US Army Corps
of Engineers
Hydrologic Engineering Center

Optimization Techniques for Hydrologic Engineering

April 1966

TP-2

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* April 1966	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Optimization Techniques for Hydrologic Engineering	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Leo R. Beard	**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-2
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 47th Annual Meeting of the American Geophysical Union, Washington, DC, 22 April 1966

14. ABSTRACT
Optimization processes show considerable promise for a reasonable solution of the increasingly complex design and operation problems that occur in water resources engineering. Gradient methods of optimization should appeal to the engineer because the methods can be used within the framework of traditional engineering analyses (e.g., multipurpose sequential routing or system simulation), where the components of the system can be changed in successive trials to obtain the best combination most rapidly. They can most easily be adapted to practical complex problems and appear to require minimum programming and computation time. Because of the large amount of computation involved, optimization procedures almost always require the use of high-speed digital computers.

15. SUBJECT TERMS
Optimization, system analysis, digital computers, hydrologic aspects, water resources, water utilization, planning, engineering, model studies, computer models

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	28	**19b. TELEPHONE NUMBER**

Optimization Techniques for Hydrologic Engineering

April 1966

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-2

Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution with the Corps of Engineers.

11 April 1966

OPTIMIZATION TECHNIQUES FOR HYDROLOGIC ENGINEERING(1)

by

Leo R. Beard(2)

INTRODUCTION

Because of the increasing complexity of water resource planning, design and operation studies, there is increasing need for a mathematical procedure that will select the optimum sizes and characteristics of components to produce a desired result. For example, there is need for a practical computational procedure to select the optimum sizes and combination of units and operation plans of a contemplated water resource system, so that some criterion such as benefit-cost ratio will be optimum. There are many other problems in hydrologic engineering where optimization procedures can be effectively applied, such as determination of storage and minimum pool requirements to provide specified services, determination of unit hydrograph coefficients, loss coefficients, routing coefficients, etc., that best explain observed phenomena. A variety of available optimization techniques is briefly discussed, and detailed description of a highly flexible and easily adaptable procedure is given herein.

(1) For presentation at the 47th Annual Meeting of the American Geophysical Union, Washington, D.C., 22 April 1966.

(2) Chief, Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Sacramento, California.

APPLICABILITY OF OPTIMIZATION PROCEDURES

In water resources design problems, it has become increasingly important to examine a range of project sizes and combinations of projects and project components in order to select the "best" design for a river development. In considering a single reservoir for a single purpose, this can be done with relative ease. When more than one purpose is served, division of project capabilities among the services need be studied, as well as project size. If this is accompanied by seasonal variations in the division and by complex conditions such as might depend on runoff forecasts, then the problem rapidly surpasses present capability to determine a complete solution. The problem is usually resolved by stipulating fixed requirements for most services and allowing only one service requirement to vary. When, in addition to a multiplicity of purposes, there is also a multiplicity of projects (reservoirs, diversions, power plant, etc.) that combine to serve the same purposes, then the practical determination of a best plan of development is clearly beyond present technical capability.

Considerable effort has been devoted during recent years to adapting mathematical optimization procedures to the solution of these complex water resources design problems. (References 4, 5 and 7 illustrate some of this work.) This has resulted in some ingenious schemes for solving simplified versions of such problems and has pointed up the fact that tremendous amounts of computation are required, probably overtaxing the capabilities of modern computers in the case of complex river development proposals. The net result in that mathematical optimization procedures promise to be highly useful in major water resources problems for the near future, but only in conjunction with the practical judgment of experienced planning engineers. Through several trials of system design, a few combinations can be selected that are considered most feasible, and the optimization procedures can be used for determination of the absolute optimum in each case. The difference in approximate solutions by judgment and accurate solutions by computer optimization may result in millions of dollars of benefit and is therefore quite significant.

In many other water resources problems, optimization procedures can provide rapid and inexpensive solutions to extremely complex problems. In all cases, work must be accomplished by electronic digital computer because of the amount of computation involved.

BASIC OPTIMIZATION APPROACHES

Although the writer knows of no case where an actual water resource system design has been based on mathematical optimization procedures, there is considerable development activity and some literature on basic optimization procedures and their potential application to water resources problems. These procedures fall into three basic groups: linear programming and some non-linear adaptations thereof, dynamic programming, and gradient methods of successive trial solutions. The first two groups provide direct solutions, but require great ingenuity for application to even moderately complex problems.

No applications of linear programming to water resources design appear in literature, and it is doubtful that the technique, by itself, will have practical application to water resource problems, because of their extreme complexity in relation to the simplicity of the linear programming model. For this reason, the procedure is not discussed further herein, but can be examined in reference 8 and other texts.

Several applications of dynamic programming to water resources problems do appear in literature, and these all concern simplified versions of comprehensive design problems. Since a direct solution is intuitively more desirable than a solution by approximation, this approach (described in references 1 and 2) has an advantage over the gradient method described in detail herein, even though experience to date indicates that water resources problems of any reasonable complexity are not solvable by this means alone. Furthermore, dynamic programming (multistage decision) concepts are naturally adaptable for use in combination with other optimization procedures. Indeed, they have been used by planners for years. A storage-cost curve of a reservoir site, for example, is a function which states that a decision involving cost can be made with no further reference to the many factors that were used to establish the various ranges of cost.

Excellent descriptions and illustrations of dynamic programming methods and application to water resources design problems are contained in references 4 and 5. A brief summary of the general concepts used is contained herein under "Multistage Decision Technique".

Methods of successive approximations are described in an excellent short exposition by Brooks in reference 3. The most common approach is the "Method of Steepest Ascent", and a similar approach, which treats one component at a time instead of all simultaneously, is the "Univariate Method". It is this last method that will be described in detail herein, because it is most easily adapted to the orthodox procedures used by engineers and can be used in conjunction with "engineering judgment". With minor changes, the description will apply to the Method of Steepest Ascent or the Method of Steepest Descent, the name depending on whether the objective function is to be maximized or minimized.

NATURE OF THE OBJECTIVE FUNCTION

In the application of any optimization procedure, it is necessary to delineate the exact basis on which the best solution is to be judged. This must be a single index which can be expressed as any function of the system components. This index is referred to variously as the "objective function", return function, value function, or criterion function. For example, it might be stated that the best system is the one which produces the greatest excess of power revenue over costs for varying storage capacity up to a specified maximum at a single reservoir, varying minimum power storage and varying power plant capacity up to a specified maximum, all operating between a full pool level on January 1, 1921 and minimum power pool level on December 31, 1940.

The example is complicated, since power revenue is a function of dependable plant capacity as well as total power generation, since power capacity and generation are complex functions of head and hydraulic losses as well as reservoir release, since evaporation losses vary with storage, season and other factors, and since the power demand pattern would vary from hour to hour, day to day and month to month throughout the year. On the other hand, the example is simplified, since it is assumed that recurrence of streamflows during a particular 20-year period is an adequate test, since no project functions other than power are considered, and since only an isolated project is studied.

In the selection of a project design, many intangible factors that cannot be readily expressed numerically as part of the objective function are often important. These are preferably to be given a numerical value, but might otherwise be given consideration in modifying the optimum system determined analytically.

THE UNIVARIATE METHOD

The "gradient"methods of successive approximation are most easily adaptable to water resources applications, because the basic hydrologic and economic analysis can be made in the traditional manner. These methods therefore require less ingenuity and less modification of engineering techniques and procedures than do other methods. Steps in the application of the Univariate Method of optimization are as follows:

1. Assign initial values to all variables in the system to be analyzed. These values should constitute a most reasonable first approximation to an optimum system.

2. Compute the objective function of the system for the initial values of variables assigned. This can be a complete basin routing (simulation) study and economic evaluation, for example.

3. Arrange the system variables in the order in which they should be changed to most rapidly approach optimum.

4. Taking each system variable (working variable) in turn, decrease its magnitude by 10 percent and by 20 percent, respectively, (or smaller proportional decrements) and compute the objective function for each change. This gives three separate system evaluations for equally spaced values of one system component with all other system components held constant.

5. Using the convergence procedure described in the following section, estimate the best value of the working variable.

6. Repeat steps 4 and 5 for all system variables. This will give a second approximation for all system components, but, since changes in one variable will affect relations of other variables to the objective function, this process must be repeated.

7. Steps 4 through 6 should be repeated at least once, and probably twice is sufficient for the first set of complete searches of all variables. As the last complete search is made, record the amount of improvement in the objective function caused by each variable change.

8. Repeat step 5 for the variable which improved the objective function most in its last change until no single change improves the objective function more than a specified percentage. This percentage would usually be about 10 percent divided by the number of system variables, but would depend on the nature and application of the objective function.

9. Make one more complete search (steps 4 through 6) of the system variables, because changes made in step 8 might provide an opportunity for improvement of variables that showed little earlier improvement. Again record the amount of improvement of each variable.

10. Repeat step 8 and declare optimization.

CONVERGENCE TECHNIQUE

Because of the large amount of computation ordinarily involved in computing the objective function for any set of values for all variables, it is important to reduce to a minimum the number of sets of values requiring computation. There appears to be little discussion in literature of this matter of convergence speed. Some suggestion is contained in reference 6, which suggests in relation to the Method of Steepest Ascent that a given "direction" of simultaneous change of all system components be pursued until an optimum for the direction is reached, rather than to re-evaluate the direction at each step. However, there appears to be no suggestion in literature relative to selecting the size of step, that is, the amount of change for each iteration. The following procedure has been found to be safe and generally rapidly converging.

For a continuous variable, the maximum of a function is located at a root of the first partial derivative of that function with respect to that variable. If methods of finite differences are used, as suggested above, the function can be evaluated in any manner, and the use of differential calculus is not required. By evaluating the objective function for three equally spaced values of a given variable, as specified in step 4 of the Univariate Method, the first and second partial derivatives of the objective function are approximated as follows:

$$y = f(x) \tag{1}$$

$$\frac{\Delta y}{\Delta x} = \frac{f(x_o+\Delta x) - f(x_o)}{\Delta x} \tag{2}$$

$$\frac{\Delta^2 y}{(\Delta x)^2} = \frac{f(x_o+2\Delta x) - 2f(x +\Delta x) + f(x_o)}{(\Delta x)^2} \tag{3}$$

With equations 2 and 3, it is possible to determine the direction in which the objective function is being improved and whether convergence is occurring. If equation 2 yields a positive value, for example, the variable x must be increased to increase the objective function and decreased to decrease the objective function. If equation 3 yields a positive value, for example, the function is convex downward, and convergence toward a minimum is indicated, but divergence away from a maximum is indicated.

By use of the Newton-Raphson method of successive approximations, equations 2 and 3 can be used to estimate the root of the first partial differential of the objective function, and hence the optimum value of the working variable if convergence is indcated. This is obtained as follows:

$$x_1 = x_0 - \frac{\Delta y/\Delta x}{\Delta^2 y/(\Delta x)^2} \qquad (4)$$

If divergence is indicated, a relatively large step can be taken in the direction of improved objective function. A factor of 1.5 constitutes a reasonable large step in many applications and, because of the uncertainty of the nature of the objective function, a limit such as a factor of 1.5 should be set on all changes. Furthermore, there is no assurance that the function is regular enough to assure improvement of the objective function when the step is taken. Accordingly, the objective function must be tested after the step is taken and before it is retained.

If the objective function is not improved after a specific step (change in one variable), it is likely that the point of optimum has been passed by at least a factor of two. Accordingly, it is good practice to reduce the step by 70 percent and re-test. If there still is no improvement, another 70 percent reduction should be taken and another test made. If there remains no improvement, the working variable should be returned to its original value with the hope that it will produce an improvement after other variables in the system have been changed.

The convergence technique described herein is very helpful in the cases of "manageable" functions, that is, those that vary gradually and continuously. In water resources design and other hydrologic engineering problems, it is possible generally to define functions so that discontinuities do not exist and so that the functions concerned do not fluctuate too rapidly.

SPECIAL CONSIDERATIONS

It is entirely possible that a solution indicated to be optimum is simply a sub-optimum and that some other combination of variables will yield a higher optimum. It is also possible that two variables can be so interrelated that opimizing one destroys the effect of the other. These are the two conditions against which it is important to guard. The first of these possibilities can be avoided when it is possible to consider all important variables and all promising ranges of those variables. The second condition can be minimized if the effect of each variable is made as nearly independent as possible of the other variables. For example, instead of expressing individually the sizes of 2 reservoirs serving the same purpose, their total capacity and the proportion in either reservoir might be used.

It is also necessary to impose constraints on each variable, where appropriate. In addition to specifiying maximum and minimum values of project components, one project function such as power generation or recreation should not be permitted to eliminate other needed functions, for example.

Such constraints on a variable can be expressed as functions of other variables, if necessary, or by attaching high "penalty" amounts to the objective function for unacceptable ranges of that variable.

In the univariate approach to optimization, the handling of constraints expressed as maximum and minimum allowable values of each component variable is relatively simple. It is necessary to assure first that the decrementing of each variable does not extend beyond the minimum allowable value. If it would, either smaller decrements or use of increments is necessary. Secondly, as soon as a step change is computed, the new value of the variable must be checked for constraints before the check is made on improvement in the objective function. If the allowable range of the working variable is exceeded, the working variable must be set at the nearest limit before proceeding further.

In the steepest ascent approach, the same type of check on constraints can be made, and each variable must be checked for allowable range and constrained accordingly before evaluating the new set of variables. Programming of this operation is much more complex than in the Univariate Method, but the end result is equivalent.

If initial values of any of the variables can be different from near-optimum by a factor of much more than 3 when using the convergence technique described above, it is possible that optimum will not be reached unless more numerous routine iterations of all variables are made. The number of routine iterations to be specified is the exponent of 1.5 necessary to produce a factor as large as the largest anticipated ratio of optimum to initial values of any variable. Also, in order to minimize the number of routine iterations necessary, the suggested initial value of each variable should be the geometric mean of anticipated extreme values of optimum for that variable.

Handling of extremely complex problems using optimization techniques can easily result in computer programs that exceed largest available memory capacities or require prohibitive execution times. This can be minimized by dividing a problem into separable components wherever possible. For example, if one portion of a river basin can be analyzed independently of the remainder, it should be, even in some cases where minor sacrifice in accuracy results.

ILLUSTRATIVE EXAMPLE

The Univariate Optimization Technique has been used in devising an automated unit-hydrograph and loss-rate analysis, which illustrates one of its many applications. In this case, the computer will solve for the best unit hydrograph and loss functions, given only observed rainfall and runoff quantities and the size of the drainage basin. The objective function to be minimized is the standard error of reconstituted streamflows. Variables used are described generally as follows:

1. Time of concentration for the unit hydrograph
2. Storage coefficient of the unit hydrograph
3. Shape index of the basin time-area curve
4. Ratio of surface imperviousness
5. Index of loss coefficient vs. accumulated loss
6. Index of loss coefficient recovery
7. Index relating loss to rain intensity
8. Index of average storm loss coefficient
9. Index of initial storm loss coefficient

The last 2 items differ for each storm. Consequently, the number of variables involved is 7 plus twice the number of storms for which reconstitutions at the location are desired.

Convergence during an early test of the program using 3 storms is illustrated in figure 1, which shows that near-optimum conditions were attained after only one complete search of all variables. In this case, two complete searches were followed by modification of most influential variable until all variables had improved the objective function less than 1 percent.

In this computer program developed in the Hydrologic Engineering Center of the Corps of Engineers, any of the above 9 variables can be fixed simply by entering a positive integer for its control index on a header card. The program is automated by suggesting reasonable values for all variables who initial values are not entered on the appropriate input card. In this particular example, the reconstitutions that would require a few days of work by an experienced engineer are done in a minute or two in a high-speed computer.

STEEPEST ASCENT TECHNIQUE

The steepest ascent technique of seeking a maximum is handled in the same way as in the univariate technique, except that a "best direction" is followed. This best direction is computed as the resultant of the partial derivatives of all system variables. Thus, each system variable is changed (in one simultaneous operation) in direct proportion to the rate at which its change improves the objective function when other variables are being held constant. Once the direction of the change vector is established, a small change in that direction is usually made, and the complete process repeated until optimum is reached.

As suggested by Kelley in his contribution to reference 6, the direction need not be re-evaluated at every step, but can be followed until an optimum value of the objective function in that direction is reached. At this point, the direction would be re-computed and the process repeated until optimum is reached. This would ordinarily save most of the computation work. A further saving can be effected in most cases by use of convergence techniques described above. However, it is likely that the objective function varies far more erratically in the direction of steepest ascent (or descent) that in a univariate direction, and the function can be expected to be far less manageable. It is partly for this reason that the univariate approach is emphasized herein.

MULTISTAGE DECISION TECHNIQUE

One of the promising approaches to water resource design optimization is dynamic programming, which consists of a multistage decision process. The stages concerned can be time or space stages. As an example of time stages, the expected monetary value of water in a reservoir at the start of a specified time interval is a function of the value of the water released during the interval and the expected value of the remaining water at the end of that interval. The optimum release for the interval can be determined by calculating the sums of these two quantities for all feasible releases and selecting the release yielding a maximum total value. This assumes that a curve of expected values at the end of the interval is available. In order to start a computation of this type, therefore, a specified condition at the end of some (the last) interval is assumed. Usually this is minimum pool stage at the end of a drought period. The computation is then worked backwards with respect to time.

The first computation is direct, establishing an expected value for each reservoir storage level at the start of the last period as the value of the release during that period that would draw the reservoir to minimum pool. The second computation maximizes the total value of period release and remaining storage for each initial condition. This then determines the optimum release for any initial stage and the corresponding expected value of that initial storage. The process can be repeated indefinitely, establishing curves of optimum release versus stage for the start of each period.

When a condition is reached in this reverse chronological computation where a specific stage is required, such as full pool at the start of a drought, the complete sequence of period releases can be determined in a forward direction by selecting the optimum release each period and computing the resulting storage at the start of the next period.

The space-stage type of dynamic programming can also be used in planning water resource projects, as illustrated in reference 4.

With a great deal of ingenuity, one can design a multistage decision model that will provide a direct solution to simplified versions of complex water resource problems. It appears, however, that the complexity of water resource problems is growing faster than our ability to devise such models that would yield satisfactory solutions. Furthermore, a vast amount of computation is necessary since so much "space" must be searched in order to assure that the optimization function at each step will include the region through which the optimum path will later pass. For these reasons, the most promising approach to system optimization in water resources project design appears to be a rapidly converging gradient procedure based on successive approximations, using dynamic programming components to the extent that they will provide a "decoupling" of a major complex into separable units.

CONCLUDING REMARKS

Optimization processes are necessary to a reasonable solution of the increasingly complex design and operation problems that occur in water resources engineering. They are of great value in the solution of lesser hydrologic engineering problems where direct solutions are infeasible.

Gradient methods of optimization should appeal to the engineer, because the methods can operate by use of traditional engineering analyses, such as multipurpose sequential routing or system simulation, changing the components of the system in successive trials so as to obtain the best combination most rapidly. They can most easily be adapted to practical complex problems, and appear to require minimum programming and computation time. Because of the large amount of computation involved, the procedures are almost exclusively adaptable to high-speed digital computers.

ACKNOWLEDGMENT

Developmental work on convergence technique and some other facets discussed herein was accomplished in the Hydrologic Engineering Center of the Corps of Engineers in Sacramento, California.

REFERENCES

1. Bellman, Richard, Dynamic Programming, Princeton University Press, 1957

2. Bellman, Richard, Adaptive Control Processess, A Guided Tour, Princeton University Press, 1961

3. Brooks, Samuel, "A Discussion of Random Methods of Seeking Optima", Journal of Operations Research, March-April 1958, p 244

4. Hall, Warren, "Aqueduct Capacity Under an Optimum Benefit Policy", ASCE Transactions, 1963

5. Hall & Roefs, "Hydropower Project Output Optimization", ASCE Journal of the Power Division, January 1966, p 67

6. Leitmann, George, Optimization Techniques, Academic Press, London, 1962

7. Maass, Arthur, Design of Water Resource Systems, Harvard University Press, 1962

8. Ralston & Wilf, Mathematical Methods for Digital Computers, John Wiley & Sons, 1964

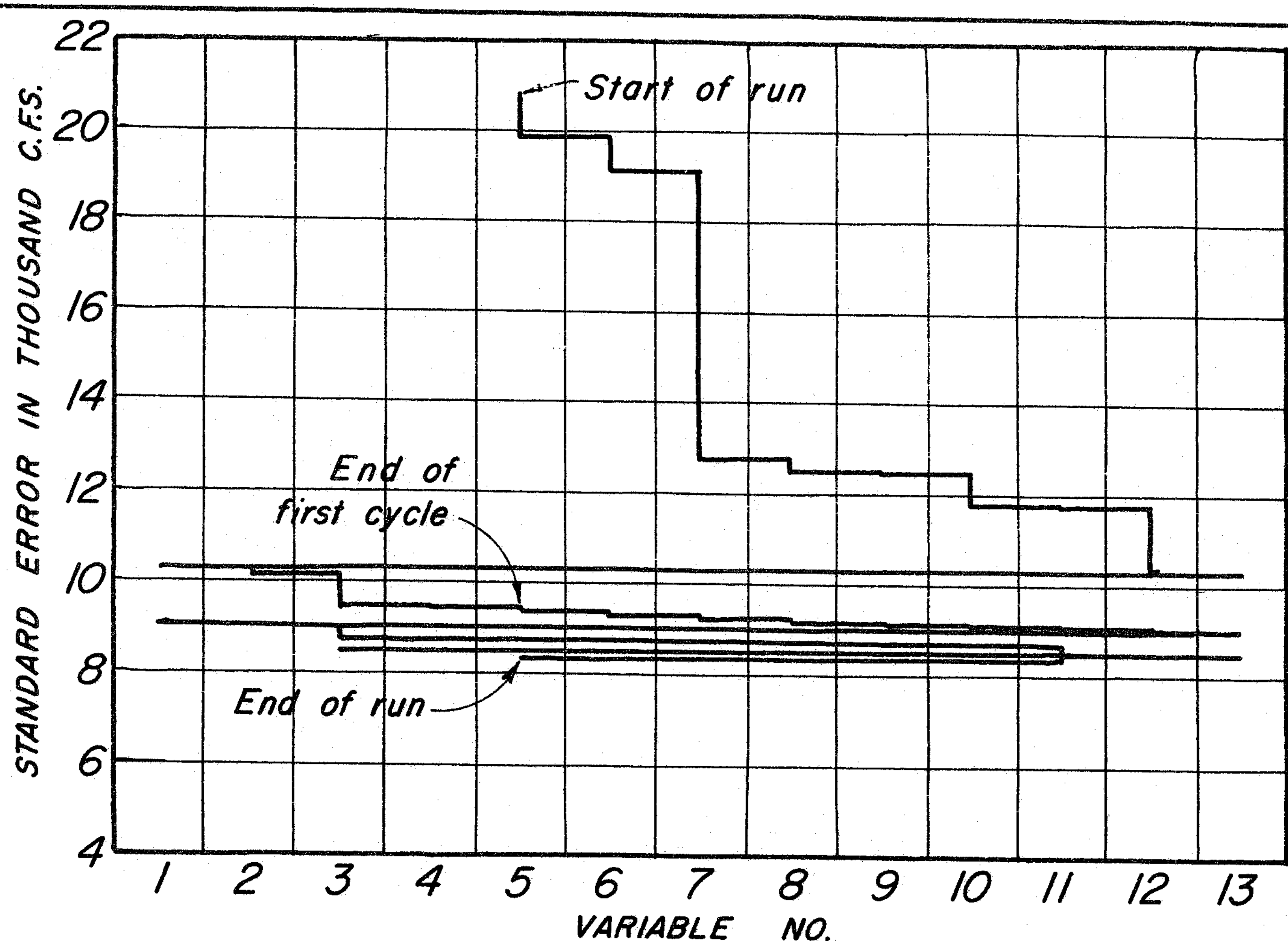

Figure 1

EXAMPLE OF CONVERGENCE

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