US Army Corps
of Engineers
Hydrologic Engineering Center

Sizing Flood Control Reservoir Systems by Systems Analysis

March 1976

TP-44

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 1976

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Sizing Flood Control Reservoir Systems by Systems Analysis

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bill S. Eichert, Darryl W. Davis

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-44

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
Prepared for the XII International Commission on Large Dams Congress, Mexico City, Mexico, March 1976.

14. ABSTRACT
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This paper discusses the scope of reservoir system formulation, modeling flood control systems, criteria and strategies for system formulation and illustrates the concepts with applications in recent systems studies.

15. SUBJECT TERMS
reservoir systems, system formulation, reservoir simulation, computer model, water resources planning

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	40	19b. TELEPHONE NUMBER

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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-44

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SIZING FLOOD CONTROL RESERVOIR SYSTEMS* BY SYSTEMS ANALYSIS

by
Bill S. Eichert[1] and Darryl W. Davis[2]

United States Committee on Large Dams

INTRODUCTION

Flood control reservoir systems are designed to reduce the intensity of flooding in flood plains to acceptable levels. Planning flood control reservoir systems requires analysis of basin-wide hydrology, individual reservoir and system operation, and system performance in reducing intensity of flooding. Sizing reservoir systems (system formulation) includes the major tasks of selecting system components from among competing alternatives and determining the flood control storage within each reservoir. Selection of system components (configuring the system) is the key element in the analysis. This paper focuses upon reservoirs as flood control measures, but it should be emphasized that non-reservoir measures, such as levees and channel work can form invaluable system components.

Analysis of the performance of alternative flood control systems is greatly complicated by the system interaction that can occur among system components. One of the important interactions in a system

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[1,2] Director, The Hydrologic Engineering Center and Chief, Planning Analysis Branch, The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

* Prepared for Presentation at the XII International Commission on Large Dams Congress, Mexico City, March 1976.

occurs when a number of reservoirs are being operated for common locations and are thus able to take advantage of inflow and release timing effects.

Because of the large number of alternative systems possible in complex river basins and due to the complexity of evaluating each system, it is essential that a reasonably structured system formulation strategy be adopted as the framework for analysis. Since many important concerns other than hydrologic and economic performance are ultimately involved in the selection of systems for implementation, automated optimization methodologies do not presently play major roles in formulation of large complex systems.

Application of a practical flood control reservoir system simulation model that yields detailed system operation of all components and summarizes hydrologic and economic performance and costs greatly assists in determining system performance. To perform the simulation, the model accepts data on (1) historical or synthetic flood hydrology, (2) reservoir system storage and operating criteria, (3) reservoir costs, and (4) damage potential at system control points.

This paper discusses the scope of reservoir system formulation, modeling flood control systems, criteria and strategies for system formulation and illustrates the concepts with applications in recent systems studies.

SCOPE OF RESERVOIR SYSTEM FORMULATION

The systems viewpoint adopted herein focuses on the physical representation of the system and the system performance, in particular hydrologic and economic performance. For the present discussion the social, political, institutional and environmental aspects are assumed to act on the system (determining acceptable performance criteria and alternatives) rather than comprising integral parts of the analysis.

The physical representation of alternative systems is determined by the potentially useful reservoir sites, and locations (termed control points) for which the systems are operated. Potential reservoir sites are determined by analysis of the physical configuration of the topography, physical and geologic characteristics of the landscape and their proximity to potential damage centers. For purposes of system formulation, a reservoir site is therefore characterized by a physical location (distance from points of interest), site storage-elevation relationship and the construction, operation and maintenance costs necessary to create the reservoir for a range of flood control storages. The stream system comprises a second important element in the physical configuration of systems. The stream system can be characterized by the "topology" (where water flows from and to) and hydrologic routing criteria that determines the conveyance and flow timing characteristics of the system. The hydrology of the region (nature and severity of floods) represents the complex rainfall-runoff relationships and can be characterized by either historic streamflow or synthetic flood events.

The performance of the system is measured by the ability to reduce the intensity of flooding. The reduction in the intensity of flooding can be viewed from both economic and public safety or risk viewpoints. Economically, the performance can be measured by the reduction in the expected value of annual damages. Risk refers to the chance (probability) of being flooded. The risk performance is commonly referred to as the degree of protection.

The economic characterization of the system is accomplished by assigning the damage potential of reaches of streams in the basin to index locations (termed damage centers) that usually are coincident with the 'control points' referred to previously. The determination of expected annual damages requires coordination of the damage potential with the flow exceedence frequency relationships. The flow exceedence frequency relationships are also needed to determine residual risk.

The scope of the 'system' therefore includes the physical representation of the system, (sites, storage, costs, stream conveyance and basin hydrology) and the economic representation of consequences of flooding (damage centers, damage potential, frequency of flooding). The 'flood control system' to be formulated consists of the reservoirs and their operating characteristics. System formulation is pursued by manipulating the components of the 'system', e.g., the size and location of reservoirs and observing the different effects on the other system elements, e.g., hydrology, costs, benefits, and performance.

Reservoir flood control systems offer great opportunities for multi-purpose development. Joint reservoir costs can be shared for such purposes as water supply, low flow regulation, and hydropower generation. To the extent the flood runoff is seasonal, joint use may be made of storage space within the reservoir. Even though most reservoir projects that become system components are multi-purpose, this paper will focus of necessity on reservoir flood control as if it were a separable feature of multi-purpose systems. Integration of other purposes into a multi-purpose system is obviously desirable and requires a similar systems viewpoint and analysis framework for each purpose.

MODELING FLOOD CONTROL SYSTEMS

Simulation of the operation and performance of flood control systems requires that the physical, economic and hydrologic elements of the system be translated to mathematical functions, and that these functions be coded into a computer program, and that the necessary data be assembled and coded into the proper format. The major requirements for modeling a flood system include (1) schematizing the basin by identifying operational control points, damage index locations, and potential reservoirs, (2) developing consistent basin-wide (control point by control point) hydrology that could include one, or preferrably more, historic events or synthetic events, (3) developing streamflow routing criteria for all stream reaches, (4) characterizing reservoirs by their storage and release capacities, (5) determining operation criteria such as selecting control points to operate for, determining their safe flow capacity, and specifying release priorities, (6) developing functional damage relations and base conditions exceedence frequency relations for each damage index location.

Computer Program HEC-5C(1), "Simulation of Flood Control and Conservation Systems," has been developed by The Hydrologic Engineering Center, U.S. Army Corps of Engineers, as a generalized tool which can be used to simulate any flood control system. The program was written to be compatible with generally accepted analysis procedures that require data normally developed in the course of studying flood control reservoirs. The general capabilities of HEC-5C are described below. The flood control features are particularly emphasized.

(1) HEC-5C, Simulation of Flood Control and Conservation Systems, Users Manual (Preliminary), The Hydrologic Engineering Center, November 1974.

HEC-5C was developed to assist in planning studies involving sizing system components for flood control and conservation requirements. The program can be used in the planning, design, operation or post flood phases of system evaluation. The program can be used to calculate the value of an existing system immediately after a flood event to demonstrate the effects of existing and/or proposed reservoirs on flows and damages in the system. The program could also be useful in selecting the proper reservoir releases throughout a system during flood emergencies.

The program simulates the sequential operation of the system components for any system configuration for short-time intervals (such as hourly) for historical or synthetic floods or for long duration time intervals, (such as monthly) for nonflood periods, or for combinations of the two. Specifically the program may be used to determine:

- Flood control and conservation storage requirements for each reservoir in the system.
- The effect of a system of reservoirs, or other structures on the spatial and temporal distribution of runoff in a basin.
- The evaluation of flood control and conservation operational criteria for a system of reservoirs.
- The expected annual flood damages, expected annual benefits, system costs, and system net benefits.

- The formulation of flood control systems comprising reservoirs and other structural or nonstructural flood management alternatives.

HEC-5C can simulate, depending upon the computer capacity available, up to 35 reservoirs, 75 control points, 11 diversions and 9 powerplants for an unlimited number of time periods for each runoff event.

Provided the limits specified above are not exceeded, any system configuration may be specified. Reservoirs with flood control storage can be operated to minimize flooding at any number of downstream control points. Reservoirs with conservation storage will be operated for their own requirements (power or low flow) and can be operated for low flow requirements for any number of downstream control points. Reservoir storage levels within conservation and flood control space are kept in balance (in the same degree of trouble) as much as possible. The program will determine all reservoir releases for all time periods but, if desired, outflows can be specified for any number of reservoirs for any or all time periods and the program will adjust other reservoir releases as necessary. Constraints at individual reservoirs are as follows:

- When the storage level of a reservoir is between the top of the conservation pool and the top of the flood pool (within the allocated flood control space), releases are made that attempt to draw the reservoir down to the top of conservation pool without the subsequent release exceeding the designated channel capacity at the reservoir.

- When the reservoir storage level is greater than the top of buffer pool (a small reserve of the conservation pool) releases are made equal to or greater than a flow termed the minimum desired flow, which is the full demand, and when the reservoir storage level is within the buffer pool (between the top of the inactive pool and the top of the buffer pool) releases are made equal to the required flow, which is a reduced high priority demand. No releases are made when the reservoir is below the top of inactive pool. Releases needed for hydropower generation will override minimum flows if they are greater than the controlling desired or required flows.

- Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, then all excess flood water is released if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Other optional emergency routines are also available.

- A rate of flow change constraint is observed in that the reservoir release is never greater (or less) than the previous period's release plus (or minus) a percentage of the channel capacity at the dam site unless the reservoir is in surcharge operation.

Operational criteria for specified downstream control points are as follows:

- Releases are not made (as long as flood storage remains) which would contribute to flooding at one or more specified downstream locations during a predetermined number of future periods except to satisfy minimum flow and rate-of-change of release criteria.

- Releases are made, where possible, to maintain downstream flows at channel capacity (for flood operation) or for minimum desired or required flows (for conservation operation). In making a release determination, local (intervening area) flows can be multiplied by a contingency allowance (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting these flows.

Operational criteria for keeping a reservoir system in balance are as follows:

- Where two or more reservoirs are in parallel operation above a common control point, the reservoir that is at the highest index level, will be operated first to try to increase the flows in the downstream channel to the target flow. Then the remaining reservoirs will be operated in a priority established by index levels to attempt to fill any remaining space in the downstream channel without causing flooding during any of a specified number of future periods.

- If one of two parallel reservoirs has one or more reservoirs upstream whose storage should be considered in determining the priority of releases from the two parallel reservoirs, then an equivalent index level is determined for the tandem reservoirs (one above the other) based on the combined storage in the tandem reservoirs.

- If two reservoirs are in tandem, the upstream reservoir can be operated for control points between the two reservoirs. In addition, when the downstream reservoir is being operated for control points, an attempt is made to bring the upper reservoir to the same index level as the lower reservoir.

A variety of streamflow routing procedures, such as the Muskingum and modified Puls methods, are available for use. The hydrologic input for flood events may be for natural or observed conditions for each control point or local contributions between control points. If natural or observed flows are provided, the local flows are computed and if local flows are provided, the natural flows are computed.

A single streamflow diversion can be made from any reservoir or control point and, if desired, proportions of the diversion can be routed and returned at any downstream control point or reservoir.

Diversions may be one of the following types:

- Diversions that are a function of inflows.
- Diversions that are functions of reservoir storages.
- Diversions that are constant.
- Diversions that include all excess water above the top of conservation pool up to the diversion facility capacity.

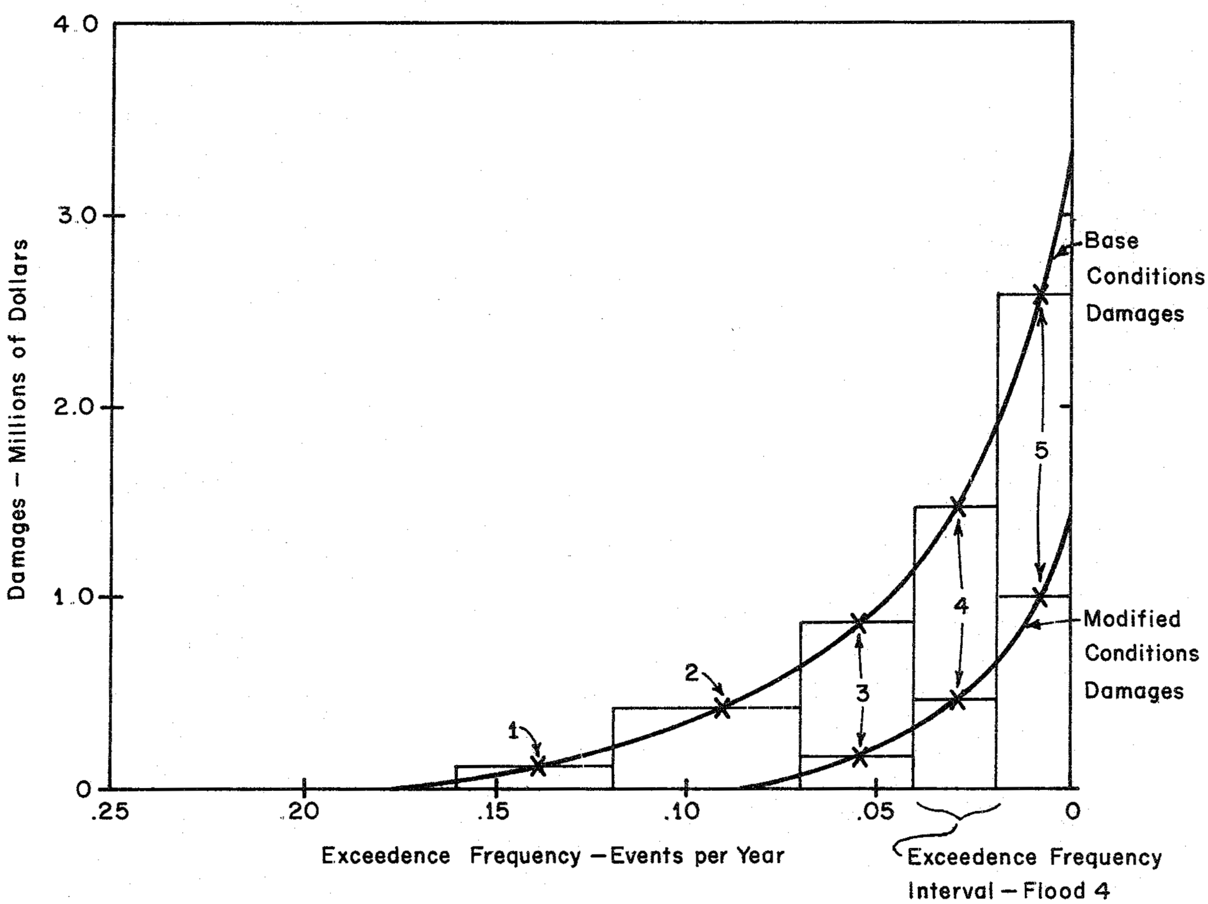
The program can operate an unlimited number of floods for a reservoir system. The series of floods can each start at different reservoir storages or from the same storages or can be continued using the storages from the previous floods. Up to nine proportions (ratios) of any or all floods may be operated. Floods extending over long periods may be processed by dividing the flood into flow events which are each less than the program limits. This may be done by manually setting in several sets of flow data (with each less than the allowable) or by allowing the computer to generate separate floods (when the data read exceeds the allowable limit).

The program can operate the system for a continuous period of record (for example, 20 years of monthly data). Also a mixture of computational intervals may be used such as a monthly operation for a few years and then operating for daily or hourly flows during a major flood and then back to a weekly or monthly routing interval. An unlimited number of events can be simulated in this manner.

Expected annual flood damages (average annual) or the damages resulting from specific flood events can be computed for up to nine damage categories for any or all control points using one or more proportions (ratios) of each of several historical or synthetic floods. Expected annual damages will be computed for (1) natural or unregulated conditions, (2) regulated conditions by the reservoir system and (3) full regulation at those reservoir sites assuming unlimited flood control storage (damage from the uncontrolled local flows). Damages calculated for base conditions (normally natural flows) using selected floods and proportions (ratios) are computed by integrating the base conditions damage-frequency curve or by using a predetermined average annual damage. Expected Annual Damages for modified conditions are computed from the sum of the products of the assigned exceedence frequency intervals (based on base conditions) and the corresponding damage based on the modified flow. Figure 1, Expected Annual Damage Computations, graphically portrays the annual damage computations. The damage from the uncontrolled local flows are also calculated in a similar manner to the modified conditions.

The damage reduction due to the proposed system is based on the difference between the expected annual damages for the base conditions and the modified conditions. If there is an existing reservoir system the damage reduction can be based on the difference between the base conditions and the modified conditions where the base conditions were determined from another simulation run in which existing reservoirs only are simulated.

A separate set of damage data can be used if the modified condition damages do not follow the base condition discharge-damage curves as would be the case for a levee, channel improvement or nonstructural alternative such as flood proofing, relocation, purchase, or flood plain zoning.



Note: 1, 2, etc. indicates Flood Number

Fig. 1 Expected annual damage computation

Cost functions for construction, operation, maintenance and replacement and amortization may be provided for reservoirs (a function of storage) and nonreservoirs (a function of design discharge). A discount rate for amortization of capital cost is also needed.

The needed input data can be scaled to the problem under study, for example, it can be minimal for very preliminary planning studies or it can be very detailed for modeling existing systems. The data requirements for a full flood control system planning study are:

- General information such as output labels, simulation control data (time periods, computation intervals, print control, etc.)

- Reservoir capacities at top of conservation and top of flood control pool elevations, downstream control points for which each reservoir is operated, and reservoir storage/outflow tables.

- Control point (including reservoirs) identification numbers and titles, channel capacities (safe flow capacity), and channel routing criteria.

- Inflow or local flow data for each control point for one or more historical or synthetic floods.

- Peak discharge-damage-frequency data for each damage index location; reservoir capital costs vs. storage or nonreservoir capital costs vs. design discharge; capital recovery factor, and annual operation and maintenance cost functions.

The program outputs a listing of input data, hydrologic results of system operation arranged by downstream sequence of control points, hydrologic results of system operation arranged by sequence of time periods; summary of flooding for system; summary of reservoir releases and control point flows by period; summary of conservation operation if monthly routing was made; summary of maximum flows, storages, etc., for each flood event; summary of maximum and minimum data for all floods; summary of expected annual damages and benefits; and summary of system costs (capital and annual) and system net economic benefits. Output can be suppressed to that of interest for a particular simulation and a number of convenient graphical displays are available.

FLOOD CONTROL SYSTEM FORMULATION

The objectives of system formulation are to (1) identify the individual components, (2) determine the size of each, (3) determine the order in which the system components should be implemented, and (4) develop and display the information required to justify the decisions and thus secure system implementation. In the interest of brevity, the following discussion is confined to identifying the components that would comprise the best system.

Formulation Criteria. - Criteria for system formulation are needed to distinguish the best system from among competing alternative systems. The definition of "best" is crucial.

a. Viewpoint. - A reasonable viewpoint would seem to recognize that simply aggregating the most attractive individual components into a system, while assuring physical compatibility, could result in inefficient use of resources because of system effects, data uncertainty, and the possibility that all components may not be implemented. It is proposed that the "best" system be considered to be:

(1) The system that includes the obviously good components (satisfy criteria below) while preserving flexibility for modification of components at future dates.

(2) The system which could be implemented at a number of stages, if staging is possible, such that each stage could stand on its own merits (be of social value) if no more components were to be added.

b. Criteria Elements. - General guidance for formulation criteria are contained in the recently published Principles and Standards(2). The criteria of economic efficiency from the national viewpoint has existed for some time (3)(4), and has been reemphasized in (2). This criteria has been interpreted to require that each component in a system should be incrementally justified, that is, each component addition to a system should add to the value (net benefits)

(2) Principles and Standards for Planning Water and Related Land Resources, Water Resources Council, published in the Federal Register, The National Archives of the United States, September 10, 1973.
(3) Proposed practices for economic analysis of river basin projects, a report to the Inter-Agency Committee on Water Resources by its Subcommittee on Evaluation Standards, May 1958, "Green Book".
(4) Policies, Standards and Procedures in the Formulation, Evaluation and Review of Plans for Use and Development of Water and Related Land Resources, 87th Congress, 2d Session, Senate Document 97, 1962.

of the total system. The second criteria proposed in (2) is that of environmental quality. The environmental quality criteria can be viewed as favoring alternatives that can be structured to minimize adverse environmental impacts and provide opportunities for mitigation measures. Additional criteria that are not as formally stated as United States national policy are important in decisions among alternatives. A formulated flood control system must draw sufficient support from responsible authorities in order to be implemented. In addition, flood control systems should be formulated so that a minimum standard of performance (degree of risk) is provided so that public safety and welfare are adequately protected.

Of these criteria, only the national economic efficiency and minimum performance standard have generally accepted methods available for their rigorous inclusion in formulation studies. Environmental quality analysis and social/political/institutional analyses related to implementation have not developed technology applicable on a broad scale. As a consequence these criteria must guide the formulation studies but as yet, probably cannot directly contribute in a structured formulation strategy. In discussions that follow, focus is of necessity upon the economic criteria with acceptable performance as a constraint, with the assumption that the remaining criteria will be incorporated when the formulation strategy has narrowed the range of alternatives to a limited number for which the environmental and other assessments can be performed.

System Formulation Strategies. - A system is best for the national income criteria if it results in a value for system net benefits that exceeds that of any other feasible system. For a few components, analysis of the number of alternative systems that are feasible is generally manageable and exhaustive evaluation provides the strategy for determining the best system. When the number of components is more than just a few, then the exhaustive evaluation of all feasible alternative systems cannot practically be accomplished. In this instance, a strategy is needed that reduces the number of system alternatives to be evaluated to a manageable number while providing a good chance of identifying the best system. The present state-of-the-art of systems analysis does not permit (in a practical application) finding the economic optimum (maximum net benefit system) for reasonably complex systems even with all hydrologic-economic data known. Since seldom will the optimum economic system be selected as best, an acceptable strategy need not make the absolute guarantee of economic optimum.

The incremental test of the value of an individual system component is definitive for the economic efficiency criteria and provides the basis for several alternative formulation strategies. If existing flood control components are present in the system, then they define the base conditions. If no flood control components exist, the base condition would be for natural conditions. The strategies described below are extensions of currently used techniques and are based upon the concept of examining in detail the performance of a selected few alternative systems. The performance is assumed to be evaluated generally by traditional methods that make use of HEC-5C.

a. Reasoned Thought Strategy. - This strategy is predicated upon the idea that it is possible to 'reason' out by judgement and other criteria, reasonable alternative systems. The strategy consists of devising through rational thought, sampling, public opinion, literature search, brainstorming, etc., a manageable number of system alternatives that will be evaluated. No more than 15 to 20 alternative systems could be evaluated by detailed simulation in a practical sense. Next, the total performance of each system in terms of economic (net benefit) and performance criteria is evaluated by a system simulation. A system (or systems if more than one have very similar performance) is selected that maximizes the contribution towards the formulation objectives (those that exhibit the highest value of net benefits while satisfying the minimum performance criteria). To confirm the incremental justification of each component, the contribution of each system component in the "last added" position is evaluated. The last added value is the difference between the value (net benefits) of the system with all components in operation and the value (net benefits) of the system with the "last added" component removed. If each component is incrementally justified, as indicated by the test, the system is economically justified and formulation is complete. If any components are not incrementally justified, they should be dropped and the "last added" analysis repeated.

The system selected by this strategy will be a feasible system that is economically justified. Assuming the method of devising the alternative systems is rational, the chances are good that the major worthwhile projects will have been identified. On the other hand the chances that this system provides the absolute maximum net benefits is relatively small. This strategy would require between 30 and 60 systems evaluations for a moderately complex (15 component) system.

b. First Added Strategy. - This strategy is designed such that its successive application will yield the formulated system. The performance of the systems, that includes the base components (if any), are evaluated with each potential addition to the system in the "first added" position. The component that contributes the greatest value (net benefit) to the system is selected and added to the base system. The analysis is then repeated for the next stage by computing "first added" value of each component to the system again, the base now including the first component added. The strategy is continued to completion by successive application of the first added analysis until no more component additions to the system are justified.

Table 1 contains information adapted from a recent study and illustrates the strategy. Components A-J are candidates for inclusion within a system. Components A, C, and E have already been implemented. Stage 1 represents the 'first added' value of the candidate system components. The incremental value (net benefits added) by component F is the largest so it is selected for inclusion in the system. Stage 2 represents the 'first added' value of the components with the base system now comprised of components A, C, E, and F. Note that many of the values change because of system effects. Component J is selected for addition to the system. The remainder of the table contains the analysis through to completion. Note that 22 first added analyses were made in the four stages required to select three new projects out of seven alternatives. Exhaustive consideration of all possibilities would have required 127 analyses whereas if all components had proven to be valuable additions to the system, 28 first added analyses would have been necessary.

TABLE 1[1/]

FIRST ADDED FORMULATION STRATEGY

Component	First Added Value ($1000 per year) Stage 1	Stage 2	Stage 3	Stage 4	Formulated System
A*	--	--	--	--	X
B	20	5	-2	-8	
C*	--	--	--	--	X
D	16	16	16**	--	X
E*	--	--	--	--	X
F	35**	--	--	--	X
G	-10	0	0	0	
H	6	-12	-12	-15	
I	-2	-2	-2	-2	
J	15	18**	--	--	X

[1/] First added value is system net benefits with the component added minus system net benefits without the component added.

* Signifies existing system component, ** signifies system addition

The strategy does have a great deal of practical appeal and probably would accomplish the important task of identifying the components that are clearly good additions to the system and that should be implemented at an early stage. The strategy, however, ignores any system value that could be generated by the addition of more than one component to the system at a time and thus could omit potentially useful additions to the system. For example, the situation sometimes exists where reservoirs on say two tributaries above a damage center are justified but either one analyzed separately is not, i.e., the system effect is great enough to justify both. The number of systems analysis required to formulate a system based on this strategy could range upwards to 120 evaluations for a moderately complex (15 component) system, which is probably close to being an unmanageably large number of evaluations.

c. Last Added Strategy. This strategy, similar to b, is designed such that successive application yields the formulated system. Beginning with all proposed components to the system, the value of each component in the "last added" position is computed. The project whose deletion causes the value (net benefit) of the system to increase the most is dropped out. The net benefits would increase if the component is not incrementally justified. The strategy is continued through successive staged applications until the deletion of a component causes the total system value (net benefits) to decrease.

Table 2 contains information adapted from a recent study and illustrates the strategy. Components K-T are candidates for inclusion within a system. Components L, P, and R have already been implemented. Stage 1 represents the 'last added' value of the candidate system components. The incremental value (net benefits lost) by adding component Q in the last position is the greatest (-30) so it is selected for deletion from the system. Stage 2 represents the 'last added' value of the components with the base system now excluding component Q. Note that a number of the values have changed because of system effects. Component K is selected for deletion. The remainder of the table contains the analysis through to completion.

TABLE 2[1/]

LAST ADDED FORMULATION STRATEGY

Component	Last Added Value ($1000 per year) Stage 1	Stage 2	Stage 3	Stage 4	Formulated System
K	-20	-10**	--	--	
L*	--	--	--	--	X
M	10	0	-4**	--	
N	6	6	6	8	X
O	8	8	8	12	X
P*	--	--	--	--	X
Q	-30**	--	--	--	
R*	--	--	--	--	X
S	0	-6	12	10	X
T	-2	0	0	2	X

[1/] Last added value is system net benefits with the component in the system minus system net benefits without the component added.

* Signifies existing system component and ** system component that is dropped.

This strategy will also yield a system in which all components are incrementally justified and in which the total system will be justified.

This strategy would probably identify the obviously desirable projects, as would the others. However, its weakness is that it is possible, though not too likely, that groups of projects that would not be justified are carried along because of their complex linkage with the total system. For example, the situation sometimes exists where reservoirs on say two tributaries above a damage center are not justified together but deletion of each from a system that includes both results in such a great loss in system value that individual analysis indicates neither should be dropped individually.

The number of systems analysis required for this strategy would be similar to the first added strategy requiring perhaps 10-20% more evaluations. Twenty-two last added analyses were made in the four stages required to select four new projects out of seven alternatives. This strategy is more efficient than the 'first added' if the majority of the potential system additions are good ones.

d. Strategy Discussion. - Each of the strategies presented had one or another shortcoming. If the system were formulated using the 'first added' strategy, then formulated using the 'last added' strategy and the formulated systems come out to be identical, the best system probably would have been formulated. It is possible, however, that the 'first added' system would not include some feasible projects and that the 'last added' system would include some that are not valid system components as described previously. One approach to arrive at the formulated system would be to formulate alternative systems comprising the common components from both systems (all of the first added) and logical combinations of those additional components included in the 'last added' formulation. The strategy described as "reasoned thought" could make a meaningful contribution at this stage.

A reasonable working strategy, as a framework that need not be rigid, would be to apply the first and last added strategies through sufficient stages to identify and screen out those components that are obviously good and obviously inferior and zero in on the system to be selected using a reasoned thought approach.

SENSITIVITY ANALYSIS

There will be varying degrees of uncertainty in the information used in system formulation. The hydrology will be better defined near gaging stations than it is in remote areas, and certain potential reservoirs will have been more thoroughly investigated than others. In addition the accuracy of economic data, both costs and value, existing or projected, is generally lower than the more physically based data. Also, conditions change over time and thus the data must be continuously updated at each decision point. The practical accommodation of information uncertainty is by limited sensitivity analysis and continuing reappraisal as each component of a system is studied for implementation.

Sensitivity analysis has as its objective, the identification of either (1) critical elements of data, or (2) particularly sensitive system components, so that further studies can be directed toward firming up the uncertain elements or that adjustments in system formulation can be made to reduce the uncertainty.

Because of the particular method used in HEC-5C to develop regulated conditions frequency relations at damage index stations, particular attention must be paid to selection or development of the system hydrology. The problem arises when evaluating complex reservoir systems with many reservoirs above common damage centers; the problem also increases with the size and complexity of the basin. There are a large number of storm centerings that could yield similar flows at a particular control point. Because of this, the contribution of a specific system component to reduced flooding at a downstream location is uncertain and dependent upon storm centering. This makes the selection or development of "representative" centerings crucial if all upstream components are to be evaluated on a comparable basis. The desired evaluation for regulated conditions is the "expected" or average condition so that economic calculations are valid. The representative hydrograph procedure used in HEC-5C where several proportions (ratios of one or more historic or synthetic events is used to represent system hydrology) is compatible with the simulation technique used but care must be taken to reasonably accommodate the storm centering uncertainty.

Testing the sensitivity of the expected annual damages to the system hydrology (event centering) is appropriate and necessary. The alternative to the representative hydrograph procedure is the use of all historical floods of record. However even this more laborious process may introduce some bias in computing expected annual damages if most historical floods were, by chance, centered over a certain part of the basin and not over others. For instance one reservoir site may have experienced several severe historical floods while another site immediately adjacent to that area may, due to chance, not have had any severe floods.

While it is possible in the program, HEC-5C, to use only a single flood event and several proportions (ratios) of that flood in computing expected annual damages, this procedure could introduce considerable bias in the results. A good approach is to use several historical floods with storm centerings throughout the basin and to use several proportions of those floods to obtain flows at the damage centers representing the full range of the flow-frequency-damage relationship for base conditions and for regulated conditions. Another approach is to synthesize events that have consistency in volumes of runoff and peak flows and be reasonably representative regarding upstream contribution to downstream flows. Table 1 contains sensitivity information developed in studies of the Susquehanna Basin, Pennsylvania.

TABLE 1

SUSQUEHANNA FLOOD CONTROL REVIEW STUDY
FLOOD EVENT SENSITIVITY ANALYSIS

Expected Annual Damage Reduction
(1,000 1974 Dollars)

Reservoir System	Hydrology A	Hydrology B	Hydrology C	Hydrology D	Hydrology E
Existing Reservoirs	26,251	37,462	39,103	33,805	36,633
112 East Guilford*	950	4,275	2,377	1,981	2,538
155 Towanda*	3,846	653	573	124	632
1902 Sinnemahoning*	5,674	5,384	5,798	2,727	4,649

* Damage reduction in first added (to existing system) position.

** Hydrology A - Tropical Storm Agnes (June 1972) used as the representative event, nine proportions (ratios) were used to cover range of damaging floods.

Hydrology B - A Standard Project Flood (SPF) (a synthetic event centered lower in the basin (Harrisburg, PA)) used as the representative event, also nine ratios used.

Hydrology C - A synthetic event representing a 10-inch storm spread uniformly over the basin, seven ratios used.

Hydrology D - March 1936 flood (flood of record in many areas of basin) used as representative event, six ratios used.

Hydrology E - Adopted system hydrology consisting of two ratios each of Agnes, the SPF, the 10-inch uniform and the 1936 flood.

The impact on system formulation of the general level of damage assessment, discount rates and costs are greatly dependent upon the relative variation in the system. For instance, difference in discount rates (higher for example), if uniform for all system components, will generally not affect the relative attractiveness (one to another) but will affect the overall attractiveness of the system. Damage potential, because it becomes integrated with hydrologic and hydraulic data to yield expected annual damages, must change significantly among control points before major differences in system formulation would result. This is not the situation which exists for costs, they enter the analysis directly and thus should receive, relatively speaking, more attention in accommodating uncertainty in system formulation.

SUMMARY

The systems viewpoint applied to reservoir flood control systems includes the physical representation of the system (sites, storage, costs, stream conveyance, basin hydrology) and the economic representation of the consequences of flooding (damage centers, damage potential, frequency of flooding). The flood control system to be formulated consists of the reservoirs and their operating characteristics. Computer Program HEC-5C, "Simulation of Flood Control and Conservation Systems," has been developed by The Hydrologic Engineering Center as a generalized tool which can be used to simulate any flood control system. The program was written to be compatible with generally accepted analysis procedures that require data normally developed in the course of studying flood control reservoirs.

A formulation strategy that identifies the obviously good system components while preserving flexibility for future changes is desirable. A practical working strategy, based on successive incremental evaluations of the value of system components, would be to apply the first and last added tests through sufficient stages to identify and screen out those components that are obviously good and obviously inferior and zero in on the system to be selected by logical combinations of the remaining projects.

Because of the uncertainty contained in the information used in system formulation, it is essential that limited sensitivity analysis be conducted that is designed to identify information inadequacies and senstitive system components. In addition continuing reappraisal of information inadequacy as each component of a system is studied for implementation is necessary.

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