APPENDIX K

APPLICATION OF THE HEC-5 HYDROPOWER ROUTINES

K-1. Introduction.

a. 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 and input specifications can be obtained from the User's Manual (40).

b. 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.

c. Program Documentation.

(1) The primary documentation for HEC-5 is the User's Manual (40). The manual describes the program capabilities, input requirements, and output. To use the program, one would need a user's manual, as this appendix 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 448-2105)

(2) Application of the program to flood control planning and operation problems is described in references (7), (8), (9), (10), and (11). "The Analysis of Structural and Nonstructural Flood Control Measures Using Computer Program HEC-5C" (21) 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 reference (25). These publications can also be obtained from the Hydrologic Engineering Center.

K-2. Program Capabilities and Limitations.

a. Introduction. The April 1982 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, Control Data CYBER 175 and Harris 500). 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, powerplants, etc., as described here.

b. Reservoir System Description.

(1) 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 library version is set with 15 control points, 10 reservoirs, and 5 powerplants. The dimension limits for the HEC maintained files are as follows:

- control points (including reservoirs): 55
- reservoirs: 35
- diversions: 11
- powerplants: 9
- power systems: 2

There is no limit to the number of time periods that can be run, although the program processes a fixed number of periods per cycle.

(2) The conceptual model of a reservoir system is a branching network with a reservoir at the start of every branch. The reservoir 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.

c. Reservoir Description. Each reservoir is described by the cumulative storage for each target level (see Section K-2e) 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.

d. Reservoir Purposes.

(1) 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.

(2) 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 pool during the recreation season.

(3) 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.

(4) 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 the power releases and/or minimum flow releases be made during flood events.

e. Reservoir Operation.

(1) The reservoir operation is primarily defined by the allocation of reservoir storage. The program has provisions for four basic storage zones; (a) inactive, (b) conservation, (c) flood

control, and (d), surcharge. There is also provision for subdividing the conservation storage into two zones with a buffer level.

(2) No releases are made from the inactive pool. The only loss of water would come from evaporation, if defined.

(3) 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, termed desired and required flow, are used. 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 just to provide for minimum required flows.

(4) 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 limit flows to channel capacity at specified downstream control points. The program also has provisions 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 release. The program also has two options for making emergency flood control releases when it is apparent that the flood control storage will be exceeded.

(5) Above the top of the 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.

(6) 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.

(7) 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 that the upper reservoir operates for the lower one.

(8) 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. Table K-1 lists the reasons for a reservoir release and the corresponding case values. The table also represents the demands and operational constraints the program considers in reservoir operation. The order of the list does not correspond to priority.

f. Time Interval and Duration.

(1) 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 certain monthly time interval data is included with the basic reservoir model. The basic reservoir model then can be used with any time interval. The program's date routine keeps track of time and provides for the capability to use time series data for any time interval (e.g., one or more hours, one day, one week, or one month).

(2) When flood flows are a concern, short interval routing is necessary to simulate 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.

(3) 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

TABLE K-1
Reservoir Release Case Values

Reservoir releases can be based on:	Case
a. Maximum reservoir release (channel capacity at the reservoir)	.01
b. Rate of change of release for flood control releases	.02
c. Not exceeding the top of conservation pool	.03
d. Not exceeding top of flood control pool (including prerelease options) (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 (3) Gate regulation operation	.04
e. Keeping tandem reservoirs in balance using target levels	.05
f. Maximum outlet capacity for given pool elevation (surcharge routing)	.06
g. Not drawing reservoir empty (below inactive pool level)	.07
h. Minimum _required_ flow	.08
i. Releases to draw reservoir down to top of buffer pool	.09
j. Power demand	.10
k. Minimum flow until fullest reservoir can release (scheduling option)	.11
l. System power requirements	.12
m. Release given on QA card	.99
n. Minimum	.00
o. Filling downstream channel at location X and time period Y for flood control or conservation operation	X.Y

"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.

(4) 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.

g. Operation Parameters.

(1) 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 Section K-2d. The index level was discussed in Section K-2e. This section presents what might be called control parameters.

(2) 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 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.

(3) In a similar vein, the future flows in the real world are not known with the certainty 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.

(4) 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.

h. Data Requirements.

(1) The data requirements for any job are dependent on the objectives and the level of the 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.

(2) 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 computations and elevations are needed for hydropower computations. Both area and elevation are given as functions of storage.

(3) 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 is 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.

(4) Flow data probably takes the most effort to develop. Flow data is usually based on historical flow, but can be used on stochastic flows from monthly models such as HEC-4, Monthly Streamflow Simulation (53). Daily and monthly flows can be obtained 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. The program can accept three types of flow data: natural, regulated, or incremental local.

(5) If natural flow data is 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 is indicated, the program averages the flows before using them.

(6) If flow data is not available at some locations, the program has provisions for computing flows as a ratio of the flow at another location in the model. The flow computed can also be lagged (forward or backward) an even number of time periods to adjust 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 is not defined, the program assumes zero inflow.

(7) Control point data is given at each reservoir and non-reservoir location. Required input is limited to a name, a control point 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.

(8) As discussed in Section K-2d, two levels of minimum flows can be specified: Desired and Required. The minimum flows can be constant, vary monthly. or vary with each time period, like flow data.

(9) 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 is required data.

(10) 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 (54). 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.

i. Storage and Yield Optimization. For a single reservoir, 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 safe yield concept. The optimized storage or yield is determined when all of the conservation storage is used to supply the conservation demands, during the most critical drawdown period.

j. Economic Capabilities.

(1) 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 outlines are given in the Users Manual.

(2) 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.

K-3. Application to Analysis of a Single Hydropower Project.

a. General. The application of the HEC-5 program to hydropower problems is presented here based on the program's capabilities in July 1983. The sections are presented as separate program features. However, they are all dependent on the same basic power data. The basic power data is presented in Section K-3c. The sections on Hydropower Systems (Section K-4), Pumped-Storage (Section K-5), and Firm Energy Optimization (Section K-6), all build on the basic capabilities described below.

b. 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 Section K-2h and include the total storage at each operating level, the downstream control points for which the reservoir is operated, and a storage-outflow relationship indicating the maximum outlet capacity. For hydropower, both reservoir areas and elevations are provided as functions of reservoir storage. The areas are needed for evaporation computations and the elevations for head determination. Standard Test

5 in Exhibit 6 of the program Users Manual shows both input and output for a single power reservoir.

c. Data Requirements.

(1) Power data is 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 (kWh or plant factors).

(2) An overload ratio is used by the program. in addition to the installed capacity. to determine the maximum energy the powerplant 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. For new plants, the current Corps policy is to make the installed capacity large enough so that the overload factor is 1.0.

(3) The terms "installed capacity" and "nameplate capacity" are used interchangeably. In some situations, the full overload peaking capability may not always be available due to head loss resulting from reservoir drawdown or tailwater encroachment during periods of high discharge. If the data is available, a variable peaking capability can be defined as a function of reservoir storage, reservoir outflow, or powerplant head.

(4) The tailwater elevation is normally specified as a constant value associated with full nameplate rating operation (block loading tailwater). Higher tailwater elevation can also be defined for flood operations as a function of reservoir releases. The average reservoir release for the routing interval is used to determine this tailwater elevation. 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 or the tailwater rating curve. If it is, then the downstream lake elevation would be used. When two or more methods are used to describe the tailwater. the higher tailwater value is used.

(5) Head loss can be defined a a constant or as a function of flow. If defined, the loss will be subtracted from the computed head (reservoir average elevation minus tailwater elevation) to determine the net head for power.

(6) Powerplant efficiency is the total efficiency of the powerplant (including generators and turbines). 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.

(7) Firm 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 megawatts-hours (MWh) 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 firm energy requirement by multiplying the plant factor times the installed capacity times the hours in the month; the product is megawatt-hours for each month.

(8) If the time interval used is less than a month, daily ratios can be given to show how the firm 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.

(9) 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 (t) in a day (24 hrs/t) 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 ratio, the values should sum to 1.0 and if no distribution is given, a uniform distribution is used.

(10) An alternative method of operation to the firm energy method discussed above is based on an individual project rule curve relating plant factor to percent of conservation storage. This method can produce more near-firm energy, but may have a few months where no energy is produced at all.

(11) Another rule curve type of operation is available using the firm energy method previously discussed. This method of operation is exactly the same as the firm energy operation except that the input firm energy requirements are used only when the reservoir is below some user specified storage index level (normally the buffer pool). When the reservoir (for the previous time period) exceeds the seasonal

rule curve storage, the input firm energy requirement is multiplied by a user supplied factor.

d. Program Operation.

(1) 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.

(2) 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:

- Estimate average storage for the time interval. (Reservoir elevation and evaporation are both dependent on average storage.) Use end of previous period's storage (S_1) initially and then in subsequent iterations use the average of S_1, and the computed end-of-period storage for the current time interval (S_2).

- Estimate tailwater elevation. Use highest elevation from block loading tailwater. or tailwater rating curve, or downstream reservoir or channel elevation.

- Compute net head by subtracting tailwater and head loss from reservoir elevation corresponding to estimated average storage.

- Compute reservoir release to meet energy requirement.

$$Q = \frac{Ec}{eHt} \qquad \text{(Eq. K-1)}$$

where: E = required energy (kWh)
c = conversion factor (11.815 English or 0.102 metric)
e = plant efficiency
H = gross head (feet or meters)
t = time (hours)
Q = reservoir release

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

- Solve the ending storage (S_1) using continuity equation:

$$S_2 = S_1 - \text{EVAP} + (\text{INFLOW} - \text{OUTFLOW}) \times \text{CQS} \qquad \text{(Eq. K-2)}$$

where: S_1 = End-of-period storage for previous period
EVAP = Evaporation during time interval
OUTFLOW = Power release and leakage
CQS = Discharge to storage conversion

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

- Check maximum energy that could be produced during time interval using overload factor and installed or variable peaking capacity.

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

- Check maximum and minimum head and/or flow, if given. Do not generate power if the head and/or flow are not within defined operation range.

(3) The program will 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 one time interval at a time. 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.

(4) 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.

e. Program Output.

(1) 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 38 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, peaking capability and plant factor. Summary tables also provide primary and secondary energy, shortages of energy, and energy benefits.

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

(3) Variable peaking capability data, if provided, is based on Reservoir Storage, Reservoir Outflow or Reservoir Operating head. Given one of the 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 times overload factor for all periods.

(4) In the summary tables for energy, the total energy generated is divided into 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 powerplant. The summary results are shown for each hydropower reservoir and for the total of all hydropower reservoirs in the system.

(5) 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 computed based on the installed capacity.

K-4. Analysis of Hydropower Systems.

a. General. 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 the individual projects operating independently. By allocating the system load dynamically (for each time period) based on each project'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 Section K-3 also applies to system analysis. Standard Test 8 in Exhibit 6 of the program Users Manual shows input and output for a three-reservoir power system.

b. Data Requirements.

(1) Additional data required for the system power routine consists 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.

(2) 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 starts 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.

(3) At each hydropower reservoir in the model, all of the power data previously described is still provided, plus the indication if the powerplant is in the power system and the maximum plant factor the project can produce which will be useable in meeting the system load. The indicator is zero if a powerplant is not to be used for system power. A value of 1 indicates system 1, and 2 indicates that the plant is in a second system. The system plant factor is used to limit the extent (or percent of time) each powerplant 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 specified plant factor can be credited as meeting the system load.

(4) The monthly at-site energy requirements at each powerplant should be reduced to some minimum value to provide the necessary operational flexibility of shifting load between projects. If the at-site requirements are not reduced, each 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 high priority at-site energy requirements for a particular project, they should be given and the other projects' minimum plant factors should be very small, allowing the maximum flexibility in those projects.

c. Program Operation.

(1) Given the system energy requirements, the program will allocate power demand to all of the projects designated in the power system. The allocation is performed at the beginning of each time step of operation, using data derived by determining the energy that can be produced by all system reservoirs releasing down to common levels. The program temporarily subdivides the conservation storage at all projects into a number of levels and then computes the energy that could be produced by releasing down to each level. Then, by using the total system demand, the program can determine by interpolation the system level and the project releases that will meet the system load and will keep the system balanced as much as possible. The program has provisions for checking minimum flow constraints to ensure the allocated release will also meet the reservoir's minimum flow requirements. 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.

(2) 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 the system requirements within a specified tolerance, 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.

(3) The input system energy requirements are presently limited to 12 monthly values. Also, the system energy allocation routine does not provide for routing between tandem reservoirs. This means that 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.

d. Program Output.

(1) 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 each time period for the first reservoir in the system. This output is available in either normal sequential output or user designed output tables.

(2) System Energy Required is the given input requirement. System Energy Usable is the sum of the energy generated from all projects in the system to meet the system demand, within each individual project's maximum plant factor for system power generation. System Energy Generated is the total generation of all projects in the system and System Energy Shortage is the deficiency in Usable System Energy.

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

K-5. Analysis of Pumped-Storage Projects.

a. General. The previous information on power reservoirs (Section K-3) applies to the pumped-storage model. This section describes the additional data required, the program operation, and the type of output available for pump-back operation. The pumped-storage capability is applicable to either an adjacent (offstream) or integral (pump-back) configuration. Routing intervals used with pumped-storage evaluation are usually daily or multihourly. Standard Test 8 in Exhibit 6 of the Users Manual shows input and output for a daily pumped-storage operation (see reservoir 99).

b. Data Requirements.

(1) To model a pump in a hydropower system, a dummy reservoir is added just upstream from the upper 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 specified efficiency for the dummy reservoir is for the pump while the upstream reservoir specifies the generating efficiency. The tailwater elevation for the pump is usually based on the elevation of the lower reservoir, and the specified energy requirement data for the pump reflects energy available for pumping. Pumping energy is usually input to the program as plant factors based on the number of hours per day that energy is available and should be used for pumping.

(2) Added data includes a maximum pump-back pool level and a diversion card to convey the pump-back discharge into the upper reservoir. The program will pump water to the upper reservoir using all the available energy during the time periods specified. However, it will stop pumping if the upstream pool reaches the top-of-conservation level or if the lower pool draws down below the buffer pool. The maximum pump-back level can be set to a lower level than the top-of-conservation pool by defining an intermediate 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 a zero lag routing criterion from the dummy reservoir. Figure K-1 shows the model arrangement for an on-stream system, and a similar approach can be applied to an off-stream system.

c. Program Operation.

(1) The estimate of the pump-back discharge is based on the available pumping energy specified as 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 specified, that discharge is subtracted from the pump-back discharge. If the minimum penstock capacity is defined, the program checks to see that value is not exceeded.

(2) The pump discharge based on available pumping energy is reduced, if necessary, to prevent the lower reservoir from being drawn

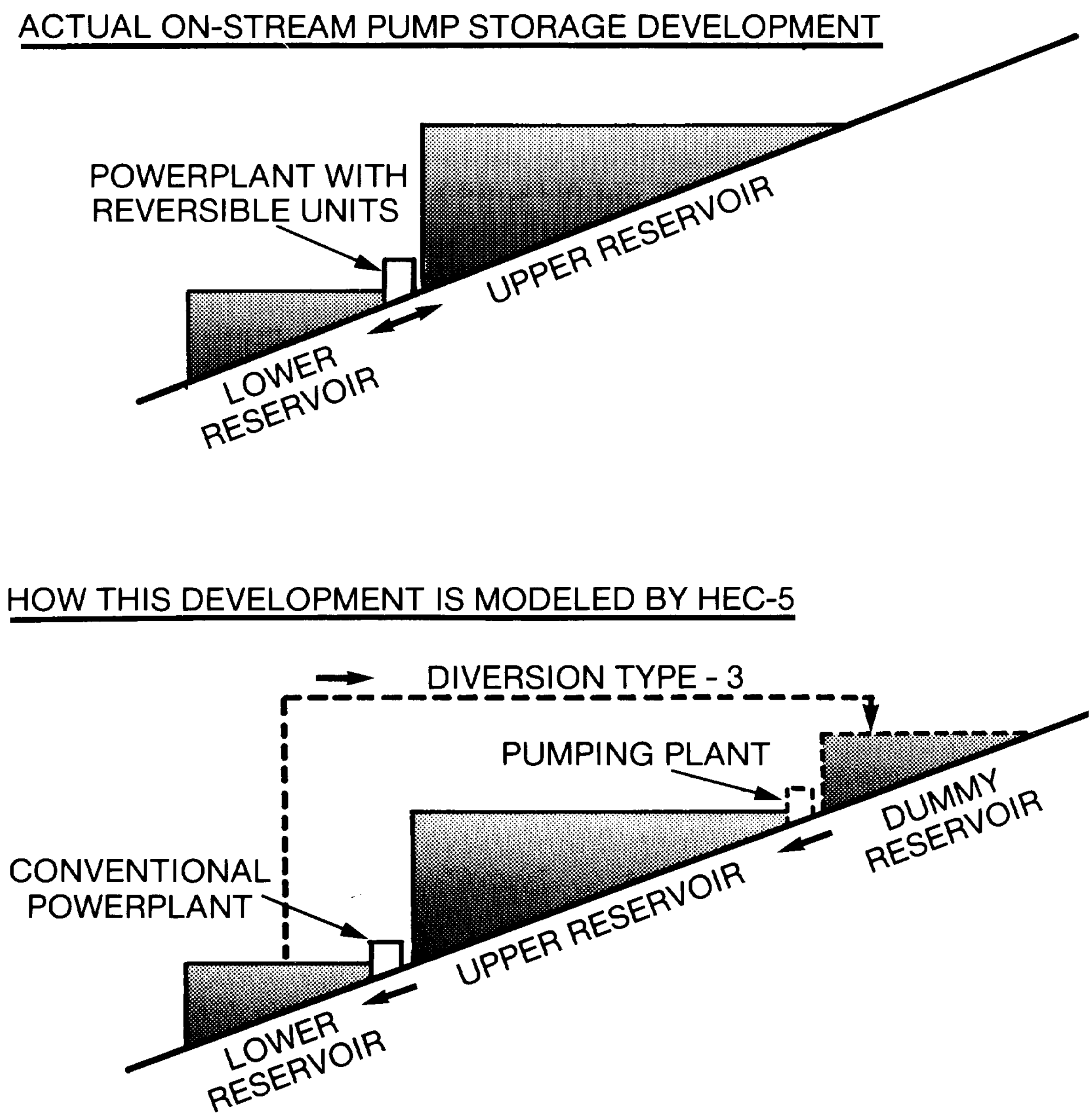

Figure K-1. Modeling of on-stream pumped-storage (pump-back) project below the buffer level. The program also prevents the pump-back discharge from exceeding the storage capacity of the upper project at the top of conservation pool or top of the pump-back pool if specified. The top of the pump-back pool can be set to a lower level to reduce the amount of pumping energy used. The pump would only be used to maintain a minimum pool level rather than full pool.

d. Program Output. No new output data has 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 pumping energy values are reported at the dummy reservoir. The Energy Required values reported for the dummy plant represent the Available Energy for pumping, and Shortage represents Available Energy that was not used for pumping. Energy Generated values represent energy used for pumping.

K-6. Firm Energy Optimization.

a. General. Energy is one of the conservation purposes the program's optimization can maximize using the firm yield concept. The previous discussions describe the use of HEC-5 for meeting specified energy requirements. In many planning studies, the objective is to determine how much firm energy a reservoir of a given size can produce or how much storage is required to produce a given amount of energy. 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 10 of the Users Manual describes the optimization capabilities of the program. Standard Test 7 in Exhibit 6 shows input and output for an energy optimization problem. This section describes the additional input requirements, the program's operation, and the type of output provided.

b. Data Requirements.

(1) The basic power reservoir model previously described would be used for the optimization routine. 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 values. 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 which could be produced from the power storage and the available flow during the estimated critical drawdown period. The length of the critical drawdown period is estimated by a routine based on an empirical

relationship between drawdown duration (in months) and the ratio of power storage to mean annual flow.

(2) The optimization routine only works with average monthly flow data. Unless otherwise requested, the program will simulate the project operation for the duration of the given inflow data. If 29 years of monthly data is 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 (J7.8), the program will identify the starting and ending points of the critical period by finding the minimum flow volume for the specified length of duration. Only the isolated critical period data would then be used for each of the iterative routings. However if the critical period does not start at the beginning of the year (as specified by ISTMO J1.2), the starting period will be automatically shifted back to the start of that year. The critical period can also be defined by specifying a starting and ending period.

c. 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 based on the minimum storage content during the routing to provide for all fixed purposes, plus the at-site energy requirements. The iterative search procedure 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.

d. Program Output.

(1) The output options previously described would normally be used with the optimization routine. For each iteration, a special table of results is provided. Program HEC-5 is actually two separate programs (HEC5A and HEC5B) normally connected together by job control cards to appear as one program. For most applications of the optimization routine, it may be desirable to just run the first half of the program HEC5A, and not get the sequential routing output displays from HEC5B for each trial. Sufficient output displays of the optimization results are provided in HEC5A. The results can be used in a complete routing (using both program parts) to obtain final output displays for the sequential routing.

(2) For program determined critical periods, an additional table can be printed that will show, for each assumed critical drawdown

duration 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 estimated value of dependable capacity is based on the minimum flow volume plus the reservoir power storage released uniformly over the number of drawdown months. The capacity value is used by the routine for the initial estimate of the dependable capacity unless input specifies (J7.7) that the P1 card capacity value should be used.

K-7. Strategies for Using the HEC-5 Progam for Power Studies.

a. General. 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 to determine the amount of reservoir storage required to accomplish the desired objectives or to determine the reservoir accomplishment possible from a given amount of reservoir storage. The relatively low cost of computer solutions compared to manual methods makes it more economical to perform more routings. However, it is easy to spend too much money in evaluating "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.

b. Large Storage Projects.

(1) In many cases, flow data is available near the project for long periods of time. In order to minimize computer time, 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 later be used to verify that the assumed yield or firm energy can be maintained throughout the entire historical record.

(2) 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:

- the storage required for a specified annual firm energy and reservoir yield, or
- the annual firm energy and/or reservoir yield that can be obtained from the specified reservoir storage.

(3) 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.

(4) Once the conservation operation has been satisfactorily determined for a range of power storages and minimum power heads using monthly flow, 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 (a) perform monthly routings during nonflood periods and daily or multihourly routings during major flood events, or (b) perform period-of-record routings for one 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. Test simulations of selected flood events using small time intervals should be made to evaluate performance. Runs should also be made to test for the desirability of using seasonally varying storage allocations (rule curves operation).

(5) 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.

c. 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 hourly or multihourly operations for selected periods. Monthly routings for pumped-storage operation would, in most cases, not be meaningful. While period-of-record runs using daily flows might be warranted for pump-back operation, most off-stream pumped-storage projects would require hour-by-hour operation during critical weeks to evaluate performance.

d. Run-of-River Projects. While run-of-river projects can be operated with other reservoirs in the system, studies using flow duration techniques are preferable to monthly sequential routings because short-duration high flows are important and cannot be captured by sequential analysis without going to daily operation. A daily flow sequential routing for the selected project would be desirable after the project characteristics have been established using daily flow-duration techniques. The HEC has developed a flow-duration program, HYDUR (45), which is available through the same sources as HEC-5 (see Program Availability).

K-8. Program Availability.

a. Introduction. The HEC-5 program, as well as other HEC programs, is available through the Hydrologic Engineering Center (FTS 448-2105). The source can be obtained from the Center or the program can be accessed by one of several commercial computing companies. The following section describes how one can gain access to the program.

b. Program Distribution.

(1) The program will be distributed without charge to Corps offices. For all others, a computer program order form must be completed and returned to the Center, together with a check payable to "FAO-USAED, SACRAMENTO", to cover handling costs. The appropriate form and information on the current handling charge can be obtained from the Center.

(2) The requested source code for the program is mailed, along with test data on magnetic tapes, either 7-tract BCD or 9-tract EBCDIC. The HEC-5 program is actually two programs which are executed together in sequence (HEC5A and HEC5B). Some applications, such as conservation optimization, only require the execution of the first program (HEC5A). Core storage requirements are 115,000 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 powerplants.

c. HEC Maintained Files.

(1) The Center maintains a complete library of its programs at the Control Data Cybernet (CDC) System. Programs at this site are updated and supported by Center personnel. Corps offices and others with access to this site can use the following job control cards to execute the HEC-5 program.

CDC

```
Your Job Card.
USER Card.
GET,HEC5A/UN=CECELB.
HEC5A.
GET,HEC5B/UN=CECELB.
HEC5B.
```

End of Record Card.
Data.
End of Information Card.

(2) 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.

d. Program Support.

(1) The Center makes every effort to support its programs. If users experience 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.

(2) The Center maintains a video tape 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 video tape catalog can be obtained by calling the Center. Most of the tapes are 3/4" U-Matic Cartridges (Sony).