requirements

The data requirements for any job are dependent on the objectives and the level of study. Often the changing data requirements reflect a need for more detailed analysis which comes from shorter time intervals and more detailed input, rather than using average values for the month.

Reservoirs are defined by a series of relationships based on reservoir storage. The storage-maximum outflow relationship is required. For conservation studies, reservoir areas are needed for evaporation computation and elevations are needed for hydropower computations. Both area and elevation are given as a function of storage.

Net evaporation data (evaporation minus precipitation) can be specified as an average monthly value (inches or millimeters) applicable for all reservoirs in the system or can be specified differently at any reservoir in the system. Evaporation defined as 12 monthly values would be used repeatedly throughout a multi-year simulation. For more detailed analysis, the evaporation data can be defined for every period of the simulation in the same way flow data are provided. Given evaporation data, the program computes the net evaporation volume for each time period based on the average reservoir area during the time interval.

Flow data probably takes the most effort to develop. Flow data are usually based on historical flows, but can be based on stochastic flows from monthly models such as HEC-4, "Monthly Streamflow Simulation," (reference 9). Daily and monthly flows can be obtained from an HEC developed routine (GETUSGS) at Lawrence Berkeley Laboratory or from the USGS WATSTORE system (see the section on Program Availability). The HEC-5 program operates with average incremental local flows for the duration of the simulation. Incremental local flows are the flows from the incremental area between adjacent locations in the model. Flow data are required at each location; however, flow at any location can be computed as a ratio of the flow data given at another location. The program can accept three types of flow data: Natural, Regulated, or Incremental Local.

If natural flow data are given, the program computes incremental local flows by routing the flow at each location down to the next location, where it computes the difference between the routed upstream hydrograph and the given downstream hydrograph. The difference is then used as the incremental local flow. If regulated flows are given, then reservoir releases must also be given so that the program can compute incremental local flows. If incremental flows are given, they would be used as given. If end-of-period flow data are indicated, the program averages the the flows before using them.

If flow data are not available at some locations, the program has provision for computing flows as a ratio of the flow at another location in the model. The flow computed can also be lagged an even number of time periods to adjust for travel time. Only one location can be used to compute flow for another location. More complicated relationships must be computed outside the program. If flow data are not defined, the program assumes zero inflow.

Control point data are given at each reservoir and nonreservoir location. Required input is limited to a name, a number, a channel capacity, and the routing criteria to the next location. Control point data can also include stage-discharge relationships, discharge-damage relationships, minimum flow requirements, and diversions.

As discussed in Reservoir Operation, two levels of minimum flows can be specified: Desired and Required. Only a constant required flow can be given, but desired flow can be constant, vary monthly, or vary with each time period, like flow data.

Diversions can be specified from reservoirs or control points. Typically, a monthly diversion schedule is given; however, diversions can be related to reservoir storage or channel discharge. If a portion of the diverted flow returns to the channel system, routing criteria and the ratio of diverted flow returning are required data.

Channel routing between adjacent locations is modeled by hydrologic routing techniques. The available techniques are the Modified Puls, Muskingum, progressive average-lag (straddle-stagger), successive average-lag (Tatum), and working R&D methods. These methods are described in Engineering Manual 1110-2-1408, "Routing of Floods Through River Channels," U.S. Army Corps of Engineers, March 1960 (reference 8). The program user should set the time interval below which the given routing criteria are used (the program's default value is 24 hours). When the time interval for simulation is above that value, the routing coefficients are set to one, and no routing will be used. If monthly or weekly simulation is performed, a "no route" criterion is usually used.

Storage and Yield Optimization

For a single reservoir or for parallel reservoirs, the program can automatically determine the conservation storage necessary to meet specified demands or determine the yield for a specified storage. The yield can be optimized for energy requirements, minimum desired or required flow, diversions, or for all of the requirements. Yield optimization for energy will be discussed in detail in the section on Hydropower Application. The Users Manual provides a description of the procedure under "Optimization of Conservation Storage." Basically, the procedure uses an iterative search technique with the the safe yield concept. The optimized storage or yield is determined when all of the conservation storage is used supplying the conservation demands, during the most critical drawdown period.

Economic Capabilities

The HEC-5 program has economic routines for flood damage assessment. Damages can be computed based on peak discharges at control points for up to nine damage categories. Provisions have also been made for a single flood event or a number of events can be used to compute the expected average value of annual damages. The data required, methods used, and output for the flood damage routines are given in the Users Manual

The only other economic capability in the program is the energy benefits computation. Based on input primary and secondary energy values, the program will compute energy benefits. There is also provision for computing a purchase cost for shortages in primary energy. The benefits for energy are provided in a standard summary table.

HYDROPOWER APPLICATION

The application of the HEC-5 program to hydropower problems is presented here based on the program's current capabilities. The sections are presented as separate program features; however, they are all dependent on the same basic power data. The basic power data are presented in the Power Reservoirs Section. The sections on System Power, Pump-Storage and Firm Energy Optimization all build on the basic capabilities described below.

Power Reservoirs

This section describes the additional data required to model a hydropower reservoir. It also tells how the program uses the data and what type of output is provided. The data required for a basic reservoir model were presented in the Data Requirements Section and includes the total storage at each operating level, the downstream control points for which the reservoir is operated, and a storage-outflow relationship. For hydropower, both reservoir areas and elevations are provided as a function of reservoir storages. The areas are needed for evaporation computations and the elevations for head determination. Standard Test 5, in Exhibit 6 of the program Users Manual, is an example of power reservoir input and output.

Data Requirements. Power data are input with reservoir data at each hydropower reservoir. The data requirements include an overload ratio, the installed capacity, a blockloading tailwater elevation, an efficiency, and the monthly energy requirements (KW-hrs or plant factors).

An overload ratio is used by the program to determine the maximum energy the power plant can produce in a time interval. The maximum production would then be a limit on how much dump energy could be generated during periods of surplus water. The program assumes a value of 1.15 if none is given.

The installed capacity is the nameplate capacity except for planning studies, where an assumed value is used. Again, with the overload ratio, the capacity defines an upper limit for power generation. If the data are available, the peaking capability can also be defined as a function of reservoir storage, reservoir outflow, or power plant head.

The tailwater elevation can be specified as a constant value associated with full capacity operation (block loading tailwater). Tailwater elevation can also be specified as a function of reservoir releases. The average reservoir release for the routing interval is used to determine the tailwater elevation. Care must be taken to define the tailwater discharge relationship consistent with the time interval used in the simulation. If a monthly time interval is used, then the computed power releases would represent average values for the month, not instantaneous discharges. Therefore, the tailwater rating curve should be monthly averages, not instantaneous discharge values. If a downstream lake elevation could affect the tailwater elevation, the program can check that elevation to see if it is higher than the block loading tailwater elevation and the tailwater rating curve. If it is, then the downstream lake elevation would be used. Where two or more ways are used to describe the tailwater, the higher tailwater value is used.

Power plant efficiency is the total efficiency of the power plant. No other energy loss is computed by the program. The efficiency can be a constant value (the program assumes 0.86 if none is given) or it can vary with head. An alternative to using efficiency directly is the kilowatt per discharge (KW/cfs) coefficient as a function of reservoir storage. Often older power studies, done by hand, used KW/cfs vs. elevation as an aid to computation. These relationships, with efficiency and tailwater elevations built into them, can be used directly in the program by relating reservoir storage to elevation.

Energy requirements can be defined for each hydropower plant using 12 monthly values or by using an energy requirement for every time period of the study. For most planning studies, the 12 monthly values are used. The monthly energy values can be given in thousand kilowatt-hours (MW-hr) or as plant factors. Plant factors are ratios indicating the portion of time (per month) that the plant is generating. If plant factors are given, the program computes the monthly energy requirement by multiplying the plant factor times the installed capacity times the hours in the month; the product being MW-hrs for each month.

If the time interval used is less than a month, daily ratios can be given to show how the energy requirement is distributed over the seven days of the week. The sum of the daily ratios provided must add up to 1.0. The program computes the weekly energy requirement from the given monthly requirement and then distributes the weekly total using the daily ratios. If no distribution is given, the program will use a uniform distribution. If daily ratios are used, the day of the week at the start of the simulation should be given. The program will assume Sunday if no starting day is given.

If the time interval is less than one day, a distribution within the day can be given. The daily distribution should provide at least as many values as there are time intervals in a day (24 hrs/Δt). The daily distribution can be as many as 24 hourly values. If 24 values are given, and the time interval is greater than hourly, the program will sum the hourly values to compute the value for the given time interval. As with the daily ratios, the values should sum to 1.0 and if no distribution is given, a uniform distribution is used.

Program Operation. For hydropower operation, the program computes the energy requirements for each time period of operation. The monthly energy requirements and given distributions or the given period-by-period energy requirements are used for this purpose.

The program cycles through the simulation one interval at a time. For the hydropower reservoirs, the following logic is used to determine a power release:

1) Estimate average storage. Use end of previous period's storage initially and then the average of computed and end-of-period storages. (Reservoir elevation and evaporation are both dependent on average storage.)

2) Estimate tailwater elevation. Use highest elevation from block loading tailwater, or tailwater rating curve, or downstream reservoir elevation.

3) Compute gross head by subtracting tailwater from reservoir elevation corresponding to estimated average storage.

4) Compute reservoir release to meet energy requirement.

$$Q = \frac{Ec}{eht}$$

where:

E = Required energy (kwh)

c = Conversion factor - (11.815 English or 0.102 metric)

e = Plant efficiency

h = Gross head (feet English or meters)

t = Time (hours)

Q = Reservoir release

5) Compute reservoir evaporation (EVAP) using reservoir area based on average reservoir storage.

6) Solve for ending storage (S_2) using continuity equation.

$$S_2 = S_1 - EVAP + (INFLOW - OUTFLOW) * CQS$$

where:

S_1 = End-of-period storage

EVAP = Evaporation during time interval

OUTFLOW = Power release and leakage

CQS = Discharge to storage conversion

7) On the first cycle, use the new S_2 and return to 1. On subsequent cycles, check the computed power release with the previous value for a difference less than 0.0001. Use up to five cycles to obtain a balance.

8) Check maximum energy that could be produced during time interval using overload factor and installed capacity.

9) Check maximum penstock discharge capacity, if given. Reduce power release to penstock capacity if computed release exceeds capacity.

The program will also determine if there is sufficient water in storage to make the power release. The buffer pool is the default minimum storage level for power; however, the user can define the inactive pool as the minimum power pool. If there is not sufficient water in storage, the program will reduce the release to just arrive at the minimum pool level. If there is sufficient water, the power release for the reservoir establishes a minimum flow at that site. The program will evaluate every reservoir and control point in the system for a time interval. For conservation operation, it will determine if additional reservoir releases are required for some downstream requirement. If not, then the power release holds. If additional water is needed for non-power uses, then the release will be increased. Credit for the additional energy generated by the larger release will be given to the Secondary Energy account. The Primary Energy account only shows the energy generated to meet the specified demand.

During flood control operation, the power release may add to downstream flooding. A user specified priority determines whether the program cuts back the release to prevent downstream flooding. (The program shorts power under default priority.) If the program cuts back on the power release, there will be an energy shortage for that time period and the shortage is shown in output as Energy Shortage. A program output variable, "Case," will show the program basis for release determination. If priority is given to hydropower, then the power release will hold and some flooding due to reservoir release will occur.

Program Output. A description of the available output from the program is provided in the Users Manual. This section describes the power output and provides some suggestions on how to check the program's results. There are 31 variables pertaining to the flow data, reservoir and control point status, and energy production. The normal sequential output provides tables of the applicable variables for each location in the system, or a user can define tables for just the variables and locations desired. The variables that deal specifically with the power reservoir are: Energy Required, Energy Generated, Energy Shortage, and Peak Capability. Summary tables also provide Primary, Secondary, and Shortages of Energy and Energy Benefits.

Energy Required lists the given energy requirements for the reservoir. Energy Generated shows the computed energy based on the reservoir release, and Energy Shortage is the deficiencies in generated Energy. If the Generated equals the Required, then the Case variable should equal .10, showing the reservoir release was for hydropower. If generated Energy was less than required, the Case variable code should show the reason (e.g., insufficient storage or flood control operation). If Generated Energy was greater than Required, the program Case should indicate a release of surplus water or that a higher required flow at another control point was operated for.

Variable peaking capability data, if provided, are based on a Reservoir Storage, Reservoir Outflow or Reservoir Operating head. Given one of peaking capability relationships, the program computes the peaking capability for each time period of the simulation. This information can be used in conjunction with peak demand information to determine the critical peaking capability for dependable capacity.

If no peaking capability function is given, the program uses the installed capacity for all periods.

In the summary tables for energy, the total energy generated is shown as Primary and Secondary Energy. The Primary Energy represents energy generated to meet the primary energy demand. The Secondary Energy is all of the surplus generated energy (dump energy). Shortage is the shortage in the firm energy for the power plant. The summary results are shown for each hydropower reservoir and for the total of all hydropower reservoirs in the system.

The Energy Benefits Summary Table provides the dollar value for Primary and Secondary Energy and the Purchase Cost based on Shortages. The benefits are computed using input unit values for the three categories. The Net Energy Value reflects the sum of Primary and Secondary less Purchases. A capacity value is based on the installed capacity.

System Power

Up to nine hydropower reservoirs can be modeled as individual power projects as described in the previous section. If some of the reservoirs are delivering power into a common system, system operation might be able to produce more energy than the sum of individuals can produce. By allocating the system load based on each projects's ability to produce power, the projects could help each other during periods of low flows. This section describes the added input, program operation and output associated with the System Power capability. Everything described in the Power Reservoirs section also applies to this section. Standard Test 8 in Exhibit 6 of the program Users Manual shows input and output for a three-reservoir power system.

Data Requirements. Additional data required for the system power routine consist of System Energy Requirements and an indication at each hydropower plant if it is in the system. One or two power systems can be used and some plants may just operate independently.

System Energy requirements are provided as 12 monthly values in MW-hrs or ratios of the annual demand. The system energy requirement represents a demand on all projects in hydropower system one. If a second set of system energy demands are given, then they represent a demand on all projects in system two. The monthly energy requirements data start with the same month used with all the other monthly varying data. The monthly system energy requirements are distributed in the same manner as the at-site energy requirements. Seven daily ratios define the total weekly energy and multi-hourly ratios define the fluctuation within each day.

At each hydropower reservoir in the model, all of the power data previously described is still provided plus the indication if the power plant is in the power system and the maximum plant factor for application to the system load. The indicator is zero if a power plant is not to be used for system power. A value of 1 indicates system 1 and 2 indicates the plant is in a second system. The system plant factor is used to limit the extent (or percent of time) each power plant can operate to meet system load. Generation rates greater than the system plant factor are allowed when excess water is available, but only the proportion up to the factor can be credited as meeting the system load.

The monthly at-site requirements at each power plant in a system should be reduced to some minimum value to provide operational flexibility. If the at-site requirements are not reduced, the plant will operate for the at-site requirements, reducing the possibility of system flexibility. Often some low plant factor is defined for at-site requirements at system power reservoirs just to ensure their operation. However, if there are some at-site requirements for a particular project, they should be given and the other projects should be allowed the maximum flexibility.

Program Operation. With system energy requirements, the program will allocate the demand to all of the projects designated in the power system. The allocation is performed at the beginning of each time step of operation by determining the energy that can be produced by system reservoirs releasing down to various common levels. The program temporarily subdivides the conservation storage into a number of levels and then computes the energy that could be produced by releasing down to each level. Then, by taking the total system demand, the program can interpolate on the levels for the projects to determine releases that will keep the system balanced as much as possible. The program has provision for checking minimum flow constraints to ensure the allocated release will also meet the reservoir's minimum flow requirement. Also, if a significant at-site requirement is given, the routine will ensure the at-site requirement is met within the total system generation. Once the allocation is made, the remaining operation for the program is the same as previously described.

The reservoir release values, based on the interpolation described above, may not actually produce the required system energy due to the nonlinearity of the relationship. If the sum of the project's energy production does not match system requirements, the program will cycle through the allocation routine up to two more times in an attempt to get the generated energy to within one percent of the requirement. If that is not close enough, the user can change the tolerance and the number of iterations to provide a closer check. For most applications, increasing the cycles is not warranted.

The system energy routine is presently limited to 12 monthly energy values; period-by-period values cannot be used. Also, the system energy allocation routine does not provide for routing between tandem reservoirs. That means the release from the upper reservoir is assumed available at the lower reservoir in the same time period. For short-interval routings with considerable travel time between tandem power reservoirs, the tandem project will not remain balanced and the actual energy generated may be lower than the system routine had computed during the allocation period.

Program Output. All of the previously described output would be available plus: System Energy Required, System Energy Usable, System Energy Generated and System Energy Shortage. The system energy variables are displayed for the first reservoir in the system when normal sequential output is used or they can be requested using user designed output tables.

System Energy Required is the given input requirement. System Energy Usable is the system energy generated to meet the system demand within the maximum plant factor for system power generation. System Energy Generated is the total generation of projects in the system and System Energy Shortage is the deficiency in Usable System Energy.

The Case code for system power is 0.12. When a project release is based on the allocation from the system power routine, a value of .12 is given. When the at-site power requirement controls, a value of .10 will still be used.

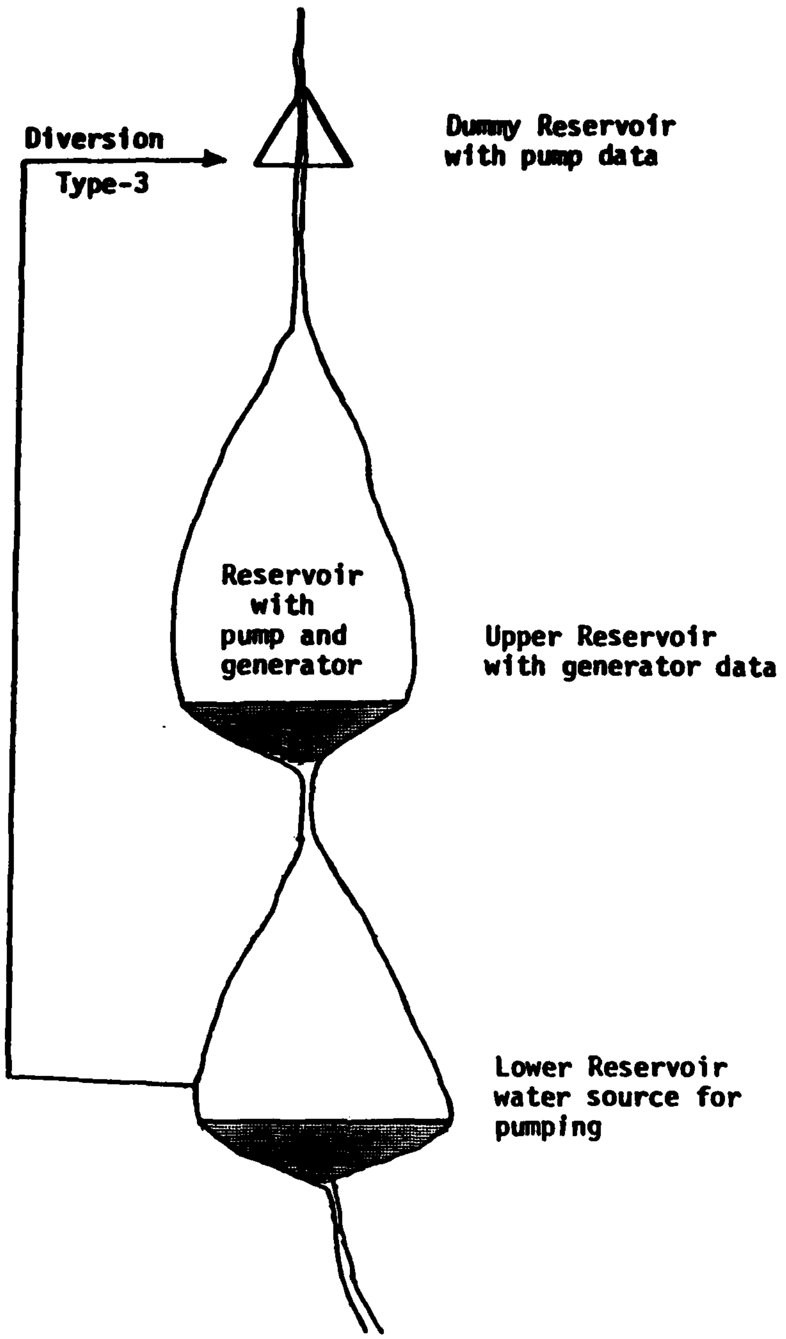
Pump Storage

The previous information on Power Reservoirs applies to the pump-storage model. This section describes the additional data required, the program operation, and the type of output available for pump-back operation. The pump-storage capability is applicable to either an adjacent or integral pump-back configuration. Standard Test 8 in Exhibit 6 of the Users Manual shows input and output for pump-back operation (see reservoir 99).

Data Requirements. To model a pump in a hydropower reservoir, a dummy reservoir is added just upstream from the power reservoir to input the pumping capabilities. The basic reservoir and power data described previously are required for the dummy location. For the power data, a negative installed capacity is used to tell the program that this is a pump and not a generator. The tailwater elevation is usually based on a lower reservoir elevation and the energy requirement data now reflect energy available for pumping.

Added data include a maximum pump-back pool level and a diversion card to handle the pump-back discharge. The program will pump to the upper reservoir until it reaches the top-of-conservation level. The maximum pump-back level can be set to a lower level by defining the pump-back level. The diversion card defines the source of the pump-back water. The input would indicate a diversion from the dummy location to the lower reservoir and the type of diversion would be -3 for pump-back simulation. The computed pump-back discharges are carried by the program as diversions from the lower reservoir to the dummy reservoir. Those diversions are then routed into the upper reservoir based on unlimited outlet capacity and the routing criteria from the dummy reservoir. The following diagram shows the model arrangement for an on-stream system, and a similar approach can be applied to an off-stream system.

MODEL FOR ON-STREAM PUMPED STORAGE



Program Operation. The initial estimate of the pump-back d'scharge is based on the available energy defined by input. The tailwater elevation will be based on the higher of the block loading tailwater elevation or the lower reservoir level. The upper reservoir elevation is used in computing the head. If pump leakage is defined, that discharge is subtracted from the pump-back discharge. If the maximum penstock capacity is defined, the program checks to see that that value is not exceeded.

The pump discharge based on available energy is reduced, if necessary, to prevent the lower reservoir from being drawn below the buffer level. The program also prevents the pump-back discharge from exceeding the storage capacity of the upper project at the top-of-conservation pool. The top of the pump-back pool can be set to a lower level by defining a pump-back level.

Program Output. No new output data have been provided for pump-back operation. The discharge values for pumping are displayed as diversions at the dummy reservoir (negative values) and at the lower reservoir (positive values). The energy values are shown at the dummy reservoir. Energy Required represents the Available Energy for pumping and Shortage represents Available Energy that was not used for pumping.

Firm Energy Optimization

Energy is one of the conservation purposes the program can maximize using the firm yield concept. The optimization routine can determine firm energy for up to nine independent reservoirs given a fixed conservation storage, or determine the required conservation storage to provide for a given at-site energy demand. Paragraph 12 of the Users Manual describes the optimization capabilities of the program. A supplemental handout, describing the optimization capabilities developed for the National Hydropower version of the program, is available through the Hydrologic Engineering Center. This section describes the additional input requirements, the program's operation, and the type of output provided. Standard Test 7 in Exhibit 6 shows input and output for an energy optimization problem.

Data Requirements. The basic power reservoir model previously described would be used for the optimization routine. The addition of one job card (J7) requests the optimization routine and tells the program which reservoirs to use and the option selected. The input values for the parameters to be optimized (e.g., storage or monthly energy) are used by the program as the initial value. In the case of energy optimization, a special capability has been developed to make the initial estimate of energy and capacity. The estimate is based on the power produced from the power storage and the available flow during the estimated critical drawdown period. The critical drawdown duration is estimated by the routine based on a relationship of drawdown duration (in months) vs. ratio of power storage to mean annual flow.

Unless otherwise requested, the program will operate the project for the duration of the given inflow data. If 29 years of monthly data are available and 4 or 5 iterations are required to obtain the desired results, a considerable amount of computation will be required. By using the critical period option (J4.7), the program will determine the starting and ending periods corresponding to the minimum flow volume for the specified duration. Only the isolated critical period data would then be used for each of the iterative routings. However, if the starting period (monthly data only) is not at the beginning of the year (as specified by ISTMO J4.1), the starting period will be automatically shifted back to the start of that year. The critical period can also be defined by a starting and ending period.

Program Operation. The program operates the power reservoirs through a complete simulation as previously described. However, at the end of the simulation, the program checks to see if all of the power storage has been used in the routing. If not, a new estimate of the monthly energy requirements is made to provide for all fixed purposes, plus the at-site energy requirements during the critical drawdown period. The iterative search procedures uses the entire inflow data set for each cycle unless the critical period option is used to limit the simulation. The allowable error in storage can be set by the user or the default value of 100 acre-foot negative error and one percent positive error are assumed. When all demands are met and the minimum storage at the reservoir is within the allowable error, the solution is obtained.

Program Output. The output options previously described would normally be used with the optimization routine. For each iteration, a special table of results is provided. For most applications of the optimization routine, it may be desirable to just run the first half of the program, HEC-5A, and not get the sequential routings for each trial. The optimization results could then be used in a complete routing. For program determined critical periods, an additional table can be printed that will show, for assumed critical drawdown durations of 1-60 months: the minimum flow volume for each duration, the starting and ending periods of the minimum flow volume, and the initial estimate of dependable capacity. The first value of capacity printed is based on the minimum flow volume only, while the second value also uses the reservoir power storage released uniformly over the number of drawdown months. The second printed value is used by the routine for the initial estimate of the dependable capacity.

Strategies for Using the HEC-5 Program for Power Studies

Strategies for using HEC-5 for project studies are similar to strategies for performing sequential routings by manual methods. The objective is to perform only those routings which are necessary in determing the amount of reservoir storage required to accomplish the desired objectives or in determining the reservoir accomplishment possible from a given amount of reservoir storage. The relative low cost of computer solutions compared to manual methods makes it more economical to perform many more routings than before. However, it is easy to spend too much money in evaluating too many "nice to know" conditions. It is, therefore, still important to restrict the number of routings to those essential to the success of the study. The following comments may help in deciding which combination of routings is required for different types of projects.

Large Storage Projects. In many geographical areas, flow data are available near the project for more than 20 years. Therefore, it is usually desirable to initially limit the duration of the routings to the critical period and to use monthly flows in the analysis. Since the critical period of record can change as the demands on the system change, the full period of flow record should be used to verify that the assumed yield or firm energy can be maintained throughout the entire historical record.

The optimization routine in HEC-5 will determine the approximate critical period (or allow the user to specify the critical period) and will perform sequential routings using that critical period to automatically determine either:

1) the storage required for a specified annual firm energy and/ reservoir yield, or

2) the annual firm energy and/or reservoir yield that can be obtained from the specified reservoir storage.

The optimization routine can also use the entire period of flow record to determine the storage or firm annual energy. The difference in computer costs between using the flows for the entire period of record versus the critical period only is approximately proportional to the number of months used in the routings. For 30 years of flow data and a 6-year critical period, the ratio of costs approaches 5 to 1. In general, it is less expensive to optimize on the critical period of record and then to verify the answer on the period of record than to optimize on the period of record.

Once the conservation operation has been satisfactorily determined for a range of power storages and minimum power heads using monthly flows, the effect of the selected project on other project purposes should be determined. If flood control is a project purpose, the program can be set up to either (1) perform monthly routings during nonflood periods and daily or multihourly routings during major flood events, or (2) perform period-of record routings for some fixed interval such as daily flows. It is particularly important to see how the proposed hour-by-hour operation affects both the power and the flood control operations. Runs should also be made to test for the desirability of using seasonally varying storage allocations (rule curves operation).

Once a satisfactory operation for a single multipurpose reservoir is obtained, the data should be expanded to include other reservoirs whose operation might affect the reservoir under study. In order to determine if a system operation for flood control or power is necessary or desirable, studies should be made comparing the effectiveness of the system with and without the system rules.

Pumped Storage Projects. While pumped storage projects can be evaluated using some of the ideas mentioned above, the primary routings will have to be made using both daily flows and multihourly operations. Monthly routings for pumped storage operation would, in most cases, not be meaningful. While period-of-record runs using daily flows might be warranted, hour-by-hour operation during certain critical weeks should also be evaluated.

Run-of-River Projects. While run-of-river projects can be operated along with other reservoirs in the system, studies using flow duration techniques are preferable to monthly routings since short-duration high flows are important and cannot be captured by sequential analysis without going to daily or hourly operation. A daily flow sequential routing for the selected project should be made after the project has been firmed up using daily flow-duration techniques. The HEC has developed a flow-duration program which should be available by June of 1980.

PROGRAM AVAILABILITY

The program is available through the Hydrologic Engineering Center (FTS 448-3285). The source can be obtained from the Center or the program can be accessed on one of several commercial computing companies. The following section describes how one can gain access to the program.

Program Distribution

To U. S. federal agencies, the program will be distributed without charge. For all others, a computer program order form must be completed and returned to the Center, together with a check payable to the Treasurer of the United States, to cover a handling charge of $120. The appropriate form can be obtained from the Center.

The requested source code for the program is mailed, along with test data on magnetic tapes, either 7-track BCD or 9-track EBCDIC. The program is actually two programs which are executed together in sequence (HEC-5A and HEC-5B). Some applications, such as conservation optimization, only require the execution of the first program (HEC-5A). Core storage requirements are 74,000 words (60 bits) and the program uses nine scratch units. The dimensions of the distributed program are set at 10 reservoirs, 15 control points, 11 diversions, and 5 power plants.

HEC Maintained Files

The Center maintains a complete library of its programs at the government-owned Lawrence Berkeley Laboratory (LBL) computer at Berkeley, California, and Boeing Computer Service (BCS) at Seattle, Washington. Programs at these sites are updated and supported by Center personnel. Corps offices and others with access to these sites can use the following job control cards to execute the HEC-5 program:

LBL

```
Your Job Card.
SFL,170000.
FETCHPS,HECLIB,LGO,HEC5A.
LGO.
FETCHPS,HECLIB,LGO,HEC5B.
LGO.
End of Record Card.
Data.
End of Information Card.
```

BCS

```
JOB,T50,CM330000,P2.
USER Card.
GET,HEC5A/UN=CECELB.
HEC5A.
GET,HEC5B/UN=CECELB.
HEC5B.
End of Record Card.
Data.
End of Information Card.
```

The HEC5A program reads the data and performs the simulation. Results are written to scratch files which are read by the second program. HEC5B reads the scratch files and provides output tables and economic calculations.

A portion of the U.S. Geological Survey (USGS) WATSTORE data base has been moved to the Lawrence Berkeley Laboratory (LBL) computer system by the Hydrologic Engineering Center. The data currently available include daily and monthly streamflow discharge, flow-duration data, and site information for all USGS sites in the United States. The daily and monthly data cover the period of record for each gage through water year 1977 or 1978. Access to the data is obtained through the program, GETUSGS. The data may be printed, plotted, and/or written to a file for other processing.

Further information is contained in the program writeup. To obtain a copy of the writeup, include the following control cards in any LBL job:

```
LIBCØPY,HECDØC,XXX,GETUSGS.
CØPY,XXX/RX,ØUTPUT.
```

Program Support

The Center makes every effort to support its programs. If users find difficulty in coding input, executing the program, or interpreting output, they can call the Center to request assistance. Every effort is made to provide timely assistance.

The Center maintains a videotape library of lectures on the application of many of its programs. For new program users, the tapes can be helpful by explaining program capabilities, input requirements, or output analysis. A videotape catalog can be obtained by calling the Center. Most of the tapes are 3/4" U-Matic Cartridge (Sony).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This training document was written to assist users of computer program HEC-5, Simulation of Flood Control and Conservation Systems in hydropower applications. This document supplements the program Users Manual, which is the basic documentation for the program. The chapters on hydropower application describe the data requirements, program operation, and program output for the HEC-5 hydropower routines. Hydropower applications cover power reservoirs, system power, pumped storage, firem energy optimization, and strategies for using the HEC-5 program. The Users Manual, available from the (CONTINUED)

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Hydrologic Engineering Center, provides the input specifications. The conceptual model of a reservoir system is a branching network with a reservoir at the start of every branch. The reservoirs and nonreservoir control points are linked to each other by routing criteria. The whole system cascades downstream and converges to a final control point. Reservoirs and control points are the only locations where flows, constraints, and demands are evaluated by the program. Diversions may be used to route flows to other locations in or out of the basin.

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