US Army Corps
of Engineers
Hydrologic Engineering Center

HEC-5
Simulation of Flood Control and Conservation Systems

User's Manual
Version 8.0

October 1998

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CPD-5

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Foreword

The HEC-5 computer program was developed at the Hydrologic Engineering Center (HEC). The original software was written by Bill S. Eichert, with the support of HEC staff. Since his retirement in 1989, the HEC-5 package of programs have been developed and maintained by Mr. Richard Hayes and Ms. Marilyn Hurst, with support and direction from Vern Bonner, Chief, Training Division. This manual was written by Messrs. Bonner and Hayes and Ms. Hurst. Mr. Darryl Davis, as HEC Director since Mr. Eichert's retirement, has actively supported the continued development and application of the HEC-5 package.

Chapter 1

Introduction

1.1 Origin of Program

The HEC-5 computer program was developed at the Hydrologic Engineering Center by Bill S. Eichert. The initial version was written for flood control operation of a single flood event and was released as HEC-5, "Reservoir System Operation for Flood Control," in May 1973. The program was then expanded to include operation for conservation purposes and for period-of-record routings. This revised program was referred to as HEC-5C up to the February 1978 version. Mr. Eichert retired from HEC in 1989 and he continues to develop his version of the program. HEC continues to develop and maintain HEC-5 and has released several versions since 1989. The HEC-5, Version 8, October 1998, is the current edition and the basis for this user's manual.

1.2 Purpose of Program

This program was developed to assist in planning studies for evaluating proposed reservoirs in a system and to assist in sizing the flood control and conservation storage requirements for each project recommended for the system. The program can be used in studies made immediately after the occurrence of a flood to evaluate pre-project conditions and to show the effects of existing and/or proposed reservoirs on flows and damages in the system. The program should also be useful in selecting the proper reservoir releases throughout the system during flood emergencies in order to minimize flooding, while maintaining a balance of flood control storage among the reservoirs. After flooding recedes, the program will empty the flood volume in storage as quickly as possible.

The purposes noted above are accomplished by simulating the sequential operation of a system of reservoirs for short-interval historical or synthetic floods, for long duration non-flood periods, or for combinations of the two. Specifically the program may be used to determine:

- Flood control and conservation storage requirements for each reservoir in the system.

- The influence of a system of reservoirs on the spatial and temporal distribution of runoff in a basin.

- The evaluation of operational criteria for both flood control and conservation purposes (including hydropower) for a system of reservoirs.

- The energy generation for specified energy demands and capability for a single project, or system of hydropower projects operating for a system demand.

- The system of existing and proposed reservoirs or other alternatives including nonstructural alternatives that results in the maximum net flood control benefits for the system by making simulation runs for selected alternative systems.

1.3 Dimension Limits

Dimension limits for the distribution version are as follows:

80	KMXCPT	=	Number of control points
40	KMXRES	=	Number of reservoirs
18	KCHSTG	=	Number of values of channel storage and discharge
40	KDIV	=	Number of diversions
40	KLEV	=	Number of reservoir target levels
60	KNCAPT	=	Number of values of reservoir storage, discharge, etc.
35	KPWR	=	Number of power plants

These dimension limits are shown at the beginning of the output file that is created during program execution.

1.4 Hardware and Software Requirements

The HEC-5 program,[1] written in FORTRAN V, was originally developed on a CDC CYBER 865 computer. PC and Unix versions have been developed. The PC version of HEC-5 runs in a MS-DOS window under Win95 or NT and operates with extended memory. Eight (8) Mb or more of RAM are recommended.

[1]The program is actually two separate programs (HEC-5A and HEC-5B) that are linked by temporary scratch files and executed in sequential order as one job by job control records. The first program reads input and simulates reservoir operation. The second program reads the scratch files and creates the output tables and performs the economic analysis. Certain applications require only the first program (conservation optimization (J7 Record) and output to DSS). If output to HEC-DSS (ZW Record) is requested, output displays, economic analyses and duration and frequency analysis can be performed by other HEC programs.

1.5 User's Manual Organization

This manual provides HEC-5 program description at two levels. The chapters present general descriptive information on program capabilities, while the appendices present more detailed information and input/output examples.

Chapter 2 presents basic capabilities

Chapter 3 presents flood reduction capabilities.

Chapter 4 provides low-flow capabilities.

Chapter 5 provides hydropower capabilities.

Chapter 6 presents system operation.

Chapter 7 gives an overview of input and output.

Appendix A presents the HEC-5 routing options.

Appendix B describes HEC-5 use of the data storage system (HEC-DSS).

Appendix C presents detailed information and examples on flood operations.

Appendix D presents detailed information and examples on water supply features.

Appendix E presents detailed information and examples on hydropower options.

Appendix F is the output description

Appendix G is the input description.

Chapter 2

Basic Capabilities and Requirements

Computer program HEC-5 is designed to perform sequential reservoir operation based on specified project demands and constraints. Demands can be minimum channel flows, diversion requirements, and energy requirements. Demands can be specified at the reservoir and at downstream locations (called Control Points). Physical reservoir constraints define the available storage for flood control and conservation purposes and maximum outlet capability. Operational constraints can include maximum non-damaging flows and reservoir release rate-of-change. The simulation is performed with specified flow data in the time interval for simulation. The simulation process determines the reservoir release at each time step and the resulting downstream flows. Detailed output is available to evaluate the reservoir performance and resulting regulated flow.

2.1 Reservoir System Configuration

Any dendritic reservoir system configuration may be used as long as dimension limits are not exceeded for number of reservoirs, number of control points, number of diversions, etc. (see Chapter 1 for dimension limits). Figure 2.1 is an example system diagram, showing basic model components of reservoirs and downstream control points. Model data are defined starting at the upstream boundaries of the system, and data for each location are entered sequentially downstream. All upstream locations must be defined before entering the data for the downstream location.

The most upstream location on each tributary must be a reservoir. If no reservoir exists, a dummy reservoir with no storage can be used.

Non-reservoir locations are called control points, where flow constraints and demands can be specified. The last (most downstream) location in the system must be a non-reservoir control point.

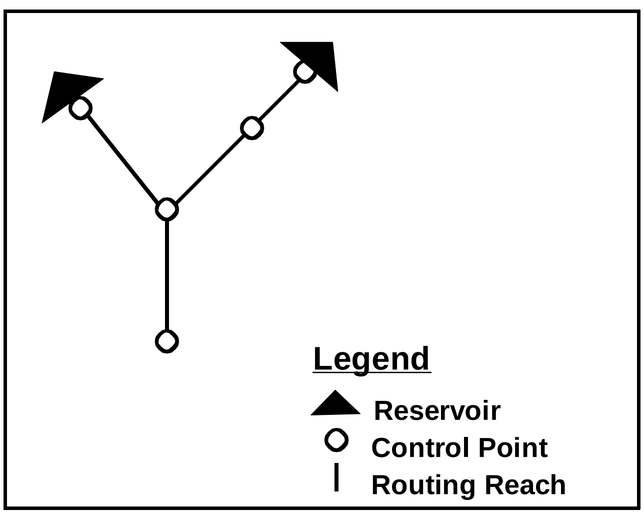

Figure 2.1 Reservoir System Diagram

All locations, including reservoirs, require control point data, which includes routing criteria to the next downstream location. The system configuration is defined by routing reaches and specified downstream locations. All locations upstream from a control point must be defined before that control point's data are defined.

The entire reservoir system, based on reservoir and control point data, is defined in an ASCII (text) data file. Then, following the model data, the flow data for simulation are provided. Together, these data constitute the input data file. The following sections provide additional information on reservoirs, control points, routing methods and flow data. The data record identifiers, associated with the different model components, are provided with the descriptions. Detailed input data description is provided in Appendix G of the User's Manual.

2.2 Reservoir Index Levels

An index level is associated with the primary reservoir storage zones: Inactive, Buffer, Conservation, and Flood Control. Figure 2.2 illustrates the levels associated with reservoir storage zones. Within a system model, all reservoirs must have the same number of levels and the Index Level for the primary storage zones must be the same. These data are defined on the first Job Record (**J1**) for all reservoirs in the model. The actual storage allocated to each level is defined with the reservoir data, on the **RL** Record.

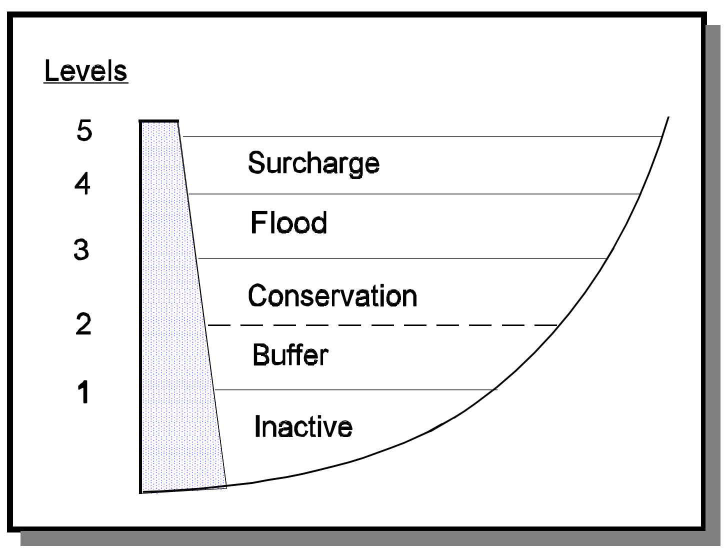

Figure 2.2 Reservoir Storage Zones and Index Levels.

Level 1 is top of the Inactive pool. No reservoir releases are made below this level. The storage at this level may be zero, or some minimum pool.

Level 2 is usually associated with the top of Buffer pool, a special subdivision of the Conservation pool. When the pool level drops into a Buffer Zone, a drought condition is indicated. Then, only essential demands will be met (Required Flow). Above the Buffer Level, all conservation demands are met (Desired Flow). If the concept of Buffer Storage is not used, the Buffer Level would also be Level 1, the top of Inactive pool.

Level 3 is usually associated with the top of Conservation pool. The conservation pool can be subdivided into multiple levels (see Chapter 6 for a description of system levels.)

The fourth essential level is the top of Flood Control pool. Typically, the zone between top of conservation and flood control is the active flood storage zone. Water is stored in this zone when it cannot be safely passed through the downstream channel system. If a reservoir in the system does not have flood control storage, the cumulative storage at the top of flood control would equal the storage at the top of conservation. If none of the reservoirs have flood storage, the Index Level for Flood Control (**J1** Record) would be the same as Conservation.

Usually, the top of Flood Control Level is not the maximum level. Typically, a reservoir has surcharge storage to accommodate water above the emergency spillway. In the surcharge zone, the outflow is determined by the spillway capacity; the reservoir no longer makes release decisions. However, this Surcharge Index Level is not explicitly defined on the **J1** Record. An Index Level, greater than the top of Flood Control would indicate the surcharge zone.

The **J1** Record allows three additional Index Levels associated with hydropower. They are left blank for non-hydropower applications. Their significance is described in Chapter 5, Hydropower Capabilities.

2.3 Reservoir Description

For a reservoir, the primary physical data are the cumulative storage for each operational zone and the maximum outflow capability, given as a function of storage. The minimum reservoir data are described below. The control point data, also required for each reservoir, are described in the following sections. Beyond the required data, optional data can be added to utilize other program features.

Storage. Each reservoir must have a starting storage and the cumulative storage at each Index Level. *(The concept of Reservoir Index Levels is described in the previous section.)* The reservoir storage for each Index Level can vary seasonally, monthly or remain constant. (**RL** Records)

Operation Locations. Each reservoir operates for itself and specified downstream control points (**RO** Record). The reservoir always considers it's own requirements. In addition to itself, only those downstream locations specified on the **RO** Record are considered before making a reservoir release.

Reservoirs which have flood control storage may be operated to minimize flooding at any number of downstream control points.

Reservoirs without flood storage will be operated for their own requirements (power or low flow) and can be operated to provide low flow requirements for any number of downstream control points (same locations as for flood control).

Upstream tandem reservoirs may not be operated directly for control points below a downstream tandem reservoir; however, the downstream tandem reservoir considers the upstream system storage when making its release.

Reservoirs in the system that operate for a common control point are kept in balance (in terms of reservoir level) for both flood and conservation operation. See Chapter 6 for information on system levels and operations.

Outlet Capacity. Each reservoir must have a table of maximum outlet capacities as a function of reservoir storages (**RS** and **RQ** Records). The table defines the maximum outflow capability for any reservoir storage, using linear interpolation on the input data. Therefore, the entire operation range of reservoir storage should be defined.

Control Point Data. Each reservoir is also considered a control point and requires control point data (**CP**, **ID**, **RT** Records). See Control Point Description below.

Identification Number. Reservoir and control point identification number (on **RL** and **CP** Records) may be any integer number up to six digits. The program uses a series of internally generated numbers for storage of variable arrays.

Additional Data. Reservoir areas, elevations, diversions, and costs can be given as a function of reservoir storages (**RA**, **RE**, **RD**, **R$**, **RS** Records, respectfully). Area data are required to compute reservoir evaporation and elevation data are required for hydropower computations; otherwise, they are informational only.

Delete Reservoirs. Reservoirs may be deleted by specifying the applicable identification number on the **J5** Record (becomes a reservoir with no storage) or by removing the appropriate records **RL - PE** (becomes only a control point).

2.4 Control Point Description

Every location in the reservoir system model must have control point data. Minimum data requirement includes an identification number, channel capacity, a location name, and the connection to the next downstream location (routing information). The required data are described in the following paragraphs. As with reservoir data, additional data can be added to use program options.

Identification Number. Each control point must have an identification number (**CP** Record). Only integer values can be used.

Channel Capacity. An operating (maximum) channel capacity must be provided. The channel capacity can be constant (**CP** Record), or vary by month, by season, or vary with channel flows at any location, or reservoir levels at any reservoir (**CP** and **CC** Records). .

Minimum Flow Requirement. Each control point can have low flow requirements (minimum desired and/or minimum required) which are constant (**CP** Record), or vary monthly, or by season, or vary period by period. (**CP** and **QM** Records)

Location Name. Each control point has an identifying alphanumeric name with up to <u>14 characters</u>. (**ID** Record)

Downstream Link. Each control point is linked to the next downstream point by specifying the channel routing reach (*route from and route to data on* **RT** Record). Stream routing options are described below. The last control point in the system must have a **RT** Record; however, the route to location and routing criteria are not specified.

Additional Data. Each control point can have a discharge-stage rating curve for determining regulated and natural stage hydrographs (**QS** and **EL** Records). Also, discharge vs. channel storage data can also be given for the channel (**QS** and **SQ** Records)

2.5 Channel Routing Methods

Stream routing procedures incorporated in the program are hydrologic routing methods, typically used in the Corps. These methods are described in Engineering Manual (EM) 1110-2-1417, "Flood-Runoff Analysis," U.S. Army Corps of Engineers, August 1994, and are briefly summarized in Appendix A. For short time-interval simulation (daily or less), the routing criteria are used to model the translation of flow through the channel system. Hydrologic routing options provided are:

- Straddle-Stagger,
- Tatum,
- Muskingum,
- Modified Puls,
- Modified Puls as a function of inflow,
- Working R&D,
- SSARR Time-of-storage, and
- direct input of routing coefficients.

The program will use the channel routing data if the time interval for simulation is equal to, or less than the value of the NOROUT variable (default value is 24 hours). For longer time intervals, the routing criteria are ignored. The NOROUT value can be changed with the **J3** Record, field 7.

The routing reach and method are defined on the **RT** Record. Each routing reach may be subdivided into several steps (field 3). For Modified-Puls, the storage is divided by the number of steps and the routing is processed sequentially through each subset for storage-outflow data.

Routing criteria for natural flow conditions can also be specified (**RT** Record, field 8).

For each routing reach, two sets of flood routing criteria (at least one linear) can be specified along with the applicable routing interval (i.e., 3-hr and 12-hr).

When reservoir releases are routed by nonlinear methods (Modified Puls or Working R&D), linear approximations are used to determine the reservoir's releases. The actual releases are then routed by the nonlinear method.

Steady state is assumed for flows prior to the first period of routing.

2.6 Flow Data

Model Structure. The format for model data attempts to separate the reservoir system data from the time dependent data, like flow. The time interval for simulation, starting date, and number of simulation periods are all defined with the flow data. The initial reservoir storage, at the start of simulation, can also be defined here using the **SS** Record (instead of using the initial storage on the **RL** Record).

Incremental Local Flow. The program uses incremental local flows (flows between adjacent control points) in the system routings. The flow data set must be in the same uniform time interval as used in the simulation. The time interval can be in minutes, or hours up to one month (720 hours).

Incremental local flows can be computed from observed discharges and reservoir releases. (**J3** Record, field 6) Incremental local flows can also be calculated from natural flows.

Computed incremental local flows can be output into a DSS file for subsequent system operations. (**JZ**, **ZW** Records)

Period Average Values. Flow data are average values. If end of period flow data are given, the program will first average the flow data. (**J3** Record, field 8)

Ratio of Flow. Flow data at some of the control points can be a ratio of the flow at another system point. The flows can also be shifted several whole computation time intervals. (**C1** Record)

Cumulative Local Flow. Cumulative local flows are computed for each downstream location. They are computed by routing and combining the incremental local flows downstream from a reservoir. The cumulative flow would represent the flow without any reservoir release. Uncontrolled cumulative local flows do not include flows above a reservoir that has more than ten acre-feet of active storage. Otherwise, uncontrolled local flows will include flows from the upstream reservoir drainage areas.

Natural Flow. The accumulation of all incremental flow, without any reservoir holdouts, represents the flow in the system without reservoirs (unregulated flow). If requested on **J3** Record, field 4, natural flows are calculated for printout purposes.

Flow Processing. Data on flow records can be for more time periods than the internal program's dimension limit and the program will automatically generate an equivalent series of events so that the entire event is operated.

Flow data are normally read in a 10 field record-image format (defined by the **BF** Record, field 1).

Flow data or any other time series data can be read from a separate data file (HEC-DSS) by entering **ZR** Records.

Flow data can be shifted in time and/or converted to any other time interval (from one hour to one month) by use of a separate program HEC-DSSMATH.

2.7 Input Data

Details on input data are provided in Appendix G. The following provides basic information on the minimum required data for reservoir system modeling. The input data for a basic HEC-5 model 1 is shown Table 2.1. Examples are also provided in the Appendices for various program applications.

All data records use the first two columns for identification.

Most data records are optional and can be omitted unless options are desired.

Input is coded into ten 8-column fields for all input <u>except</u> for the **ID**, **ZR** and **ZW** Records.

A blank field is taken as a zero input.

Table 2.1 HEC-5 Data Input Example

```
T1      Single Flood Control Reservoir Operating One Downstream Location
T2      Basic Flood Control Options, Metric Units
T3      Rocky River Basin, Aaron Dam Site to Zachary
J1     1       1       5       3       4       2
J2    24     1.2       0       0       0
J3     5                      -1               1
JZ333.09  333.10  333.12  333.13  222.04  222.17  222.18  222.02  333.22  333.11
C
C  ============= Aaron Dam =============
RL   333  188000  131400  146500  188000  562200  630100
RO     1     222
RS    12       0  124100  146500  188000  253600  362000  417700  465200  546300
RS562200  589300  630100
RQ    12       0     660     680     727     800     870     910    2320    5660
RQ  6460    7650    9630
RE    12   209.7   249.6   251.5   255.6   262.1   270.5   274.3   277.4   282.2
RE 283.2   284.7   286.8
CP   333     425      80       3
IDAARON DAM
RT   333     222     1.2     0.3     3.0       0
C
C  ============== Zachary ==============
CP   222     450
IDZACHARY
RT   222
ED
C    ------------------- Flood of 20-28 Dec 1964 -------------------------------
BF     2      72       0     64121924       0       3                      1900
C    ------------------ Inflow at Aaron Dam Site -----------------------
IN   333
IN   193     193     198     217     242     272     286     290     297     297
IN   297     418     559     715     909     973    1005    1104    1260    1522
IN  1933    2478    2896    3087    3016    2705    2400    2174    2096    2060
IN  1947    1791    1749    1827    1912    1890    1763    1593    1437    1345
IN  1296    1267    1218    1161    1104    1048     984     935     899     857
IN   826     797     767     746     722     701     687     667     647     632
IN   609     581     552     523     487     453     425     396     375     354
IN   326     297
C    ----------- Local Incremental Flow at Zachary ------------------------
IN   222
IN    49      49      54      63      89     102      94      94      95     102
IN   122     192     248     367     531     539     473     460     509     608
IN   756     934    1036     982     815     629     474     426     517     606
IN   577     480     454     517     627     670     587     459     377     346
IN   335     325     335     378     400     350     286     288     300     288
IN   276     282     309     321     332     345     323     285     256     239
IN   223     209     200     189     174     129     151     190     167     173
IN   177     173
ZW   A=ROCKY RIVER     F=METRIC TEST
EJ
ER
```

All records used must be in correct order (as shown in the sequence of input records summary on the inside back cover of Appendix G); and, control points must be in sequential order of treatment in routing and combining flows.

Either SI (Metric) or English units can be used.

Input data (T1 through BF only) can be checked for possible errors by the use of separate program CKHEC5.

2.8 Basic Reservoir Model Data

The example input shown in Table 2.1 illustrates the format and basic input for a flood control reservoir model, with one reservoir operating for one downstream control point.

2.9 Reservoir Routing

Reservoir routing is performed sequentially, in the order the reservoir data are given. All locations are processed for each time interval of flow data. The primary decision variable is the reservoir release for each time interval. Once the release is determined, the reservoir end-of-period storage is computed using the Accounting Method. However, when the proposed release exceeds the outlet capability of the reservoir, Surcharge Routing is used. And, when the flood control storage is going to fill to capacity, Emergency Release determination can be invoked.

Accounting Method. When the reservoir release is determined based on specified operation goals, reservoir end-of-period storage is equal to the previous period's storage, plus the average inflow, minus the outflow and reservoir evaporation (if specified).

Surcharge Routing. When the desired release is greater than the physical outlet capacity, an iterative method is used to find the outflow. This method provides the same results as the Modified-Puls method.

Emergency Releases. When the desired release for the current period plus channel capacity releases for future periods (up to the limit of foresight specified) would cause a reservoir to exceed maximum flood storage in the current or future periods, a release can be made for the current period so that the reservoir does not exceed the top of flood pool in the near future.

2.10 Reservoir Operation

Reservoir operation simulation primarily depends on the state of the reservoir at each time interval. The general goal is to keep the reservoir at the top of the conservation pool. As the pool level moves into flood control, conservation, and inactive storage zones, the operation goals change.

Flood Control Zone. If there is flood control storage and the pool level is in that zone, the reservoir will operate for flood control goals and try to evacuate the flood water as quickly as possible.

Conservation Zone. If the pool level is in the conservation storage zone, the program will only release water when it is necessary to meet specified conservation demands (e.g., minimum flow, diversions, or energy requirements).

Inactive Zone. No reservoir releases can be made when the pool level drops below the top-of-inactive storage.

2.10.1 Flood Operations

Flood control operation will attempt to keep channel flow, at specified downstream control points, at or below control point channel capacity. Excess water is stored in the reservoir pool to avoid control point flooding within a specified future time window (foresight). When downstream flows decrease, excess water is evacuated from the flood control pool as rapidly as possible. A more detailed discussion of flood reduction capabilities is described in Chapter 3.

Space. The concept of SPACE is used to define how much additional flow can be added to the downstream control point without exceeding its channel capacity. SPACE is computed by taking the difference between the control point local flow and the defined channel capacity. Then, considering routing criteria, the reservoir release to fill the available SPACE can be computed.

Release estimate. The determination of a reservoir release required to bring the flow at a downstream control point to channel capacity is based on solving the following linear-routing equation:

$$O_n = C_1 R_n + C_2 R_{n-1} + C_3 R_{n-2} + \dots \qquad (2\text{-}1)$$

where:

O_n = Routed release at a downstream location at time n.

R_n, R_{n-1}, etc. = Reservoir releases at times n, n-1, etc.

C_1, C_2, etc. = Routing coefficients, as coefficients of inflow

The routing coefficients in equation (2-1) are determined from routing criteria input to the program. Theoretically, there can be an infinite number of coefficients; however, the sum of the coefficients will equal 1.

Contingency Factor. A contingency factor (**J2**, Record, field 2) can be used to temporarily increase the downstream local channel flow to allow for uncertainty in flow forecast. By using the contingency factor, the computed SPACE and the reservoir release will be smaller. This is to recognize the effects of forecast errors (that the actual flows may be larger than input values).

Foresight. Reservoir operations do not have unlimited knowledge of future flows. The limited future information can be evaluated by specifying the number of hours of foresight on inflows (**J2** Record, field 1). The program will be limited to that foresight when making release determinations.

Rate-of-change on Releases. A rate-of-change variable can limit how rapidly the reservoir release can be increased, or decreased. The default value is equal to the channel capacity at the reservoir over a 24 hour period (**J2** Record, field 3; or **R2** Record).

2.10.2 Conservation Operations

In addition to flood control operation, conservation operation may be specified to provide minimum flows at one or more downstream locations, meet diversion schedules and generate hydropower. Water supply capabilities are described in more detail in Chapter 4 and hydropower is described in Chapter 5.

Minimum Flow. Minimum flow requirements can be defined at any location (control point). Based on reservoir storage level, two levels of flow target can be defined: desired and required. Desired flows are met when there is sufficient water supply above the buffer level (**J1** Record, field 6). Required flows are met when water in storage drops into the buffer pool.

Hydropower. A power reservoir can operate to meet at-site firm energy requirements or allocated system firm energy in kilowatt-hours (kWh). A power reservoir can also operate based on a rule curve relating plant factors to percent of conservation storage.

Specified Releases. Outflows can be specified for any number of reservoirs for any or all time periods (**QA** Records). Provided there is sufficient water and outlet capacity, the release will made. If not, the program will adjust the reservoir releases as necessary.

Limited Simulations. System operation can be made for a fewer number of time periods than are input on the flow records (**BF** Record, field 6). Also, part of the system can be operated without removing the remaining system records by stopping the operation at a mainstream control point (**J2** Record, field 7).

2.11 Reservoir Releases

In addition to making the reservoir release decision for each time interval, the program provides output for a CASE variable to indicate the basis for the reservoir release. In some instances, there may be more than one reason; however, only one value can be given. It is often helpful to review the reason for the release determination along with the actual release and resulting downstream flows. Table 2.2 shows the primary CASE options.

2.12 Output

Input data record images and a rearranged labeled input summary are provided in the output file. A description of the available output from the program is provided in Chapter 7. Appendix F provides a detailed description and examples of the available output options. The following output can be requested (**J3.1** and **J8** or **JZ** Records):

- Flow data.
- Computation of incremental local flows.
- Results of system operation arranged in downstream sequence for reservoirs and control points (all defined output data are shown).
- Reservoir data by period (Inflow, Outflow, EOP Storage, Case, Level, and Equivalent Level for all reservoirs).
- Rreleases and control point regulated flow by period.
- Summary of flooding in system for each flood.
- Summary of maximum and minimum values for all floods.
- Economic output, including summaries of expected annual damages for system, and of reservoir and control point costs and system net benefits for flood control.
- Frequency curve printer plot.
- Hydrologic efficiencies based on multi-flood events.
- Summaries of hydropower energy and benefits.
- Annual summaries of sum, maximum, minimum or average for selected variables at selected control points.
- Specified variables at selected control points can be printed for all time periods (user determined output using **J8** and **JZ** Records).
- Selected output (**JZ** Record) from the program can be stored in a data file (HEC-DSS) for later processing by other standard HEC programs by using a **ZW** Record.
- Trace features can be used for printing out intermediate answers for specified control points (**TC** Record), time periods (**TP** Record) and subroutines (**TS** Record).
- Output error check.

Table 2.2 CASE Options

Basis for reservoir release	Case[1]
• Based on **channel capacity** at dam	.01
• Based on **rate-of-change** of release	.02
• Based on not exceeding the **top of conservation pool**	.03
• Based on **emergency releases** (see also cases 20-24):	
Outflow based on holding storage at **top of flood control pool**	.04
Surcharge routing (**maximum outlet** capacity)	.06
Pre-release based on not exceeding flood control pool during foresight period	.29
• Based on keeping **tandem** reservoirs in balance	.05
• Based on **maximum outlet** capacity	.06
• Based on not drawing reservoir **empty** (level 1)	.07
• Based on **minimum required** low flow at the dam	.08
• Based on releases to draw to **top of buffer** pool	.09
• Based on **primary energy** demand for hydropower	.10
• Based on minimum release if all higher priority reservoirs in parallel with this project are not releasing	.11
• Based on **system energy** requirement allocation	.12
• Based on **power** release (**leakage**)	.13
• Based on **power** release (**penstock limit**)	.14
• Based on **power** release (**generator capacity**)	.15
• Based on emergency **gate regulation** curve operation	
(a) Gate regulation curve release - rising pool	.20
(b) Emergency release - partial gate opening	.21
(c) Emergency release - transition	.22
(d) Emergency release - outflow = inflow	.23
(e) Emergency release - gates fully opened	.24
• Based on release given on **QA** Record	- *release*
• Based on **minimum desired** low flow at the dam	.00
• Can be based on filling the downstream channel at location X at Y time periods in the future for either flood control or conservation operation	X.Y

[1] Shown in HEC-5 Output

Chapter 3

Flood Reduction Capabilities

The basic program capabilities were described in Chapter 2, which presented the primary considerations for simulating reservoir operation. In HEC-5, flood operations are a priority in release determination. This chapter provides more detailed information on the concepts and procedures used in the program to support the flood reduction goal. In Appendix C, three example problems are provided to illustrate some of the program considerations during release determination for flood reduction.

3.1 Basic Flood Operation Data

Three important items of input in an HEC-5 flood control simulation are:

① the number of hours of **foresight** on inflows and local flows used in system operation,

② the coefficient by which flows are multiplied as a **contingency** allowance in the determination of flood control releases, and

③ the maximum **rate-of-change** of reservoir releases during a specified time period.

Special attention should be given to determine appropriate values for these key parameters because reservoir operation during a flood is particularly sensitive to these three variables. Default values are used in the program simulation if input is left blank. The simulation time intervals for flood operations should be 24 hours or less to obtain accurate simulations. Also, some of the flood control options are not used for intervals longer than 24 hours because channel routing is not normally applicable to weekly or monthly intervals.

Foresight. The number of hours of foresight for all reservoirs in a system is given on the **J2** Record in field 1. In addition, foresight may be specified for individual reservoirs on the **R2** Record in field 5. This number should be approximately equal to a reasonable meteorological forecasting period in the basin. A longer forecast period will produce a better operation but may not be realistic. Typically, 24 hours is used in flood studies. However, if there is a long travel time for releases to get to downstream locations, a larger foresight may be required to "see" the impact of current releases on those distant locations. In the summary tables for input data (see "*Routing / Operation Summary"), HEC-5 provides the cross products of routing coefficients from reservoirs to operational control points. These routing coefficients are the ratios of flow and indicate how many periods it will take for a current release to reach each location. For real-time water control applications the time of foresight should typically as long as the travel time of the longest set of coefficients shown in the listing of routing coefficients. The default value for foresight is 24 hours.

Contingency. A contingency allowance is a coefficient by which local flows are temporarily adjusted when used in the determination of upstream flood control releases. The inflows are multiplied by this factor, for the forecast period, before the available SPACE is computed. A value of 1.2 is typically used for flood studies, which indicates a 20% uncertainty in the local flow data. For real-time water control applications, a contingency value of 1.0 may be used if the flow data embodies the uncertainty of rainfall forecasts. If, however, forecasted flows do not reflect the uncertainty, a contingency value greater than 1.0 may be appropriate. The contingency allowance is input for all locations in a system on the **J2** Record in field 2. In addition, the contingency allowance may be specified for individual control points on the **CP** Record in field 6. The default value for contingency allowance is 1.0.

Global Maximum Rate-of-Change of Reservoir Releases. The maximum rate-of-change at the reservoir may be based on the downstream channel's ability to accept decreasing amounts of water without bank sloughing, or other considerations. However, it is also a simulation tool to prevent the reservoir releases from changing too much between time steps. The rate-of-change is entered on the **J2** Record in field 3 as a ratio of the channel capacity during a one hour time period. The default rate-of-change is .043 times the channel capacity at the reservoir per hour. For a 3-hour simulation interval, the rate-of-change is 12.9% (.043 x 3) of channel capacity.

Maximum Rate-of-Change For Individual Reservoir. The rate-of-change given on the **J2** Record applies to all reservoirs in the system, unless a different rate is given on an **R2** Record for a specific reservoir. The rate-of-change on the **R2** Record can be defined either as a ratio, or as a fixed value in m^3/s (ft^3/s) per hour, and can be different for increasing or decreasing releases (fields 1 and 2, respectively).

Flooding Priority. When flood control releases conflict with conservation releases in a multi-purpose reservoir system, a priority of operation must be defined. In general, the default (normal) priorities in HEC-5 are to operate for flood control first, and conservation second. The priorities can be changed by entering the appropriate priority code in field 4 of the **J2** Record (see Appendix G, Input Description, for listing of codes).

3.2 Special Flood Operation Data

The basic options provide the "default" HEC-5 operation for flood reduction. Generally, the program will store excess water until it is safe to release it. The channel capacity at specified locations is the primary concern. This style of operation will generally provide the maximum downstream protection, if there is sufficient reservoir storage.

The basic HEC-5 reservoir operation is classified in Corps of Engineer practice as "Method A" regulation. The classification of regulation types in to Methods A, B and C is documented in Section 3-3, Development of Regulation Schedules and Water Control Diagrams, *Management of Water Control Systems*, EM 1110-2-3600 (USACE, 1987). A summary of these regulation types follows:

Method A - Regulation is based on maximum beneficial use of available storage during each flood event. Reservoir releases may be reduced to zero when flooding is occurring at downstream locations.

Method B - Regulation is based on control of the reservoir design flood. Reservoirs using this type of regulation may be characterized as having limited flood control storage and a primary operation goal of minimizing losses during a specified design flood. During minor floods, regulation is based on providing continual releases that increase as flood storage is filled. Reservoir release rates are determined such that all the flood storage capacity is utilized during the regulation of the design flood.

Method C - Regulation is based on a combination of Methods A and B. With this type of regulation, minor floods are regulated with a Method A style which switches to a Method B style when a specified portion of the flood storage is filled. Method C regulation could also be achieved by regulating with a Method B regulation during winter months when the probability of large floods is greatest and Method A during the remainder of the year.

Many reservoirs have insufficient flood storage capacity and should not be operated with a Method A style of regulation. To change from the default HEC-5 operation to a Method B or C style requires application of one of the following special options:

Storage-Release Schedules. The simplest implementation of Method B regulation may be specified by the addition of pre-defined storage-based releases on **RD** Records (**RD** Record, field 1 = -1), which are paired with **RS** Record storage values, and the selection of the storage-based diversion option (**DR** Record, field 7 = -2). With these data, excess flood waters are handled as diversions to a specified location below the dam.

Pre-Release Options. The pre-release options are sometimes useful in managing large floods. With this option, the program will change its operation once it determines that the remaining flood space will be filled within "foresight" time. There are two pre-release options defined by a code specified on the **J2** Record, field 5.

① Option 1 will make releases equal to the channel capacity at the reservoir as soon as it can be determined that the reservoir will exceed the flood control storage within the allowable foresight period (**J2** Record, field 1). For pre-release option 1, a value of 1 is entered on the **J2** Record, field 5.

② Option 2 allows releases to be made which are larger or smaller than channel capacity so that the top of the flood control pool will just be reached within the foresight period. For pre-release option 2, a value of 2 is entered on the **J2** Record, field 5.

Gate Regulation Curves. HEC-5 also includes an option to simulate the operation of gated spillways during large floods. This option is based on the development of "gate regulation curves" which determine reservoir releases as a function of the elevation and rate-of-rise of the reservoir. Required data for this option (which includes definition of a induced surcharge storage pool, physical description of the gated spillway, a hydrograph recession parameter and operational criteria) are input on the **RG** Record. The basis for this procedure is documented in Section 4-5 Induced Surcharge Storage, *Management of Water Control Systems*, EM 1110-2-3600 (USACE, 1987).

Information required to develop the gate regulation curves includes an "induced surcharge envelope curve" (ISEC). The program allows the user to enter a specified ISEC or optionally it will determine a default ISEC.

① The user-specified ISEC is entered on **RD** records. Discharge data on the **RD** Records correspond to storages, discharges and elevations on **RS**, **RQ** and **RE** records. Typically, additional data must be added to the **RS-RE** records to provide sufficient detail at the top of the flood pool (and above) to adequately define the shape of the ISEC.

② The program-developed ISEC is defined by the specification of three parameters on the **RG** Record: the top and bottom of the induced surcharge pool (**RG** Record fields 1 and 2 respectively); and, the discharge of the ISEC (**RG** field 3) at the top of the flood pool (bottom of the induced surcharge pool).

Clock Times for Reservoir Release Decisions. The HEC-5 program makes a release determination every time step. However, in practice, reservoir release decisions may be made less frequently. To provide a more realistic operation, an option to specify clock times when reservoir release decisions are made can be entered using **JR** Records. With this option release changes will only be made on the day of the week and time specified on the **JR** Records, during all other time periods the release determined in the last **JR** decision period will be repeated until the next **JR** decision period. The **JR** Records are inserted after the **J8/JZ** Records. If **JR** Records are omitted, release decisions are made for all time periods.

Release Scheduling. The HEC-5 default procedure for determining reservoir releases (to fill space during flood operation) is based on the assumption that in future periods, releases will be reduced to zero at a rate governed by the rate of change. This assumption enhances the program's ability to maximize releases and fill downstream space, however, it often results in releases with large fluctuations. Even with "rate-of-change" controlling how quickly releases can be increased or decreased, there are situations when there may be large fluctuations in reservoir releases. The scheduling option will calculate reservoir releases assuming future releases are the same as the current period's release. As a result, releases determined with the scheduling option tend to be more realistic. The release scheduling option is requested with a 10 in field 6 of the **J2** Record.

Reservoir Guide Curves. In regions with distinct seasonal variability in precipitation, reservoir storage allocated to flood control is typically greatest during the wet season and is reduced during the dry seasons. Correspondingly, storage allocated to conservation purposes is at a minimum during the wettest season and must be greatest during the dry season. In HEC-5 flood control and conservation storage zones are defined by reservoir index levels (**RL** Records). In practice index levels are referred to as Guide Curves or Rule Curves. Three options are available in HEC-5 to define reservoir guide curves. The reservoir levels can remain constant during the year, can vary monthly, or can vary seasonally. For seasonal input, HEC-5 requires a definition of the seasons in number of days from December 31 (**CS** Record), and the corresponding reservoir storage values for each season are specified on the **RL** Records. Up to 36 seasons are allowed and any or all reservoir index levels may vary. Twelve seasons are not allowed on the **CS** Record to avoid confusion with monthly storage variations.

3.3 Reservoir Operation Criteria

The simplified operation goals for flood control, in priority are:

① Do not endanger the dam
② Do not contribute to downstream flooding
③ Do not unnecessarily store water in the flood control pool
④ Evacuate flood control storage as quickly as possible

Reservoirs are operated to satisfy constraints at individual reservoirs, and to maintain specified flows at downstream control points. Constraints at individual reservoirs with gated outlets are as follows:

① When the level of a reservoir is between the top of conservation pool and the top of flood pool, releases are made in an attempt to draw the reservoir to the top of conservation pool without exceeding the designated channel capacity at the reservoir or at operational downstream control points. Operational control points are those specified on the **RO** Record.

② Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, and then all excess flood water is dumped if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Input options permit channel capacity releases (or greater) to be made prior to the time that the reservoir level reaches to top of the flood pool if forecasted inflows are excessive (Pre-release option).

③ Rate-of-change criteria specifies that the reservoir release cannot deviate from the previous period release by more than a specified percentage of the channel capacity at the dam, unless the reservoir is in surcharge operation.

④ Releases are made equal to, or greater than, the minimum desired flow when the reservoir storage is greater than the top of buffer storage, and equal to the minimum required flow if between level one and the top of buffer pool. No releases are made when the reservoir is below level one (top of inactive pool). Releases calculated for hydropower requirements will override minimum flows if they are greater than the controlling desired or required flows.

Operation criteria for gated reservoirs for specified downstream control points are as follows:

① Releases are not made, as long as flood storage remains, which would contribute to flooding at one or more specified downstream locations within the foresight allowed. The limitation is the smaller of foresight or number of routing coefficients.

② Releases are made, where possible, to exactly maintain downstream flows at channel capacity (for flood operation), or for minimum desired or required flows (for conservation operation). In making a release determination, local intervening area flows are adjusted by the contingency factor (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting flow.

3.4 Channel Routing

For short-interval simulations, channel routing must be incorporated in reservoir release determination. Generally, HEC-5 simulation considers short-interval as a computational time interval of 24 hours, or less. The **NOROUT** Variable (**J3** Record, field 7) tells the program to not use routing when the time interval for simulation is greater than its value. The default value is 24 hours.

HEC-5 routing methods are described in Appendix A. For reservoir release determination, the basic linear-routing equation 3-1 is applied. When non-linear routing methods are used, a linear estimate is made for release determination. However, the release is routed with the input routing option and data as described in the following sections on SPACE and release determination.

$$O_n = C_1 R_n + C_2 R_{n-1} + C_3 R_{n-2} + \ldots \qquad (3\text{-}1)$$

where:

O_n = Routed release at downstream location at time n

R_n, R_{n-1}, etc. = Reservoir releases at times n, n-1, etc.

C_1, C_2, etc. = routing coefficients, as coefficients of inflow

3.5 Channel SPACE

SPACE is defined as the difference between the local flow, plus routed previous reservoir releases, and the channel capacity. It is the measure of the residual capacity in the channel for release of flood water from the reservoir. As previously stated, the determination uses a local flow adjusted by the contingency factor to account for uncertainty in flow forecasts.

The computed SPACE is transferred up to the reservoir by "reverse routing." That is, the downstream SPACE is divided by the routing coefficients to obtain the upstream releases that would just fill the remaining SPACE. Because routing distributes the release over time, the previous period releases will continue to reduce future SPACE in the channel. Therefore, SPACE must be computed for each time period.

3.6 Reservoir Release Determination

For the coefficient routing methods, the reservoir releases will be determined with the coefficients. However, for non-linear storage methods, there is no single set of coefficients. The program will make a linear approximation of the storage-outflow relation and use the coefficients from that to make the release estimate to fill SPACE. The actual release is routed with the given routing criteria. The program will check to determine if the estimated value was within five percent of the actual value.

The release determination for the current time step must recognize the rate-of-change criteria. That is, a current period release may also set future minimum releases based on the rate-of-change for decreasing releases. For example, a channel capacity release at the current time step will require four 6-hour periods to reduce the flow to zero if the rate of change is .043 per hour (the program default).

During flood operations, the program will make the maximum release possible based on the considerations described. If the constraint was at the reservoir, the CASE variable will be a decimal code indicating the controlling rule. If a downstream location defined the maximum possible release, the location number and the number of future time periods that the constraint occurred is displayed in the CASE variable. For example: a value of 100.02 for the CASE variable would indicate that location 100, two time periods in the future, defined the maximum release that could be made at the current time. Often, in flood operations for downstream locations, the first occurrence will be at the limit of the foresight time.

Chapter 4

Water Supply Capabilities

The basic model data, described in Chapter 2, are required for most HEC-5 reservoir models. In addition, model data can be added to utilize other program features. This chapter summarizes options typically associated with low flow augmentation and water supply purposes. However, the options also can be applied to flood operations. Appendix D provides examples with more detailed descriptions of options available for Water Supply simulation.

4.1 General Capabilities

Reservoir operation to provide water supplies to meet downstream flow requirements such as municipal, industrial, irrigation, navigation, fishery maintenance, recreation or water quality needs may be simulated with HEC-5. The water supply demands are either defined as specified minimum flow targets at control points or diversion schedules from reservoirs or control points. As with flood control operations, the reservoirs are told which locations they operate for (**RO** Records) to meet the specified demands. The reservoir simulation will attempt to meet the specified flow and diversion demands by releasing supplemental water whenever the local flow is not sufficient to supply the demands.

4.2 Seasonally Varying Conservation Storage

The basic allocation of reservoir storage is accomplished with **RL** Records. Generally, these storage values remain constant throughout the year. For many regions there is a reliable seasonal variation in flow, which allows for changes in the space required for flood storage and conservation storage through the year. In HEC-5, the reservoir storage allocation to some levels can remain constant while others vary. The storage allocation can be varied monthly or seasonally.

Monthly Storage Allocation. To vary the storage monthly, additional **RL** Records are required, a set for each level. The first field indicates the level number, and the sets are input in increasing order of level starting with level one. The third field indicates how the storage varies: constant, monthly, or seasonally. For monthly values, the third field is zero and the fields 5 - 10 provide the first six monthly values and a second **RL** provides the remaining six values (fields 5 - 10).

Seasonal Storage Allocation. The seasonal storage input is similar to the monthly, in that additional **RL** Records are input for each level. For seasonal, the third field indicates the number of seasonal values. The seasons are defined by cumulative days, from December 31, on the **CS** Record.

4.3 Evaporation

While evaporation can be simulated in any reservoir model, it is usually ignored for flood studies. That is why reservoir evaporation is typically considered as a water supply or hydropower option. The evaporation data are defined in units of depth and the program computes the evaporation volume based on the average pool area for the time interval. Therefore, reservoir area data (**RA** Records) are required to compute evaporation.

The input evaporation depths are considered **net evaporation**. This reflects the reservoir gains from precipitation directly on the surface area, as well as the evaporation loss. If the reservoir were not there, the precipitation would fall on the ground and only a portion would runoff to the stream. With the reservoir in place, all of the precipitation on the pool surface area is available. Therefore, when precipitation exceeds the evaporation there is a net gain to the reservoir. For time-periods where there is a gain, the net evaporation is negative.

Evaporation data can be defined on a monthly schedule or on a period-by-period basis:

(1) Monthly evaporation data can be read for the entire basin (**J6** Records). Every reservoir in the system would be subject to the same evaporation rates.

(2) Evaporation data are input for individual reservoirs by monthly periods (**R3** Records). Different rates can be defined for each reservoir.

(3) Period-by-period evaporation data can be provided for any reservoir in the system (**EV** Records). This data would be input with the time-series data (after the **BF** Record).

4.4 Minimum Channel Flow

Instream flow demands may be specified at control points within the system being simulated. They may represent a variety of low-flow requirements: minimum flows for fishery or wildlife, navigation, stream recreation, minimum water quality flows, and various other water supply purposes. Two types of low-flow may be specified: **minimum desired** and **minimum required**.

Minimum desired flows are the targets when reservoir storage is above the top of the buffer level. This would be the normal (typical) operation goal.

Minimum required flows would be the essential flow target during drought conditions. When streamflow is low and reservoir storage is low (below the top of the buffer) the minimum required flow allows the user to cut-back and reduce requirements allowing minimum needs to be met until supplies are replenished.

Four options exist for specifying desired or required flow: constant, monthly, seasonally or period-by-period.

(1) **Constant desired and required flow.** A constant desired and/or required flow target can be defined at any location on the **CP** Records, fields 3 and 4 respectively.

(2) **Monthly desired flow.** A monthly desired flow target varies from month to month, but not year to year. The **QM** Records are used to define the monthly values. The first monthly value is for the starting month, usually January (**J1** Record, field 2).

Monthly required flow. Since there is no separate input record for monthly required flow, the **QM** Record is used. By setting the constant required value to minus one (**CP** Record, field 4 = -1), the data input on the **QM** Record will define the minimum required monthly schedule. Because only one set of **QM** Records can be input at a control point, it is necessary to add an extra control point to define both desired and required flows on a monthly schedule. The desired flow schedule would be input at one location and the required flow schedule at the other.

(3) **Seasonally varying desired and required.** In addition to desired or required flows varying monthly, the user can also specify a seasonal rule curve to vary desired or required flows. The **CS** Record defines the seasons for the year (up to 36 seasons in number of cumulative days from December 31). A companion **CG** Record can be used to specify the reservoir elevations corresponding to the defined seasons. Minimum desired or required flows on **QM** Records can vary throughout the year and the target release is based on the reservoir level for the specified season. Each minimum flow given on the **QM** Records corresponds to one seasonal guide curve on the **CG** Record. To vary required flows instead of desired flows, use a -1 in field 4 of the **CP** Record, as previously described for monthly varying flows.

(4) **Period varying desired and required flow.** Each period may be assigned a minimum flow value with **MR** Records. The period-by-period data are input after the **BF** Record with other time series data. This record is used to define minimum desired flow. As in the monthly varying options, a -1 in field 4 of the **CP** Record will indicate that the period varying flows are required, not desired. Also, when both desired and required flows vary by period, an extra control point must be added, one defining desired and the other required.

4.5 Diversions

Diversions may be specified from any control point or reservoir. However, there can only be one diversion from that location. Diversion records (**DR**) are input at the locations where the flow is diverted from and are not used at the locations where the flow returns to the system. The maximum number of diversions is 40.

Diversions can be returned to any downstream control point or reservoir, or they can also leave the system. A special option also allows a diversion to an upstream location. If diversions return to the system, they may be routed using any linear method allowed and multiplied by a constant representing the ratio of return flow.

Eight types of diversions may be specified:

(1) Diversions can be constant (**DR** Record, field 8).

(divert a constant 150 from location 55 to location 77)

DR 55	77	0	0	0	0	0	150		

(2) Diversions can vary monthly **(DR** and **QD** Records).

(divert 90-150 from location 55 to location 77)

DR 55	77					1			
QD 90	90	100	100	110	120	150	150	150	130
QD 95	90								

(3) Diversions can be a function of inflows (**DR**, **QS** and **QD** Records).

(divert variable 0-100 from location 55 to location 77)

DR 55	77					-1			
QS 5	0	100	110	500	600	10000			
QD 5	0	0	10	10	100	100			

(4) Diversions can be a function of reservoir storage (**RS**, **RD**, and **DR** Records).

(divert variable 0-600 from location 55 to location 77)

RS 7	100	2500	10000	33000	50000	150000	250000		
RD 0	0	0	100	100	500	600	600		
...									
DR 55	77	0	0	0	0	-2	0		

- OR -

(divert excess flood water from location 55 to location 77)

RS 7	100	2500	10000	33000	50000	150000	250000		
RD -1	0	0	100	100	500	600	600		
...									
DR 55	77	0	0	0	0	-2	0		

(5) Diversions can be a function of energy for pumped storage hydropower analysis (**RL-RT** and **DR** Records).

(divert based on energy schedule at reservoir 55 and available storage at reservoir 77)

RL - RT for reservoir 55									
DR 55	77	0	0	0	0	-3	0		

(6) Diversions can be pumped to upstream location 55 from downstream location 77 (**DR** and **QD** Records).

(pump 90-150 from location 77 to location 55)

DR 55	77					-4			
QD -90	-90	-100	-100	-110	-120	-150	-150	-150	-130
QD -95	-90								

(7) Diversions can vary by period (**DR** Record plus **QD** Records in time series data).

(diversions which vary by period (20 periods) from location 55 to location 77)

DR 55	77					-5			
...									
ED									
BF 2	20	etc.							
QD 55									
QD 66	66	77	88	90	91	92	96	87	83
QD 46	54	33	0	0	100	150	130	130	200

(8) Diversions can be a function of flow at another location (**DR** Record, field 10).

(diversion from location 55 to location 77 will be 75% of the flow at location 33)

DR	77	0	0	0	0	-6	0	.75	33

In addition to the above diversion types, "water rights" limits may also be applied (**WR** Record) in conjunction with the **DR** Record as shown in the following example:

(divert 120 acre-feet, from location 55, at the rate of 1.5 ft^3/s during Julian days 105-185)

WR370610 105 185 120									
DR 55	0	0	0	0	0	0	1.5		

4.6 Yield or Conservation Storage Determination

To assist in sizing reservoir projects for conservation purposes and in evaluating effects of reallocating storage, a procedure has been developed to automatically determine either the required storage to meet a specified demand or the maximum reservoir yield that can be obtained from a specified amount of storage. The procedure is designed for a single reservoir using average monthly flow. However, up to four reservoirs can be analyzed in a single run, provided the reservoirs being optimized operate independently (tandem reservoirs cannot be optimized at the same time). All of the conservation requirements, as well as the conservation storage, may vary monthly.

Conservation Storage. The **J7** Record is used to describe the function to be optimized for each reservoir, as explained in Appendix G. The first option determines the seasonal reservoir conservation storage required to meet all specified reservoir demands. This is determined iteratively by multiplying the reservoir storage for top of conservation (on **RL** Record) by a coefficient (which varies for each trial), operating the project for the period of flow data on the **IN** Records, determining the error in reservoir drawdown storage, and making a new estimate of the coefficient. This process is continued until the error in storage is within the allowable error defined on the **J7** Record, field 10.

Yield Determination. Given a fixed storage, the potential yield for any specified conservation purpose can be determined, while still providing for all other demands on the project. The yield can be determined for: monthly firm energy, minimum monthly desired flow, minimum monthly required flow, monthly diversions, or all of the conservation purposes. An iterative search procedure is used with a ratio adjustment of the target demands until all of the conservation storage is utilized during the critical flow period within the given data set.

Initial Estimate. The initial estimate of the variable being analyzed is normally the value specified on input. In the case of energy, 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 based on a relationship of drawdown duration (in months) to ratios of power storage to mean annual flow.

Critical Period Analysis. Unless otherwise requested, the program will operate the project for the duration of the given inflow data. If twenty 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 (**J7** Record, field 8), the program will determine the starting and ending periods corresponding to either an input period or the minimum flow volume for the specified duration. Initially, only the estimated critical period data would be used for each iteration.

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 for the initial estimate of the dependable capacity.

Solution Cycles. If the analysis is performed for the estimated critical period first (Cycle 1), a single routing can then be made for the period of record to see if the most severe critical period has been found (Cycle 2). If a new critical period is found, then Cycles 3 and 4, and possibly 5 and 6, can be made for the new critical period and then a single routing for the period of record (see **J7** Record, field 9).

Chapter 5

Hydropower Capabilities

The application of the HEC-5 program for hydropower analysis is presented here. 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 Determination all build on the basic capabilities described below. Appendix E provides more detailed information on the program's data use and solution techniques for various hydropower options.

5.1 Power Reservoirs

This section describes the additional data required to model a hydropower reservoir. The data required for a basic reservoir model were presented in Chapter 2, 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 storage. The areas are needed for evaporation computations, described in Chapter 4, and the elevations are needed for head determination. Example 7 in Appendix E is an example of power reservoir input and output.

5.1.1 Data Requirements

Power data are input with reservoir data at each hydropower reservoir. The data requirements include the installed capacity, an overload ratio, a tailwater elevation, an efficiency, and the monthly energy requirements (mW-hrs or plant factors). The primary hydropower plan data are defined on the **P1** Record and optional data is included on the **P2** Record.

Installed Capacity. The installed capacity is the nameplate capacity except for planning studies, where an assumed value is used. The capacity, times the overload ratio, 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.

Overload Ratio. 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.

Tailwater Elevation. 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. For most power plants, the units are on a portion of the time, however, in the program the reservoir release is an average for the simulation interval. 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. Where two or more ways are used to describe the tailwater, the higher tailwater value is used.

Power Efficiency. Power plant efficiency is the total efficiency (generator efficiency X turbine efficiency) of the power plant. No other electrical-mechanical 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 ($kW/ft^3/s$) coefficient as a function of reservoir storage. Often in older power studies done by hand, $kW/ft^3/s$ vs. Elevation was used 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.

Firm Energy Requirements. The energy requirements can be defined for each hydropower plant using 12 monthly values (**PR** Records) or by using an energy requirement for every time period of the study (**PV** Records). For most planning studies, the 12 monthly values are used. The monthly energy values can be given in thousand kilowatt-hours (mW-hrs) or as plant factors. Plant factors are ratios indicating the portion of time (average per month for **PR** Records) 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.

Daily Energy Distribution. If the time interval used is less than a week, daily ratios can be given to show how the energy requirement is distributed over the seven days of the week (**PD** Records). The first value is for Sunday and 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. For the simulation, the program determines the day of the week based on the input starting date for the flow data (**BF** Record, field 5).

Hourly Energy Distribution. If the time interval is less than one day, a distribution within the day can be given (**PH** Records). 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.

Power Guide Curve. An alternative to defining firm energy requirements allows input of plant factors as a function of percent power storage available (**PC** and **PF** Records). The concept provides for increased generation when water supply is high and decreased generation when supplies get low. The guide curve is not considered a firm energy option because the amount of energy generated is dependent on the amount of water available.

5.1.2 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 power head by subtracting tailwater and loss from reservoir elevation, corresponding to the estimated average storage.

(4) Compute reservoir release to meet energy requirement.

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

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

(7) After the first cycle, use the new S_2 and return to step 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 (see **J2** Record, field 4). 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 each time interval. For conservation operation, it will determine if additional reservoir releases are required for some downstream requirement. If not, then the power release will be made. 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 power 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 (see **J2** Record, field 4). (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 be made and some flooding due to reservoir release may occur.

5.1.3 Program Output

A description of the available output from the program is provided in Chapter 7. This section describes the hydropower output and provides some suggestions on how to check the program's results. There are 41 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: the energy requirements specified for the reservoir
- Energy Generated: the computed energy based on the reservoir release
- Energy Shortage: the deficiencies in generated Energy
- Power Capability: either constant or variable based on input option
- Power Spill: the discharge not used for generation
- Power Head: the elevation difference between the reservoir and tailwater minus hydraulic losses
- Power Plant Factor: the ratio reflecting the percent of time the plant is generating

Summary tables also provide Primary, Secondary, and Shortages of Energy and Energy Benefits, if benefit values were provided.

Case. If the Generated energy equals the Required energy, then the Case variable should equal 0.10, 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.

Power Capability. Variable peaking capability data, if provided, are based on a Reservoir Storage, Reservoir Outflow or Reservoir Operating head (**PP** and **PS** Records). 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.

Summary Tables. 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 (firm energy). 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.

Energy Benefit Table. 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.

5.2 System Power

Up to 35 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 individual projects can produce. By allocating the system load 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 the Power Reservoirs section also applies to this section. Example 9 in Appendix E of the program User's Manual shows input and output for a three-reservoir power system.

5.2.1 Data Requirements

Additional data required for system power operation consist of System Energy Requirements and an indication at each hydropower plant if it is in the system. One power system can be used; however, some of the hydropower plants may operate independently of the power system.

System Energy. System energy requirements are provided as 12 monthly values (**SM** Records) in mW-hrs or as ratios of the system power rule curve (**SC** and **SF** Records). The system energy requirements represent a demand on all projects in the hydropower system. The monthly energy requirements data start with January. The monthly system energy requirements are distributed in a similar manner as the at-site energy requirements. Seven daily ratios define the distribution of weekly energy (**SD** Record) and multi-hourly ratios define the distribution within each day (**SH** Records).

System Power Rule Curve. An alternative to defining firm system energy requirements allows for the input of plant factors (**SF** Records) as a function of total system power storage (**SC** Record). This energy definition is analogous to the application of **PC** and **PF** Records for at-site generation.

Power System Project. At each hydropower reservoir in the model, all of the power data previously described is still provided. Added input includes indication if the power plant is in the power system (**P2** Record, field 3). The indicator is zero if a power plant is not to be used for system power, and 1 if the plant is in the system.

System Plant Factor. The maximum plant factor for the project contribution to the system load is defined on the **P2** Record, field 4. The system plant factor is used to limit the extent (or percent of time) each power plant can operate to meet the system load. Generation rates greater than the system plant factor are allowed when excess water is available, but only the portion up to the maximum plant factor can be credited as meeting the system load.

At-site Energy Requirements. The monthly at-site requirements at each power plant in the system (**PR** Records) 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.

5.2.2 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 provisions 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 program 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 procedure 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 procedure up to two more times in an attempt to get the generated energy to within one percent of the requirement.

The system energy operation is limited to 12 monthly energy values; period-by-period values cannot be used. Also, the system energy allocation procedure 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 energy that was computed during the allocation period.

5.2.3 Program Output

All of the previously described output would be available plus:

- System Energy Required: the total energy required from all system plants
- System Energy Generated: the total energy generated by all system plants
- System Energy Usable: the total system energy generated, limited by the maximum plant factors for system power generation (**P2** Record, field 4)
- System Energy Shortage: the deficiencies in usable system energy

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.

The Case variable for system power is 0.12. When a project release is based on the allocation from system power operation, a value of 0.12 is shown. When the at-site power requirement controls, a value of 0.10 will be shown.

5.3 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. Example 8 in Appendix E of the User's Manual shows input and output for pump-back operation.

5.3.1 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 indicate to 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 requirements data now reflect energy available for pumping. Added data include a maximum pump-back (penstock) discharge and head loss.

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 (**J1** Record, field 7).

The diversion record (**DR**) 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. Figure 5.1 shows the model arrangement for an on-stream pump-back system. A similar approach can be applied to an off-stream system.

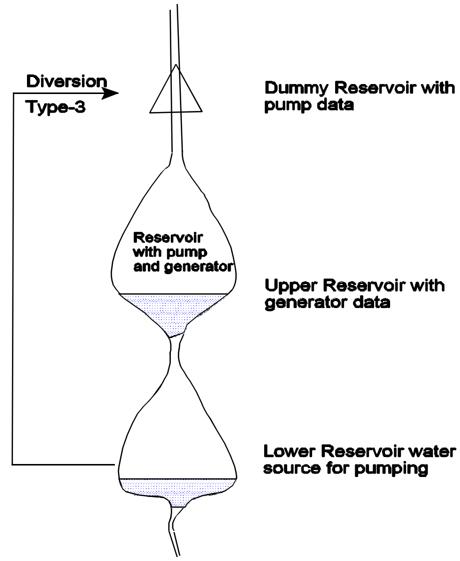

Figure 5.1 Model for on-stream pumped storage.

5.3.2 Program Operation

The initial estimate of the pump-back discharge 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, from the end of the previous period, 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 the 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.

5.3.3 Program Output

No additional 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 <u>was not used</u> for pumping.

5.4 Firm Energy Determination

Energy is one of the conservation purposes the program can maximize using the firm yield concept. The optimization procedure can determine firm energy for up to four independent reservoirs given a fixed conservation storage, or determine the required conservation storage to provide for a given at-site energy demand. Chapter 4 described the optimization capabilities of the program. This section describes the additional input requirements, the program's operation, and the type of output provided.

5.4.1 Data Requirements

The basic power reservoir model previously described would be used for the optimization procedure. The addition of one job record (**J7**) requests that optimization be performed 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 twenty 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 (**J7** Record, field 8), 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. With monthly data, the starting period should be January. If it is not, the program will automatically shift back to the start of the year.

5.4.2 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 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.

5.4.3 Program Output

The output options previously described would normally be used with the optimization procedure. For each iteration, a special table of results is provided. For most applications using optimization, 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 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 for the initial estimate of the dependable capacity.

5.5 Strategies 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 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 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 overburden a study by 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.

5.5.1 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 procedure in HEC-5 will determine the approximate critical period and will perform sequential routings using that critical period to automatically determine either:

1. the storage for a specified annual firm energy or reservoir yield, or

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

The optimization procedure can also use the entire period of flow record to determine the storage or firm annual energy. The difference in compute time between using the flows for the entire period of record vs. 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 compute time approaches 5 to 1. In general, it is advantageous to optimize on the critical period of record and then to verify the answer on the period of record than to optimize on the entire 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 non-flood periods and daily or multi-hourly 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 multi-purpose 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 which compare the effectiveness of the system, with and without the system rules.

5.5.2 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 multi-hourly 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.

5.5.3 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's size has been determined using daily flow-duration techniques.

Chapter 6

Reservoir System Simulation

This chapter presents operation criteria for single and multiple reservoirs, system operation concepts, and multi-flood simulation. Multi-flood is the term used for options to divide a flow-data series into multiple sets for processing in HEC-5.

6.1 Reservoir System Operation Criteria

Reservoirs are operated to satisfy constraints at individual reservoirs, to maintain specified flows at downstream control points, and to keep the system in balance. The process starts with the current state of the reservoir and its requirements. Then the reservoir examines the specified downstream locations and evaluates their requirements and constraints. If more than one reservoir operates to meet the needs of a control point, the relative levels of the reservoirs are evaluated to determine which reservoir has the higher priority. If possible, the release decision will attempt to balance the levels of the reservoirs operating for a common control point, and balance levels in tandem reservoirs.

6.1.1 Operational Criteria for Individual Gated Reservoir

The reservoir first evaluates its current state to determine an initial release. Constraints at individual reservoirs with gated outlets are as follows:

(1) When the level of a reservoir is between the top of conservation pool and the top of flood pool, releases are made to attempt to draw the reservoir to the top of conservation pool without exceeding the designated channel capacity at the reservoir or at downstream control points for which the reservoir is being operated.

(2) Releases are made equal to or greater than the minimum desired flows when the reservoir storage is greater than the top of buffer storage, and equal to the minimum required flow if between level one and the top of buffer pool. No releases are made when the reservoir is below level one (top of inactive pool). Releases calculated for hydropower requirements will override minimum flows if they are greater than the controlling desired or required flows.

(3) Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, and

then all excess flood water is dumped if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Input pre-release options permit channel capacity releases (or greater) to be made prior to the time that the reservoir level reaches the top of the flood pool if forecasted inflows are excessive.

(4) Rate-of-change criteria specifies that the reservoir release cannot deviate from the previous period release by more than a specified percentage of the channel capacity at the dam site, unless the reservoir is in surcharge operation.

6.1.2 Operational Criteria for Specified Control Points

After an initial release estimate is determined, the reservoir will “look” at the requirements and constraints at all the specified downstream control points for which it operates (**RO** Record). Constraints and considerations include:

(1) Releases are not made (as long as flood storage remains) which would contribute to flooding at one or more specified downstream locations during a predetermined number of future periods. The number of future periods considered, is the lesser of the number of reservoir release routing coefficients or the number of local flow forecast periods.

(2) Releases are made, where possible, to exactly maintain downstream flows at channel capacity (for flood operation) or for minimum desired or required flows (for conservation operation). In making a release determination, local (intervening area) flows can be multiplied by a contingency allowance (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting these flows.

6.1.3 Operation Criteria for Balancing Flood Control Reservoirs

If more than one reservoir operates to meet the needs of a control point, there is a system decision to make. Which reservoir to release from and how much? The concept of system balance, described later in the section on Equivalent Reservoirs, is used to determine priority among reservoirs. Considerations for balancing reservoirs include:

(1) Where two or more reservoirs are in parallel operation for a common control point, the reservoir that is at the highest index level, assuming no releases for the current time period, will be operated first to try to increase the flows in the downstream channel to the target flow. Then the remaining reservoirs will be operated in a priority established by index levels to attempt to fill

any remaining space in the downstream channel without causing flooding during any of a specified number of future periods.

(2) If one of two parallel reservoirs has one or more reservoirs upstream whose storage should be considered in determining the priority of releases from the two parallel reservoirs, then an equivalent index level is determined for the tandem reservoirs based on the combined storage in the tandem reservoirs.

(3) If two reservoirs are in tandem, the upstream reservoir can be operated for control points between the two reservoirs. In addition, when the upstream reservoir is being operated for the downstream reservoir, an attempt is made to bring the upper reservoir to the same index level as the lower reservoir based on index levels at the end of the previous time period.

6.1.4 Parallel Conservation Operation Procedures

Parallel conservation operation procedures are utilized when one or more gated reservoirs are operated together to serve some common downstream flow requirement. The following steps are utilized by HEC-5 to determine the reservoir releases necessary for a downstream location:

(1) Determine all reservoirs operating for the downstream location.

(2) Determine priorities of reservoirs operating for the downstream location based on index levels.

(3) Calculate table of releases to bring all other parallel reservoirs to level of each reservoir in turn.

(4) Calculate release to bring all parallel reservoirs to each target storage level. Also, determine sum of releases to bring system to top of conservation and top of buffer pools.

(5) If no upstream parallel reservoir has been operated for flood control or water supply at the downstream location and no requirement for low flow exists and no flooding will occur at the downstream location within the forecast period, skip operation for the downstream location.

(6) Check for future flooding at the downstream location within forecast period. If flooding occurs, operate for flood control.

(7) If no flooding, determine conservation releases for each parallel reservoir to bring system reservoirs to some appropriate level as follows:

(a) If the release to satisfy minimum desired flow is less than the release to bring system to top of buffer level -- then the release at each reservoir is based on the minimum DESIRED flow at the downstream location.

(b) If not, and the release required to satisfy minimum required flow is greater than the release to bring system to top of buffer level -- then the release at each reservoir is based on the minimum REQUIRED flow at the downstream location.

(c) Otherwise -- release the flow required to bring system to top of buffer level (more than required flow but less than desired flow).

(d) If release for minimum required flow exceeds discharge to bring system to level 1, only release to level 1.

6.1.5 Tandem Conservation System Operational Procedures

Tandem reservoir operation occurs when an upstream reservoir is directed to operate for a downstream reservoir (**RO** Record). Conservation system operational procedures will attempt to balance the conservation storage in the system based on storage target levels. The user, therefore, must desire to have the two reservoirs at the same relative level. If that is not the case, the upstream reservoir should not be directed to operate for the downstream reservoir. These procedures are based on the previous period's storage levels; therefore, they may not make sense when simulation is in large time steps, e.g., monthly.

When the upstream reservoir, for the previous time period, is at an index level below that of the downstream reservoir and both are below the index level for the top of conservation pool, releases from the upstream project are made to satisfy the upstream project's minimum flow requirement. When the upstream reservoir's index level, for the previous time period, is greater than the index level for the downstream reservoir, the upstream reservoir is operated to bring the upstream reservoir down to the level of the downstream reservoir for the previous time period. Two additional criteria must also be satisfied.

(1) First, the release from the upstream reservoir must not be allowed to cause the lower reservoir to spill or waste water just due to balancing levels.

(2) Second, the downstream reservoir must not be required to empty all of its conservation storage in meeting its requirements if there is still water in the upstream projects. This condition could occur due to the use of the previous time period for the balancing level. It is necessary to use the previous period's index level because the reservoir release for the downstream project, for the current time period, is not known when the upstream reservoir's release is being calculated.

6.1.6 Reservoir Operation Priority

Reservoir operation priority for different purposes is input on the **J2** Record, field 4. Table 6.1 summarizes these priorities for reservoir operation.

Table 6.1
Reservoir Operation Priority

Condition	Normal Priority	Optional Priority
During flooding at downstream location	No release for energy requirements	Release for primary power
If primary power releases can be made without increasing flooding downstream:	Release down to top of buffer pool	Release down to top of inactive (Level 1)
During flooding at downstream location:	No release for minimum flow	Release minimum flow
If minimum desired flows can be made without increasing flooding downstream:	Release minimum flow between top of conservation and top of buffer pool	Same as normal
If minimum required flows can be made without increasing flooding downstream:	Release minimum flow between top of conservation and top of inactive pool	Same as normal
Diversions from reservoirs (except when diversion is a function of storage):	Divert down to top of buffer pool	Divert down to top of inactive pool (Level 1)

6.2 System Operation Concepts

As indicated in previous paragraphs, the index levels assigned to each reservoir are used to determine priority of releases among reservoirs. The program operates to meet specified constraints throughout the system and then to keep all reservoirs in the system in balance if possible. A system is "in balance" when all reservoirs are at the same index level. To determine the reservoir index level at each time step of a simulation, the program interpolates linearly on a table of index level vs. storage (**RL** Record).

In balancing levels among reservoirs, priority for releases is governed by index levels such that reservoirs at the highest levels at the end of the current time period (assuming no releases are made) are given first priority for the current time period. The following sections show how the index levels can be used to specify operating rules for a system.

6.2.1 Equivalent Reservoirs

In determining the priority of reservoir releases among parallel reservoirs, or among subsystems of a reservoir system, where some tandem reservoirs are present, the concept of an "equivalent" reservoir is used. The concept is based on weighting the level of each reservoir in a subsystem by the storage in the reservoir to determine a storage-weighted level for the subsystem. For example, consider a situation in which two parallel reservoirs are upstream from a third, as shown in Figure 6.1.

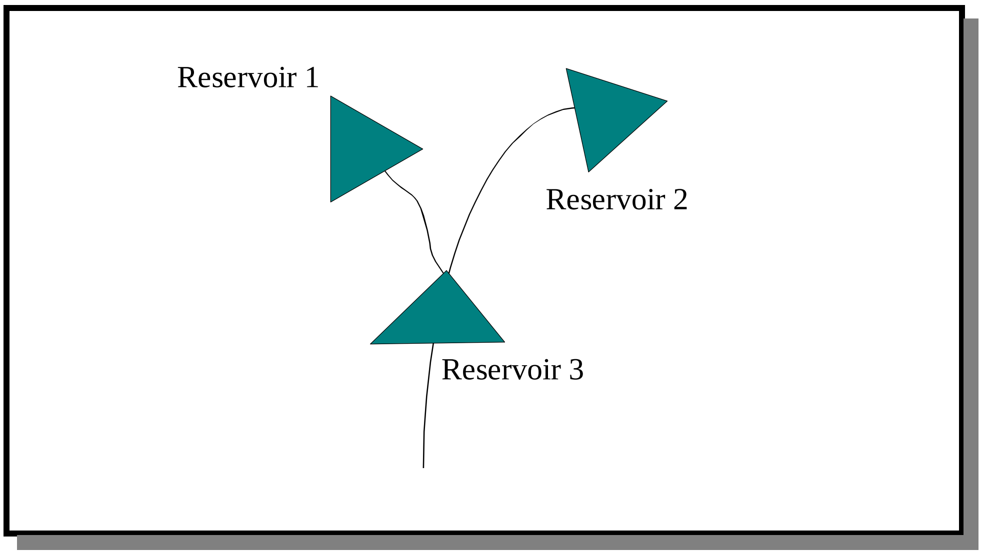

Figure 6.1 Reservoir Configuration for Equivalent Reservoir Example.

Table 6.2 shows the level-storage characteristics of the equivalent reservoir.

Table 6.2
Equivalent Reservoir Level - Storage Characteristics

Cumulative Storage - Acre Feet				
Index Level	Reservoir 1	Reservoir 2	Reservoir 3	Equivalent Reservoir
5	40	20	8	68
4	30	15	6	51
3	20	10	4	34
2	10	5	2	17
1	0	0	0	0

Suppose that it is desired to determine the amount of release to make from Reservoirs 1 and 2 and that storages in Reservoirs 1, 2 and 3 at the end of the previous time period are 35, 12.5 and 3, respectively. For these storages, the equivalent reservoir storage is 50.5. By interpolation, the equivalent level is 3.97 for the equivalent storage. (From Table 6.2, The equivalent storage of 50.5 is just below the Level 4 equivalent storage of 51). The levels of Reservoirs 1, 2, and 3 are: 4.5, 3.5 and 2.5, respectively, as shown in Table 6.3.

Table 6.3
Equivalent Level Determination

	Reservoir 1	Reservoir 2	Reservoir 3	Equivalent Reservoir
Storage	35	12.5	3	50.5
Level	4.5	3.5	2.5	3.97

The criterion used in the HEC-5 computer program is that releases will be made from an upstream reservoir if its level is above the greater of the level of downstream reservoir or the equivalent reservoir level. Therefore, a release would be made from Reservoir 1 and not from Reservoir 2 because the level of Reservoir 1 is above the equivalent reservoir level and the level of Reservoir 2 is below the equivalent reservoir level. However, the releases would also be governed by physical and other constraints that have been specified.

Figure 6.2 and Table 6.4 illustrate the use of the equivalent reservoirs concept with both parallel and tandem reservoirs operating as a system for location D. Table 6.4 shows three (3) reservoirs with the same flood control storage. Values are given in percent of storage filled.

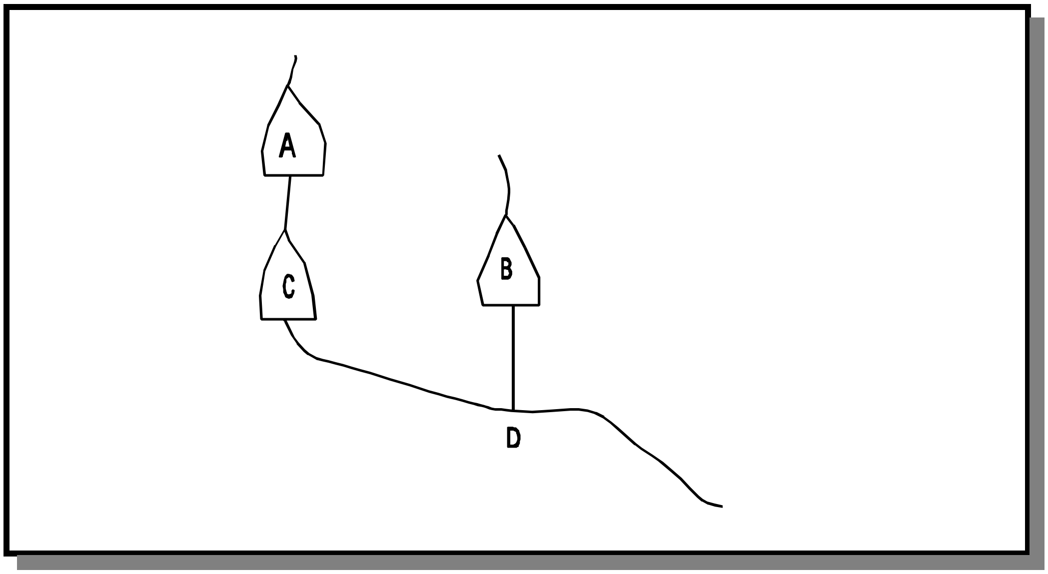

Figure 6.2 Example for Reservoirs in Parallel and Tandem.

Table 6.4
Release Priority for Tandem and Parallel Reservoirs
(Percent of Storage Filled)

A (%)	**C** (%)	**Equivalent A&C** (%)	**B** (%)	**Highest Priority B or C**	**Release from A**
60	40	50*	30	C	Yes
60	20	40*	30	C	Yes
30	20	25*	30	B	Yes
15	35*	25	30	C	No

***** Highest of C or A&C

6.3 Reservoir Priority Using Levels

Release priorities among reservoirs are an important reservoir operating criterion which must be specified for most system operations. Reservoirs first operate for their own requirements and then for downstream locations. When two or more reservoirs operate for a common location, the question is: *Which reservoir should be operated first?* The HEC-5 program uses the concept of Levels to determine reservoir release priority. The reservoir at the higher level is the priority reservoir to make a release. When all reservoirs are at the same level, the system is in balance.

Figure 6.3 shows the primary reservoir levels graphically. Additional levels can be defined within the primary levels. To illustrate the technique for setting priorities among reservoirs, the following example has been prepared:

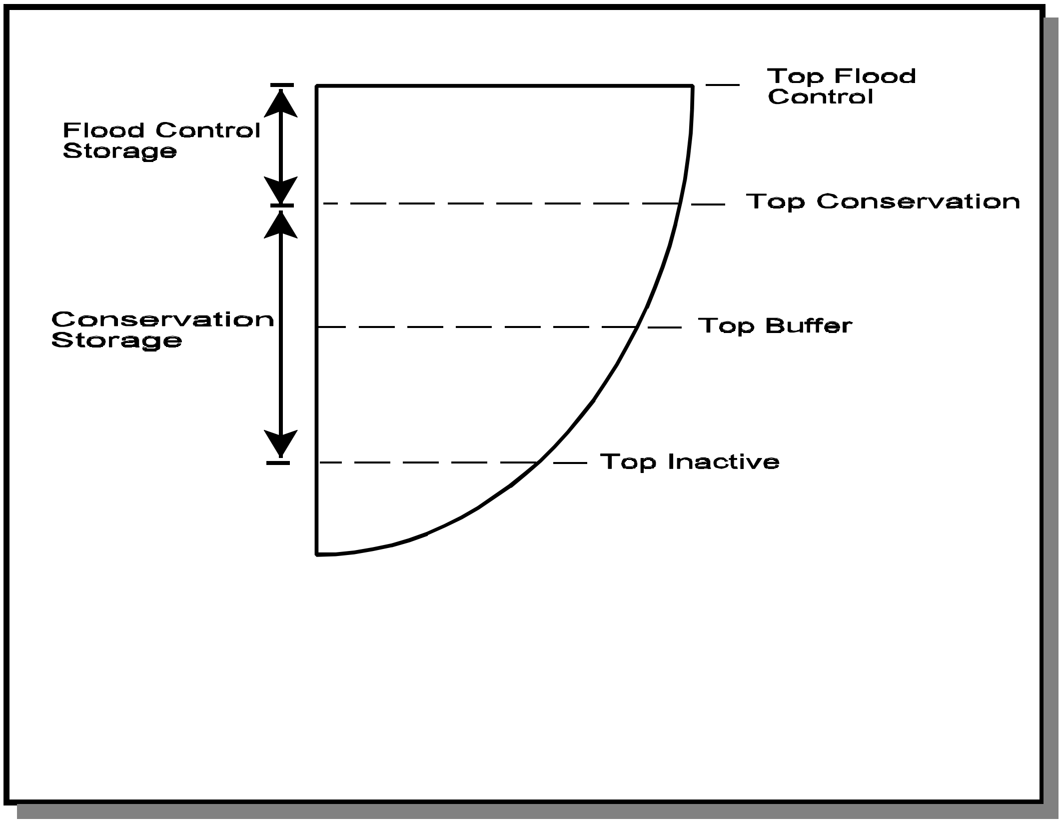

Figure 6.3 Reservoir Storage Levels.

Assume the information shown in Table 6.5 is known for each of four reservoirs which constitute a reservoir system.

Table 6.5
Reservoir Storage Levels
Cumulative Storage (acre-feet)

Reservoir Number	Top of Inactive	Top of Buffer	Top of Conservation	Top of Flood Control
11	1,000	5,000	50,000	100,000
22	5,000	10,000	100,000	200,000
33	10,000	20,000	150,000	500,000
44	50,000	100,000	200,000	700,000

It is desired to operate this example system according to the following rules:

1. Release flood control storage to top of conservation, equally.
2. Release Reservoir 11 conservation storage above top of buffer.
3. Next release Reservoirs 22 and 33 conservation storage above top of buffer.
4. Next release Reservoir 44 conservation storage above top of buffer.
5. Release conservation storage below top of buffer, equally.

To specify these operating criteria in HEC-5, each storage level in each reservoir is assigned an integer number from 1 to a maximum of 40. The number of levels used is the minimum number required to specify the desired operating rules. In this example, six levels were found to be necessary. The lowest level, Level 1, corresponds to the top of inactive pool. The highest level, Level 6, corresponds to the top of flood control pool. See Table 6.6.

The program makes releases from storage between the highest and next highest level until the water stored between these levels is exhausted; then it goes to the next lower level, and so on in descending order. All reservoirs with storage between the same successive pair of levels make releases where possible to maintain the same degree of risk. The specific criteria depends upon the system configuration.

Levels 2 through 5, in this example, are assigned in such a way that the system operates as desired. Because operating Rule 1 desires that all reservoirs release from flood control storage equally, by assigning Level 5 to the top of conservation (bottom of flood control) for all reservoirs, this rule is achieved.

Operating Rule 2 desires that all conservation storage from Reservoir 11, above the top of buffer, be released first. By assigning Level 4 to the top of buffer for Reservoir 11, and top of conservation for all other reservoirs this rule is achieved. This limits the available storage between Levels 4 and 5 to the conservation storage in Reservoir 11, thus it will be exhausted before water is released below Level 4.

Operating Rule 3 is achieved in a similar manner, by assigning Level 3 to the top of buffer for Reservoirs 22 and 33 and to the top of conservation for Reservoir 44. Conservation storage volume is provided between Levels 3 and 4 for Reservoirs 22 and 33, but not for Reservoirs 11 and 44.

Lastly, Level 2 is assigned to the top of buffer for all reservoirs. Below the top of buffer, all reservoirs are to release equally. This is achieved since Level 2 for all reservoirs is the top of buffer.

Table 6.6
Assigned Storage Levels

Level	Reservoir 11	Reservoir 22	Reservoir 33	Reservoir 44
6	100,000	200,000	500,000	700,000
5	50,000	100,000	150,000	200,000
4	5,000	100,000	150,000	200,000
3	5,000	10,000	20,000	200,000
2	5,000	10,000	20,000	100,000
1	1,000	5,000	10,000	50,000

To summarize, Figure 6.4 shows the level numbers corresponding to primary storage volumes for each reservoir. Reservoir storage volumes (corresponding to level numbers) are specified as input on the **RL** Record. During simulation, the system operates as follows: any water stored between Levels 5 and 6 is released from each reservoir. When the water stored between Levels 5 and 6 has all been released, water between Levels 4 and 5 is released. In this example, only Reservoir 11 has a storage volume between Levels 4 and 5. When the volume stored between 4 and 5 is exhausted, releases are made from storage between Levels 3 and 4, (this means from Reservoirs 22 and 33). Next, storage between Levels 2 and 3 is exhausted, therefore, Reservoir 44 releases are made. Finally, storage between Levels 1 and 2 is released. This technique for specifying reservoir operating rules has proven to be an effective way to handle most operating criteria.

Table 6.7
Reservoir System Priority of Operation (Storages and Levels)

Storage for:	**Res 11**	**Res 22**	**Res 33**	**Res 44**
Top of Flood Control	6	6	6	6
Top of Conservation	5	4, 5	4, 5	3, 4, 5
Top of Buffer	2, 3, 4	2, 3	2, 3	2
Top of Inactive	1	1	1	1

While this example treated priorities among the reservoir conservation storage, the concept applies to any component of reservoir storage. That is, the levels could be placed within the flood control or conservation storage pools. One reservoir could be drawing down one-half of its storage while another is drawing down all of its storage. In this manner, complex relationships among reservoirs, operating for a common target, can be developed.

Care must be taken when "balancing" reservoirs with large differences in their storage. If the reservoir has very little storage in a level, there will be a dramatic change in index level with small changes in storage. Because the program balances on the level, the small-storage reservoir will tend to be "out of balance" with the larger reservoirs in the system.

6.4 Alternative Reservoir Systems

When studies are being performed to evaluate proposed reservoirs, the reservoir system data set should include all proposed reservoirs, even if some of them would serve as alternatives to others. Control points should be selected and coded for all damage centers, reservoir-operational locations, and information points. Once the entire system is defined, a **J5** Record can be used to delete reservoirs from the system for each alternative system selected. The **J5** Record can be used to delete any reservoir in the system except for downstream tandem reservoirs (these reservoirs can be deleted by removing the reservoir records, while leaving the control point records).

The program has features to compute expected annual flood damage, or flood damage for a single flood. However, the preferred approach is to perform simulations with HEC-5 and write the computed regulated flows to an HEC-DSS file. The Flood Damage Analysis (HEC-FDA) and Project Benefits Accomplishments (HEC-PBA) computer programs are designed to read the flows from HEC-DSS and perform flood damage and benefit calculations based on current Corps of Engineers criteria.

The HEC-5 economic analysis capability can be evaluated at any number of control points by using **DA-DC** Records. Reservoir costs can also be evaluated by using the **R$** Record to show how the costs vary with reservoir storage (**RS** Records). The reservoir cost is based on the top of flood control storage value. If costs and expected annual flood damages are calculated, the net system flood benefits will be printed out for each alternative system operated. By careful selection of alternative systems, the system that produces the maximum net flood-damage reduction benefits can be determined by a reasonable number of separate program executions.

6.5 Non-Reservoir Alternatives

Some structural alternatives to reservoirs can also be evaluated in the system simulation. The existence of a levee or channel modification can be reflected in the reservoir system operation by changing the channel capacity (**CP** Record, field 2) and by changing the routing criteria (**RT** Records), if appropriate. The performance can be evaluated using a revised damage function. Two sets of routing criteria can be defined for each reach and thus the natural and modified routings can use different criteria. The natural flows can also be calculated by a separate program execution and entered as **NQ** Records when evaluating modified conditions.

6.6 Multi-Flood Options

In this context a flow data set is called a "flood," even when it represents non-flooding conditions. There are several options for defining more than one flow-data set to the program. The following lists the options available:

(1) The multi-flood option may be used to operate the system for a continuous period of record with a mixture of computation intervals. A monthly operation could be used for a few years (assuming no routing is desired), and then operate for daily or hourly flows during a major flood (with detailed flood routing), and then back to a weekly or monthly routing interval, etc. A maximum of 80 events can be simulated in this manner in a single execution.

(2) Up to 10 ratios of any or all input floods can be run in a simulation operation (see **FC** Record).

(3) Each flood in a series of floods can start at different reservoir storage on **R1** Record (or **SS** Record), or from the same storages, or can be transferred using the storages from the previous flood (**BF** Record, field 3).

(4) Long floods may be simulated by dividing the flood into flow events which are less than the "Maximum Number of Periods per flow Sequence" (see HEC-5 output). This may be done by manually setting up several sets of flow data (with each less than the maximum) or by allowing the computer to generate separate floods (when the data read exceeded the maximum but is less than 2000 periods). A minimum of a 10-period overlap between floods is used to preserve continuity in channel routing.

(5) For period-of-record daily-flow simulation, it is convenient to divide the flow sequence into sets of four years (1461 periods including leap year). An overlap between flow sets is required if channel routing is used.

6.7 Automatic Flow Subdivision

Because all input arrays involving time periods are stored in the computer program's memory, each complete system operation can be made for only a certain number of periods at one time. The time period limit is variable depending on the number of reservoirs and control points in the simulation. Thus, if the number of time periods is dynamically limited to 50 and the number of flow periods read is 60, two sets of flow data must be stored in memory and operated upon separately. These two flow sets are called Floods 1 and 2, even though they may represent a single input flood event (**BF-EJ** Records).

For the example of 60 periods of flow data, HEC-5 will automatically store the data as two floods, will operate the system for the first flood, and will store the results. The program then will transfer the last 10 flows, plus a forecast period (**J2** Record, field 1) to the beginning of the next flood. Then, the program will read the second flood flows, will operate the system for the second flood and print out all the results as if it were one flood.

Chapter 7

HEC-5 Input and Output

7.1 Organization of Input

The input structure is designed to be flexible with respect to specifying characteristics of the reservoir system. Each input record is described in detail in Appendix G. Inside the back cover of Appendix G is a summary titled "Sequence of HEC-5 Input Records" that shows the order in which the records should be placed.

7.2 Types of Input Records

The various types of records used are identified by two characters in record columns 1 and 2. These characters are read by the program to identify the record. Types of records are as follows:

7.2.1 Comments - C .

Comments can be placed anywhere within the model data, but **not** within the flow data. The comments will be included in the output listing of input data.

7.2.2 Title Records - T1, T2, T3.

Three title records are required for each job. The titles specified on the records are read in alpha format and printed at the beginning of each job.

7.2.3 Job Records - J1 - JR.

These records are used to specify general information used throughout the reservoir-river system. The **J1-J3** Records are required input. The **J1** Record specifies the data units (metric of English) and the number of definition of primary storage levels for all reservoirs in the system. The **J2** Record specifies computational limits as well as policy parameters. The **J3** Record selects program output and defines the type of flow data (incremental, natural or observed) entered in the time series data. Records **J4-JR** are optional and are summarized below:

J4 Record	defines benefit and cost data
J5 Record	is for deleting reservoirs
J6 Record	represents basin evaporation
J7 Record	requests conservation optimization
J8 Record	allows for user-designed output tables
JZ Record	specifies which data are to be written to HEC-DSS
JR Record	specifies the clock times when reservoir releases will be made

7.2.4 System Energy - SM, SD, SH, SC and SF.

These records provide the system energy requirements by month (**SM**), and the daily (**SD**) and multi-hourly (**SH**) distributions for the monthly values. The **SC** and **SF** Records are used when specifying a system power rule curve.

7.2.5 Trace Records - TC, TP, TS.

These records are optional and are used to indicate the control points (**TC**), time periods (**TP**), and subroutines (**TS**) for which detailed output (trace information) is requested. Use of these records is not generally recommended since knowledge of the program is essential and the FORTRAN source code of the HEC-5 program is required for interpretation of the trace information.

7.2.6 Reservoir Records - RL, RO, RS, QQ, RQ, RA, RE, RD, R$, R1, R2, R3, and RG.

These records are used to describe characteristics of each reservoir. The **RL**, **RO**, **RS**, and **RQ** Records are required and are used to specify the reservoir storages for each index level (**RL** Record), the downstream control points that the reservoir is operated for (**RO** Record), and the reservoir storage-outflow characteristics (**RS** and **RQ** Records).

Optional records are used to describe multiple reservoir outlet capacities (**QQ** Record), reservoir areas (**RA**), elevations (**RE**), reservoir diversions (**RD**), and costs (**R$**). The optional **R1** Record is used to describe the initial storages for multiple events or for multiple ratios of the same event. The **R2** Record is to define rate-of-change variables and the **R3** Record provides monthly reservoir evaporation data for the reservoir. The **RG** Record is used to specify gate regulation curve data for induced surcharge flood routing.

7.2.7 Power Reservoir Records - P1, P2, PC, PF, PB, PR, PD, PH, PQ, PT, PL, PP, PS, and PE.

The **P1** and **PR** Records are required for a reservoir which has a power plant, but are omitted for all other reservoirs and non-reservoirs. Records **P1** and optional **P2** describe the general power characteristics. The **PR** Record specifies the monthly firm energy requirements.

The **PC**, **PF** and **PB** Records, if used, specify the rule curve power operation relating plant factor to percent of conservation storage. The optional **PD** and **PH** Records are used to specify the daily and multi-hourly distribution of power demands. The optional **PQ**, **PT** and **PL** Records describe tailwater and hydraulic loss rating curves, and the optional **PP**, **PS**, and **PE** Records describe the peaking capabilities, power storage and power efficiencies, respectively.

7.2.8 Control Point Records - CP, ID, C1, C2, RT, CR, WR, DR, QS, SQ, QD, EL, C$, CL, CC, CS, GS, CG, QM, WA, DA, DB, DF, DQ, and DC.

The **CP**, **ID**, and **RT** Records are required for each control point. They are used to identify the control point number, to specify channel capacity, to provide a name, to indicate the next downstream control point and to specify routing criteria. Control point data is required for all locations (reservoirs and non-reservoirs).

The optional **C1** and **C2** Records provide other general information for the control point. For routing with input coefficients, the optional **CR** Record defines the coefficients. For non-linear routing, the **QS** and **SQ** Records are used to input a storage-outflow table for routing to the next downstream control point.

The optional **QM** Record is used for specifying minimum desired (or required) flows that vary monthly or seasonally. When desired flows are based on ratios of natural flows, then the **WA** Record is used.

Control Point Diversion Records - WR, DR, QS, QD. Optional diversion data for a control point is primarily described by the optional **DR** Record. If water rights are considered, then the **WR** Record is used. If the diversions are a function of flow, the flow data are input on the **QS** Record. For several diversion types, the diversion schedule is input on the **QD** Record (e.g., monthly diversions).

Control Point Stage/Elevation Data - QS and EL. The optional **EL** Record contains stage or elevation data corresponding to discharge data in a similar field of the **QS** Record.

Control Point Cost Data - C$. The optional **C$** Record is used for control point costs (such as levees, etc.)

Variable Channel Capacity - CC. The optional **CC** Record allows channel capacities to vary monthly, seasonally, or be a function of the inflows or reservoir levels.

CC Record can define the monthly channel capacity
CC - **CS** Records define the seasons for the variable channel capacity.
CC - **QS** Records define the flows at another location for channel capacity.
CC - **CL** Records define reservoir levels for variable channel capacity.
CC - **CS & CG** Records define season and reservoir level or elevation (guide curves) for variable channel capacity.
CC - **CS, GS, & CG** Records define season and percent of total system flood control storage as a basis for defining variable channel capacity.

7.2.9 Damage Data Records - DA, DB, DF, DQ, and DC.

Flood damage computations in the Corps are now computed by other programs. The damage input and computations in HEC-5 have been left in the program to support older model data. These optional records are also control point records and are, for a given control point, used in computing damage for a single flood or expected annual damage. If damages are to be calculated for a given control point, all of these records except the **DB** Record are required. The **DA** Record is for predetermined expected annual damages for natural conditions while the **DB** Record is for base conditions (existing reservoir system). The **DF**, **DQ** and **DC** Records are for corresponding damage frequencies (**DF**), damage discharges (**DQ**), and damages (**DC**).

7.2.10 End of Data Record - ED.

The required **ED** Record follows the data records for the most downstream control point in the system. It indicates the end of model data. Time series data follows this record.

7.2.11 Time Series Specification - BF, FC, SS, ZR and ZW.

The **BF** Record is required to describe the conditions for the subsequent time series data records, IN-PV, such as the number of flows, the starting date of the simulation, the computational interval, etc. The optional **FC** Record specifies up to 10 ratios of the flows which will be used in up to 10 system simulations. The optional **SS** Record provides for starting storages for any of the reservoirs. The optional **ZR** and **ZW** Records allow for reading from (**ZR**) and writing to (**ZW**) an HEC-DSS file. The **JZ** Record defines which variables to write to HEC-DSS.

7.2.12 Time Series Data Records - IN, QA, NQ, MR, QD, EL, EV, PV, CC and ST.

These records are used to describe the sequential time series data for each control point. The required input is the flow data for model locations, defined on the **IN** Record. For convenience only, all of the **IN** Records for the system should be input first.

Reservoir releases can be specified with **QA** Records, which follow **IN** Records. When reservoir releases are not specified, the HEC-5 program will determine the release. Specified releases on **QA** Records will be made by the program, unless they are limited by physical constraints.

The optional **NQ** Records can be used to describe base conditions for computing expected annual damages. When this data are provided, it is treated as natural flows, instead of the computed natural flows.

Other optional records are **MR** Records to specify minimum flows, **QD** Records for diversions, **EL** Records for stages, **EV** Records for evaporation data, **PV** Records for power demands, **CC** Records for period varying channel capacities, and **ST** Records for specifying reservoir target storages (Top of Conservation storage varies each period). These optional records can be selectively used for individual control points/reservoirs on any flow sequence.

7.2.13 End of Job Record - EJ.

The **EJ** Record is read following the last data <u>for each time series set</u> (BF-EJ).

Multiple Floods. Up to eighty (80) sets of flow-data records (e.g., BF through EJ Records) can follow the ED Record.

7.2.14 End of Run Record - ER.

The **ER** Record is the required end-of-run indicator. It is the last input record in the data file.

7.3 Output

The amount of program output can be controlled by the program user. A series of pre-defined Standard Output Tables are available for selection with the **J3** Record, field 1. The Standard Output Tables are listed and described below and are presented with descriptions in Appendix F. In addition to the Standard Output Tables, the user can define User-Designed tables.

7.3.1 Standard Output Tables

The output to be provided is based on the input sum of Table Codes on the **J3** Record, field 1. As shown in the list below, items 1 through 5 are printed from the HEC-5A program. The HEC-5B program prints all the remaining output. The two programs are run sequentially in a single batch job. The input summary table names are prefaced with an " ***** " which provides a unique character string to facilitate easy location of a specific output table within a large output file. The sequence of possible output from the program is:

1. Printout of input data, including a sequential listing of the HEC-5 input data set (**T1-ER** Records) and the following summary tables: *Input Summary; *Routing Data; *Rule Curve Summary; *Operation Summary; *Map 1; *Map 2; *Reservoir Data; *Diversion Data; and, *Routing/Operation Summary.

2. Input flow data (`*FLOWS`) formatted in 10-field record image.

3. Computation of incremental local flows (`*LOCFL`)

4. Printout of optimization trials and summary (`*OPTRY` and `*OPSUM`)

5. Tables of maximum flows, levels, storages and elevations for reservoirs and non-reservoirs (Summary of Maximums)

6. Results of all variables defined and requested by input data for the system operations arranged by downstream sequence of control points (`*NORML`)

7. Results are arranged by sequence of time periods (`*ROPER`)

8. Summary of releases from reservoirs and actual flow at all other control points, arranged by period (`*RRPER` and `*RQPER`)

9. Tables of diversions and diversion shortages (`*DVPER` and `*DVSHORT`)

10. Table of percent of flood control storage utilized (`*FCPCT`)

11. User designed output based on J8/JZ Record input (`*USER5A` or `*USERS`)

12. Summary of flooding occurring during each flood event (`*SUMF1`)

13. Flood event summaries for multi-flood events (`*SUMFS` and `*SUMPO`)

14. Economic input data and damage computation (`*ECDAM`)

15. Flood frequency plots (`*EPLOT`)

16. Summary of damages or average annual damages, system costs and net benefits (`*ESUMD, *ESUMC` and `*ESUMB`)

17. Summary of discharge and stage reduction at each non-reservoir control point for each flood event (`*HYEFF`)

18. Computer check for possible errors (`*ERROR`), and

19. Listing of Case designations defining reservoir releases (`*CASES`).

7.3.2 User-Designed Output Tables

The program has a provision for creating User-Designed Output Tables using the **J8** and/or **JZ** Records. The **J8** produce period-by-period summary tables in the output file. Multiple tables are created with multiple **J8** Records. The input description for the **J8** Record in Appendix G provides a description of the options available.

There is a similar user-defined option to write results to an HEC-DSS file using the **JZ** Record. With the **JZ** Record (in conjunction with a **ZW** Record), the requested information is written to an HEC-DSS file and is also shown in the output file.

There are 41 variables available for display by time period in summary tables. The tables are defined by *Location ID***.***Variable Code* and are printed in column sequences, in the order defined.

7.3.3 Traces

In addition to ordinary output, trace information showing intermediate computations can be requested. Traces show the computation process as the program processes the information. There are several levels of trace (specified on the **TP** Record, field 10), as described in Appendix G. The choice of trace level depends on the extent and detail of information desired. Trace information can be requested at specific control points with a **TC** Record, for specific time periods with a **TP** Record and for specific subroutines with a **TS** Record. <u>The user is cautioned to use traces sparingly because large volumes of output can be generated and a program source listing is required to interpret the information.</u>