US Army Corps of Engineers
Hydrologic Engineering Center

HEC Activities in Reservoir Analysis

June 1980

TP-75

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 1980	Technical Paper	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
HEC Activities in Reservoir Analysis	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Vernon R. Bonner	
	5e. TASK NUMBER
	5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687	TP-75

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
Presented at the Symposium on Surface-Water Impoundments, Minneapolis, Minnesota, 2 June 1980.

14. ABSTRACT
Over the last fifteen years, the Hydrologic Engineering Center (HEC) has been developing, applying, and distributing computer programs dealing with various aspects of hydrologic engineering, including reservoir analysis. The Center has developed several models for the simulation of reservoir operation and has supported the development of a water quality model for reservoirs and rivers. This paper presents review of model development and an overview of the capabilities and type of applications for the most recent computer programs, "Simulation of Flood Control and Conservation Systems" (HEC-5) and "Water Quality for river-Reservoir Systems" (WQRRS). Also, current research and development dealing with reservoir analysis are described.

15. SUBJECT TERMS
reservoirs, mathematical models, reservoir operation, water quality, water resources

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

HEC Activities in Reservoir Analysis

June 1980

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-5

HEC ACTIVITIES IN RESERVOIR ANALYSIS[1]

by

Vernon R. Bonner[2]

INTRODUCTION

Over the last 15 years, The Hydrologic Engineering Center (HEC) has been developing, applying, and distributing computer programs dealing with various aspects of hydrologic engineering, including reservoir analysis. The Center has developed several models for the simulation of reservoir operation and has supported the development of a water quality model for reservoirs and rivers. This paper presents a review of model development and an overview of the capabilities and types of applications for the most recent computer programs, "Simulation of Flood Control and Conservation Systems" (HEC-5) and "Water Quality for River-Reservoir Systems" (WQRRS). Also, current research and development dealing with reservoir analysis are described.

PROGRAM DEVELOPMENT

The Hydrologic Engineering Center has been involved with the development, distribution and support of computer programs since its inception in 1964. Early programs were small, single-purpose routines like Gate Regulation Curve (1), Spillway Rating and Flood Routing (2), and Reservoir Yield (3). All three programs were released in 1966.

During the mid-sixties, the computer program, "Reservoir System Analysis for Conservation" (HEC-3) (4) was developed by Leo R. Beard. Program capabilities were expanded and by 1974, the fourth generation model was released with a full range of capabilities to simulate a reservoir system for typical conservation objectives of minimum flows, diversions and hydropower generation. During the early seventies, the HEC-3 program was applied to a number of reservoir studies at the Center. (5,6,7). The program is still actively used and at last count, 200 source decks had been distributed.

Although the HEC-3 program was adequate for conservation studies, there was a need for flood control simulation within the Corps. During the early seventies, Bill S. Eichert developed a model for flood control simulation which was released in 1973 as HEC-5, "Reservoir System

[1] Presented at the Symposium on Surface-Water Impoundments; June 2, 1980, Minneapolis, Minnesota.

[2] Hydraulic Engineer, U. S. Army Corps of Engineers, The Hydrologic Engineering Center, 609 Second Street, Davis, California 95616.

Operation for Flood Control." (8) After its release, Mr. Eichert continued to develop the model, adding conservation capabilities that were available within HEC-3. By 1975, a new version labeled HEC-5C was released with both flood control and conservation simulation capabilities. The HEC-5C label was carried by the program until a new release was made in June 1979. Now, HEC-5, "Simulation of Flood Control and Conservation Systems," (9) is our primary reservoir simulation program. Since its June release, 59 copies of the new program have been distributed. Prior to that date, there were 124 copies of earlier versions released.

Program development in the water quality area centered on reservoir temperature models during the sixties. In 1969, the Center released a monthly reservoir temperature stratification model (10) that simulates temperature variations between horizontal strata within a reservoir. During the early seventies, the need for more comprehensive quality analysis led to the development and application of several mathematical computer models. (11) The Center has adopted the ecological model of Drs. Chen and Orlob and has supported the expansion of that model with a river ecological model, developed by Mr. William Norton. Other modifications were made, and in 1974 the Center released the program, "Water Quality for River-Reservoir Systems." (WQRRS) (12) The model was capable of analyzing 18 different physical, chemical and biological water quality parameters.

In 1975, the streamflow routing capability was added to WQRRS, and in 1976 the capability to analyze branched and loop stream systems was added. The current model was created in 1978 when the preprocessors were integrated into the individual modules of the program. Today the program is distributed as three separate but integrable modules: the reservoir module, the stream hydraulics module, and the stream quality module. The stream quality module has no hydraulic computation capability and requires the hydraulic data file generated by the hydraulics module.

PROGRAM CAPABILITIES AND APPLICATIONS

The early studies with HEC-5 were generally flood control planning studies. The program flood control operation is based on maintaining nondamaging discharges at designated downstream locations while observing constraints on outlet capacity, rate of change on releases, and limits on the future foresight of inflow and inflow accuracy. Economic routines provide flood damage estimates for individual floods or expected annual damages based on multiple flood analysis. The expected value of damages is used as a basis for evaluating alternative flood control plans. (13,14,15)

More recently, the conservation capabilities of HEC-5 are being applied to reservoir yield determination problems. The program can simulate reservoir operations for minimum flow requirements, diversions, and hydropower. Hydropower operation can be for individual sites or system power requirements, and pump storage operation can also be simulated. Table 1 lists the systems simulated with HEC-5 in which the Center has had a major role.

TABLE 1

SYSTEMS SIMULATED BY HEC-5

River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)
Trinity	Texas	15	28	24
Merrimack	New England	5	11	3
Susquehanna	Pennsylvania	34	75	4
Schuylkill	Pennsylvania	12	26	3
Potomac	VA,MD,PA	26	39	2
Red River-North	Minnesota	13	29	24 & 720
Feather	California	3	4	2
Pajaro	California	3	6	1 & 720
Grand (Neosho)	Oklahoma	24	86	2
James	Virginia	22	35	6
Red River	Texas,Arkansas	14	28	6
Hudson	N.Y.,PA	3	5	720
Morova	Yugoslavia	7	14	4
Little River	Oklahoma	4	9	6 & 720
Marshall Fork	Texas	1	2	24
Catskill Aqueduct	Hudson River	2	5	720
Sacramento River	California	11	16	2
Shasta-Red Bluff	California	2	5	2
Roaring Fork	Colorado	1	4	24
San Joaquin	California	22	56	6
Salt River Basin	Arizona	7	12	2 & 720
Savannah Pumped Storage	Georgia	3	5	1 & 24
White River Pumped Storage	Arkansas	3	4	1 & 24 & 720

A recent operation study (16) analyzed the impact of pump-back operation on hydropower production and recreation usability of a reservoir system on the Savannah River. The total energy requirements were specified for the three tandem reservoir system and the program allocated the energy requirements to the individual projects based on balancing the reservoir storage levels. The system allocation routine also accounts for the pump-back water and the downstream minimum flow requirements.

The need for a water quality evaluation of existing and proposed project conditions on the Trinity River in Texas required the analysis of both reservoir and stream channel conditions. These requirements led to linking of the water quality models described earlier. Existing and project conditions have also been simulated for or by other Corps offices at the proposed Tocks Island Lake, Lake Koocanusa (Libby Dam), and Lincoln Lake using variations of the Chen-Orlob model. (11)

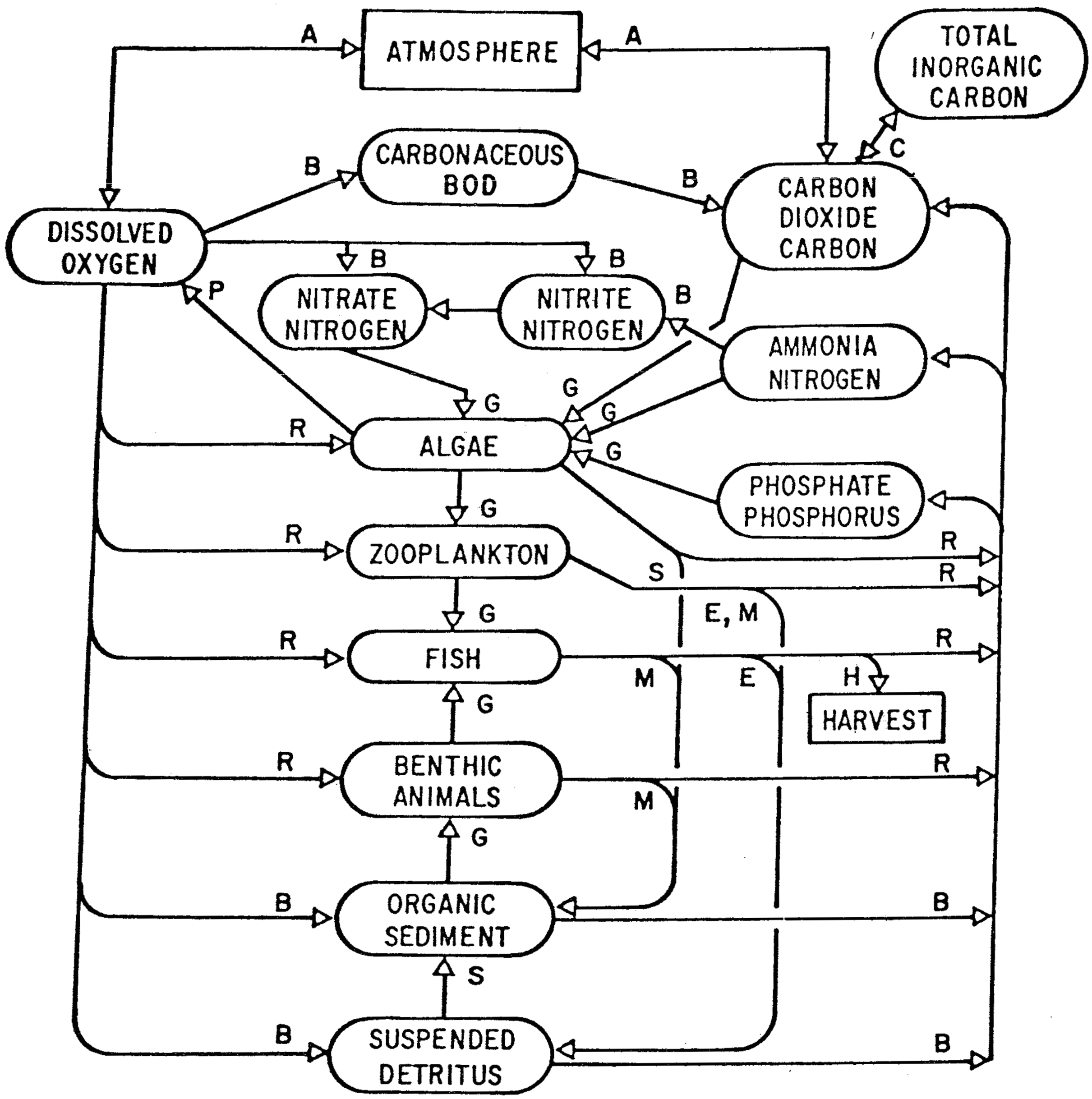
The WQRRS model reflects an attempt by HEC to provide a generalized river-reservoir water quality model which is continuously updated and maintained with the best available concepts. The reservoir module of the program is applicable to aerobic impoundments that can be represented as one-dimensional systems having horizontal isotherms. This approximation is generally satisfactory in medium to moderately large lakes or reservoirs with long residence times. The approximation may be less satisfactory in shallow impoundments or those having a rapid flow-through time. Systems that have a rapid flow-through time are often fully mixed and can be treated as slowly moving streams using the stream quality module. The reservoir model is designed to provide a detailed portrayal of the important processes that determine the thermal and water quality characteristics of lakes and reservoirs. The interdependence of constituents is shown in Figure 1.

The stream hydraulic module provides six hydraulic computation options. They are 1) steady gradually varied flow (backwater), 2) solution to the full St. Venant equations, 3) stage-flow relationship, 4) kinematic wave, 5) Muskingum, and 6) modified Puls.

In the stream quality module, the rate of transport of quality parameters can be represented for aerobic streams. Peak pollutant loads can be routed through steady or unsteady flow conditions using the routing from the stream hydraulic module. If a steady state stream water quality analysis is desired, it can be simulated by holding inputs constant for a few computation periods. Field verification of the river water quality module is currently underway for the Allegheny River.

CURRENT ACTIVITIES

Current reservoir system activities are in three functional areas: hydropower, real-time flood operations, and water quality analysis. The hydropower activity is supported by Corps Research and Development funds as well as by the Department of Energy and the Corps National Hydropower Study.



A Aeration
B Bacterial Decay
C Chemical Equilibrium
E Excreta
G Growth
M Mortality
P Photosynthesis
R Respiration
S Settling
H Harvest

Figure 1. QUALITY AND ECOLOGIC RELATIONSHIPS

An extensive data file system has been developed by the Center for use in the inventory of some 7,000 dams as a part of the National Hydroelectric Power Study. Computer software has also been written to develop HEC-5 input data automatically from the file system. With the developed software, a global request or specific site request can be made to automatically generate HEC-5 input and operate the model to determine dependable capacity, firm annual energy and average annual energy for any storage project in the files. The results are automatically returned to the files and used for economic analysis.

The HEC-5 program is also being used to determine the potential gains from reallocation of flood control storage. Using the program's yield optimization feature, the potential gain in firm and average annual energy is being determined for all existing power projects with significant flood control storage. The program's flood damage routines will provide estimates of the potential cost from loss of flood control storage.

The real-time operation work has focused on flood flow forecasts, improved linkage between forecast model and operation model, and improved interaction between the operation model and the program user. The concept of linking a forecast model with HEC-5 and providing convenient interactive output displays of operation results was demonstrated in 1975 for the Merrimack River Basin. (17) Subsequent software development has provided a new interactive output display package that provides both graphical and tabular displays of simulation results. Included in the package is the capability to create and store menus that can be utilized for input/output requests to the program and an automatic procedure to graphically input hydrographs to the model. The input hydrographs can be forecasted inflows or proposed reservoir release schedules. With the new output routines, it is possible to quickly simulate and display the program's flood operation. The operator can display results, make decisions, and reoperate the model with the new input (e.g., release schedule). The package was demonstrated at the National Workshop on Reservoir System Operations at Boulder, Colorado in August 1979. (18)

Through the Los Angeles District of the Corps of Engineers, the Salt River Project (SRP) of Phoenix, Arizona, heard about the new capabilities and requested assistance in applying the operation model to their system. Earlier planning studies had been performed using HEC-5; therefore, it was easy to develop the data files for a "real-time" operation. In mid-December 1979, a three-day training/work session was provided at the Center to demonstrate how the Salt River System could be modeled and analyzed. The Project staff made arrangements with the National Weather Service to obtain the necessary inflow forecasts. They also contracted with the computer service company where the software was developed so there would be no difficulty in transferring the data files and programs. By January they were operational and began testing the software.

The January-February flood season was a major test for project operations and the computer programs. Mr. Thomas Sands, Senior Engineer with SRP, feels the program has become an important tool during times of critical reservoir operations. As reported in the March 20, 1980 edition of PULSE,* a record 35 computer simulations were made during the storms of February 13 and 22, 1980. The simulations were made not only to assist in reservoir release decisions, but also to provide downstream flow predictions for the bridges in Phoenix. SRP reports the program has extended their ability to analyze the effects of potential storms.

The water quality calculations are being incorporated into the reservoir simulation model HEC-5. The objective is to provide a computer program and methodology for total water management capability for complex systems of reservoirs. The model will evaluate flood control, hydropower, water quality and other project purposes and determine the "best" system regulation to meet all downstream water needs. The resultant model will also provide the first step toward a long-term water quality regulation for large multiple-purpose reservoir systems.

The first phase, completed last year, linked water temperature algorithms to HEC-5. The model, called HEC-5Q, was applied to a single reservoir operation. The second phase is now expanding the model to simulate additional water quality parameters and operate with two parallel reservoirs and two tandem reservoirs. The contract also requires solving a test case and providing appropriate documentation. Next year, the third phase will provide the capability of simulating a comprehensive reservoir system. Example operations and appropriate documentation will also be required. If it appears feasible, the model will be modified to include real-time regulation capability.

CONCLUSIONS

The need for comprehensive models to analyze reservoir-river systems is evident. The program capabilities, wide distribution, and support of HEC-5 and WQRRS make them attractive tools for the analysis of reservoir systems. Past applications of the models to a variety of problems show their worth for planning studies. With the current model development, they may also be useful tools for application to operation problems on a "real-time" basis.

*PULSE is a weekly public affairs newsletter published by the Salt River Project.

REFERENCES

1. The Hydrologic Engineering Center, "Gate Regulation Curve," Computer Program Documentation, February 1966.

2. The Hydrologic Engineering Center, "Spillway Rating and Flood Routing," Computer Program Documentation, October 1966.

3. The Hydrologic Engineering Center, "Reservoir Yield," Computer Program Documentation, August 1966.

4. The Hydrologic Engineering Center, "HEC-3 Reservoir System Analysis for Conservation," Users Manual, July 1974.

5. Davis, C. Pat and Fredrich, A.J., "Development of System Operation Rules for an Existing System by Simulation," The Hydrologic Engineering Center Technical Paper No. 31, August 1971.

6. Beard, L.R., Weis, Arden, and Austin, T.A., "Alternative Approaches to Water Resource System Simulation," The Hydrologic Engineering Center Technical Paper No. 32, May 1972.

7. Fredrich, A.J., and Beard, Leo R., "System Simulation for Integrated Use of Hydroelectric and Thermal Power Generation," The Hydrologic Engineering Center Technical Paper No. 33, October 1972.

8. The Hydrologic Engineering Center, "HEC-5 Reservoir System Operation for Flood Control," Users Manual (out of print), May 1973.

9. The Hydrologic Engineering Center, "HEC-5 Simulation of Flood Control and Conservation Systems," Users Manual, June 1979.

10. The Hydrologic Engineering Center, "Reservoir Temperature Stratification," Users Manual, January 1972.

11. Willey, R.G., "Water Quality Evaluation of Aquatic Systems," The Hydrologic Engineering Center Technical Paper No. 38, April 1975.

12. The Hydrologic Engineering Center, "Water Quality for River-Reservoir Systems," Draft Users Manual, October 1978.

13. Eichert, Bill S., "HEC-5C, A Simulation Model for System Formulation and Evaluation," The Hydrologic Engineering Center Technical Paper No. 41, March 1974.

14. Eichert, B.S., "Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems," The Hydrologic Engineering Center Technical Paper No. 43, August 1975.

15. Eichert, B.S., and Davis, D.W., "Sizing Flood Control Reservoir Systems by Systems Analysis," The Hydrologic Engineering Center Technical Paper No. 44, March 1976.

REFERENCES (cont)

16. McMahon, G.F., Bonner, V.R., and Eichert, B.S., "Operational Simulation of a Reservoir System with Pumped Storage," ASCE Journal of the Water Resources Planning and Management Division, Vol. 106, No. WR1, March 1980.

17. Eichert, B.S., Peters, J.C., and Pabst, A.F., "Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin," The Hydrologic Engineering Center Technical Paper No. 45, November 1975.

18. Eichert, B.S., and Bonner, V.R., "HEC Contribution to Reservoir System Operation," The Hydrologic Engineering Center Technical Paper No. 63, August 1979.

Technical Paper Series

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