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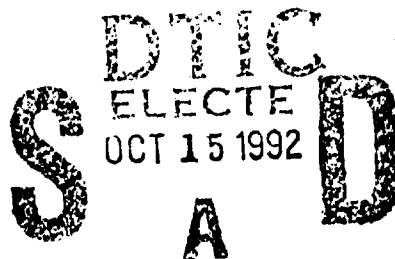


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A Generalized Simulation Model for Reservoir System Analysis

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A Generalized Simulation Model for Reservoir System Analysis¹

By Richard J. Hayes and Marilyn B. Hurst²

Abstract

The U.S. Army Corps of Engineers has planning and management responsibility for over 500 reservoirs across the United States. Although the primary purpose of most of these projects is flood control, many also include water supply, hydropower or water quality as authorized purposes. A generalized reservoir system simulation model suitable for both planning and real-time operation analysis has been developed by the Hydrologic Engineering Center (HEC).

This paper will overview the general capabilities of the model with emphasis on the features of the current release of HEC-5, Version 7.2, dated March 1991.

Background

The development of computer program HEC-5, "Simulation of Flood Control and Conservation Systems" (USACE, 1982) has been driven by the changing requirements of the Corps of Engineers. As with the other generalized programs of the Hydrologic Engineering Center, the needs of Corps field offices have provided the major determinant for continued program development.

The initial formulation of the program began in 1972, as a single event, multi-reservoir, flood control only model. The goal was to develop a computer program useful for planning and design studies with the anticipated eventual extension to include project operation in real-time. The importance of a generalized flood simulation model was demonstrated almost immediately as HEC-5 made it possible to model the Susquehanna, Potomac, James and Schuylkill River basins to evaluate the impact of Tropical Storm Agnes on various combinations of existing and proposed reservoirs.

In 1974, the model was expanded from single event to multi-event with basic water supply and hydropower analysis capabilities. Average annual flood damage and benefit computations were also added.

The requirement to evaluate pumped-storage hydropower fostered the development of HEC-5's system power and pumped-storage hydropower analysis capability in 1977. These developments coincided with the addition of firm-yield optimization of conservation features (including installed capacity and firm-energy). The usefulness of a generalized hydropower model was proven decidedly with thousands of HEC-5 applications made in support of the National Hydropower Study during 1978 to 1981.

The HEC-5 water quality modeling capability was initiated in 1979 with the addition of the capability to simulate water temperature for a single reservoir. In the following four years the ability to simulate a multi-reservoir system for up to eight water quality constituents was developed and field tested. In support of the Columbia River System Operation Review, a major expansion of the HEC-5 water quality analysis capability is presently underway.

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² Hydraulic Engineer and Computer Programmer, respectively, US Army Corps of Engineers, Water Resources Support Center, Hydrologic Engineering Center, Davis, CA.

In 1980, HEC-5 was modified to transfer data to and from the newly developed HEC Data Storage System, HEC-DSS (USACE, 1990). The development of this link with the Corps rainfall-runoff forecasting program, HEC1F (USACE, 1989), has proven to be significant in advancing the original goal of computer aided real-time water control. Since 1980 a major emphasis of HEC-5 development has been real-time water control.

Program Modernization

The development of HEC-5 from its inception until the early 80's occurred on large mainframe computers. In 1980, HEC acquired a HARRIS mini-computer and a gradual transformation of HEC-5 began. Modernization of the HEC-5 source code began in earnest in 1984 with the primary goal of minimizing the cost of program support, eliminating potential malfunctions, and facilitating the addition of future enhancements.

Major tasks of the modernization process included: (1) conversion of the FORTRAN IV code to FORTRAN-77 specifications; (2) subdivision of 12 large subroutines into 102 smaller modules; (3) redesign of COMMON blocks and subroutine arguments; (4) development of PARAMETER statements; (5) extensive internal documentation; and (6) centralization and simplification of primary program logic. In addition to the code modernization effort, over 90 new test data sets (which test most of the HEC-5 flood control, water supply, and hydropower features) were developed to enhance program quality assurance.

As a continuation of these modernization efforts, HEC-5 was adapted to an HP-9000 computer, an AMDAHL computer and finally in 1987 to a PC. Currently, HEC-5 is being adapted to a variety of UNIX workstations.

Two major benefits of this modernization effort have been noted. First, the adaptation of this very large and rather complex program from mainframe computers to the ubiquitous PC was made possible; and, second, since the retirement of HEC-5 author Bill S. Eichert in February 1989, the HEC staff responsible for HEC-5 have been able to continue maintenance and development.

Model Operation

The basic reservoir system analysis provided by HEC-5 is typically categorized as descriptive simulation. This type of model illustrates the consequence of a set of decisions (operational rules and goals) given a sequence of events. As an example, a descriptive simulation reservoir model shows the effect of a system of reservoirs with specified storage allocations, given downstream channel capacities and a specified series of historical or hypothetical flows.

The results of an HEC-5 simulation are comparable to those obtained with the optimization technique termed "preemptive goal programming", as described by Loganathan and Bhattacharya (1990). For each simulation period, seventeen releases are determined and evaluated for each reservoir.

The normal bias of HEC-5 is to favor flood control operation over conservation operation. The program user however can change the prioritization of release selection to favor hydropower or water supply operation over flood control.

To evaluate flood control, the model determines releases based on the following conditions: (1) channel capacity at the reservoir, (2) channel capacity at downstream locations, and (3) rate-of-change rising. The smallest of these releases is selected as the flood control release. To evaluate potential conservation releases, the following are determined: (1) water supply at the reservoir, (2) water supply for downstream locations, (3) at-site power, and (4) system power. The largest of these is selected as the conservation release.

A release check is made during each simulation period to insure that the tentatively selected release is as least as large as the computed emergency release (if any) or rate-of-change falling. As a final check on operation, the tentative release is limited by outlet capacity and availability of water.

Data Requirements

The basic input requirements consist of three types of data: (1) **Physical data** including: storage-discharge capacity curves, linkages defining the system structure, hydrologic routing criteria; (2) **Operational data** including: allocation of reservoir storage volumes to project purpose (rule curves), forecast ability, maximum allowable flow goals (channel capacities), minimum flow goals; and (3) **Hydrologic time-series data** consisting primarily of flow data.

Program Capabilities

HEC-5 is capable of simulating the operation of simple or complex systems of reservoirs of almost any configuration. Analysis may be made in a planning mode, or when coupled with HEC runoff forecast programs through the data storage system, analysis may be made in a real-time mode.

Hydrologic time-series data may be specified in a variety of simulation time intervals including minutes, hours, days, weeks, 10-daily, half-months and months. Flow data may be specified as end-of-period or period-average. Analysis may be made for single events, multiple events or period-of-record analysis. General capabilities are summarized in Table 1.

Table 1 HEC-5 General Capabilities

- English or SI Units
- Up to 20 Reservoirs
- Up to 40 Control Points
- 7 Hydrologic Routing Methods
- Linked to HEC-DSS Data Storage System
- Simulation Intervals from Minutes to a Month
- Single Event or Period-of-Record Simulation
- Flood Control, Water Supply, Hydropower and Water Quality Analysis

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Flood Control

During a flood event, the model operates the reservoirs to minimize flood damages by limiting releases such that the routed reservoir releases when combined with local runoff will not exceed downstream channel capacities. To do this, the model stores inflows in the flood storage pool. When downstream local flows decrease, the model will increase reservoir releases to return the flood storage pool to an empty condition as rapidly as possible.

For a system of flood control reservoirs, releases are determined to balance the flood control storage among the reservoirs based on the specified storage "levels". These levels may be used to prioritize flood control storage usage among system reservoirs to reflect the probability of filling, or some other "balancing" criteria.

For planning applications, realistic flood control simulation is achieved through the use of a limit on forecast ability both in time and precision of flow forecast. Economic evaluation of flood damage computations may be made for historic floods or on an average annual basis.

For real-time water control applications, HEC-5 is used in conjunction with the HEC runoff forecasting program HEC1F and other programs of the HEC water control software system. Water control operators can efficiently evaluate HEC-5 real-time simulations via graphical output from the HEC-DSS graphics program DISPLAY. Flood control features are summarized in Table 2.

Table 2 HEC-5 Flood Control Features

- Balanced Pool System Operation
- Gated Spillway Simulation
- Rate-of-Change Constraints
- Pre-Release Options
- 7 Variable Channel Capacity Options
- Forecast Limits and Contingency Factors
- Flood Damage Economic Computations

Water Supply

During a low-flow sequence, reservoir releases (combined with downstream local flows) are made to satisfy downstream instream and diversion water supply demands. When downstream local flows are capable of satisfying these demands, the releases are reduced until the conservation pool is filled or until water supply requirements again require additional releases.

Reservoir systems are operated for water supply goals in a balanced pool mode utilizing conservation zone storage levels in the same way as flood control operation (e.g. reservoirs with higher levels release first to meet downstream demands).

HEC-5 also provides the ability to optimize reservoir storage, reservoir yield, diversions and downstream flow goals on a firm-yield basis. Water supply features are summarized in Table 3.

Table 3 HEC-5 Water Supply Features

- Variable Instream Flow Goals
- 7 Diversion Types
- Evaporative Losses/Gains
- Firm-Yield Optimization of Storage, Yield, Diversions, Downstream Goals

Hydropower

HEC-5 hydropower simulation capabilities include analysis of run-of-river, peaking, pumped storage and system power. To simulate hydropower operation, reservoir releases are determined to meet power production goals which may vary on a monthly, daily, or hourly basis. In addition, at-site and system power requirements may be specified as a function of storage.

HEC-5 also includes the ability to optimize installed capacity and firm energy on a firm-yield basis. Hydropower features are summarized in Table 4.

Table 4 HEC-5 Hydropower Features

- Peaking Power
- Run-of-River Generation
- System Power Operation
- Leakage Specification
- Penstock capacity and losses
- Efficiency a function of Storage or Head
- Capacity as a function of Storage, Head or Release
- Monthly, Daily and Hourly Power Demands
- Firm-Yield Optimization of Energy and Capacity

Water Quality

Program HEC-5Q (USACE, 1986) is a specialized edition of HEC-5 which in addition to flood control, water supply, and hydropower also includes water quality analysis. The capabilities of this water quality edition are summarized in Table 5.

Table 5 HEC-5Q Water Quality Features

- Operation of Multi-Level Discharge Ports
- Downstream Temperature Goals
- Downstream Dissolved Oxygen Goals
- Up to 3 Conservative Constituents
- Up to 3 Non-Conservative Constituents

Program Configurations and Availability

Prior to 1987, HEC-5 was available to Corps offices as a mainframe executable program. FORTRAN source code was available for non-Corps offices. In 1987 the first PC edition of HEC-5 was released. This edition was developed for INTEL 8088 DOS based PCs (e.g., IBM-XT). Due to the limited memory addressing inherent with 8088 systems, this edition relied upon an extensive overlay structure and a reduction in both temporal and spatial capabilities. This overlaid edition was released to both Corps and non-Corps offices.

In 1988, an extended memory edition was developed utilizing licensed extended memory management software rather than an overlay scheme. The extended memory edition provided mainframe capabilities and a significant increase in execution speed. However, due to the licensing requirements these editions were released only to Corps offices.

The current release of HEC-5 is Version 7.2, dated March 1991. Three PC DOS configurations include: (1) an overlaid edition suitable for XTs with 640kb memory, math coprocessor, and a hard disk; (2) an extended memory edition which suitable for a 386 PC with math coprocessor, hard disk and 2-4 Mb of memory; and (3) an extended memory edition of HEC-5Q suitable for a 386 PC with math coprocessor, hard disk and 2-8 Mb of memory. HEC software including HEC-5 are available from the National Technical Information Service (NTIS) as well as software vendors.

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