US Army Corps of Engineers
Hydrologic Engineering Center

HEC Contribution to Reservoir System Operation

August 1979

TP-63

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
August 1979	Technical Paper	

4. TITLE AND SUBTITLE
HEC Contribution to Reservoir System Operation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bill S. Eichert, Vern R. Bonner

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
TP-63

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Paper describing HEC exhibits at National Workshop on Reservoir System Operations at Boulder, Colorado, 13-17 August 1979.

14. ABSTRACT
The development, support, and application of HEC computer programs for reservoir system analysis are described. Applications of the programs to many types of reservoir studies are reviewed and referenced.

15. SUBJECT TERMS
reservoir operation, mathematical models, reservoir system analysis, water resource management

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER**
U	U	U	UU	34	

HEC Contribution to Reservoir System Operation

August 1979

US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

TP-63

HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION[1]

by

Bill S. Eichert[2] and Vernon R. Bonner[3]

INTRODUCTION

This paper describes the role of The Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers in developing and distributing information concerning the use of mathematical models for reservoir system operations. The paper describes the work of the Center in this area, and presents background information on the exhibits used by HEC during the workshop. Exhibits include several wall board displays, a table display of pertinent HEC publications, a slide-voice cassette on HEC activities, and a cathode ray tube (CRT) demonstration of HEC capability to simulate real-time operations of several flood control reservoirs.

The wall board displays include exhibits illustrating HEC's technology transfer mechanisms (see reference 1) which include videotape distribution of lectures on Reservoir Analysis; source deck distribution of the generalized computer programs, Reservoir System Analysis for Conservation (HEC-3) and Simulation of Flood Control and Conservation Systems (HEC-5); and training courses in Reservoir System Analysis, Hydropower, and Real-Time Control of Water Projects. Other wall displays cover descriptions of computer program

---

[1] Paper describing HEC exhibits at National Workshop on Reservoir System Operations at Boulder, Colorado, August 13-17, 1979.

[2] Director, The Hydrologic Engineering Center, U. S. Army Corps of Engineers, Davis, California.

[3] Hydraulic Engineer, The Hydrologic Engineering Center.

capabilities for HEC-3 and HEC-5 and charts showing reservoir systems where these models have been used. A table display contains samples of various HEC publications concerning reservoir system operation, including training course manuals, technical papers and program manuals. A 35mm slide presentation, with audio cassette, is used to describe the various activities of the Center.

The interactive session on a cathode ray tube terminal demonstrates the results of HEC research in developing techniques for flood forecasting, simulating the reservoir operation and displaying information in tabular and graphical forms for flood control systems. A separate paper, "On-Line Reservoir System Analysis," describes the interactive session. The development, support, and application of HEC reservoir system programs are described in the following sections.

COMPUTER PROGRAM DEVELOPMENT

The need for comprehensive generalized computer programs for use in planning and operating multipurpose reservoir systems arises from the large investments in manpower and money required to develop separate programs for each system. The cost of a separate computer program for a system would depend upon many factors, but costs of $50,000 to $200,000 would be the approximate range of such special programs. Several generalized programs have been developed for these purposes, including two such programs at HEC. Well-known generalized computer programs for flood forecasting include the National Weather Service models (references 2 and 3), the United States Army Corps of Engineers North Pacific Division (NPD) model called SSARR (reference 4), the Hydrocomp model (reference 5) and the HEC-1 model (reference 6). Well-known simulation models for multipurpose reservoir operation include HEC-3 (references 7 and 8), HEC-5 (reference 9), the NPD SSARR-HYSIS (reference 10) models and the SUPER program (reference 11) which was developed by the Southwestern Division office of the Corps of Engineers.

The initial effort at HEC in reservoir system operation started in 1966 with the development of a monthly multipurpose reservoir operation model (HEC-3) to be used in the planning of reservoir systems including flood control, hydropower and water supply. Numerous basins have been modeled with this program as shown in Table 1 and discussed in the program application part of this paper.

The development of a generalized model which would handle short-interval system operation required for planning and real-time reservoir operation was started in 1972 with the development of the HEC-5 computer program. The HEC-5 model was constructed so that it could perform monthly operations of multipurpose reservoir systems similar to the HEC-3 model, but which could also simulate short-interval routings (i.e., daily or multi-hourly) and mixtures of the time intervals. Some of the applications of the model are shown in Table 2 and are discussed in the applications section of this paper.

Comparisons of the HEC-3 and HEC-5 reservoir operation models along with the HEC rainfall-runoff model, HEC-1, are shown in Table 3. A brief overview of the capabilities of HEC-1, HEC-3 and HEC-5 are shown in Figures 1-3. Technical procedures used in the models are shown in references 12-14. Training course manuals, which also present technical procedures and program usage, are shown in references 15-17. Other related HEC documents are shown in the publications list, reference 18. Videotapes of various HEC lectures on technical procedures and the use of the computer programs are contained in the HEC videotape catalog (reference 19).

COMPUTER PROGRAM SUPPORT

The Center plays a key role in the dissemination of information on hydrologic and analytical planning techniques to practicing engineers. Information is disseminated primarily to Corps offices; however, hundreds of offices in other U.S. federal and state agencies, and at universities, consulting engineering firms and foreign governments receive our programs and publications. The Center uses several methods to disseminate technical information as discussed in the following paragraphs (also see HEC Technical Papers 29 and 49).

Source Deck Distribution

As shown in Table 4, the HEC has distributed thousands of source decks to a variety of different offices. Based on our latest survey in November 1976, over 2,000 source decks are still considered active by the using offices. Each year approximately 600 new source decks are requested. Assistance to program users is provided, to the extent possible, in implementing the models on their equipment, answering questions on use of models and eliminating program malfunctions. These services are provided without charge except that non-U.S. federal agencies are charged a reproduction and handling fee for each source deck provided.

Documentation

Computer program documentation is generally accomplished with separate users (see references 7 and 9) and programmers manuals (see reference 8). The programmers manual provides useful information for getting the program running on the users computer, and the users manual explains what the program does, the technical procedures used, how to code input for the program, and how to interpret output. Notification of program error corrections and improvements is made to all current source deck holders periodically. Other HEC publications include training course manuals, newsletters, professional papers and computer program abstracts. The Center also provides "on-line" information on the two computer systems used by most Corps offices.

Formal Training Courses

Each year, approximately 24 weeks of training are provided by HEC for Corps personnel in 1 to 2-week courses. Approximately 2 to 4 spaces in these courses are reserved for personnel from other U.S. federal, state and university offices. Two special 4-week courses were given to foreign representatives in 1972 and 1974 as a United States contribution to the International Hydrological Decade. HEC course manuals for reservoir systems are contained in references 15-17. Many universities are using HEC-developed training course materials and/or HEC computer models in their courses. Even with the courses now offered, there is insufficient training available to the non-Corps program user.

Videotapes and Instructional Material

Many of the lectures in HEC courses have been videotaped (see reference 19) and the tapes are being loaned out along with instructional material (lecture notes, visual aids and references). These tapes are particularly useful when someone who has taken the course is available to answer questions after the tapes are viewed. Visitors to HEC desiring individual training on a computer model often use these videotapes before getting individual help on solving a particular problem. Ten visitors from Brazil recently received 4 weeks of training at HEC using this approach.

Publications

Application papers are often prepared as HEC assists various Corps offices in using computer programs in planning and operational studies. Table 5 shows all of the HEC technical papers dealing with reservoir system analysis. Additional information on applications is distributed through HEC courses, training documents (20), and seminars (see references 21, 22).

User Assistance

Other ways of supporting the computer programs besides formal information dissemination vehicles include assisting offices in using the programs when problems arise, making modifications to programs to assist user's needs and developing supplemental software to enhance the use of the programs. Examples include the GETUSGS routines developed to provide USGS daily and monthly flows on computer systems used by the Corps, and a program which develops inflows for the HEC-5 using real-time information on reservoir releases, pool elevations, and river stages.

Personal Contacts

Technology transfer is also greatly enhanced by personal conversations by telephone, by visits to HEC and by HEC personnel attending professional conferences and writing papers.

COMPUTER PROGRAM APPLICATIONS

Over the years, both HEC-3 and HEC-5 have been applied to many different types of reservoir problems. The applications listed in Tables 1 and 2 and discussed here are limited to those the Center has had a major role. Many of the studies have been presented in the HEC Technical Papers (T.P.) shown in Table 5. The applications outlined here were selected as examples of various types of planning and operational studies.

Yield Potential

The basic procedures for safe yield analysis were presented by Beard in 1965 (T.P. 3). He concluded that the detailed routing studies using historical streamflow sequences was the general procedure used in the United States. The Reservoir Yield Program (reference 23) was released in 1966 to perform multipurpose, single-reservoir yield studies. A demonstration of the advantages of detailed sequential analysis over "short cut" methods is presented in T.P. 14 and an application is shown in the update determination of the Delaware River yield (T.P. 16). A comparison of HEC-3 with the Texas Water Development Board's SIMYLD program is given in T.P. 32 and a comparative study on drought severity and water supply dependability was performed with HEC-3 (T.P. 30).

Storage Requirements

The storage requirement type of study is the complement of the yield study in that the demand is given and the required storage is the unknown. In T.P. 7, the Reservoir Yield Program was used to determine storage required to meet water quality demands. The HEC-4 program, Monthly Streamflow Simulation (reference 24) was used to estimate the missing monthly flows for the selected study period. A total of 46 sites were evaluated for actual water demands and 10 times those demands. The use and advantages of using simulated streamflow in water yield analysis are presented in T.P. 10.

Reservoir System Expansion

The argument for the use of a generalized reservoir system program for planning and analysis was made by Beard in 1967 (T.P. 4). At that time, HEC-3 had been used in preliminary studies to evaluate the Susquehanna and Willamette River Basins and several smaller systems. Technical Papers 4 and 9 are mainly descriptive of the HEC-3 program capabilities. Application of HEC-3 to the Kanawha River Basin is presented in T.P. 23. The study involved alternative plans with 13 to 18 reservoirs and 16 control points. While most typical project purposes were evaluated in the study, the paper only discusses water quality, reservoir recreation and stream recreation and fishery.

Reservoir system expansion for flood control on the Susquehanna River System was studied using the HEC-5 program (T.P. 44). Technical Paper No. 44 describes the HEC-5 program and the flood control system formulation strategy. The program's capability to compute the Expected Annual Damages from flooding was used to evaluate alternative reservoir systems. An interesting aspect of the study was the sensitivity of the expected annual damages to the system hydrology.

Hydropower Potential

None of the Technical Papers describes the application of HEC-3 or HEC-5 to the problem of determining the power potential of a site. HEC-3 has been used in several studies (Willamette River Basin in Oregon and Cache and Keetna Projects in Alaska) to determine power potential. The HEC-5 program has been applied to 80 existing reservoirs to automatically determine dependable capacity and firm energy on promising sites determined from the Phase I screening of the National Hydropower Study. Software has been developed to create the input data files for HEC-5, and it is expected to be applied to approximately 2,500 power sites.

Flood Control Measures

Both HEC-1 and HEC-3 have been used for flood control planning. A special version of HEC-1 has the capability to optimally size flood control measures in an urban flood control system (T.P. 42). However, the current flood control reservoir studies are utilizing HEC-5. (T.P. 41 and 43). Training Document No. 7 (reference 20) demonstrates the basic approach used with HEC-5 to perform flood control planning. Measures evaluated include (1) reservoirs, (2) levees or floodwalls, (3) channel modifications, (4) diversions, (5) flood forecasting, (6) flood proofing, (7) relocation, and (8) flood warning. Concepts of system formulation and assessment are also presented.

Power Operations

A major power operation study was performed with HEC-3 on the Arkansas-White-Red River Basins (T.P. 24, 28, 31 and 33). The system consisted of 23 existing or authorized projects, in three river basins, operating in an interconnected electrical system. The system operates for flood control, hydroelectric power, water supply, navigation, fish and wildlife, water quality and recreation. The constraints of the many project purposes and legal-institutional constraints made the allocation of system power demands to the 19 power projects a difficult problem. Technical Paper No. 24 describes the model and the system; T.P. 28 describes the system study; T.P. 31 describes rule curve development; and T.P. 33 describes integrated use of hydroelectric and thermal power.

An operating study using HEC-5 to simulate a tandem three-reservoir system with pump-back capability is described in Technical Paper No. 60. The program's system power routine was used to keep the system in balance while meeting downstream minimum flow constraints. The study was made to determine the effects pump-back operation might have on energy production and other project purposes. Simulation results for daily and hourly routings included reservoir areas, elevations and pool fluctuations, as well as energy production data.

Storage Allocation

The allocation of flood control storage in a multiple-purpose project is described in Technical Paper No. 34. The analysis was based on an economic analysis for all purposes in an attempt to derive the economically optimum flood control diagram. The univariate gradient technique (reference 25) in HEC-1 was the optimization procedure employed. The expected value of flood damages was weighed against the economic benefits from conservation storage to determine the "optimum" allocation.

Flood Control Operations

The application of a reservoir simulation model to real-time flood control operations requires streamflow forecasting, an operation model, and rapid analysis. The development of all three, using HEC-5 as the operation model, is described in T.P. 45. The application of the HEC-5 Flood Damage Calculations to evaluate alternative operation plans is also described. The expected value of annual damages provides a quantitative measure of the benefits from various forecasting and operational schemes.

There have been other studies, as varied as reservoir problems can be. Unfortunately, many of the studies were never described in a complete paper or report. These few examples, however, show the variety of possible applications of generalized simulation models.

REFERENCES

1. Eichert, Bill S., "Experience of HEC in Disseminating Information on Hydrologic Models," Technical Paper No. 49, The Hydrologic Engineering Center, Davis, CA, 1978.

2. National Weather Service, "National Weather Service River Forecast System Forecast Procedures," NOAA Technical Memo, NWS HYDRO-14, Silver Spring, MD, 1972.

3. Burnash, Robert J.C., R. Larry Farral, and Richard McGuire, "A Generalized Streamflow Simulation System," Joint Federal-State River Forecast Center, Sacramento, CA, 1973.

4. U.S. Army Engineer Division, North Pacific, "Program Description and User Manual for SSARR Model," Portland, OR, September 1972/June 1975.

5. Hydrocomp, Inc., "Hydrocomp Simulation Programming Operations Manual," Fourth edition, Palo Alto, CA, January 1976.

6. The Hydrologic Engineering Center, "Flood Hydrograph Package, HEC-1," U.S. Army Corps of Engineers, Davis, CA, 1973.

7. The Hydrologic Engineering Center, "HEC-3, Reservoir System Analysis for Conservation-Users Manual," U.S. Army Corps of Engineers, Davis, CA, July 1974.

8. The Hydrologic Engineering Center, "HEC-3 Reservoir System Analysis for Conservation-Programmers Manual," U.S. Army Corps of Engineers, Davis, CA, January 1976.

9. The Hydrologic Engineering Center, "HEC-5 Reservoir System Operation for Flood Control and Conservation-Users Manual," U.S. Army Corps of Engineers, Davis, CA, June 1979.

10. U.S. Army Engineer Division, North Pacific, "Hydropower System Regulating Analysis Computer Program (HYSYS)," Portland, OR, May 1971/July 1978.

11. U.S. Army Engineer Division, Southwestern, "Regulation Simulation and Analysis of Simulation for a Multi-Purpose Reservoir System," Programs I and II, Dallas, TX, March 1972.

12. The Hydrologic Engineering Center, "Flood Control by Reservoirs," IHD volume 7, U.S. Army Corps of Engineers, Davis, CA, February 1976.

13. The Hydrologic Engineering Center, "Reservoir Yield," IHD volume 8, U.S. Army Corps of Engineers, Davis, CA, January 1975.

14. The Hydrologic Engineering Center, "Reservoir System Analysis for Conservation," IHD volume 9, U.S. Army Corps of Engineers, Davis, CA, June 1977.

15. The Hydrologic Engineering Center, "Reservoir System Analysis," Training Course Manual, Davis, CA, February 1978.

16. The Hydrologic Engineering Center, "Hydrologic Aspects of Hydropower," Training Course Manual, Davis, CA, January 1979.

17. The Hydrologic Engineering Center, "Real-Time Control of Water Resource Projects," Training Course Manual, Davis, CA, January 1977.

18. The Hydrologic Engineering Center, "Publications," U.S. Army Corps of Engineers, Davis, CA, May 1979.

19. The Hydrologic Engineering Center,"Video Tape Catalog," U.S. Army Corps of Engineers, Davis, CA, September 1978.

20. Johnson, W. K., and D. W. Davis, "Training Document No. 7, Analysis of Structural and Nonstructural Flood Control Measures Using Computer Program HEC-5C," The Hydrologic Engineering Center, Davis, CA, November 1975.

21. The Hydrologic Engineering Center, "Proceedings of a Seminar on Reservoir Systems Analysis," U.S. Army Corps of Engineers, Davis, CA, November 1969.

22. The Hydrologic Engineering Center, "Proceedings of a Seminar on Real-Time Water Control Management," U.S. Army Corps of Engineers, Davis, CA, November 1975.

23. The Hydrologic Engineering Center, "Reservoir Yield," Users Manual, U.S. Army Corps of Engineers, Davis, CA, August 1966.

24. The Hydrologic Engineering Center, "HEC-4, Monthly Streamflow Simulation," Users Manual, U.S. Army Corps of Engineers, Davis, CA, February 1971.

25. Beard, Leo R., "Optimization Techniques for Hydrologic Engineering," Technical Paper No. 2, The Hydrologic Engineering Center, Davis, CA, April 1966.

TABLE 1

SYSTEMS SIMULATED BY HEC-3

	River Basin	Location	Reservoirs	Study Purpose
1.	Grand River	South Dakota	46 sites	Screening sites for low flow augmentation
2.	Willamette River	Oregon	14	Hydropower operation study
3.	Cache and Keetna Projects	Alaska	2	Hydropower potential
4.	San Dieguito River	California	4	Operation study
5.	Northeast Water Supply (Connecticut, Hudson, Delaware, Raritan, and Husatonic)	New England	35 plans	Screening sites for water yield
6.	Arkansas-White-Red Rivers	South-Central	23 (19 hydro)	System power analysis
7.	Delaware River	New York	7	Water yield
8.	Chakachatna River	Alaska	-	Hydropower potential
9.	Four River	Florida	15	Water supply and flood control planning
10.	Minnesota River	Minnesota	6	Flood control and low flow analyses
11.	Des Moines River	Iowa	2	Sizing storage
12.	Gila River	New Mexico	1 + water rights	Operation study water supply
13.	Red River of the North	North Dakota Minnesota	10	Planning flood control and conservation
14.	Kanawaha	West Virginia	18 sites	Screening study

TABLE 2

SYSTEMS SIMULATED BY HEC-5

River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Area (mi^2)
1. Trinity	Texas	15	28	24	18,000
2. Merrimack	New England	5	11	3	4,400
3. Susquehanna	Pennsylvania	34	75	4	24,000
4. Schuylkill	Pennsylvania	12	26	3	1,900
5. Potomac	Virginia Maryland Pennsylvania	26	39	2	12,000
6. Red River of the North	Minnesota	13	29	24 & 720	40,000
7. Feather	California	3	4	2	5,900
8. Pajaro	California	3	6	1 & 720	400
9. Grand (Neosho)	Oklahoma	24	86	2	5,900
10. James	Virginia	22	35	6	6,800
11. Red River	Texas Arkansas	14	28	6	12,000
12. Hudson	New York Pennsylvania	3	5	720	500

TABLE 2 (cont)

SYSTEMS SIMULATED BY HEC-5

	River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Area (mi^2)
13.	Morova	Yugoslavia	7	14	4	
14.	Little River	Oklahoma	4	9	6 & 720	4,100
15.	Marshall Fork	Texas	1	2	24	
16.	Catskill Aqueduct	Hudson River	2	5	720	
17.	Sacramento River	California	11	16	2	12,500
18.	Shasta-Red Bluff	California	2	5	2	
19.	Roaring Fork	Colorado	1	4	24	800
20.	San Joaquin	California	22	56	6	14,000
21.	Salt River Basin	Arizona	7	12	2 & 720	13,700
22.	Savannah Pumped Storage	Georgia	3	5	1 & 24	6,100
23.	White River Pumped Storage	Arkansas	3	4	1 & 24 & 720	11,000

TABLE 3

COMPARISONS OF HEC PROGRAMS
(HEC-1, 3, 5)

Item	HEC-1	HEC-3	HEC-5
1. Determines runoff from rainfall	Yes	No	No
2. Runoff input by incremental local flows	Yes	Yes	Yes
3. Runoff input by cumulative local flows	No	Yes	No
4. Allows period-of-record runs	No	Yes	Yes
5. Allows for individual and group reservoir operation for:			
a. Any configuration system	Yes	Yes	Yes
b. Flood Control			
(1) Routing by linear and nonlinear methods	Yes	No	Yes
(2) Operation for downstream flooding	No	No[1]	Yes
(3) By lagging of flows	No	Yes	Yes
c. Water Supply			
(1) For minimum flows at reservoir	Yes	Yes	Yes
(2) For minimum flows at downstream points	No	Yes	Yes
(3) Diversions	Yes	Yes	Yes
(4) Considers Evaporation	No	Yes	Yes
d. Hydropower (load and head)			
(1) Individual Reservoirs	No	Yes	Yes
(2) Reservoir Systems	No	Yes	Yes
e. Quality Evaluation in Reservoirs			
(1) Non-degradable	No	No[2]	No
(2) Degradable	No	No	No
f. Economic Evaluation			
(1) Flood Control	Yes	No[3]	Yes
(2) Conservation	No	Yes	Hydropower

[1] Observes flood control constraints for current period with no routing.

[2] Single reservoir conservation program has this ability.

[3] Available for special version (no routing).

TABLE 4

HEC COMPUTER PROGRAM DISTRIBUTION

Program	Program Size		Source Deck Distribution During FY 1978			Mail List Total 2/79
	No. of Statements	Core Storage (Words)	Corps*	Other Govt. Univ. and Foreign	Private	
HEC-1, Flood Hydrograph Package	3,800	62K	1	51	30	473
HEC-2, Water Surface Profiles	9,200	60K	3	78	62	529
HEC-3, Reservoir System Analysis for Conservation	3,700	60K	1	18	6	157
HEC-4, Monthly Streamflow Simulation	2,000	60K	0	20	7	170
HEC-5, Simulation of Flood Control and Conservation Systems	19,200	74K	1	26	9	119
HEC-6, Scour and Deposition in Rivers and Reservoirs	7,000	40K	2	26	7	125
Urban Runoff: Storage, Treatment, and Overflow (STORM)	5,800	50K	2	30	8	274
Flood Flow Frequency Analysis	1,600	15K	1	4	0	31
Gradually Varied Unsteady Flow Profiles	4,300	50K	7	13	8	52
Water Quality for River-Reservoir Systems	15,000	60K	1	18	6	84
All Others	--	--	37	63	51	229
Total			56	347	194	2,243

*Many Corps offices use HEC-maintained files on central computers.

TABLE 5

HEC TECHNICAL PAPER SERIES ON RESERVOIR SYSTEMS

Paper No.	
3	METHODS FOR DETERMINATION OF SAFE YIELD AND COMPENSATION WATER FROM STORAGE RESERVOIRS, Leo R. Beard (August 1965)
4	FUNCTIONAL EVALUATION OF A WATER RESOURCES SYSTEM, Leo R. Beard (January 1967)
7	PILOT STUDY FOR STORAGE REQUIREMENTS FOR LOW FLOW AUGMENTATION, A. J. Fredrich (April 1968)
9	ECONOMIC EVALUATION OF RESERVOIR SYSTEM ACCOMPLISHMENTS, Leo R. Beard (May 1968)
10	HYDROLOGIC SIMULATION IN WATER-YIELD ANALYSIS, Leo R. Beard (1964)
14	TECHNIQUES FOR EVALUATING LONG-TERM RESERVOIR YIELDS, A. J. Fredrich (February 1969)
16	A HYDROLOGIC WATER RESOURCE SYSTEM MODELING TECHNIQUE, L. G. Hulman (1969)
17	HYDROLOGIC ENGINEERING TECHNIQUES FOR REGIONAL WATER RESOURCE PLANNING, A. J. Fredrich and E. F. Hawkins (October 1969)
23	USES OF SIMULATION IN RIVER BASIN PLANNING, William K. Johnson and E. T. McGee (August 1970)
24	HYDROELECTRIC POWER ANALYSIS IN RESERVOIR SYSTEMS, A. J. Fredrich (August 1970)
25	STATUS OF WATER RESOURCE SYSTEMS ANALYSIS, Leo R. Beard (January 1971)
26	SYSTEM RELATIONSHIPS FOR PANAMA CANAL WATER SUPPLY, L. G. Hulman (April 1971)
27	SYSTEMS ANALYSIS OF THE PANAMA CANAL WATER SUPPLY, D. C. Lewis and L. R. Beard (April 1971)
28	DIGITAL SIMULATION OF AN EXISTING WATER RESOURCES SYSTEM, A. J. Fredrich (October 1971)
30	DROUGHT SEVERITY AND WATER SUPPLY DEPENDABILITY, L. R. Beard and H. E. Kubik (January 1972)

TABLE 5 (cont)

HEC TECHNICAL PAPER SERIES ON RESERVOIR SYSTEMS

Paper No.	
31	DEVELOPMENT OF SYSTEM OPERATION RULES FOR AN EXISTING SYSTEM BY SIMULATION, C. Pat Davis and A. J. Fredrich (October 1971)
32	ALTERNATIVE APPROACHES TO WATER RESOURCE SYSTEM SIMULATION, L. R. Beard, Arden Weiss, and T. Al Austin (May 1972)
33	SYSTEM SIMULATION FOR INTEGRATED USE OF HYDROELECTRIC AND THERMAL POWER GENERATION, A. J. Fredrich and L. R. Beard (October 1972)
34	OPTIMIZING FLOOD CONTROL ALLOCATION FOR A MULTIPURPOSE RESERVOIR, Fred K. Duren and L. R. Beard (August 1972)
41	HEC-5C, A SIMULATION MODEL FOR SYSTEM FORMULATION AND EVALUATION, Bill S. Eichert (March 1974)
42	OPTIMAL SIZING OF URBAN FLOOD CONTROL SYSTEMS, Darryl W. Davis (March 1974)
43	HYDROLOGIC AND ECONOMIC SIMULATION OF FLOOD CONTROL ASPECTS OF WATER RESOURCES SYSTEMS, Bill S. Eichert (August 1975)
44	SIZING FLOOD CONTROL RESERVOIR SYSTEMS BY SYSTEMS ANALYSIS, B. S. Eichert and D. W. Davis (March 1967)
45	TECHNIQUES FOR REAL-TIME OPERATION OF FLOOD CONTROL RESERVOIRS IN THE MERRIMAC RIVER BASIN, B. S. Eichert, J. C. Peters, and A. F. Pabst (November 1975)
60	OPERATIONAL SIMULATION OF A RESERVOIR SYSTEM WITH PUMPED STORAGE, G. F. McMahon, V. R. Bonner, and B. S. Eichert (February 1979)

FIGURE 1

HEC-1 FLOOD HYDROGRAPH PACKAGE

1. Rainfall-Runoff Model using unit hydrographs or kinematic wave for short-time interval floods.

2. Basin average rainfall from recorders and nonrecorders or given basin average precipitation.

3. Rainfall and snowmelt excess from either simple or complex loss function.

4. Snow accumulation and snowmelt computations for a number of elevation zones within each subbasin.

5. Optimization features for deriving unit hydrograph and loss rate coefficients or stream-routing criteria.

6. Subbasin hydrographs are computed, combined and routed throughout any complex basins which may include reservoirs with simple storage-outflow relationships.

7. Hydrographs are from input historical or design rainfall or based on depth-area-duration data for synthetic floods.

8. Computation of multiflood, multiplan schemes to compute average annual damages of various types at specified damage centers for each plan of development.

9. Determination of effect of tributary reservoir project on floods at downstream locations, without using numerous storm centerings, through stream-system computation.

10. Optimization of components of a flood control system based on minimum cost from flood damages and component costs.

FIGURE 2

HEC-3 RESERVOIR SYSTEM ANALYSIS FOR CONSERVATION

1. Monthly or weekly period Reservoir System (any configuration) Operation simulation assuming no routing (flows are available instantaneously throughout basin).

2. Individual and groups of reservoirs operating for desired targets of water quantity at selected downstream control points based on balancing storages in reservoirs.

3. Groups of reservoirs operating for system power requirements in up to three different power systems.

4. Flood control constraints are observed on monthly or weekly basis.

5. Optimization routines for determining maximum firm yield at a specified downstream control point from specified storages in upstream reservoir or system of reservoirs.

6. Diversions for irrigation or other purposes are allowed at any reservoir or downstream location to any other downstream point in the system or out of the system.

7. Relates hydrologic or physical variables (flow, reservoir storage, hydropower) to economic returns through the use of benefit functions.

FIGURE 3

HEC-5 SIMULATION OF FLOOD CONTROL AND CONSERVATION SYSTEMS

1. Short-interval (and monthly) period multipurpose Reservoir System (any configuration) Operation simulator using linear or nonlinear channel routing. Also continuous period-of-record analyses possible.

2. Individual and system reservoirs operate to minimize flooding or provide low flow at prescribed downstream points and to evacuate flood storage as rapidly as possible.

3. Hydropower reservoirs operate for project requirements and/or for allocated system energy requirements. Pump-storage operation is also available.

4. Optimization routines can size conservation storage or determine conservation yield (including hydropower).

5. When there is a choice, selection of reservoirs to release from is based on balancing reservoir storages using desired target levels.

6. Diversions (based on given schedules, channel flows or reservoir storages) may be made at any location and a portion may be routed and returned at any downstream location.

7. Regulated and unregulated flow hydrographs are computed along with flooding by reservoirs and total releases from upstream reservoirs.

8. Multiple flood or multiple ratios of a given flood may be computed at the same time.

9. Extended duration floods, requiring more core storage than available for single flood, are operated automatically as a series of floods using the multiple flood option with an overlap between floods to maintain continuity.

10. Average annual damages and net system benefits can be calculated for a series of alternative systems until best system is found (process requires user to select each alternative system).

Technical Paper Series

TP-1 Use of Interrelated Records to Simulate Streamflow
TP-2 Optimization Techniques for Hydrologic Engineering
TP-3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4 Functional Evaluation of a Water Resources System
TP-5 Streamflow Synthesis for Ungaged Rivers
TP-6 Simulation of Daily Streamflow
TP-7 Pilot Study for Storage Requirements for Low Flow Augmentation
TP-8 Worth of Streamflow Data for Project Design - A Pilot Study
TP-9 Economic Evaluation of Reservoir System Accomplishments
TP-10 Hydrologic Simulation in Water-Yield Analysis
TP-11 Survey of Programs for Water Surface Profiles
TP-12 Hypothetical Flood Computation for a Stream System
TP-13 Maximum Utilization of Scarce Data in Hydrologic Design
TP-14 Techniques for Evaluating Long-Tem Reservoir Yields
TP-15 Hydrostatistics - Principles of Application
TP-16 A Hydrologic Water Resource System Modeling Techniques
TP-17 Hydrologic Engineering Techniques for Regional Water Resources Planning
TP-18 Estimating Monthly Streamflows Within a Region
TP-19 Suspended Sediment Discharge in Streams
TP-20 Computer Determination of Flow Through Bridges
TP-21 An Approach to Reservoir Temperature Analysis
TP-22 A Finite Difference Methods of Analyzing Liquid Flow in Variably Saturated Porous Media
TP-23 Uses of Simulation in River Basin Planning
TP-24 Hydroelectric Power Analysis in Reservoir Systems
TP-25 Status of Water Resource System Analysis
TP-26 System Relationships for Panama Canal Water Supply
TP-27 System Analysis of the Panama Canal Water Supply
TP-28 Digital Simulation of an Existing Water Resources System
TP-29 Computer Application in Continuing Education
TP-30 Drought Severity and Water Supply Dependability
TP-31 Development of System Operation Rules for an Existing System by Simulation
TP-32 Alternative Approaches to Water Resources System Simulation
TP-33 System Simulation of Integrated Use of Hydroelectric and Thermal Power Generation
TP-34 Optimizing flood Control Allocation for a Multipurpose Reservoir
TP-35 Computer Models for Rainfall-Runoff and River Hydraulic Analysis
TP-36 Evaluation of Drought Effects at Lake Atitlan
TP-37 Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes
TP-38 Water Quality Evaluation of Aquatic Systems
TP-39 A Method for Analyzing Effects of Dam Failures in Design Studies
TP-40 Storm Drainage and Urban Region Flood Control Planning
TP-41 HEC-5C, A Simulation Model for System Formulation and Evaluation
TP-42 Optimal Sizing of Urban Flood Control Systems
TP-43 Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-44 Sizing Flood Control Reservoir Systems by System Analysis
TP-45 Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-46 Spatial Data Analysis of Nonstructural Measures
TP-47 Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-48 Direct Runoff Hydrograph Parameters Versus Urbanization
TP-49 Experience of HEC in Disseminating Information on Hydrological Models
TP-50 Effects of Dam Removal: An Approach to Sedimentation
TP-51 Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-52 Potential Use of Digital Computer Ground Water Models
TP-53 Development of Generalized Free Surface Flow Models Using Finite Element Techniques
TP-54 Adjustment of Peak Discharge Rates for Urbanization
TP-55 The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-56 Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-57 Flood Damage Assessments Using Spatial Data Management Techniques
TP-58 A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-59 Testing of Several Runoff Models on an Urban Watershed
TP-60 Operational Simulation of a Reservoir System with Pumped Storage
TP-61 Technical Factors in Small Hydropower Planning
TP-62 Flood Hydrograph and Peak Flow Frequency Analysis
TP-63 HEC Contribution to Reservoir System Operation
TP-64 Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study
TP-65 Feasibility Analysis in Small Hydropower Planning
TP-66 Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-67 Hydrologic Land Use Classification Using LANDSAT
TP-68 Interactive Nonstructural Flood-Control Planning
TP-69 Critical Water Surface by Minimum Specific Energy Using the Parabolic Method

TP-70 Corps of Engineers Experience with Automatic Calibration of a Precipitation-Runoff Model
TP-71 Determination of Land Use from Satellite Imagery for Input to Hydrologic Models
TP-72 Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality
TP-73 Flood Mitigation Planning Using HEC-SAM
TP-74 Hydrographs by Single Linear Reservoir Model
TP-75 HEC Activities in Reservoir Analysis
TP-76 Institutional Support of Water Resource Models
TP-77 Investigation of Soil Conservation Service Urban Hydrology Techniques
TP-78 Potential for Increasing the Output of Existing Hydroelectric Plants
TP-79 Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U.S. Hydropower Reservoirs
TP-80 Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects
TP-81 Data Management Systems of Water Resources Planning
TP-82 The New HEC-1 Flood Hydrograph Package
TP-83 River and Reservoir Systems Water Quality Modeling Capability
TP-84 Generalized Real-Time Flood Control System Model
TP-85 Operation Policy Analysis: Sam Rayburn Reservoir
TP-86 Training the Practitioner: The Hydrologic Engineering Center Program
TP-87 Documentation Needs for Water Resources Models
TP-88 Reservoir System Regulation for Water Quality Control
TP-89 A Software System to Aid in Making Real-Time Water Control Decisions
TP-90 Calibration, Verification and Application of a Two-Dimensional Flow Model
TP-91 HEC Software Development and Support
TP-92 Hydrologic Engineering Center Planning Models
TP-93 Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program
TP-94 Dredged-Material Disposal Management Model
TP-95 Infiltration and Soil Moisture Redistribution in HEC-1
TP-96 The Hydrologic Engineering Center Experience in Nonstructural Planning
TP-97 Prediction of the Effects of a Flood Control Project on a Meandering Stream
TP-98 Evolution in Computer Programs Causes Evolution in Training Needs: The Hydrologic Engineering Center Experience
TP-99 Reservoir System Analysis for Water Quality
TP-100 Probable Maximum Flood Estimation - Eastern United States
TP-101 Use of Computer Program HEC-5 for Water Supply Analysis
TP-102 Role of Calibration in the Application of HEC-6
TP-103 Engineering and Economic Considerations in Formulating
TP-104 Modeling Water Resources Systems for Water Quality
TP-105 Use of a Two-Dimensional Flow Model to Quantify Aquatic Habitat
TP-106 Flood-Runoff Forecasting with HEC-1F
TP-107 Dredged-Material Disposal System Capacity Expansion
TP-108 Role of Small Computers in Two-Dimensional Flow Modeling
TP-109 One-Dimensional Model for Mud Flows
TP-110 Subdivision Froude Number
TP-111 HEC-5Q: System Water Quality Modeling
TP-112 New Developments in HEC Programs for Flood Control
TP-113 Modeling and Managing Water Resource Systems for Water Quality
TP-114 Accuracy of Computer Water Surface Profiles - Executive Summary
TP-115 Application of Spatial-Data Management Techniques in Corps Planning
TP-116 The HEC's Activities in Watershed Modeling
TP-117 HEC-1 and HEC-2 Applications on the Microcomputer
TP-118 Real-Time Snow Simulation Model for the Monongahela River Basin
TP-119 Multi-Purpose, Multi-Reservoir Simulation on a PC
TP-120 Technology Transfer of Corps' Hydrologic Models
TP-121 Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin
TP-122 The Estimation of Rainfall for Flood Forecasting Using Radar and Rain Gage Data
TP-123 Developing and Managing a Comprehensive Reservoir Analysis Model
TP-124 Review of U.S. Army corps of Engineering Involvement With Alluvial Fan Flooding Problems
TP-125 An Integrated Software Package for Flood Damage Analysis
TP-126 The Value and Depreciation of Existing Facilities: The Case of Reservoirs
TP-127 Floodplain-Management Plan Enumeration
TP-128 Two-Dimensional Floodplain Modeling
TP-129 Status and New Capabilities of Computer Program HEC-6: "Scour and Deposition in Rivers and Reservoirs"
TP-130 Estimating Sediment Delivery and Yield on Alluvial Fans
TP-131 Hydrologic Aspects of Flood Warning - Preparedness Programs
TP-132 Twenty-five Years of Developing, Distributing, and Supporting Hydrologic Engineering Computer Programs
TP-133 Predicting Deposition Patterns in Small Basins
TP-134 Annual Extreme Lake Elevations by Total Probability Theorem
TP-135 A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks
TP-136 Prescriptive Reservoir System Analysis Model - Missouri River System Application
TP-137 A Generalized Simulation Model for Reservoir System Analysis
TP-138 The HEC NexGen Software Development Project
TP-139 Issues for Applications Developers
TP-140 HEC-2 Water Surface Profiles Program
TP-141 HEC Models for Urban Hydrologic Analysis

TP-142 Systems Analysis Applications at the Hydrologic Engineering Center
TP-143 Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds
TP-144 Review of GIS Applications in Hydrologic Modeling
TP-145 Application of Rainfall-Runoff Simulation for Flood Forecasting
TP-146 Application of the HEC Prescriptive Reservoir Model in the Columbia River Systems
TP-147 HEC River Analysis System (HEC-RAS)
TP-148 HEC-6: Reservoir Sediment Control Applications
TP-149 The Hydrologic Modeling System (HEC-HMS): Design and Development Issues
TP-150 The HEC Hydrologic Modeling System
TP-151 Bridge Hydraulic Analysis with HEC-RAS
TP-152 Use of Land Surface Erosion Techniques with Stream Channel Sediment Models
TP-153 Risk-Based Analysis for Corps Flood Project Studies - A Status Report
TP-154 Modeling Water-Resource Systems for Water Quality Management
TP-155 Runoff simulation Using Radar Rainfall Data
TP-156 Status of HEC Next Generation Software Development
TP-157 Unsteady Flow Model for Forecasting Missouri and Mississippi Rivers
TP-158 Corps Water Management System (CWMS)
TP-159 Some History and Hydrology of the Panama Canal
TP-160 Application of Risk-Based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems
TP-161 Corps Water Management System - Capabilities and Implementation Status