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Systems Analysis Applications at the Hydrologic Engineering Center

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In the broadest sense of systems analysis, the Hydrologic Engineering Center (HEC) has been actively applying systems analysis techniques since its inception in 1964. HEC's basic systems analysis method has been the simulation of watershed and river basin processes. Several other systems analysis activities are an outgrowth of that basic simulation capability: automated parameter estimation algorithms, synthetic streamflow generation, network analysis, branch-and-bound search techniques, numerical methods, risk and uncertainty analysis, and expert systems. Systems analysis at the HEC has been an approach to problem solving as mush as the actual technical methods. This philosophy of problem solving can be likened to a local hardware store's approach to do-it-yourself home repair. The hardware tools, supplies, and advice to solve the problem. Examples of these systems analysis techniques and their application to hydrologic engineering problem solving, are presented in this paper.

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Systems Analysis Applications at the Hydrologic Engineering Center

By Arlen D. Feldman[1]

Abstract: In the broadest sense of systems analysis, the Hydrologic Engineering Center (HEC) has been actively applying systems analysis techniques since its inception in 1964. HEC's basic systems analysis method has been the simulation of watershed and river basin processes. Several other systems analysis activities are an outgrowth of that basic simulation capability: automated parameter estimation algorithms, synthetic streamflow generation, network analysis, branch-and-bound search techniques, numerical methods, risk and uncertainty analysis, and expert systems. Systems analysis at the HEC has been an approach to problem solving as much as the actual technical methods. This philosophy of problem solving can be likened to a local hardware store's approach to do-it-yourself home repair. The hardware store personnel make a genuine effort to understand the homeowner's problem; then, they offer tools, supplies, and advice to solve the problem. Examples of these systems analysis techniques and their application to hydrologic engineering problem solving are presented in this paper.

Introduction

As the Corps' national center for hydrologic engineering and analytical planning methods, the Hydrologic Engineering Center's (HEC) work is motivated by the needs of the Corps' district and division offices. The main responsibilities of those field offices have been flood control, hydropower, and navigation, and HEC developed simulation models to meet those needs. The majority of the models address the hydrologic engineering aspects of the Corps' flood control studies. Most are for physical-process simulation.

Hydrologic analyses for flood control typically involved flood frequency and duration, spillway adequacy, reservoir storage, channel and floodway capacity, water surface elevations, flow velocity, and flooded area computations. Because of the Corps' primary interest in the larger, damaging flood events, HEC chose to simulate flood hydrographs with a so-called single-event watershed model. The HEC-1 flood hydrograph package (*HEC-1* 1990) and its predecessors only simulate a single flood event, although that one event may be of long duration for a complex river system. In addition to computing flood hydrographs, the HEC models were expanded to include expected annual damage computations. With the inclusion of the flow-frequency and flow-damage data, expected annual damages for different flood control alternatives could be computed. Interactive simulations were made to obtain the best alternatives. This simulation and search approach is one of HEC's main applications of systems analysis techniques.

Statistical analyses initially concentrated on flood flow frequency analysis. Later, stochastic streamflow simulation techniques (called lag-one Markov) were developed and applied in the Corps' reservoir system operation studies. After the development of a monthly streamflow simulation model in the early 1970s, only a few stochastic streamflow studies have been made.

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Several channel hydraulics and sedimentation analyses computer programs are available (*Computer* 1991). The HEC-2 steady state water surface profile program (*HEC-2* 1990) is used heavily in floodplain information and insurance studies. Now, unsteady flow models (single and multidimensional) are used to analyze complex flood waves and river and reservoir geometries.

Reservoir and other water control projects are simulated by the HEC-5 simulation of flood control and conservation systems computer program (*Simulation* 1989). This model operates reservoirs to minimize flooding at specified control points. The original HEC-5 analyzed flood events only, but it was later expanded to analyze reservoir yield as well. The multipurpose requirements of reservoir projects demanded not only simulation of dynamic flood events but also simulation of periods of record for hydropower and water supply. HEC-5 provides an important capability in HEC's simulation systems analysis capability.

SYSTEMS ANALYSIS BACKGROUND

Definition

Systems analysis is often used synonymously with operations research, but it has a much broader connotation. Systems analysis was originally a term used for mathematical analysis of systems of equations; operations research derived from procedures for solving complex scheduling problems during World War II (*Systems Analysis* 1975). Today, systems analysis implies a systematic solution procedure involving complex equations and interdisciplinary trade-offs. Operations research usually connotes linear and dynamic programming techniques, but it can also be interpreted to mean systems analysis.

Systems Analysis (1975), defined a variety of mathematical tools that comprise the capability of systems analysis: "There are a number of ways the different mathematical modelling techniques can be divided into classes. A useful aggregate classification is that of analytical optimization models, probablistic models and techniques, statistical techniques, and simulation and search or sampling techniques."

This paper discusses HEC's system analysis endeavors in those four areas identified by *Systems Analysis* (1975): Simulation and search, probabilistic, statistical, and analytical optimization.

Simulation and search techniques are mathematical models of a process that has quantifiable relationships among the variables. The search techniques usually explore the simulation model results by varying input data and/or the models parameters. Probabilistic models describe stochastic processes. Statistical techniques include multivariate analysis, statistical inference, and decision theory. Analytical optimization techniques include the mathematical programming techniques such as linear and dynamic programming.

HEC's Systems Analysis Tools

HEC has applied all four classes of systems analysis tools. The principal technique has been mathematical simulation. A fundamental understanding and representation of the physical processes of hydrology and the impact of water management projects were important objectives of HEC. The resulting tools were watershed models, river and floodplain hydraulics models, reservoir operation models, and flood damage computation models.

Simulation and search techniques were developed to seek and identify best-fit parameters of a physical process (e.g. infiltration and unit hydrograph parameters in a watershed model), and the best size of projects in a flood control system to optimize economic efficiency. Parameter estimation for real time flood forecasting is another application of search techniques, and an intelligent search technique called branch-and-bound enumeration has been applied to floodplain management planning.

Probabilistic models have not been developed or applied by HEC as much as the other systems analysis methods. The HEC-4 monthly streamflow-simulation computer program (*Monthly Streamflow* 1971) uses an autoregressive lag-one Markov process to estimate missing streamflows at gauges in a region. It can also generate synthetic streamflow sequences. The synthetic streamflow sequence is not new data, it is just one possible outcome from the input streamflow statistics. We used the monthly streamflow model in a Monte Carlo simulation to derive the probability distribution for future streamflows.

Statistical techniques have been used by HEC since its inception. HEC's first director, Leo R. Beard, wrote *Statistical Methods* (Beard 1964). It describes analytical methods for flood frequency computation and multivariate regression analyses to estimate hydrologic parameters. Expected annual damage is a basic measure of flood damage-mitigation project performance. It is derived from flow-frequency and stage and flow-damage relationships using techniques that are now embodied in HEC's *Flood Damage* (1988).

Analytical optimization models received little application at HEC in the early years but are now gaining acceptance. During the early 1960s linear, dynamic, and other mathematical programming techniques promised great advances in systemizing and automating decision making for water resources studies. However, efforts to capitalize on the promise have largely eluded the water resources community. There are many reasons for this, including the unwillingness of experienced hands to try something new; the failure of field professionals to understand the methods involved; and the fact that sometimes the actual physical system must be inordinately simplified to enable operations research techniques to be used. This was and still is especially true for attempts to use operations research techniques for reservoir system operations, but the operations research techniques have been applied in reservoir system planning.

The hydrologic engineer analyzes many detailed processes (reservoir inflow, outflow, and storage; downstream inflow; and channel hydraulics) to make a reservoir release decision. Often this must be accomplished during very short time intervals. The HEC-5 model (*Simulation* 1989) was developed beginning in the early 1970s to provide the needed detailed reservoir system operation simulation. Several internal and external attempts were made to apply linear and dynamic mathematical programming methods to solve this same problem. These attempts were not pursued because of lack of detail, perceived or real, in the solution techniques, and because of limited resources.

Two applications of analytical optimization models have been successful at HEC. A network linear programming method coupled with branch-and-bound enumeration was used to identify disposal sites for dredged material. A nonlinear mathematical programming algorithm was used in conjunction with a reservoir simulation model to determine optimal releases from the reservoir.

Application Philosophy

HEC has developed and supported a full range of simulation models for understanding how water resources systems function. It is assumed that experienced professionals can deduce the appropriate solution to a problem given the insight provided by selective execution of the simulation models. This deduction process has historically been the dominant methodology for planning and operational decisions in the water resources community, and it continues.

We have used systems analysis methods in a variety of situations with notable success. General applications were noted in the previous section; specific examples will be given in the following section. HEC's guiding principles for systems analysis applications have been: (1) Apply the techniques to solvable problems; (2) adapt the solution to the problem (not the other way around); (3) avoid inappropriate simplification of the problem; (4) use traditional simulation analysis tools in the system analysis solution where appropriate; and (5) use system analysis tools in an explainable manner.

Ford and Davis (1989) likened HEC's approach to problem solving to that of a successful hardware store. The hardware store staff works to understand a home-improvement project. The store offers a variety of tools and supplies to help the homeowner. They promote solutions of large problems by successfully completing small projects. The store services what it sells. HEC has followed a similar process for developing and applying systems analysis products. Ford and Davis's hardware-store-like rules are:

1. Invest the resources necessary to understand the planning problem.
2. Seek application rather than publication.
3. Consider a variety of system analysis tools. Select and fit the tools to the planning problem at hand.
4. Address solvable problems.
5. Train the user. Support continued use of the tools.

SYSTEMS ANALYSIS APPLICATIONS

Each of the four classes of systems analysis methods has been used by HEC to solve the Corps' water resources problems. Mathematical simulation models have played the major role. The models developed have been successful because of the technology transfer and computer program support provided by HEC (*Technology Transfer* 1988). From the Center's inception, technology transfer and computer program support have been set forth as primary responsibilities in conjunction with simulation model development. The following sections summarize the major types of technology developed in each of the four classes of systems analysis methods.

Simulation and Search Techniques

Simulation Models

The writer gave a brief history of HEC's simulation models development (Feldman 1981). The earliest models simulated the rainfall and snowmelt process and river hydraulics. Later, reservoir operation models were developed. Fig. 1 (Feldman 1981) summarizes the interconnected use of models for a floodplain information study. The HEC-1 watershed model and the HEC-2 water surface profile program were typical of the deterministic math-

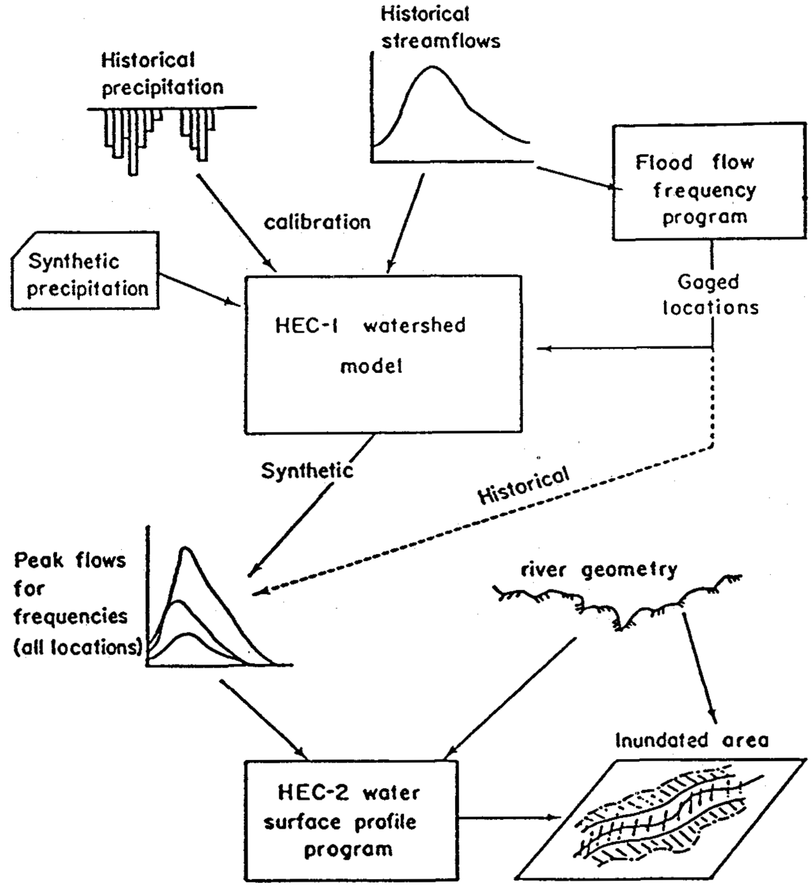


FIG. 1. Floodplain Information Study

ematical simulation models developed in the profession. Reservoir operation, flood damage, and river and reservoir hydraulics and sedimentation models were also developed. See *Computer* (1991) for a summary of current computer programs.

Univariate Search Techniques

Simulation models require calibration of their parameters to enable them to reproduce observed flood events. Manual sensitivity analysis was costly, so automated search techniques were developed. Beard used the univariate search technique in HEC-1 to obtain the best estimates of infiltration and unit hydrograph parameters. Automated sizing of urban flood control projects was also achieved with the univariate search technique. Davis (1975) used the technique to search for project sizes within the HEC-1 runoff model, which also included flood damage computation. All that was needed was to add project size-versus-cost data and to use the existing univariate technique to search the objective function. The objective function was to minimize the sum of project costs and expected annual flood damage (equivalent to maximizing net benefits) while using penalty functions to achieve performance targets.

Branch-and-Bound Techniques

As noted in HEC's history document (*The Hydrologic* 1989) the current thrust is to implement the branch-and-bound enumeration method for HEC computer programs. This method allows the nomination of alternatives in a manner consistent with current planning practice. The alternatives are specified as distinct measures with specific sizes and operation characteristics. The method has been documented for manual application on flood control systems. It was successfully implemented using the HEC-5 reservoir system model to analyze the effectiveness of a set of flood damage reduction measures and the expected annual flood damage program to perform the economic analysis (*Branch-Bound* 1987). Fig. 2 (Ford and Oto 1989) depicts the use of simulation and branch-and-bound enumeration for floodplain management planning.

Flood Forecast, Observation and Update Process

Real time flood forecasting uses some aspects of control theory developed by industrial engineers for manufacturing processes. The process here is the watershed runoff and reservoir regulation system. The real process is observed through precipitation and streamflow measurements. Runoff forecasts are made with the simulation models. Then, when the forecasted point in time is actually observed, the parameters of the models can be updated to reflect the true observation as shown in Fig. 3. The parameter update process is complex because state variables (e.g. accumulated infiltration) of the model must be modified via the model's hydrologic processes. Reservoir

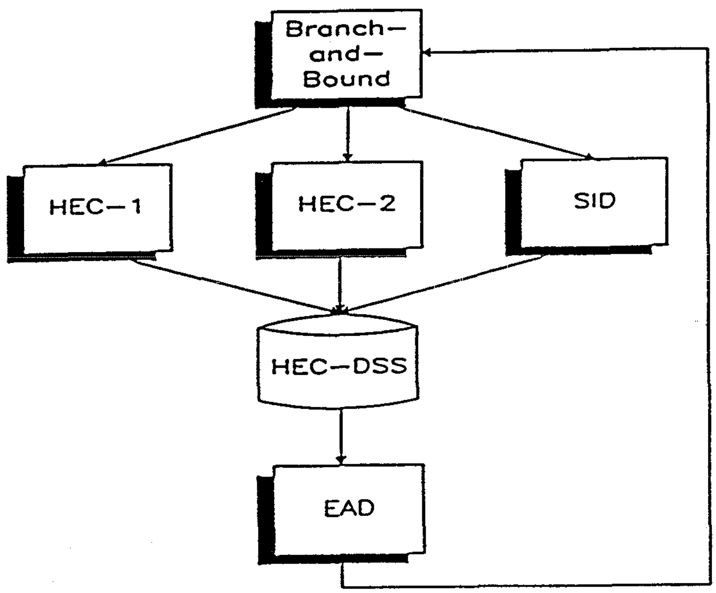


FIG. 2. Simulation with Branch-and Bound Enumeration

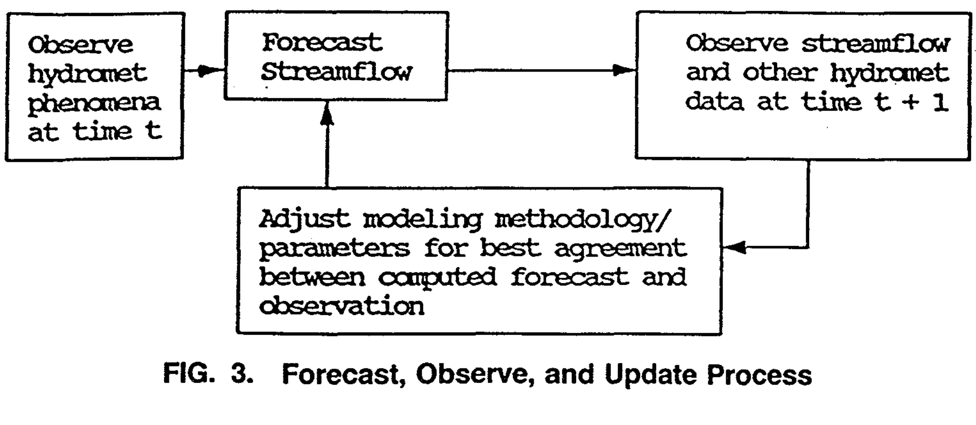


FIG. 3. Forecast, Observe, and Update Process

regulation is adjusted accordingly as the magnitude and distribution of the flood is observed (*A Software System* 1983).

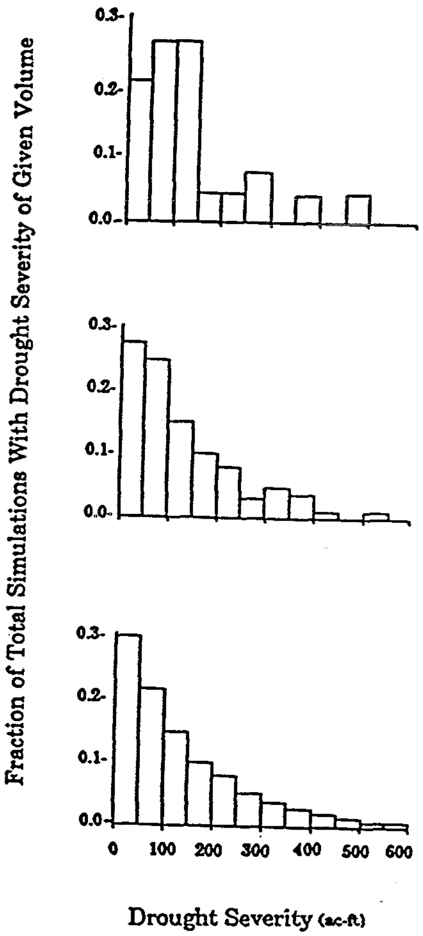
Probabilistic Methods

Some of HEC's earliest work was in the use of stochastic hydrology to simulate monthly streamflow (*Monthly Streamflow* 1971). Stochastic hydrologic methods have been difficult for water managers to accept. This is because of managers' reliance on observed historical streamflow sequences to set water rights and obligations. Observed streamflow is natural; synthetic streamflow could make water managers liable for system failure.

One successful application of stochastic hydrology has been to forecast water supply during drought. HEC-4 and Monte Carlo simulations were used to derive a conditional probability distribution for the next month's flow given the observation of the current month's flow. The development of a derived distribution for various drought criteria using Monte Carlo simulations with HEC-4 is described in *Stochastic Analysis* (1985) and shown in Fig. 4.

Statistical Methods

Similar to probabilistic methods, HEC's work in statistical methods dates back to the Center's beginnings. The techniques used have been flood and



Normal Distribution Parameters

Annual Stream Flow Volume Statistics	μ 372.6 (ac-ft)	σ 74.8 (ac-ft)	ρ_1 .17
Sample Statistics From Monte Carlo Simulation	m	s	r_1
100 Simulations	357.8	75.3	.039
1000 Simulations	372.6	75.3	.173
100,000 Simulations	372.7	74.6	.167

FIG. 4. Drought Severity Histograms by Monte Carlo Simulation

low-flow frequency analysis and multiple linear regression. The log-Pearson III frequency distribution recommended by HEC was adopted by the U.S. Water Resource Council for their uniform method for flood frequency computation. Regression analysis has provided a means to estimate hydrologic parameters in ungauged basins. The correlation of known hydrologic parameters to measurable basin characteristics has been a common practice in the profession. Regionalization studies have also been used for flood frequency statistical parameters such as skew.

Analytical Optimization Models

Implementing mathematical programming methods such as linear and dynamic programming has achieved limited success. There are two applications that have met with success: (1) Network programming for dredged material disposal; and (2) nonlinear programming for single reservoir operation.

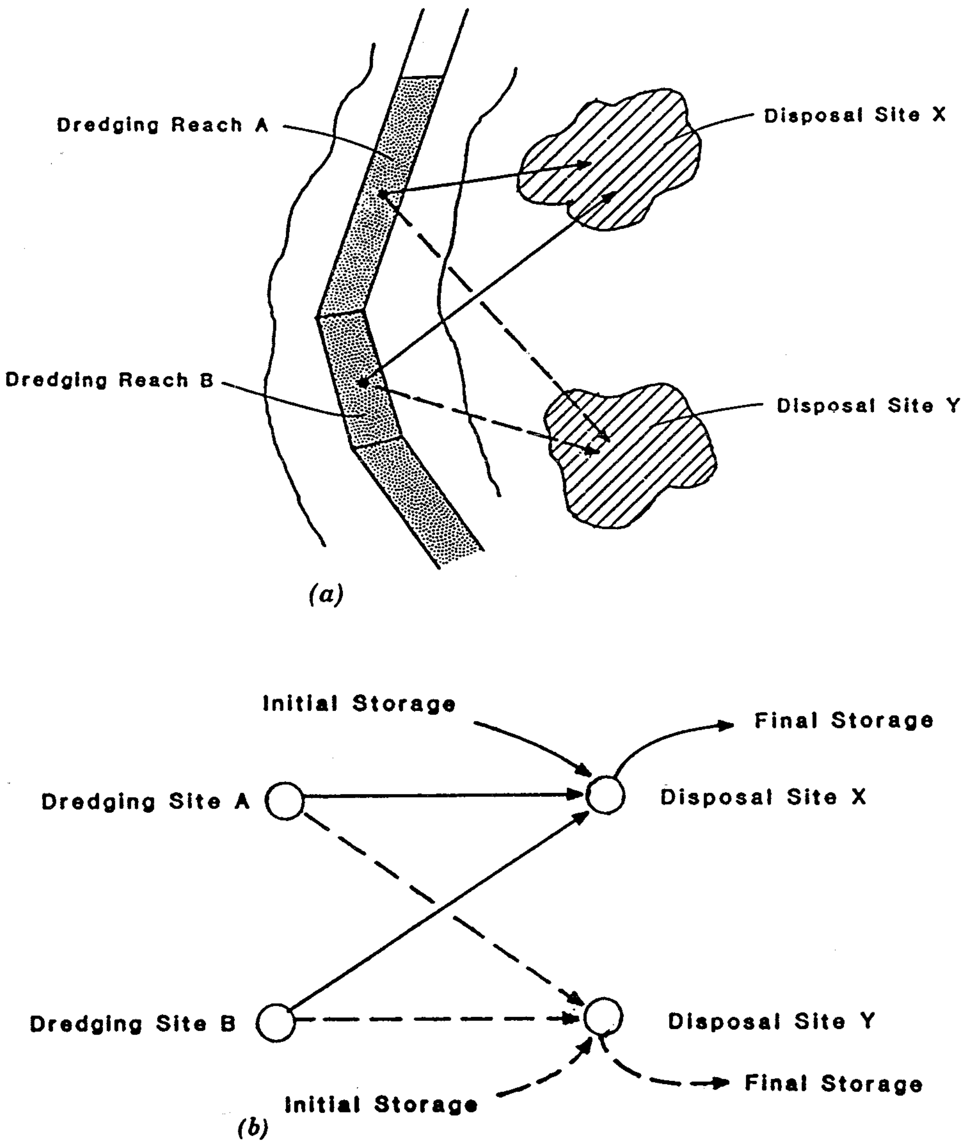


FIG. 5. Network Representation for Dredged-Material Disposal: (*a*) Disposal System; (*b*) Arc-Node Representation of Disposal System

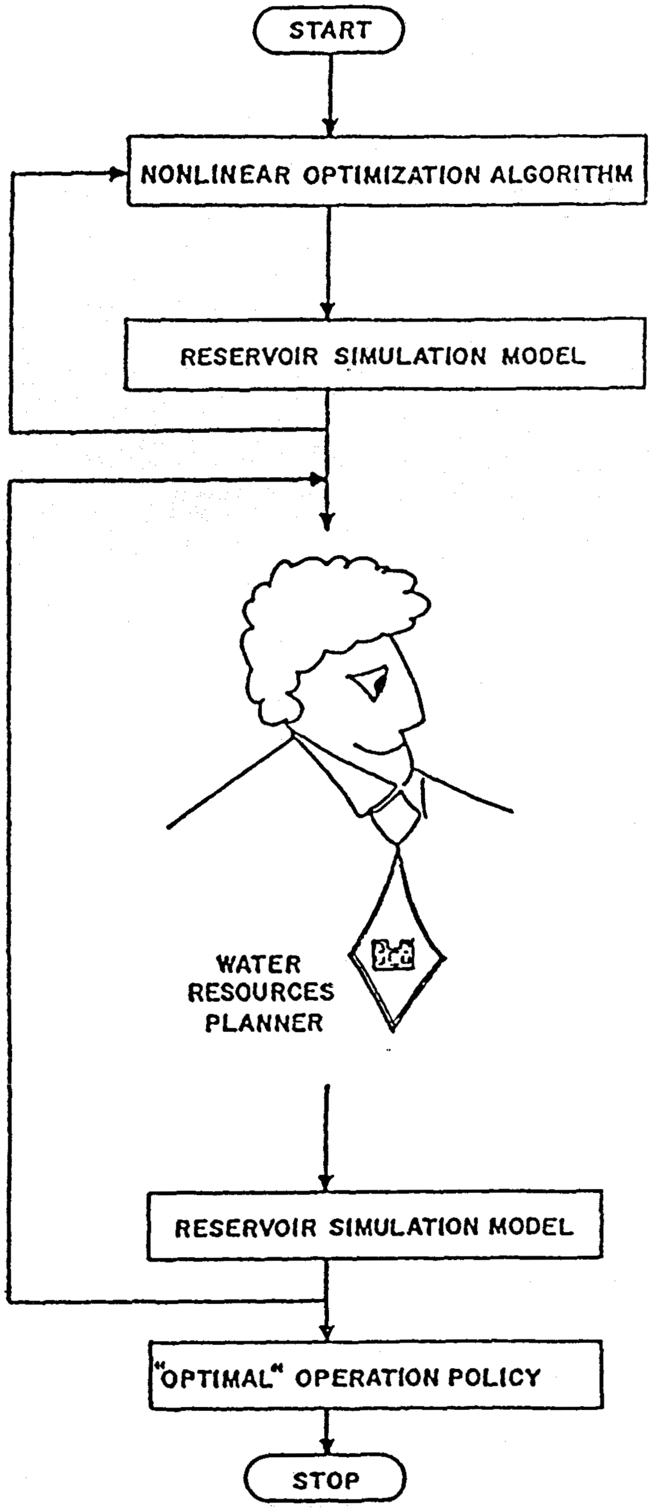


FIG. 6. Schematic of Solution Methodology

Network Programming

Dredged-material disposal sites in the Delaware estuary were becoming full, but dredging needed to continue. The correct decision, whether to buy new sites, extend leases and intensively manage existing sites, or close some navigation channels, was not obvious. HEC created a minimum-cost network-flow programming model of the dredge disposal system (*Dredged-*

Material 1984). The program formulates the optimization problem transparent to the user, solves the network (e.g. Fig. 5), and presents the results in user-specified output reports. The least-cost routing of sediment is a "network-with-gain" problem solved with an "out-of-kilter" algorithm. Management options are selected via branch-and-bound enumeration. District staff still use the program for strategic planning six years after the original development.

Nonlinear Mathematical Programming

The Sam Rayburn Reservoir in southeast Texas operates to prevent saltwater intrusion, to generate hydropower, to provide recreation, and to control floods. The operation to prevent saltwater intrusion is especially important to the downstream economy, which obtains freshwater from the river. If the reservoir releases cannot be maintained high enough to stop the saltwater intrusion, a saltwater barrier dam is constructed in the river. That barrier is washed out at higher flows.

In 1978, an existing single-reservoir simulation model was imbedded within a nonlinear programming algorithm to search for optimal operating policies for the Sam Rayburn Reservoir. Fig. 6 depicts the solution procedure developed by Ford et al. (1981). The optimization model is formulated as a constrained nonlinear programming problem. The variables are the volumes of storage allocated to four different operation levels. A box complex algorithm is used to solve the problem. The resulting operation of Sam Rayburn Reservoir with this methodology has been most successful at improving project performance and reducing the cost of operations. The saltwater barrier has not been necessary in the 10 years since this operation was adopted. Prior to that, the barrier was installed once or even twice a year. A follow-up analysis of the hydrology and operational results for the past 10 years is now being prepared.

CONCLUSIONS

The several systems analysis methods used at the HEC have been beneficial to the Corps' water resources development and management program. These techniques are not without their faults, however. We have followed a set of rules, like those used to run a hardware store, that have made these applications successful. Technology transfer and follow-up support of the techniques are key ingredients to successful application. The Sam Rayburn multipurpose reservoir operations project identified two important conclusions about successful systems analysis application. Ford et al. (1981) stated that:

1. "planners and engineers involved in planning and managing water resources projects will accept application of systems analysis techniques to problems they face if such applications can be demonstrated to: (1) Provide additional information for use in decision making; (2) reduce the time, money, or computer memory requirements for plan formulation or evaluation; or (3) increase the project benefits by identifying solutions that satisfy the practical constraints on operation and are sufficiently resilient to respond to changing conditions. Integrated use of a nonlinear programming formulation with the reservoir yield program for simulation of system operation, followed by an interactive smoothing process that allows input from the water managers satisfies these requirements."

2. "the resource managers/systems operators must be included in the policy formulation-evaluation 'DO-Loop' at many points." "Corps personnel who are involved daily with the operation were consulted in definition of the problem, in identification of the critical characteristics of the system that should be modeled, and in evaluation of the solutions developed by application of the optimization-simulation methodology. The results of the initial simulations of system operations were reviewed carefully by Corps District and Division personnel to assure that the modified reservoir simulation program adequately modeled the system operation."

Future Applications

Future application of systems analysis techniques at HEC will be to reservoir system regulation planning and expanded capabilities for simulation models. Both applications will support the Corps' objective to operate existing reservoir systems more efficiently and to design more effective projects for the future.

Reservoir System Operation Planning

Reservoir systems analysis will explore the use of network programming algorithms to improve regulation plans for multiple-use, multiple-reservoir systems. A project to help analyze the Missouri River main stem reservoir system operation is just being undertaken by HEC. The system of six reservoirs and seven downstream control points is being formulated as a minimum-cost, network-flow problem. Penalty functions (costs) are used to force the operation of the reservoirs system to meet desired goals and flow and storage constraints. Penalty functions were developed for flood damage, water supply, recreation, hydropower, navigation, and environmental interests. The environmental penalty (fish and wildlife protection) is not as directly based on real costs as the other penalties, but it serves to input explicitly a value on that resource. The sensitivity of the reservoir system performance to changes in water values for different purposes can be readily evaluated (*Missouri River* 1991).

The Missouri River is being analyzed for 92 years of monthly flows. Approximately 750,000 network equations are necessary to describe the objective function, continuity equations, and boundary constraints for that time period. For such a large system, the network solver becomes critical to timely completion of the computations. HEC is currently investigating several network solvers to reduce the computation time.

This initial, successful application of network systems analysis on the Missouri River system has given new insight to Corps water control managers. One problem that HEC is currently addressing is how to translate the results of the network analysis, such as time traces of optimal flows, storages, and penalties, into practical rules for real time reservoir operation. Applications of this network analysis capability are envisioned for several other Corps reservoir systems.

Next Generation Simulation Models

In 1990, HEC embarked on a project to develop the next generation of its simulation models. The objectives of the new modeling capabilities were to provide the user with better means to visualize and understand the process being simulated, and to build more engineering expertise into the models themselves. With the recent advances in computer hardware, it was no longer necessary to have the computer programming constrained by the limitations of old machines. It was quite evident that the old batch processing format would not suffice and that interactive processing was necessary. The capabilities of modern workstation computers using the UNIX operating system offered a new level of processing power that could meet these next-generation software needs.

The intent of the next-generation models (called NexGen) is to put the users inside the model and give them the tools to easily work with the data, simulation processes, and results. It is planned to have the models interact with a data base for their input and for storing output results. The user will enter data into a data base that is constructed in a logical engineering-analysis format, not a format for some computer input device. Output will also be stored in the data base for ready analysis. A graphical user interface will facilitate the user's interaction with the computer. High-level graphics will let the user view the data, computations, and results for maximum understanding and analysis of the data and the physical processes.

Four technical areas are being addressed in the current NexGen effort, river hydraulics, watershed runoff, reservoir system, and flood damage analysis. The new models will have most of the capabilities of the existing HEC models in those areas plus new algorithms where appropriate. For example, current river hydraulics modeling capabilities require reformatting the river geometry differently for each analysis—steady state, unsteady, and multi-diversional. The new river analysis system of software will use consistent geometric representation of the river and floodplain for all applications. The simulation results will also be shown on the same geometric representations.

The ultimate goal is to have smarter models that automatically evaluate numerical stability (time and distance steps) and physical constraints of the process being simulated. The user will be advised of process-simulation problems, and alternative methods and analyses will be recommended where possible. Thus, more engineering expertise will be built into the model to enhance its application and interaction with the user. The NexGen project is a five-year effort, and interim products will be made available as the work progresses.

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